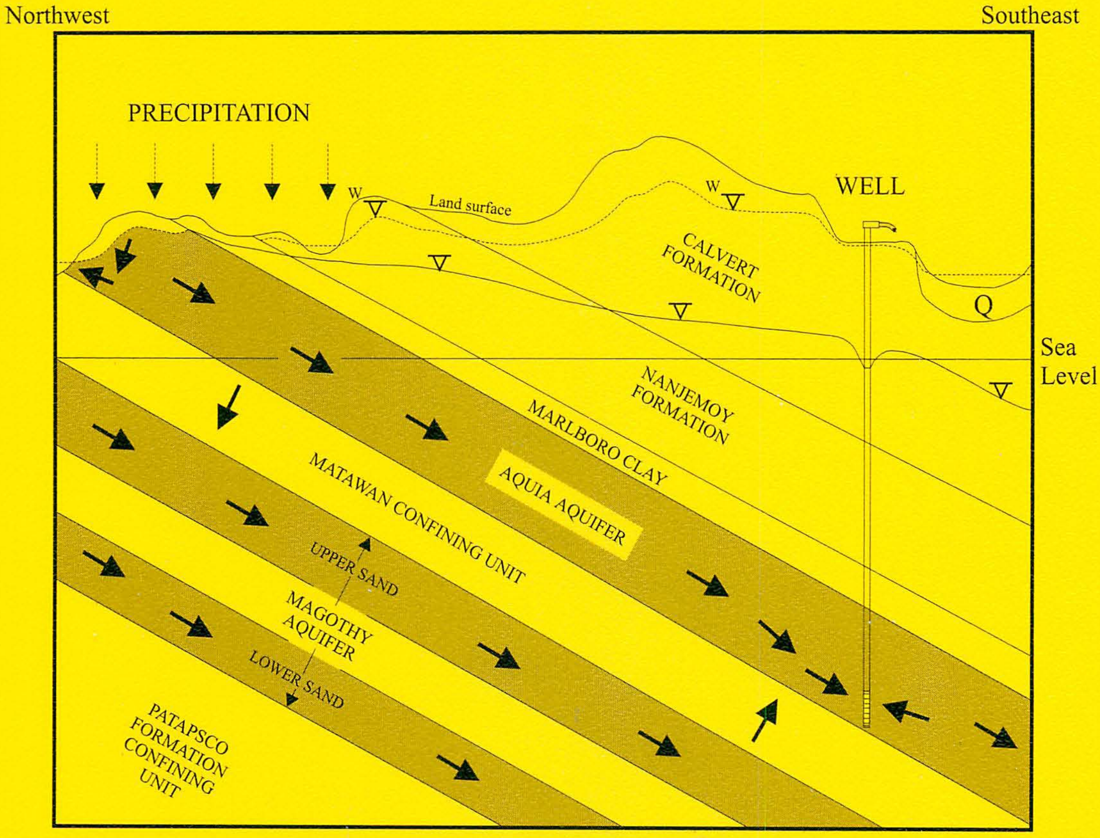
REPORT OF INVESTIGATIONS NO. 74
2002

HYDROGEOLOGY, WATER QUALITY, AND WATER-SUPPLY POTENTIAL OF THE AQUIA AND MAGOTHY AQUIFERS IN SOUTHERN ANNE ARUNDEL COUNTY, MARYLAND

by
David C. Andreasen



Prepared in cooperation with the
Anne Arundel County Office of
Land Use and Environment

Department of Natural Resources
Maryland Geological Survey
Emery T. Cleaves, Director

ABBREVIATIONS

ft	feet
ft/d	feet per day
ft^2	feet squared
ft^2/d	feet squared per day
ft/mi	feet per mile
ft/yr	feet per year
gal/d	gallons per day
gal/min	gallons per minute
GAPA	Gross alpha-particle activity
GBPA	Gross beta-particle activity
in.	inch
in./yr	inches per year
l/d	cubic feet per day per cubic foot
Mgal/d	million gallons per day
MCL	Maximum Contaminant Level
mg/L	milligrams per liter
mi	mile
mi^2	mile squared
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
pCi/L	Picocuries per liter
SMCL	Seconary Maximum Contaminant Level
µg/L	micrograms per liter
USEPA	U.S. Environmental Protection Agency

Department of Natural Resources
Resource Assessment Service
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KEY RESULTS

Water use in Southern Anne Arundel County consists primarily of self-supplied domestic use from the Aquia aquifer. The deeper Magothy aquifer is utilized to a lesser extent as a source for mobile home parks and irrigation. A total of approximately 1.8 and 0.22 million gallons per day were pumped from the Aquia and Magothy aquifers in 2000, respectively. Total water demand in Southern Anne Arundel County may increase from about 2.0 million gallons per day in 2000 to a total of 2.8 million gallons per day by 2020 to support a projected population of 32,750. The Aquia and Magothy aquifers are the most likely sources for future withdrawals, although deeper aquifers in the Potomac Group are also available. The natural water quality of the Aquia and Magothy aquifers is generally acceptable for self-supplied domestic use; however, the Magothy aquifer contains iron concentrations at levels requiring treatment. A ground-water-flow model of the Aquia and Magothy aquifers was developed to determine: (1) the effect of projected (2020) water use on water levels in the Aquia and Magothy aquifers; (2) maximum yield of the Aquia and Magothy aquifers; and (3) effect on water levels from pumpage in the Aquia aquifer in Calvert and St. Mary's Counties. The model consisted of three layers representing the water-table aquifer, the Aquia aquifer, and the Magothy aquifer. The model was calibrated using water levels measured during 2000, and by comparing simulated and measured water levels for observation wells with long-term record.

What are the hydrogeologic characteristics of the Aquia and Magothy aquifers in Southern Anne Arundel County? (pgs. 9 to 32)

- The Aquia aquifer is a medium to coarse sand consisting of clear and white quartz and dark-green, brown, and black glauconite. Shell beds and iron- or calcite-cemented layers are common. The Magothy aquifer consists of medium to coarse, well sorted, white sand interbedded with black and gray, lignitic clay.

- The top of the Aquia aquifer ranges from about 100 feet above sea level in its outcrop area northwest of the study area to as much as 250 feet below sea level in the southern part of the study area. By comparison, the top of the Magothy aquifer ranges from 150 to 500 feet below sea level at those same locations.

- Transmissivity of the Aquia and Magothy aquifers ranges from 930 to 2,680 feet squared per day and 450 to 4,570 feet squared per day, respectively.

- Water levels have declined at rates ranging from 0.2 to 1.4 feet per year in the Aquia aquifer and 0.7 to 0.9 feet per year in the Magothy aquifer since the 1970s.

- The available drawdown in the Aquia aquifer in 2000 ranged from 0 feet through the central part of Southern Anne Arundel County to 150 feet at Rose Haven. Water levels exceeded the management level within a 2-mile-wide band located in the central part of Southern Anne Arundel County. By comparison, available drawdown in the Magothy aquifer in 2000 ranged from approximately 125 feet in the Davidsonville area to 360 feet at Rose Haven.

What is the natural water quality of the Aquia and Magothy aquifers? (pgs. 38 to 41)

- Water produced from the Aquia and Magothy aquifers is a calcium bicarbonate type. The pH of the Aquia aquifer ranges from 7.3 to 8.0, while the pH of the Magothy water is about neutral (pH=7).

- Iron concentrations in the Aquia and Magothy aquifers range from 0.15 to 4.5 and 3.6 to 7.6 milligrams per liter, respectively. Iron concentrations greater than about 0.3 milligrams per liter may require treatment to increase potability.

What is the simulated effect of pumping an additional 0.8 million gallons per day from the Aquia and Magothy aquifers to support a projected 2020 population of 32,750 in Southern Anne Arundel County ? (pgs. 59 to 67)

- If withdrawn from the Aquia aquifer, the increased withdrawals combined with increased withdrawals to the south will cause water levels in the Aquia aquifer to decline by as much as 22 feet. The Aquia aquifer can supply the projected 2020 water demand without depleting the available drawdown in most of Southern Anne Arundel County. However, water levels exceed the management level (as currently defined) in a band as much as 3.5 miles wide extending from Waysons Corner to Rhode River. Constraining the use of the Aquia aquifer in Southern Anne Arundel County and Calvert County will reduce drawdown in Southern Anne Arundel County.

- If withdrawn from the Magothy aquifer, the increased withdrawals combined with regional withdrawals will cause water levels in the Magothy aquifer to decline about 20 feet by 2020. Available drawdown ranges from 100 to 350 feet. The Magothy aquifer can supply the projected increase in water demand through either individual residential wells or public-supply wells without a significant reduction in available drawdown. However, greater drilling depths, treatment costs for the removal of iron, and the practicality and expense of centralized public-water systems are important considerations related to its use. Water levels in the Aquia aquifer will not be affected by the increased pumpage from the Magothy aquifer.

Will water levels in the Aquia and Magothy aquifers in Southern Anne Arundel County stabilize if withdrawals in these aquifers are held constant at the 2000 amount? (pg. 67)

- When Aquia withdrawals in the model area and in areas farther to the south are held constant at the 2000 level (1.8 million gallons per day in Southern Anne Arundel County), simulated water levels in the Aquia aquifer stabilize with respect to those withdrawals in less than 1 year.

- Simulated water levels in the Magothy aquifer stabilize within about 3 months when withdrawals in the Magothy aquifer are held constant at the 2000 level (0.22 million gallons per day in Southern Anne Arundel County).

What is the total simulated water-supply potential of the Aquia and Magothy aquifers in Southern Anne Arundel County? (pgs. 67 to 73)

- Available drawdown in the Aquia aquifer in most areas can sustain an increase in withdrawals. In addition, recharge from the outcrop area could be induced by the increase in withdrawals. However, increasing withdrawals from the Aquia aquifer will cause water levels to exceed management levels in the central part of Southern Anne Arundel County. As of 2000, water levels in the Aquia aquifer have exceeded the management level within a 2-mile-wide band located in the central part of Southern Anne Arundel County. Therefore, as defined by the present management guideline, the Aquia aquifer in Southern Anne Arundel County has reached its maximum allowable yield.

- The maximum simulated yield of the Magothy aquifer is approximately 38 million gallons per day based solely on the available drawdown in the Magothy aquifer. When pumped continuously at this rate at 26 hypothetical wells for the period 2000 to 2020, water levels in the Magothy aquifer are as deep as 280 feet below sea level in Southern Anne Arundel County. The vertical hydraulic gradient that develops between the Magothy and Aquia aquifers under this pumping scenario causes some leakage of water from the Aquia aquifer downward to the Magothy aquifer. Simulated water levels in the Aquia aquifer decline by as much as 22 feet from 2000 levels. Lowering pumpage in the Magothy aquifer to 7 million gallons per day reduces drawdown in the Aquia aquifer to less than 4 feet. The drawdown caused by pumping the Magothy aquifer at 7 million gallons per day can be offset by reducing pumpage in the Aquia aquifer to a rate 25 percent below the 2000 level (or approximately 1.4 million gallons per day). Reducing pumpage in the Aquia aquifer further will allow a greater amount to be pumped from the Magothy aquifer.

What is the simulated effect of projected 2020 withdrawals from the Aquia aquifer in Calvert and St. Mary's Counties on water levels in Southern Anne Arundel County? (pgs. 74 to 75)

- Withdrawals from the Aquia aquifer are projected to increase to 8.2 million gallons per day in Calvert County and 11.3 million gallons per day in St. Mary's County by 2020. Pumpage values, derived from population projections made by the Maryland Office of Planning for Calvert County and the St. Mary's County Metropolitan Commission for St. Mary's County, represent high growth estimates for each county. Simulated withdrawals in Calvert and St. Mary's Counties cause water levels in the Aquia aquifer to exceed the management level in a band as much as 3 miles wide, extending from Waysons Corner to Rhode River.

- Constraining withdrawals in Calvert County will reduce the amount of future drawdown in Southern Anne Arundel County. Decreasing withdrawals in Calvert County to 6.1 million gallons per day based on a 2020 population projection by the Calvert County Department of Planning and Zoning reduces the width of the area where the management level was exceeded by about 1 mile.

INTRODUCTION

BACKGROUND

Water for domestic use in Southern Anne Arundel County is pumped almost entirely from individual wells screened in the Aquia aquifer. Large, individual supplies (public or commercial) account for a relatively small part of the total water pumped. The Aquia aquifer is the most desirable source of ground water in the area, given its relatively shallow depth and generally acceptable water quality. The deeper Magothy aquifer—capable of supplying large quantities of water to wells—is an additional, easily obtained source of ground water. However, elevated iron concentrations makes it less appealing for self-supplied domestic use. In 2000, the Magothy aquifer was used primarily for irrigation and minor public supply. Approximately 0.22 million gallons per day (Mgal/d) was pumped from the Magothy aquifer in Southern Anne Arundel County in 2000, and approximately 1.8 Mgal/d was pumped from the Aquia aquifer. Increased demand on the Aquia aquifer in Southern Anne Arundel County and in areas to the south has caused water levels to decline at rates of up to 1.4 feet per year (ft/yr). Future demand for water by the growing population will cause water levels to decline further. Although withdrawals in the Magothy aquifer are relatively low in Southern Anne Arundel County, water levels are declining at rates similar to those in the Aquia aquifer.

Water quality of the Aquia aquifer is generally good; however, at some locations, elevated iron, hydrogen sulfide ("rotten-egg smell"), and calcium concentrations result in poor water quality. These constituents do not pose health risks, but are aesthetically undesirable. Residential water-treatment systems are widely used to correct these water-quality problems at varying levels of effectiveness and cost. Treatment of water produced from the Magothy aquifer would also be required to reduce iron concentrations.

PURPOSE AND SCOPE

The main purpose of this study is to: (1) determine the hydraulic characteristics of the Aquia and Magothy aquifers, and quantify their water-supply potential in Southern Anne Arundel County; and (2) determine the cumulative impact of increased withdrawals in the Aquia aquifer in Anne Arundel, Calvert, and St. Mary's Counties on future water levels in Southern Anne Arundel County. An additional purpose of the study is to determine the natural water quality of the Aquia and Magothy aquifers in Southern Anne Arundel County.

The study focuses on the Aquia and Magothy aquifers in Anne Arundel County south of Mayo Peninsula. However, to simulate ground-water flow conditions properly, it was necessary to expand the model area to include surrounding areas (central Anne Arundel County, Mayo-Edgewater, eastern Prince George's County, and northern Calvert County).

LOCATION OF STUDY AREA

The study area consists of the southern part of Anne Arundel County south of Route 214 (fig. 1). In this report, Southern Anne Arundel County is defined as the area bound by Route 214 on the north; Patuxent River on the west; Rhode River, West River, Herring Bay, and Chesapeake Bay on the east; and Calvert County to the south. Mayo Peninsula and Edgewater are not included in the study area. To simulate ground-water flow in the Aquia and Magothy aquifers adequately, a larger area was chosen for the ground-water-flow model. The model area includes central and southern Anne Arundel County, the northernmost part of Calvert County, and the easternmost part of Prince George's County.

METHODS OF INVESTIGATION

Literature and unpublished data on file at the Maryland Geological Survey were reviewed to obtain information concerning the geologic, hydrologic, and chemical characteristics of the sediments underlying the study area. In addition, six test wells were drilled under contract by A. C. Schultes of Maryland to determine the depth, thickness, lithology, and hydraulic properties of the Aquia and Magothy aquifers in Southern Anne Arundel County. The test wells are located at the following four sites: (1) Deale Athletic Field–AA Fe 91 (probe hole), AA Fe 92 (Aquia aquifer) and AA

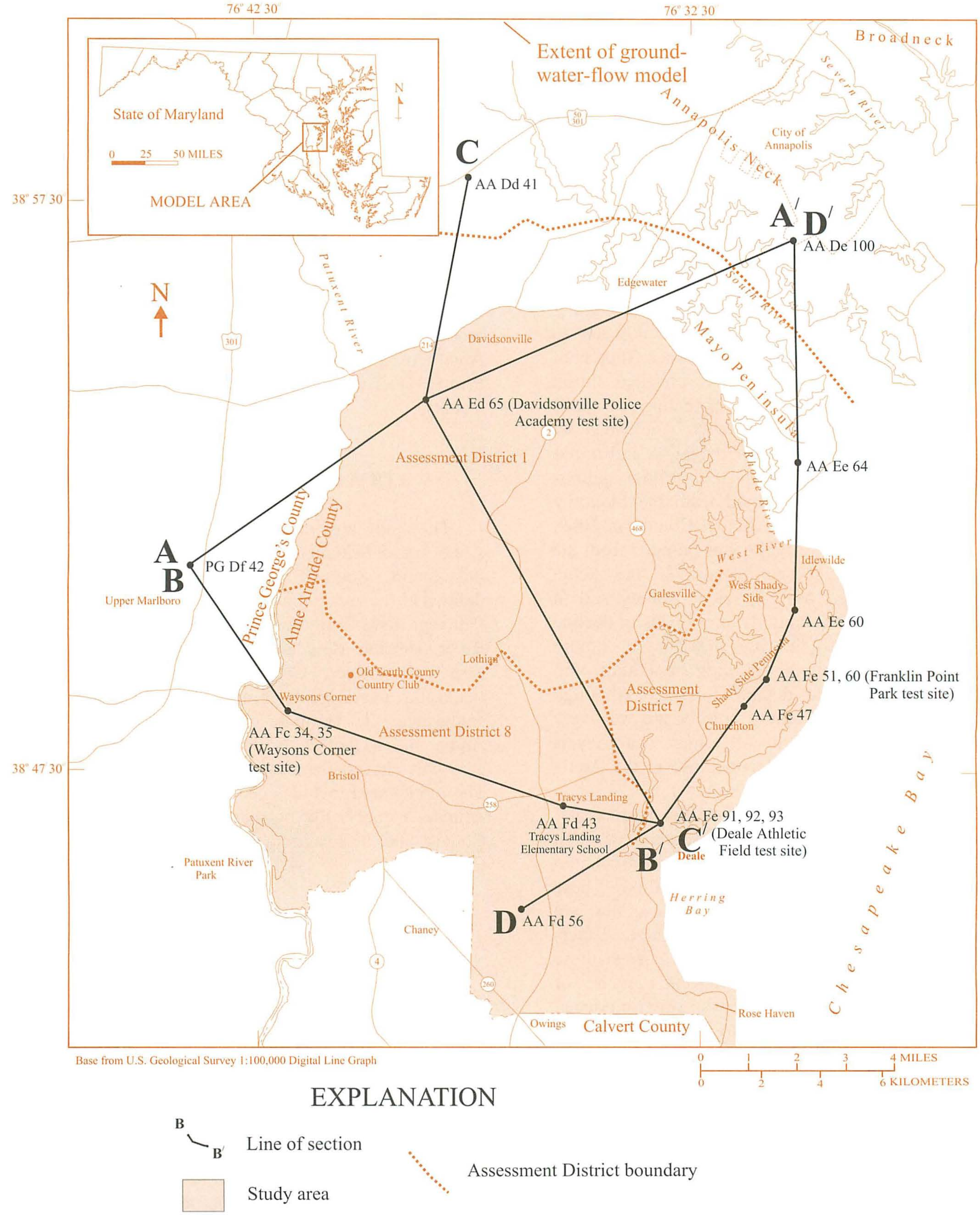

Figure 1. Location of study area.

Fe 93 (Magothy aquifer); (2) Franklin Point Park–AA Fe 60 (Aquia aquifer); (3) Waysons Corner–AA Fc 34 (Magothy aquifer) and AA Fc 35 (Aquia aquifer); and (4) Davidsonville Police Academy–AA Ed 65 (Magothy aquifer) (fig. 1). Existing test wells were located at Franklin Point Park (AA Fe 51, screened in the Magothy aquifer), and Davidsonville Police Academy (AA Ed 45, screened in the Aquia aquifer). At each site 9 7/8-inch- (in.) diameter pilot holes were converted to wells using 4 ½-in. SDR-17 PVC casing. Thirty feet (ft) of 0.02-in. slot, 4 ½-in., SDR-17 PVC well screen was installed in each well, with the exception of AA Ed 65 in which 20 ft was used. Drill cuttings, collected at 10-ft intervals, were washed, examined, and described using a 60X-power binocular microscope (app. B.). Geophysical logs (16- and 64-in. normal resistivity, 6-ft lateral resistivity, single-point resistivity, and gamma radiation) were completed prior to well construction. After test-well construction was completed, a constant-rate aquifer test was performed on each well with water-level measurements recorded during 8 hours of drawdown and 8 hours of recovery. Near the end of each test, water samples were collected for chemical analysis. Continuous-reading water-level recorders were installed on the wells.

During the study, well-construction data for 73 wells were inventoried (app. A., pl. 1). The majority of the wells were residential. Synoptic water-level measurements were made in approximately 80 wells during the spring and fall of 2000. Water levels were adjusted to sea level using Anne Arundel County topographic maps (2- and 5-ft contour intervals). The synoptic water-level measurements were augmented by continuous-reading water-level data collected in the six test wells and in two additional wells—AA Fe 56 (Magothy aquifer) at Deale, and AA Fe 95 (Aquia aquifer) at Churchton (pl. 1). The effects of irrigation withdrawals at two sod farms were further investigated through the collection of monthly water-level measurements in both the Aquia and Magothy aquifers at those sites. Water-level and well-construction data are stored in the U.S. Geological Survey's National Water Information System (NWIS).

Wells are identified in this report using the Maryland Geological Survey well-numbering system. In this numbering system, the first two letters are the county prefix (for example, AA for Anne Arundel County). The second part of the identifier consists of two letters that designate a 5-minute quadrangle within the county; the first letter (upper case) denotes a 5-minute segment of latitude from north to south, and the second letter (lower case) denotes a 5-minute segment of longitude from west to east. The locations of 5-minute quadrangles in the study area are shown on plate 1. The wells are numbered sequentially in the order they were inventoried within each 5-minute quadrangle.

Water samples were collected from 18 residential wells and one commercial well. Samples were taken after the specific conductance and temperature of the water stabilized. The water was analyzed for major inorganic constituents in addition to arsenic, nitrogen, and bromide by the U.S. Geological Survey's National Water-Quality Laboratory (NWQL) in Denver, Colorado (app. H.). Water samples collected from the test wells were also analyzed for long-term alpha and beta radiation by the NWQL (app. H.). Water-quality data for these sites are stored in the U.S. Geological Survey's NWIS. A field survey of chloride concentrations and specific conductance was also conducted on selected wells screened in the Aquia aquifer on the northern end of Shady Side peninsula.

A ground-water-flow model was developed using the U.S. Geological Survey's three-dimensional, finite-difference ground-water-flow modeling code MODFLOW. The model was used to simulate ground-water flow in the Aquia and Magothy aquifers based on: (1) steady-state, pre-pumping conditions; (2) transient conditions (1900-2000); and (3) future conditions (2001-2020) using various pumpage scenarios.

PREVIOUS INVESTIGATIONS

Brief descriptions of the Aquia and Magothy aquifers in central and southern Anne Arundel County are given in Little and others (1917), Clark and others (1918), Bennion and Brookhart (1949), and Otton (1955). The Clark report includes a chemical analysis of water produced from a well screened in the Aquia aquifer near Galloway (now named Galesville). The Bennion and Brookhart report contains well-construction data, drillers' logs, and water-quality analyses for selected wells. The water-supply potential of the Aquia aquifer in Southern Maryland was evaluated by Kapple and Hansen (1976), Chapelle and Drummond (1983), and Achmad and Hansen (1997, 2001a). The

hydrogeology of the Magothy aquifer in Anne Arundel County was investigated by Mack (1974) and its water-supply potential evaluated by Mack and Mandle (1977). Water-supply potential of the Aquia and Magothy aquifers in the Deale-Shady Side area was estimated by Mack and Richardson (1962). The hydrogeology of the Magothy and Aquia aquifers, with emphasis on brackish-water intrusion in the Aquia aquifer on Annapolis Neck and Mayo Peninsula, was addressed in Fleck and Andreasen (1996). Well data for selected wells in Anne Arundel County is given in Lucas (1976). Ground-water levels in the Aquia and Magothy aquifers have been monitored by the U.S. Geological Survey and the Maryland Geological Survey for over 25 years. During this period, maps showing potentiometric surfaces and differences between potentiometric surfaces for selected years for the Aquia and Magothy aquifers have been published by the U.S. Geological Survey as Open-File Reports or Water-Resources Investigations. The most recently published maps are: (1) Potentiometric surface during the fall of 1999 in the Aquia aquifer (Curtin and others, 2001a), and the Magothy aquifer (Curtin and others, 2001b); and (2) Difference between the 1982 and 1999 potentiometric surfaces of the Aquia aquifer (Curtin and others, 2001c), and the 1975 and 1999 potentiometric surfaces of the Magothy aquifer (Curtin and others, 2001d). A comprehensive listing of published potentiometric and difference maps is referenced in a compilation of ground-water levels and pumpage data for the major Coastal Plain aquifers in Southern Maryland (Achmad and Hansen, 2001b). The natural water chemistry of the Aquia aquifer on Annapolis Neck and Mayo Peninsula, and the Magothy aquifer on Annapolis Neck and Broadneck was discussed in Fleck and Andreasen (1996). Bolton and Hayes (1999) published a pilot study of carcinogens in ground water in Anne Arundel County which included seven wells screened in the Aquia aquifer in Southern Anne Arundel County. The pilot study revealed elevated radium concentrations in the Magothy and Patapsco aquifers in northern Anne Arundel County. A follow-up report described in more detail the lateral and vertical distribution of radium in those aquifers (Bolton, 2000).

ACKNOWLEDGMENTS

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HYDROGEOLOGY OF THE AQUIA AND MAGOTHY AQUIFERS IN SOUTHERN ANNE ARUNDEL COUNTY

HYDROGEOLOGIC FRAMEWORK

The occurrence, movement, and quality of ground water are controlled by the geologic setting. The lithology, permeability, and structure of the earth material comprising the geologic setting form the framework of the ground-water-flow system. In Southern Anne Arundel County the geologic setting is characterized by a wedge-shaped mass of relatively flat-lying, unconsolidated Coastal Plain deposits. The sediments consist of interbedded layers composed of admixtures of sand, gravel, silt, and clay that overlie consolidated Triassic, Lower Paleozoic, or Precambrian basement rock. Predominantly sandy and gravelly layers, capable of yielding water to wells, form aquifers, while fine-grained layers (silt and clay) impede the flow of water and form confining units. The amount of water that can be withdrawn from an aquifer is dependant in part on its thickness, hydraulic conductivity, available drawdown, and lateral extent (boundary conditions). Confining units serve important functions within the ground-water-flow system by controlling the vertical flow of water between aquifers and the downward flow of potential contaminants from the land surface. Clay layers can also contribute recharge to aquifers through the slow drainage of water contained in storage.

The study area is located within Maryland's Coastal Plain Physiographic Province. The Coastal Plain sediments were deposited in marine and fluvial (river) environments ranging in age from Cretaceous to Quaternary. The sediments are gently inclined to the southeast; thickness ranges from a few tens of feet near the Fall Line to more than 7,700 ft at Ocean City (Hansen and Edwards, 1986). In Southern Anne Arundel County, the thickness of the Coastal Plain sediments was estimated to range from 1,600 ft in the Davidsonville area to 2,500 ft at Rose Haven (Vroblesky and Fleck, 1991). The major aquifers underlying Southern Anne Arundel County include, from deepest to shallowest, the Potomac Group aquifers (consisting of the Patuxent, lower Patapsco, and upper Patapsco aquifers), the Magothy aquifer, and the Aquia aquifer. This report addresses the Aquia and Magothy aquifers, and the Nanjemoy, Marlboro, Matawan, and Patapsco confining units (tab. 1).

The Magothy Formation consists of medium-to-coarse, white, gray, and clear quartz sand interbedded with black and gray, lignitic clay (app. B.). The age of the formation is Late Cretaceous. The Magothy Formation is characterized by massive beds of well-sorted, coarse-grained sands. In outcrop, the formation is described as a fine to coarse-grained sand with pebbly sand or gravel, commonly sugary in appearance, and interbedded with dense chocolate or dark gray clay (Glaser, 1976). The quartz grains appear pink, purple, and blue because of mineral coatings and inclusions. In Southern Anne Arundel County, the Magothy Formation consists of two sandy layers separated by 20 to 50 ft of clay (figs. 2-5). The degree of hydraulic connection between these sands is unknown, but in this report they are treated as a single aquifer. In the Annapolis area the clay layer is generally absent resulting in a continuous sand layer approximately 150 ft thick (fig. 2; Fleck and Andreasen, 1996). The Magothy aquifer outcrops in an irregular area, 1 to 4-mi-wide, extending from Bowie in Prince George's County to the mouth of the Patapsco River (Glaser, 1976). In southwestern Prince George's County the Magothy aquifer is overlain by younger formations and does not outcrop (Hansen, 1972).

The Magothy Formation overlies the Patapsco Formation (tab. 1). The Patapsco Formation consists of coarse, gray-to-brown sand, interbedded with mottled, reddish clay. In drill cuttings, sands from the Magothy and Patapsco Formations are not easily distinguishable. The contact between the Magothy and Patapsco Formations is problematic because it may occur within sand beds that are difficult to differentiate using either drill cuttings or geophysical logs. The base of the Magothy aquifer, therefore, is defined by the first occurrence of reddish, mottled clay. Consequently, Patapsco sands occurring above the first-reported, reddish clay are placed in the Magothy aquifer. For example, Mack (1974, p. 12) defined the Magothy aquifer in Southern Maryland as "those layers of light-gray sand, interbedded with relatively thin layers of clay, that occur in the geologic section

Table 1. Generalized stratigraphic, lithologic, and hydrologic characteristics of geologic formations underlying Southern Anne Arundel County

System	Series	Group	Formation	Average thickness (feet)	General lithology	Hydrologic character	Hydrogeologic unit
Quaternary	Holocene		Alluvium and terrace deposits	20	Sand, gravel, silt, and clay	Confining unit in most places, limited aquifer in some places	Not recognized
	Pleistocene		Talbot Formation	20	Clay, silt, brown to gray with some glauconite and pebbles	Confining unit	Talbot confining unit
Tertiary	Miocene	Chesapeake	Calvert Formation	75	Sandy clay and fine sand, fossiliferous, diatomaceous earth	Confining unit and limited aquifer	Chiefly a water-table aquifer
	Eocene	Pamunkey	Nanjemoy Formation	50	Glauconitic sand, silt, and clay	Confining unit and limited aquifer	Nanjemoy aquifer
	Paleocene		Marlboro Clay	15	Clay, silvery gray to pink	Confining unit	Marlboro confining unit
			Aquia Formation	130	Glauconitic, greenish to brown sand with thin indurated or "rock" layers, and silt layers	Aquifer	Aquia aquifer
			Brightseat Formation	15	Silt and clay, olive-gray to black, glauconitic	Leaky confining unit	
Cretaceous	Upper Cretaceous		Severn Formation	45	Sand, silty to fine, glauconitic	Limited aquifer	
			Matawan Formation	60	Silt and fine sand, clayey, dark green to black, glauconitic	Confining unit	Matawan confining unit
			Magothy Formation	120	Sand, light-gray to white, with interbedded layers of gray and black, organic clay	Aquifer	Magothy aquifer
	Lower Cretaceous	Potomac	Patapsco Formation	>250(?)	Sand, fine to coarse, brown, with layers of tough variegated clay.	Aquifer and confining unit	Patapsco aquifer and confining unit

above the tough reddish clay layers of the Patapsco Formation…".

Pollen and spore microfossils from a core sample collected in test well AA De 100 (Annapolis Middle School) indicate that the contact between the Magothy and Patapsco Formations is below 383 ft. The contact may be at the clay kick on the gamma radiation log at 404 ft (figs. 2 and 5; Mack, 1974). At well PG Df 42 (Beechwood Golf Course) the base of the Magothy aquifer may be as deep as 398 ft at the first occurrence of a multi-colored clay described in the driller's log (figs. 2 and 3). The base of the Magothy aquifer at well AA Dd 41 (Rutland Road) occurs at about 305 ft, at the top of a 25-foot-thick clay layer (fig. 4). This clay, described in a core sample collected from an adjacent test hole (AA Dd 43), is light- to medium gray in color. The first occurrence of red or mottled clay at this site occurs at about 485 ft; however, using that depth for the bottom of the Magothy aquifer probably

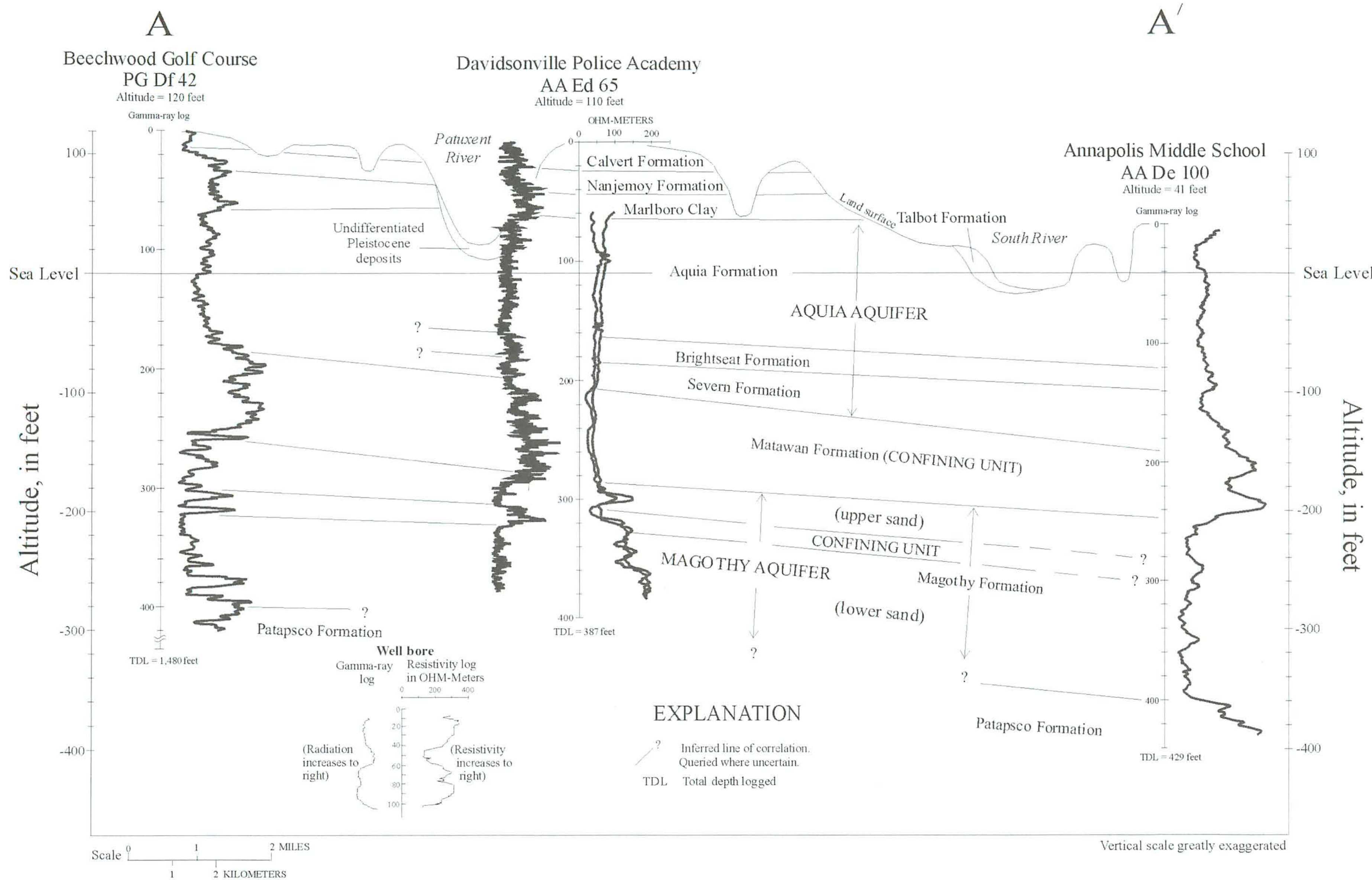


Figure 2. Hydrogeologic section A - A′ from Beechwood Golf Course, near Upper Marlboro, Prince George's County, to Annapolis Middle School, Anne Arundel County.

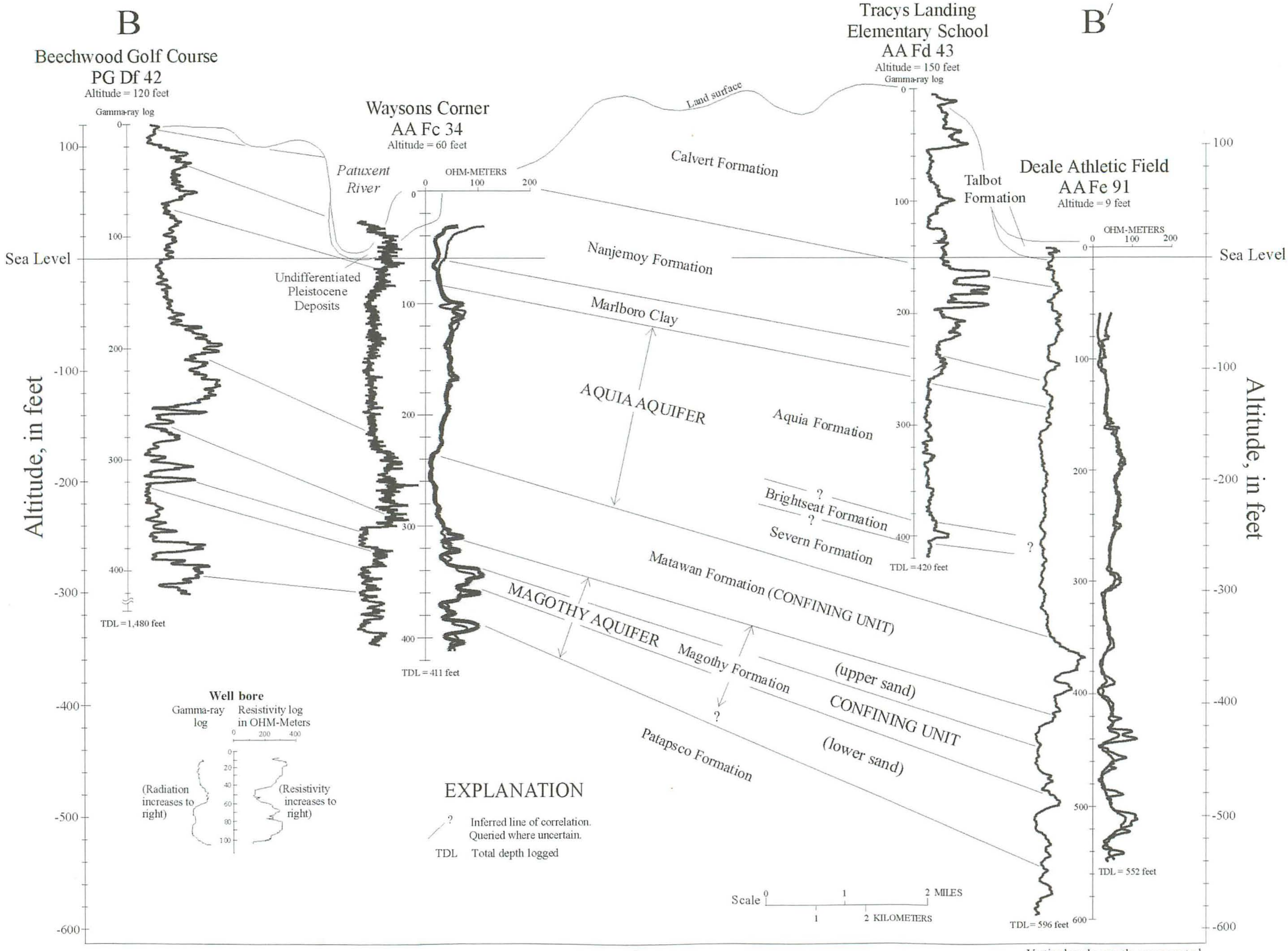


Figure 3. Hydrogeologic section B - B′ from Beechwood Golf Course, near Upper Marlboro, Prince George's County, to Deale Athletic Field, Anne Arundel County.

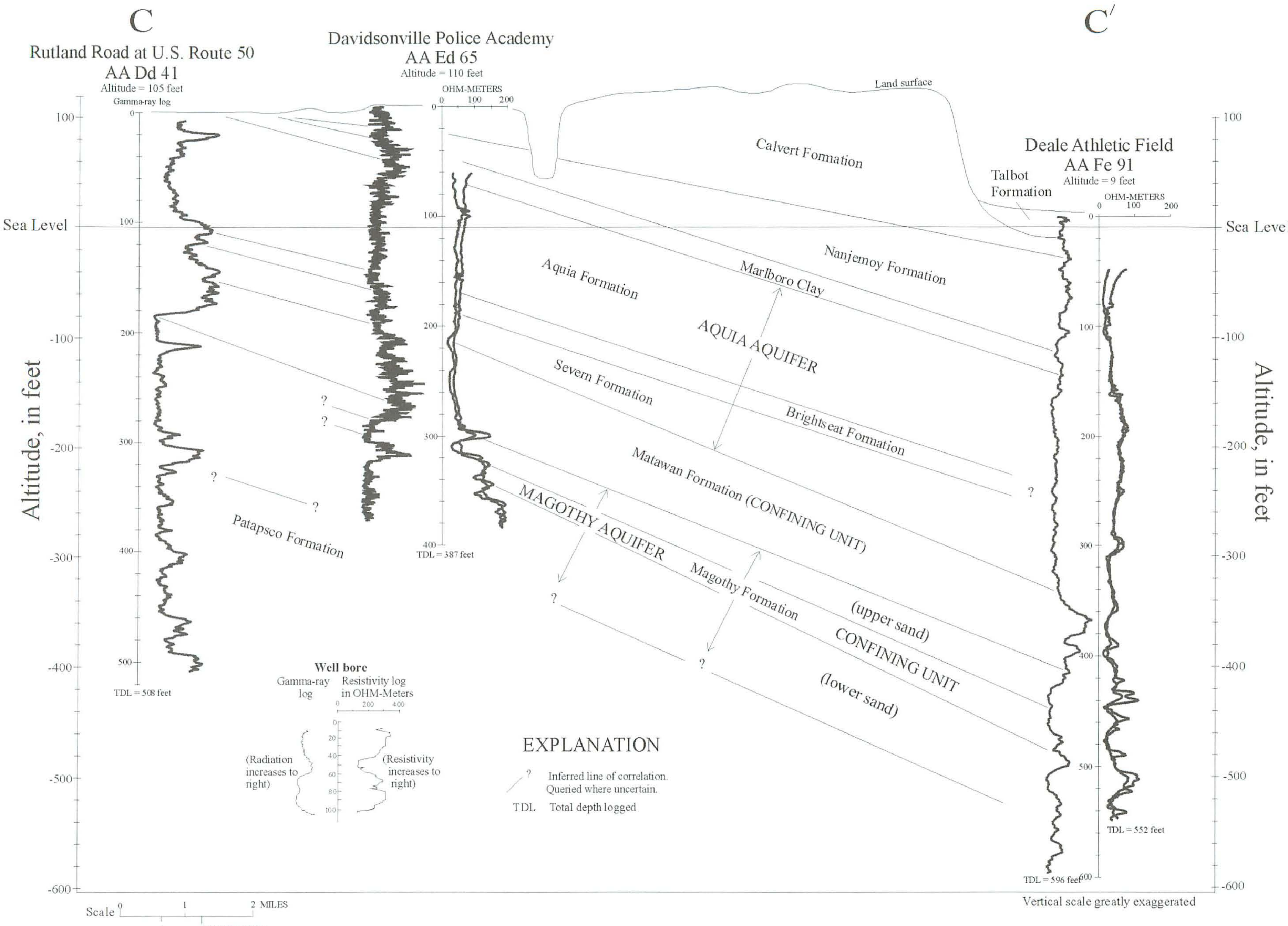


Figure 4. Hydrogeologic section C - C′ from Rutland Road at U.S. Route 50 to Deale Athletic Field, Anne Arundel County.

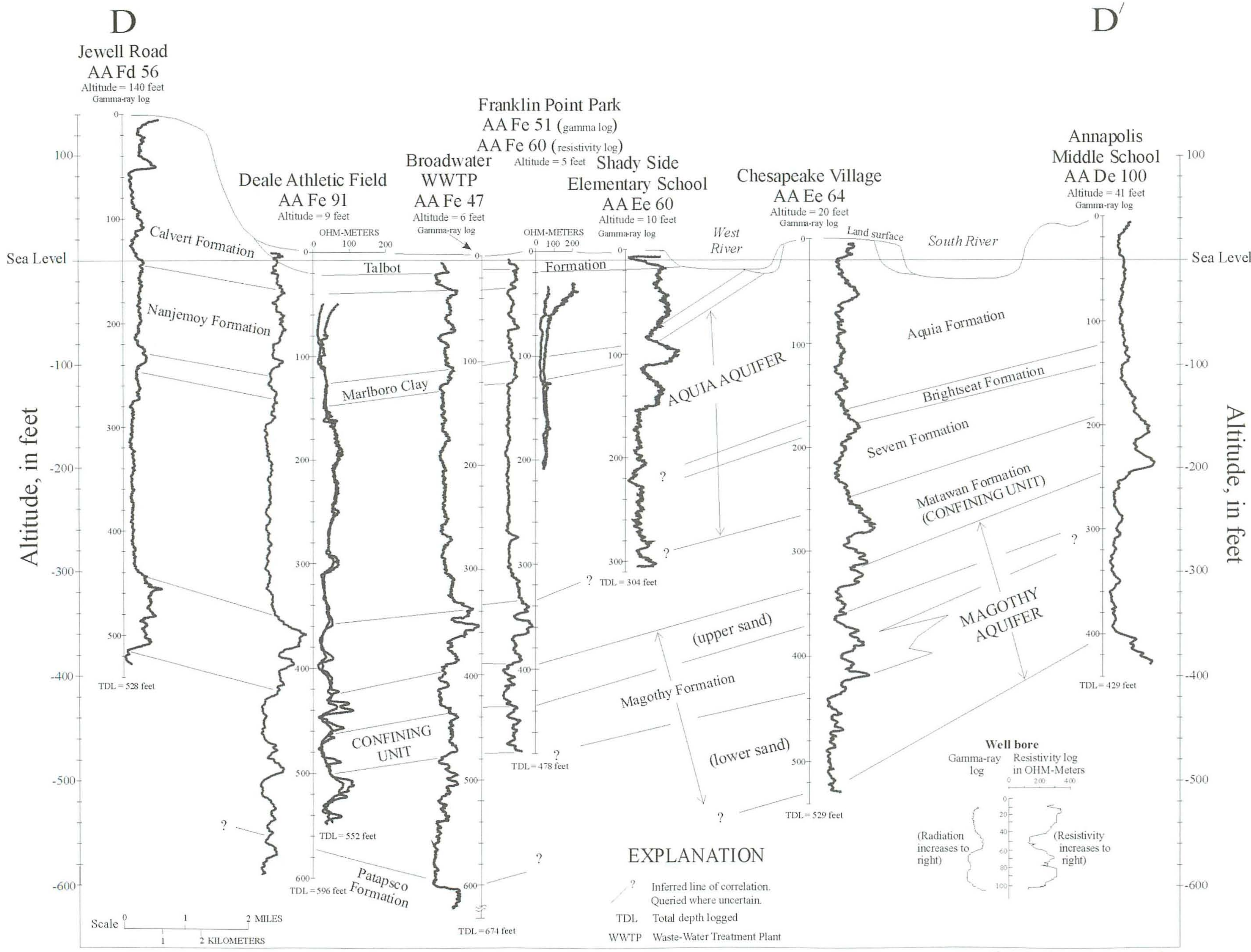


Figure 5. Hydrogeologic section D-D' from Jewell Road to Annapolis Middle School, Anne Arundel County.

exaggerates its thickness at this location. The Upper Patapsco confining unit was fully penetrated in Southern Anne Arundel County at the Old South County Country Club (fig. 1). The total clay thickness of the confining unit at that location is approximately 110 ft.

On Broadneck, a discontinuous clay layer approximately 20 ft thick separates the Magothy aquifer from the Upper Patapsco aquifer (Fleck and Andreasen, 1996, p. 8). Because gaps in the clay layer result in a hydraulic interconnection between the two aquifers, pumpage in the Upper Patapsco aquifer causes water levels to decline in the Magothy aquifer (Fleck and Andreasen, 1996, pgs. 25, 27, and 29). Presently, there is no evidence of a direct hydraulic interconnection between the Magothy and Upper Patapsco aquifers in Southern Anne Arundel County.

The top of the Magothy aquifer (upper sand) ranges from about 150 ft below sea level at Davidsonville to 500 ft below sea level at Rose Haven (fig. 6). In the Deale-Shady Side area the altitude of the top of the aquifer is approximately 400 ft below sea level. The top of the aquifer dips at a rate of approximately 25 feet per mile (ft/mi). The bottom of the Magothy aquifer (lower sand) ranges from about 250 ft below sea level at Davidsonville to more than 600 ft at Rose Haven (fig. 7). Thicknesses of the upper and lower sand units within the Magothy aquifer range from about 15 to 40 ft and about 40 to 90 ft, respectively.

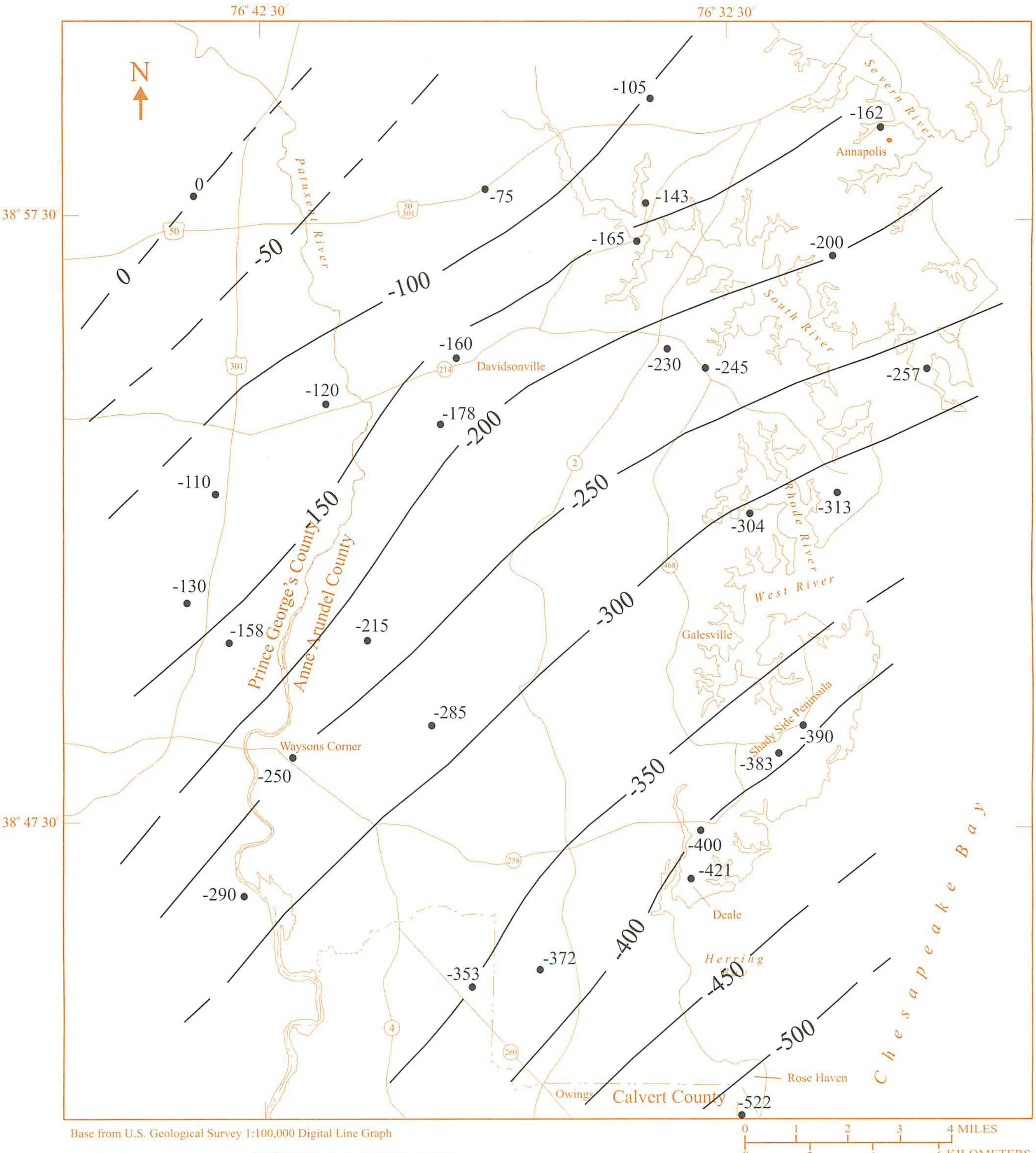
The Matawan Formation overlies the Magothy aquifer. The contact is marked by a lithologic change from coarse sand to clay. The Matawan Formation consists of dark gray and black silty clay. At many locations, the clay is divided into two distinct layers by a sandy zone composed predominantly of fine to coarse-grained quartz and black glauconite, which is a microcrystalline silicate mineral rich in iron and potassium. The relatively low permeability clay layers function as a confining unit. Total clay thickness ranges from about 55 to 75 ft (figs. 3 -5).

The Severn and Brightseat Formations overlie the Matawan Formation. The Severn Formation is primarily a glauconitic and quartz silt that grades upward to a fine-grained sand (Fleck and Andreasen, 1996). Light-gray clay lenses, and to a lesser extent, hard indurated layers occur throughout the formation. Thickness ranges from about 20 to 70 ft (figs. 2-5). The Brightseat Formation is a dark-gray, silty and clayey, fine quartz sand (Minard, 1980) that is typically less than 20 ft thick. The Brightseat forms a leaky confining unit. Often the Brightseat and Severn Formations are difficult to differentiate in drill cuttings and geophysical logs.

The Aquia Formation overlies the Brightseat Formation. The Aquia Formation consists of medium to coarse, clear and white quartz sand with moderate amounts of dark-green, brown, and black glauconite. Glauconite typically accounts for less than 30 to 40 percent of the sand. The Aquia Formation outcrops over much of Annapolis Neck and within a 1- to 2-mile- (mi) wide band bordering the south side of the South River (fig. 8) (Glaser, 1976). The formation is also exposed in stream cuts of Patuxent River tributaries in the northwestern part of the study area and in neighboring Prince George's County. Irregular, brownish patches consisting of weathered grains of glauconite and goethite (an iron hydroxide mineral) and iron-stained quartz occur throughout the formation. Cemented iron-oxide crusts and layers are present, particularly in highly weathered parts of the formation. Shelly layers of cemented sandstone are present in less weathered areas where leaching of calcareous material has not occurred, as, for example, at the Deale Athletic Field site (AA Fe 91). Sand thickness of the Aquia Formation in the study area is approximately 100 ft (figs. 2-5).

The Aquia and Severn Formations are hydraulically connected and together form the Aquia aquifer. Total aquifer thickness in Southern Anne Arundel County ranges from approximately 110 to 180 ft. The aquifer is thickest in the southern part of the study area. The Aquia is a water-table aquifer in its outcrop area, which includes most of the Mayo-Edgewater area (fig. 8). The most productive section of the aquifer and the section most frequently utilized for wells occur in the Aquia Formation. The top of the Aquia aquifer ranges from 100 ft above sea level in the outcrop area to 250 ft below sea level at Rose Haven (fig. 8). The bottom of the Aquia aquifer ranges from approximately 50 ft below sea level near the outcrop area to approximately 470 ft below sea level at Rose Haven (fig. 9).

The Marlboro Clay, consisting of pink to silvery gray clay, overlies the Aquia aquifer throughout most of Southern Anne Arundel County. Although typically less than 20 ft thick, its low hydraulic conductivity makes it an effective confining unit. This formation is laterally extensive, occurring throughout Southern Maryland and in parts of

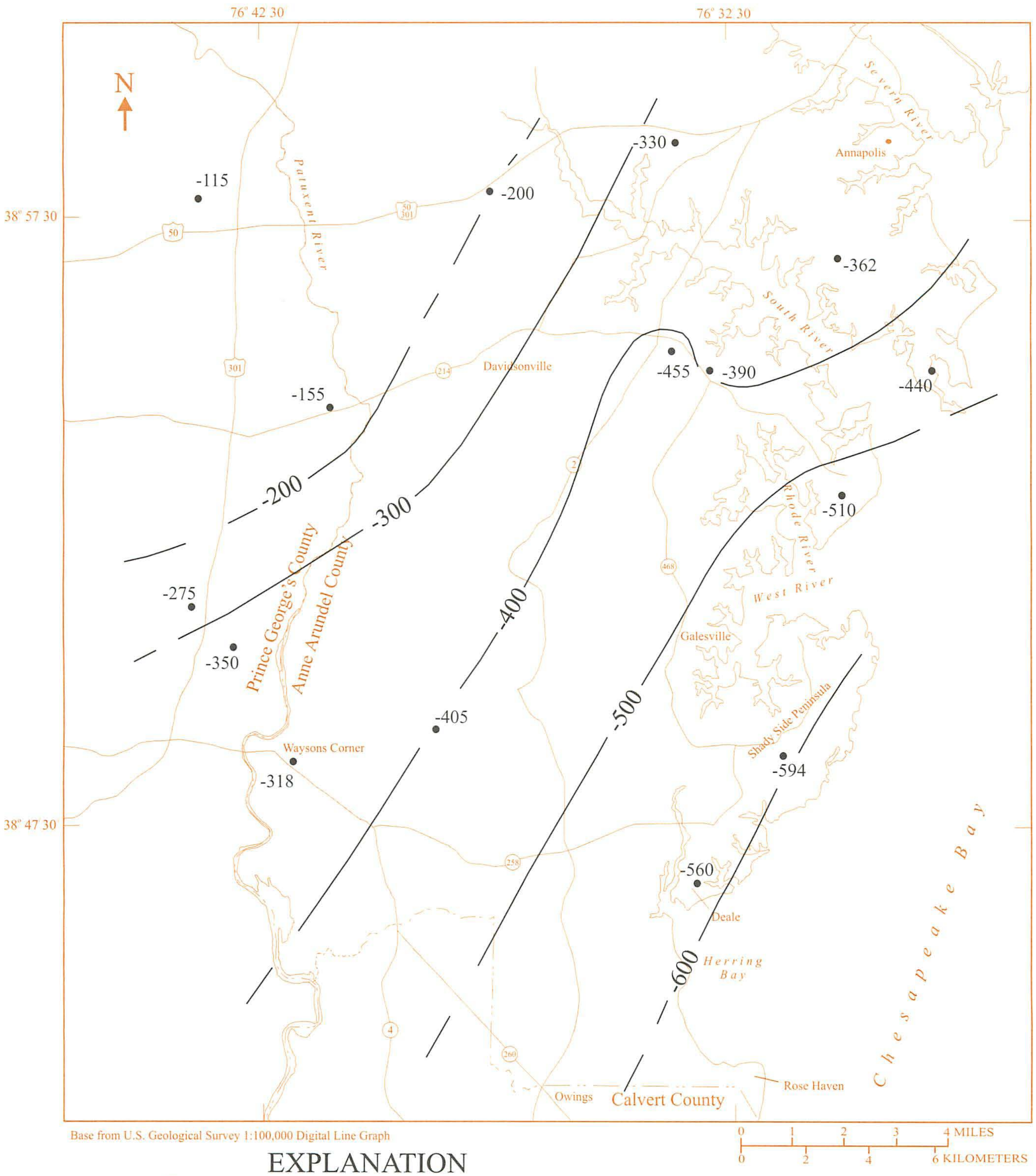


EXPLANATION

-350 LINE OF EQUAL ALTITUDE OF THE TOP OF THE MAGOTHY AQUIFER -- Dashed where uncertain. Interval 50 feet. Datum is sea level.

•-290 WELL-DATA POINT -- Number is altitude of the top of the Magothy aquifer, in feet. Datum is sea level.

Figure 6. Altitude of the top of the Magothy aquifer (upper sand).

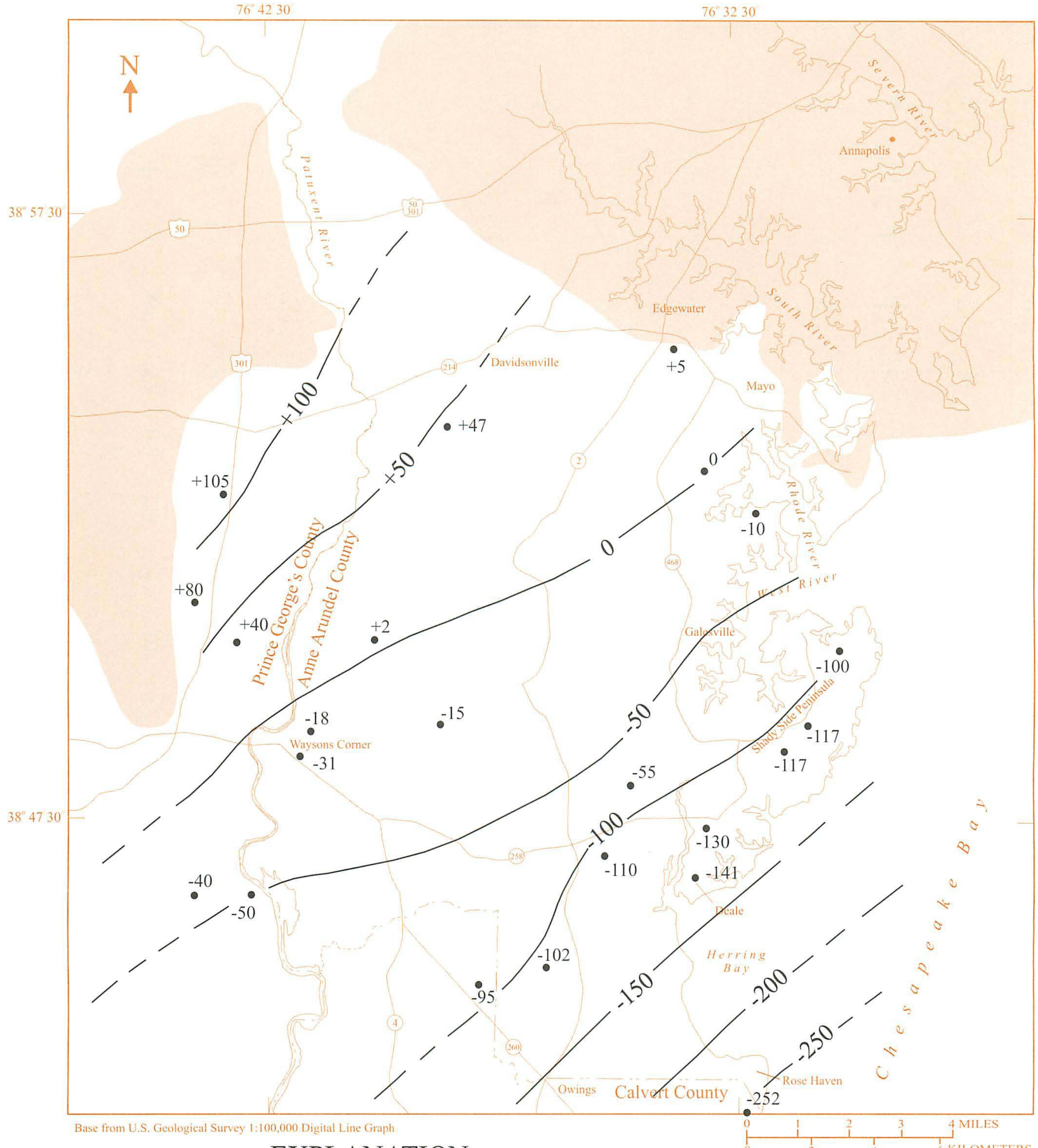


EXPLANATION

-400 LINE OF EQUAL ALTITUDE OF THE BOTTOM OF THE MAGOTHY AQUIFER -- Dashed where uncertain. Interval 50 feet. Datum is sea level.

-405 WELL-DATA POINT -- Number is altitude of the bottom of the Magothy aquifer, in feet. Datum is sea level.

Figure 7. Altitude of the bottom of the Magothy aquifer (lower sand).



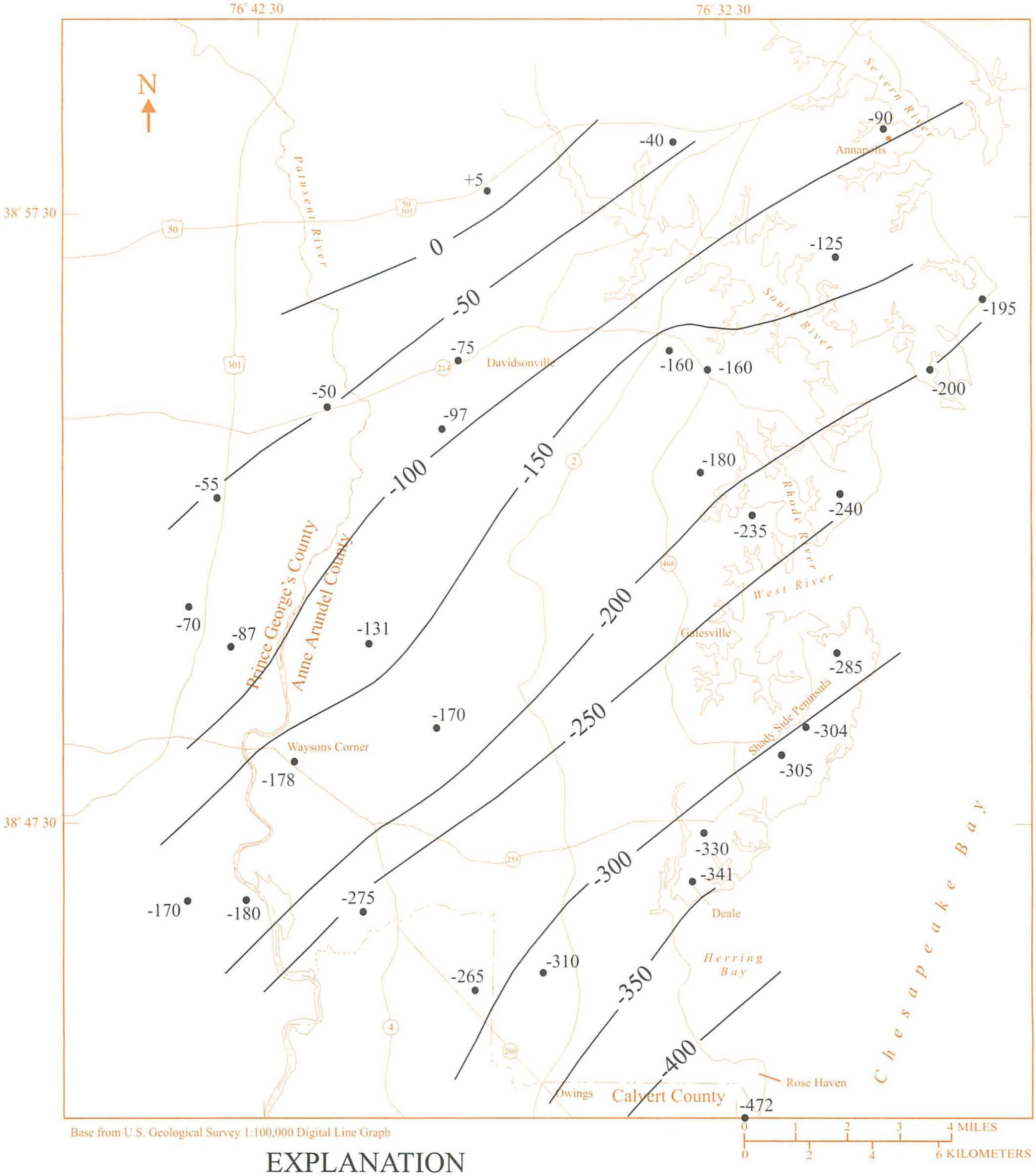
EXPLANATION

-150 — LINE OF EQUAL ALTITUDE OF THE TOP OF THE AQUIA AQUIFER -- Dashed where uncertain. Interval 50 feet. Datum is sea level.

•-40 — WELL-DATA POINT -- Number is altitude of the top of the Aquia aquifer, in feet. Datum is sea level.

GENERALIZED OUTCROP AREA OF THE AQUIA FORMATION -- Modified from Glaser (1976).

Figure 8. Altitude of the top of the Aquia aquifer.



EXPLANATION

-300 LINE OF EQUAL ALTITUDE OF THE BOTTOM OF THE AQUIA AQUIFER -- Dashed where uncertain. Interval 50 feet. Datum is sea level.

•-265 WELL-DATA POINT -- Number is altitude of the bottom of the Aquia aquifer, in feet. Datum is sea level.

Figure 9. Altitude of the bottom of the Aquia aquifer.

adjacent Virginia (Darton, 1951). Recent (2001) construction activity on the north side of Route 214 approximately 1 mi east of Davidsonville provided a good exposure of the Marlboro Clay; otherwise, outcroppings of Marlboro Clay in Southern Anne Arundel County are limited.

The Nanjemoy and Calvert Formations overlie the Marlboro Clay. The Nanjemoy Formation consists of gray quartzose and dark green to black glauconitic sand with varying amounts of silty, gray clay. The Nanjemoy Formation outcrops in the northeastern part of Southern Anne Arundel County and in stream cuts leading to the Patuxent River between Route 214 and the Anne Arundel–Calvert County boundary (Glaser, 1976). The formation is well exposed on the east side of the intersection of Route 468 and Mill Swamp Road near Muddy Creek (pl. 1). In the subsurface, geophysical logs indicate that the Nanjemoy is predominantly clayey throughout Southern Anne Arundel County (figs. 3-5). Many drillers' logs describe the Nanjemoy Formation as a black, gray, and green clay, although medium to coarse, dark green and brown sand is logged occasionally. The Nanjemoy is not considered a major water-bearing formation in Anne Arundel County, although it is used in a few places. The Calvert Formation consists chiefly of dark to light gray clay interbedded with layers of fine gray quartzose and black glauconitic sand. The Calvert Formation is a minor aquifer in Anne Arundel County and is historically the source of water for shallow, dug wells.

HYDRAULIC PROPERTIES

Flow of water through an aquifer is directly related to the hydraulic head gradient and the transmissivity of the aquifer. The hydraulic head is elevation of the water in a piezometer or well. Hydraulic head gradient is the difference between heads divided by the distance between wells (Fetter, 1980, pps. 125-126). Transmissivity is a product of the water-transmitting property of the sediment and the sediment thickness. Relatively thick layers of coarse-grained sand and gravel transmit water more easily than thinner, fine-grained sands, and, therefore, have higher transmissivity values. Aquifers with higher transmissivity values yield greater quantities of water to wells with less drawdown in water levels.

Transmissivity values of the Aquia and Magothy aquifers were calculated from aquifer tests performed on the test wells drilled during the study. During the aquifer tests, each well was pumped at a constant rate for 8 hours. Pumping rates ranged from 75 to 101 gallons per minute (gal/min). Water levels were recorded in the pumped wells during an 8-hour pumping period (drawdown phase) and for an additional 8 hours after pumping stopped (recovery phase). The drawdown and recovery water-level data were plotted against time since pumping began and stopped, respectively. The water-level data were analyzed by the Jacob straight-line method as described in Fetter (1980, p. 266). At the Waysons Corner test site, a privately-owned well (AA Fc 36) screened in the Aquia aquifer was used as an observation well during the aquifer test of AA Fc 35 (also screened in the Aquia aquifer). The observation well was 120 ft from AA Fc 35. Water-level data from AA Fc 36 were analyzed using the Theis type-curve method as described in Heath (1995).

Results of the aquifer-test analyses are presented in table 2. The calculated transmissivity of the Aquia aquifer ranged from 930 to 2,680 feet squared per day (ft^2/d) for the drawdown phases and 1,060 to 3,420 ft^2/d for the recovery phases. The highest value occurred at Franklin Point Park in Shady Side and the lowest occurred at Waysons Corner. Transmissivity calculated using the drawdown data was consistently less than that using the recovery data. Actual transmissivity of the Aquia aquifer is probably higher because only 30 ft of the aquifer was screened in each well. Total aquifer thickness at the test wells ranged from 100 to 140 ft.

A map of the transmissivity distribution of the Aquia aquifer in Southern Anne Arundel County is shown in figure 10. Transmissivities calculated for the test wells are supplemented by three values in northern Calvert County (D. C. Andreasen, 2002, unpub. data) and with three values from Chapelle and Drummond (1983). Transmissivity of the Aquia aquifer is less than 2,000 ft^2/d in Southern Anne Arundel County except in the Deale-Shady Side area and the Owings area in Calvert County. Transmissivity of the Aquia aquifer in Southern Anne Arundel County is the highest for the entire Southern Maryland region. In Calvert and St. Mary's Counties to the south, transmissivity is typically less than 1,500 ft^2/d (Chapelle and Drummond, 1983).

Table 2. Transmissivity of the Aquia and Magothy aquifers at test-well sites in Southern Anne Arundel County

Test site	Well number	Aquifer	Transmissivity, feet squared per day	
			Pumping phase	Recovery phase
Davidsonville Police Academy	AA Ed 65	Magothy	1,170	1,220
Waysons Corner	AA Fc 35	Aquia	930	1,060
	AA Fc 36[1]	Aquia	1,280	--
	AA Fc 34	Magothy	2,810	4,570
Deale Athletic Field	AA Fe 92	Aquia	980	2,250
	AA Fe 93	Magothy	700	965
Franklin Point Park	AA Fe 60	Aquia	2,680	3,420
	AA Fe 51[2]	Magothy	450	540

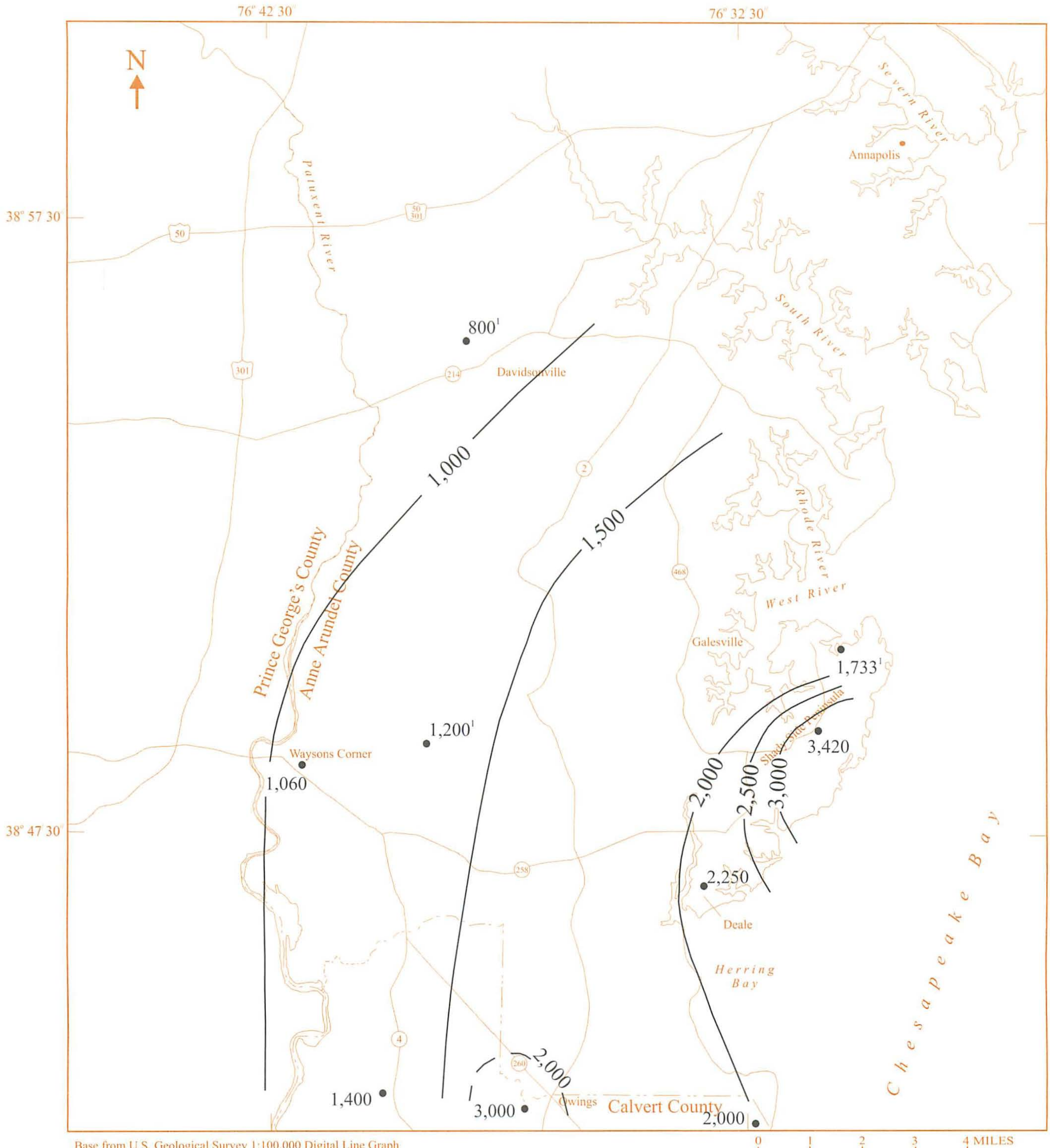
[1] Observation well during aquifer test of AA Fc 35, located at a distance of 120 feet from AA Fc 35
[2] Aquifer test conducted in 1989 (Earth Data, Incorporated, 1989)

Transmissivity of the Magothy aquifer determined in the test wells ranged from 450 to 2,810 ft^2/d for the drawdown phases and 540 to 4,570 ft^2/d for the recovery phases (tab. 2). The highest value was at Waysons Corner and the lowest value at Franklin Point Park. The upper sand of the Magothy aquifer was screened at the Deale Athletic Field site (AA Fe 93) and the Davidsonville Police Academy site (AA Ed 65). Transmissivity based on the recovery data at those sites ranged from 965 to 1,220 ft^2/d, respectively. Transmissivity of the lower sand of the Magothy aquifer, partially screened at the Waysons Corner site (AA Fc 34), was higher at 4,570 ft^2/d. These transmissivity values are only a partial measure of the total transmissivity of the Magothy aquifer since the full thickness of both the upper and lower sands were not screened in the test wells. At two well sites near Edgewater, Mack (1974, p. 50) reported transmissivity values of 12,000 ft^2/d for the upper sand at observation well AA De 103 and 11,000 ft^2/d for the lower sand at observation well AA De 101. A transmissivity value of 6,000 ft^2/d was calculated from an aquifer test conducted in 1960 on production well AA Dd 36 for the Davidsonville Elementary School. That well had a 5-foot section of well screen set in the upper sand.

Reported values of storage coefficient that were calculated from aquifer tests in the Aquia aquifer range from 0.0001 to 0.0004 (Hansen, 1972). A storage coefficient of 0.005 was determined in test well AA Fc 36 (Aquia aquifer) at Waysons Corner during the aquifer test of AA Fc 35 using the Theis type-curve method (Heath, 1995). A storage coefficient of 0.0001 was reported for the Magothy aquifer at both Upper Marlboro and Annapolis (Hansen, 1972, p. 60).

The Marlboro Clay confines the Aquia aquifer throughout most of Southern Anne Arundel County. In the study area, a vertical hydraulic conductivity of 3.4×10^{-5} feet per day (ft/d) for the Marlboro Clay was reported near Edgewater (Mack, 1974, p. 16). By comparison, the vertical hydraulic conductivity of the Marlboro Clay determined by laboratory analysis ranged from 2.7×10^{-4} ft/d in Prince George's County to 9.5×10^{-5} ft/d in St. Mary's County (Chapelle and Drummond, 1983, p. 14).

The vertical hydraulic conductivity of the Matawan confining unit, which separates the Aquia and Magothy aquifers, was determined by constant flow and consolidation tests on core samples taken at Annapolis Neck and Broadneck (Mack, 1974, p. 16). Values for vertical hydraulic conductivity



EXPLANATION

1,000 — Line of equal measured transmissivity. Contour interval is 500 feet squared per day.

● 1,200[1] Transmissivity, in feet squared per day

([1] from Chapelle and Drummond, 1983)

Figure 10. Transmissivity of the Aquia aquifer based on aquifer tests.

ranged from 3.68 x 10^{-3} to 2.56 x 10^{-5} ft/d, with an average of 1.28 x 10^{-3} ft/d. A vertical hydraulic conductivity of 7.2 x 10^{-6} ft/d for the Matawan confining unit was obtained from a calibrated steady-state ground-water-flow model (Mack and Achmad, 1986). The thick (50-60 ft) clay beds of the Matawan Formation combined with the low vertical hydraulic conductivity result in an effective confining unit.

No data are available in the study area for vertical hydraulic conductivity of the Patapsco confining unit. Vertical hydraulic conductivity of this material determined by constant-flow and consolidation tests on a core sample taken at Annapolis (AA De 100) ranged from 1.08 x 10^{-5} to 7.36 x 10^{-6} ft/d (Mack, 1974, p. 16). The core sample consisted mostly of dense, reddish-brown clay, with some silt and fine sand. Mack and Mandle (1977, tab. 2) calculated vertical hydraulic conductivity of the Patapsco confining unit for sites in Calvert and Prince George's Counties using consolidation tests. Those values ranged from 2.7 x 10^{-6} to 5.9 x 10^{-7} ft/d.

GROUND-WATER USE

In 2000, ground water in Southern Anne Arundel County is mainly used for domestic purposes and withdrawn from individual, residential wells screened in the Aquia aquifer. Historically, water was probably supplied by shallow, dug wells completed in the Calvert, Nanjemoy, or Pleistocene Formations. In the early part of the 1900's, deeper drilled and driven wells of narrow diameter were constructed (Clark and others, 1918, p. 367). The Aquia aquifer was tapped most frequently by these wells, as indicated by H.P Little (1917, p. 132) in a Maryland Geological Survey report describing ground-water use in the Deale-Shady Side area, historically known as "The Swamp":

> "The waters of the Eocene [now considered Paleocene] are extensively utilized in the southern part of the county where these beds are covered by the younger formations and are not dissected by streams. Such an area is found in the general region of The Swamp....The water-bearing horizon seems to be about midway in the Aquia."

In the first half of the 1900's, population in Southern Anne Arundel County remained relatively constant at approximately 5,000 (Anne Arundel County Department of Planning and Code Enforcement, 2000) (fig. 11). The corresponding self-supplied water use at that time was probably less than 0.03 Mgal/d. The early wells supplied water primarily to farms and small fishing communities. Self-supplied water use probably increased during summer months in the first half of the 1900's with the growth of summer bay-side communities. Those withdrawals, however, are not represented in figure 11 because most of the growth consisted of seasonal use by non-residents that are unaccounted for in the population figures. During the second half of the 1900's many summer cottages were converted to year-round residences. Further growth occurred with the infilling of existing platted subdivisions and with the construction of new housing developments. In 2000, the population in Southern Anne Arundel County served by individual wells was approximately 26,400, and self-supplied water use was approximately 1.6 Mgal/d assuming a per capita water-use rate of 60 gallons per day (gal/d).

In 2000, the Aquia aquifer was still the primary source for self-supplied domestic wells in Southern Anne Arundel County. This conclusion is based on an examination of well-completion records maintained by the Maryland Department of the Environment. The altitudes of screened intervals of approximately 5,200 residential wells constructed between 1945 and 1997 were compared to altitudes of the Nanjemoy and Aquia aquifers. Well-screen depths reported in feet below land surface were adjusted to sea-level datum for comparison with the top and bottom altitudes of the aquifers. To reduce the error resulting from uncertainty in land-surface altitude, wells were selected in the Deale, Shady Side, Churchton, and Galesville areas where land-surface altitude is relatively uniform. The remaining areas in Southern Anne Arundel County were not included in the analysis because the error associated with estimating land surface altitude could be greater than the difference between depths of the Nanjemoy and Aquia aquifers. The analysis reveals that only 200 wells were screened in the Nanjemoy aquifer with the remaining wells (about 5,000) screened in the Aquia aquifer.

The Maryland Department of the Environment issues permits for the use of ground water for municipal, institutional, industrial, commercial, and agricultural purposes. A permit is also required for new subdivisions obtaining ground water from either a central supply or individual wells. This

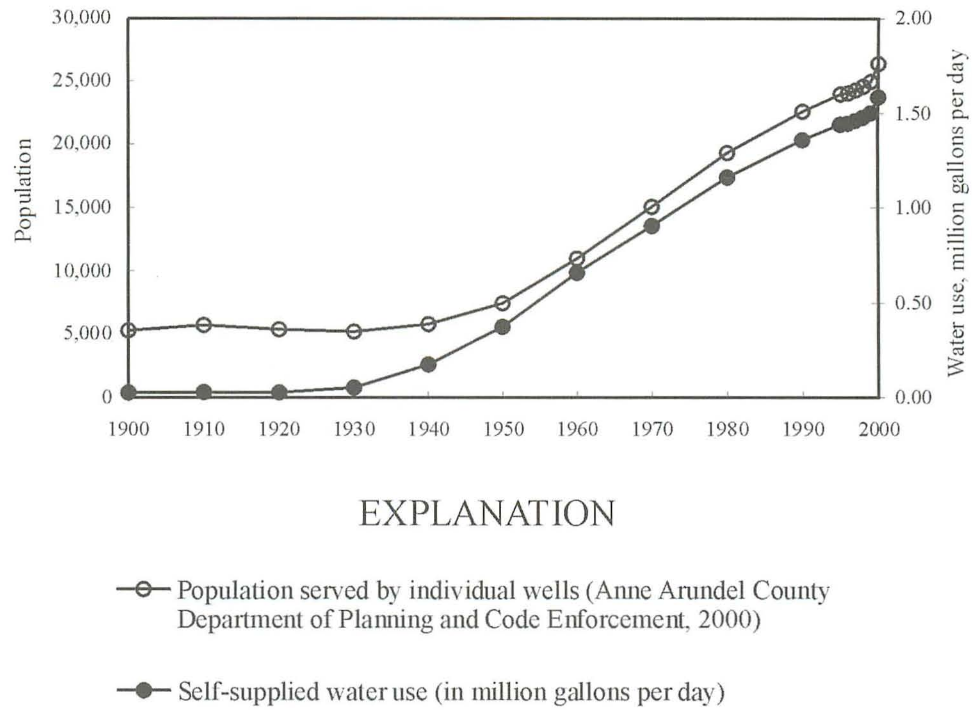


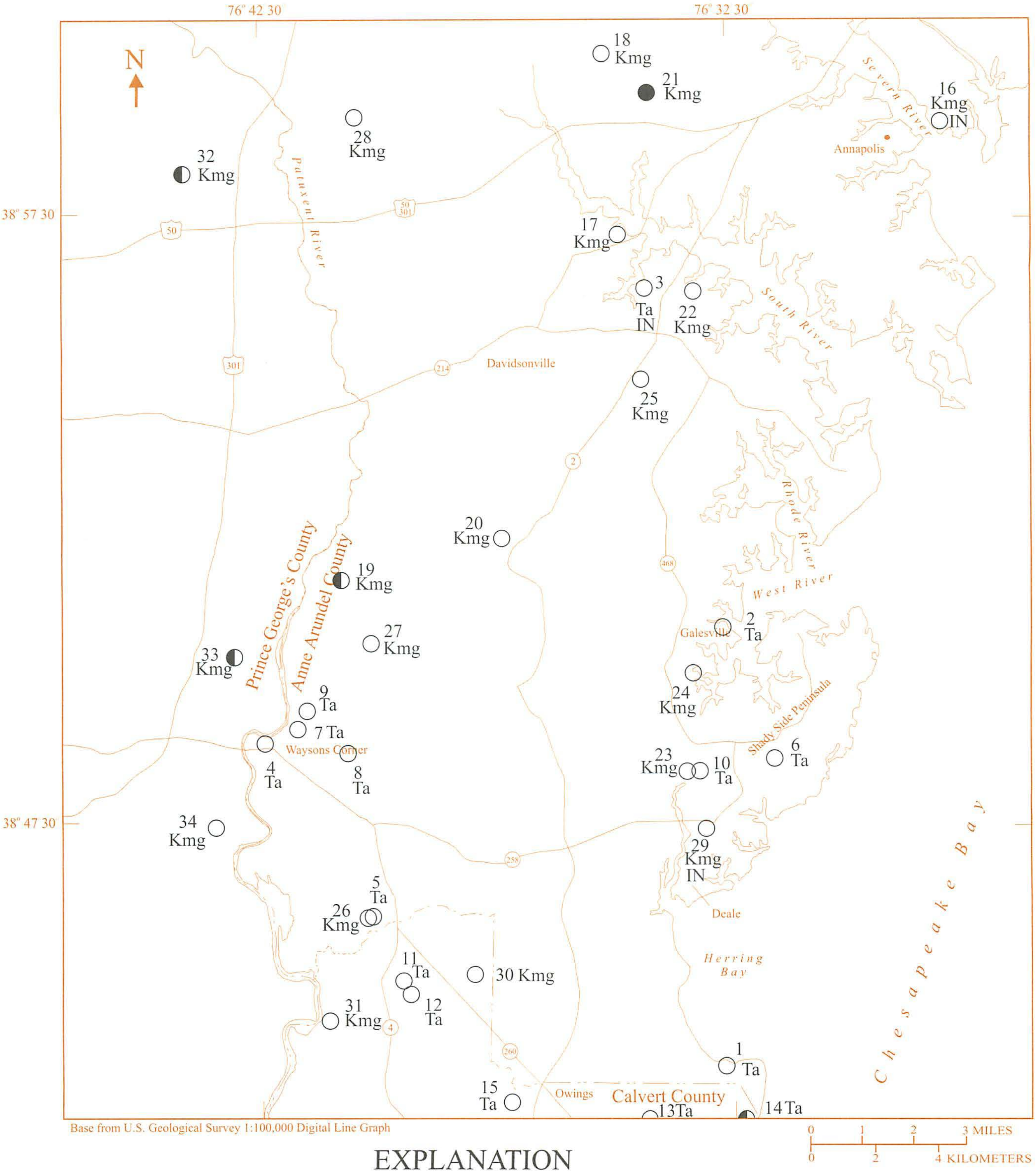
Figure 11. Self-supplied water use and population trends in Southern Anne Arundel County, 1900-2000.

department requires users of 0.01 Mgal/d or more to report monthly pumpage. In Southern Anne Arundel County, appropriation permits for approximately 0.4 Mgal/d have been issued for the Aquia aquifer (fig. 12; app. C.) to users of more than 10,000 gal/d. Reported withdrawals by those appropriated users totaled approximately 0.18 Mgal/d in 2000. Most of the appropriated usage in 2000 consisted of 0.17 Mgal/d from privately-owned public-supply wells, chiefly withdrawals for mobile-home parks. The remainder (0.012 Mgal/d) was pumped for sod-farm irrigation, commercial, and public-utility use. Most of the appropriated use in the Aquia aquifer occurred in the Deale-Shady Side and Waysons Corner areas (fig. 12). Within the ground-water-flow model area, an additional 0.3 Mgal/d from the Aquia aquifer has been appropriated to five users in northern Calvert County (app. C.). In 2000, these users pumped approximately 0.2 Mgal/d. Appropriated users of less than 10,000 gal/d are not required to report their pumpage; however, the amount pumped by these users is less than 5 percent of the total appropriated withdrawals (Judith Wheeler, U.S. Geological Survey, personal communication, 2002).

Appropriation permits totaling approximately 0.6 Mgal/d have been issued for the Magothy aquifer in Southern Anne Arundel County to users of more than 10,000 gal/d (fig. 12; app. C.). Reported withdrawals by those appropriated users totaled approximately 0.22 Mgal/d in 2000. The pumpage was divided between 0.16 Mgal/d for public supply at mobile-home parks and 0.06 Mgal/d for sod-farm and golf-course irrigation. Within the ground-water-flow model area, an additional 3.0 Mgal/d from the Magothy aquifer has been appropriated to users in central Anne Arundel County, Prince George's County, and northern Calvert County (app. C.). Most of that amount is for public supplies at the City of Annapolis and Marlboro Meadows. In 2000, these users pumped approximately 2.3 Mgal/d.

Appropriation permits for the Nanjemoy aquifer totaling approximately 0.0041 Mgal/d in 2000 have been issued to five small commercial users in Southern Anne Arundel County (Cynthia Latham, Maryland Department of the Environment, personal communication, 2001).

Use of the deeper Patapsco aquifers in Southern Anne Arundel County is limited to two irrigation wells at Old South County Country Club near Waysons Corner (GAP AA1989G041), and one public-supply well at Maryland Manor Mobile Home Park (GAP AA1999G041). Wells at both of



EXPLANATION

Well or well field. Number next to symbol is the site identifier (see Appendix C).

25 ○ 10,000 to 100,000 gallons per day ◐ 100,000 to 1,000,000 gallons per day ● Greater than 1,000,000 gallons per day

Kmg -- Magothy aquifer; Ta -- Aquia aquifer; IN -- Appropriation permit inactive

Figure 12. Location of wells and well fields appropriated for greater than 10,000 gallons per day in the Aquia and Magothy aquifers in 2000.

these sites are screened in the Upper Patapsco aquifer, which underlies the Magothy aquifer. Pumpage from the Upper Patapsco aquifer at Old South County Country Club is typically less than 10,000 gal/d. Use of the Upper Patapsco well at Maryland Manor Mobile Home Park has been sporadic because of problems associated with treating the high iron concentrations.

WATER-LEVEL TRENDS

Aquifer water levels provide important information regarding the direction of ground-water flow and the effect that stresses, such as changes in recharge rates and withdrawals, have on the ground-water-flow system. Trends associated with these stresses can be determined by systematically monitoring water levels. This information can be used to develop and assess ground-water management strategies.

In the early 1900's, wells screened in the Aquia aquifer flowed in topographically low (less than about 10 ft above sea level) areas of Southern Anne Arundel County (Clark and others, 1918). The natural flow rates were generally adequate for domestic supply. The early wells were typically constructed using 1½-in. steel casing. Wells were equipped with suction pumps as flow rates diminished in response to decreased hydraulic pressure in the aquifer caused by withdrawals. The last evidence of a naturally flowing well screened in the Aquia aquifer was recorded at Deale in 1962. Between 1978 and 2001, water levels declined in the Aquia aquifer at rates ranging from 0.2 ft/yr at Waysons Corner to 1.4 ft/yr at Tracy's Landing (fig. 13). In northern Calvert County at Paris Oaks, the rate of decline was about 2 ft/yr (fig. 13). Water levels declined at a rate of approximately 1 ft/yr in the Deale-Shady Side area and about 0.3 ft/yr at Davidsonville near the outcrop area. The increase in the rate of decline southward is attributed in part to pumpage in Southern Maryland (Curtin and others, 2001c). Aquia water levels also exhibit an increasing seasonal fluctuation caused by increased water use. Water levels decline during the summer and fall when water use is more intensive, and rise during the winter and spring. The seasonal decline in water level may be accentuated during periods of drought as water use increases. The maximum lift capacity of suction pumps (approximately 30 ft) was exceeded in many areas as water levels declined in Southern Anne Arundel County. This resulted in a series of well failures in the Deale-Shady Side area during the 1980's. Wells constructed using 4-in. upper casings and 2-in. lower casings (so-called telescope wells) also failed when their submersible pumps could not be lowered below the constriction. The water-level trend on Mayo Peninsula as illustrated in well AA Ef 17 is flat because the Aquia aquifer is under water-table conditions in this area and is recharged rapidly from direct infiltration (fig. 13).

The potentiometric surface of the Aquia aquifer during the fall of 2000 is shown in figure 14. The potentiometric surface is the altitude to which water levels will rise in wells tapping a confined (artesian) aquifer. The highest water levels occur in the Davidsonville area near the outcrop area. Water levels in that area were as high as 64 ft above sea level. The potentiometric surface decreases southward toward Calvert County. The deepest water level measured in Southern Anne Arundel County was 35 ft below sea level at Rose Haven. Water levels in the Deale-Shady Side area range from approximately 10 to 30 ft below sea level.

Between 1970 and 2001, water levels declined in the Magothy aquifer at rates ranging from approximately 0.7 ft/yr at Harwood to 0.9 ft/yr at Shady Side (fig. 15). The decline is probably caused by a regional lowering of water levels associated with pumpage in central Anne Arundel and northern Charles Counties (Curtin and others, 2001d). The rate of decline was 1.2 ft/yr in northern Calvert County at Chaney and 1 ft/yr in the eastern part of Prince George's County at Patuxent River Park. At Rutland Road near U.S. Route 50, approximately 6 mi southeast of the outcrop area of the Magothy aquifer, the rate of decline was 0.6 ft/yr. Long-term water-level records in the Magothy aquifer in the Annapolis area show a relatively flat trend (Andreasen and Fewster, 2001). Water levels measured in the Magothy aquifer at the City of Annapolis well field (observation well AA De 1), while responding to short-term pumping cycles, have been in equilibrium with respect to pumpage over the observation period 1970 to 2001 (fig. 15). Withdrawals from the Magothy aquifer by the City of Annapolis averaged approximately 3 Mgal/d between 1970 and 1985 and 1.8 Mgal/d between 1986 and 2002. A flowing well (AA Fe 47) screened in the Magothy aquifer at Shady Side ceased to flow in 1980 as a result of declining water levels (fig. 15).

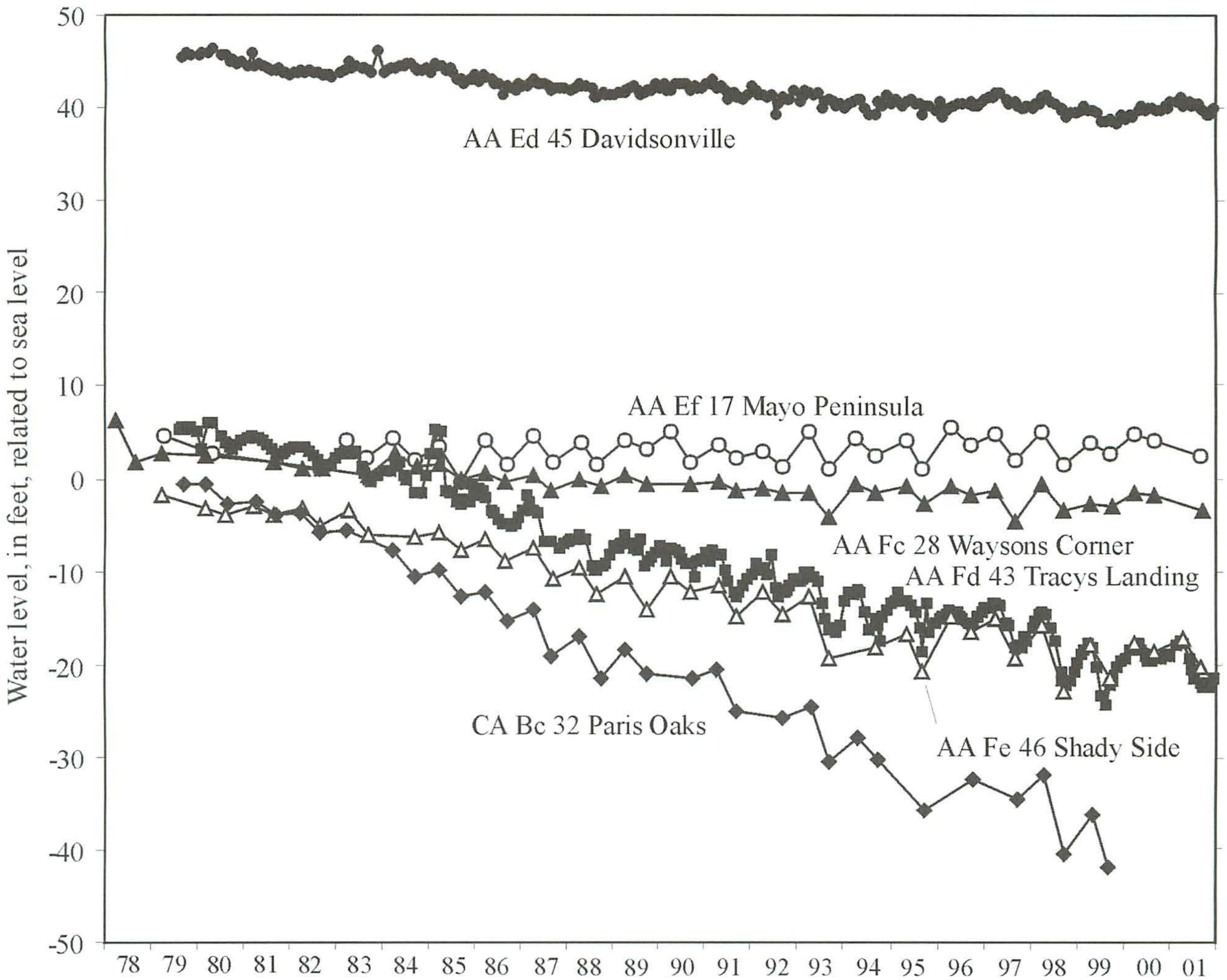
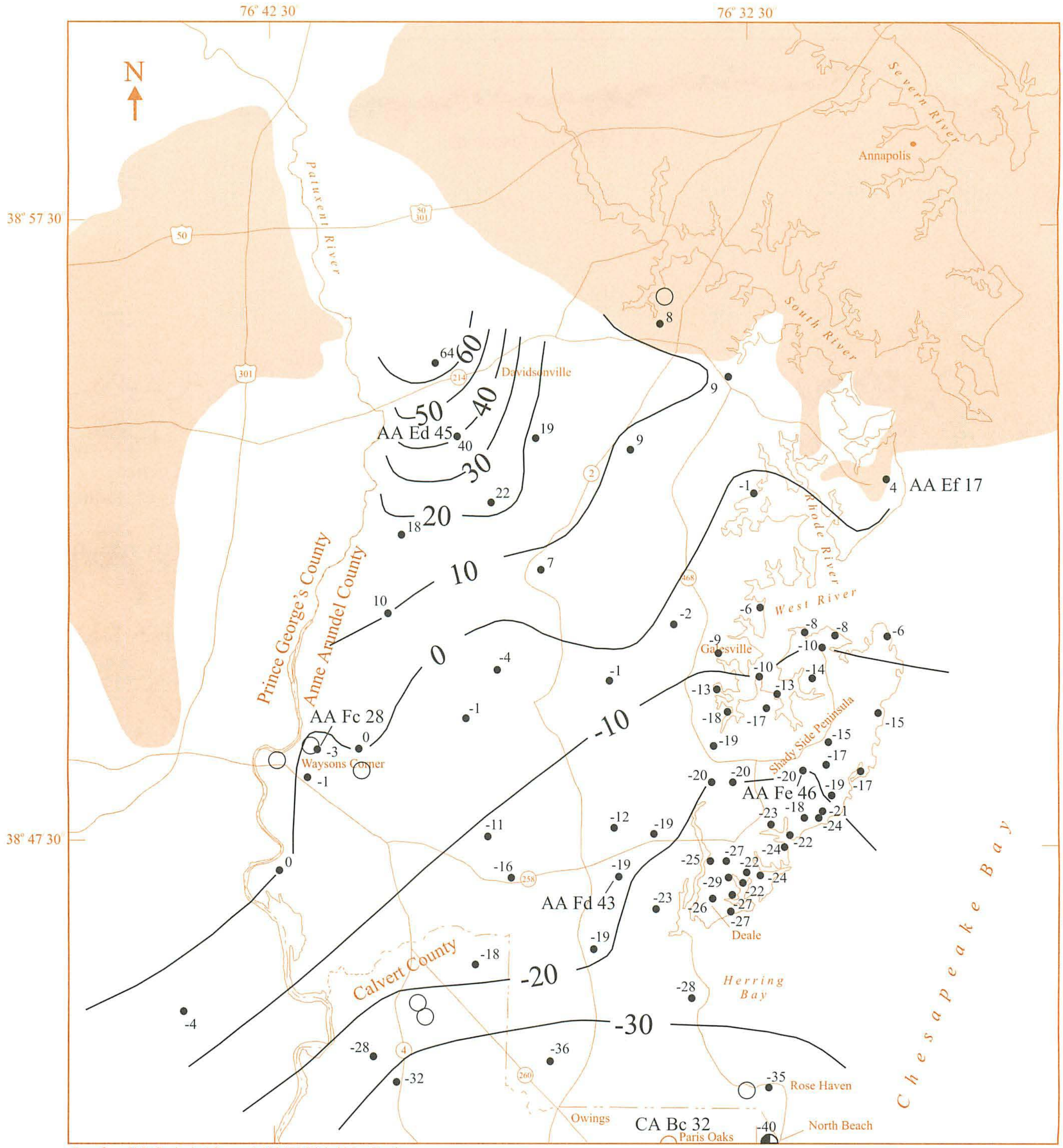


Figure 13. Water-level trends in the Aquia aquifer, 1978-2001.

The potentiometric surface of the Magothy aquifer in 2000 ranged from 7 ft above to 10 ft below sea level in Southern Anne Arundel County (fig. 16). The highest water levels in the surrounding area were at the City of Bowie well field in Prince George's County. From that point the potentiometric surface decreases toward the east-southeast. The deepest water level was 13 ft below sea level at the City of Annapolis well field which pumped 1.7 Mgal/d in 2000. In Southern Anne Arundel County, water levels are above sea level in the area between Davidsonville and Waysons Corner and below sea level southeast of that area.

Water levels in the Aquia aquifer in the fall of 2000 were 10 to 20 ft deeper than water levels in the Magothy aquifer in the southern part of the study area and as much as 50 ft higher near the outcrop area of the Aquia aquifer north of Davidsonville (figs. 14 and 16).

Water levels in the Aquia and Magothy aquifers were monitored continuously between April 2000 and March 2002 at the four test-well sites located at Davidsonville, Deale, Franklin Point Park (Shady Side), and Waysons Corner (figs. 1 and 17). Water levels were also recorded in the Magothy aquifer at an additional site ("Safeway site") at Deale. The location of that well (AA Fe 56) is shown on plate 1.



0 1 2 3 MILES
0 2 4 KILOMETERS

EXPLANATION

GENERALIZED OUTCROP AREA OF THE AQUIA FORMATION--Modified from Glaser (1976)

-10 — POTENTIOMETRIC SURFACE -- Shows approximate altitude of water level, in feet related to sea level. Contour interval 10 feet.

-4 ● OBSERVATION WELL -- Number is water level in feet related to sea level.

PRODUCTION WELL

○ 10,000 to 100,000 gallons per day

◐ 100,000 to 1,000,000 gallons per day

AA Ed 45 -- Observation well with hydrograph shown in figure 13.

Figure 14. Altitude of the potentiometric surface of the Aquia aquifer during the fall, 2000.

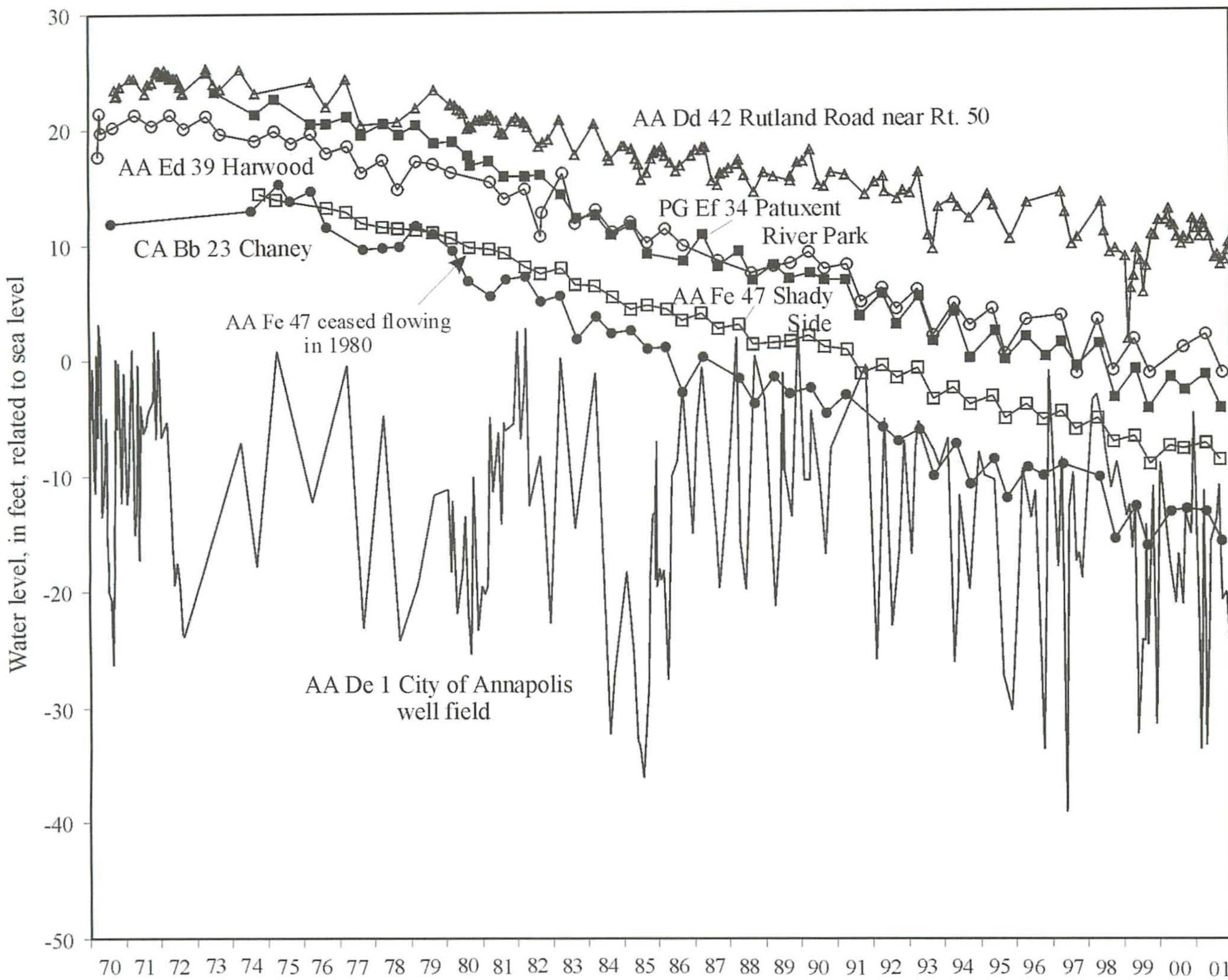
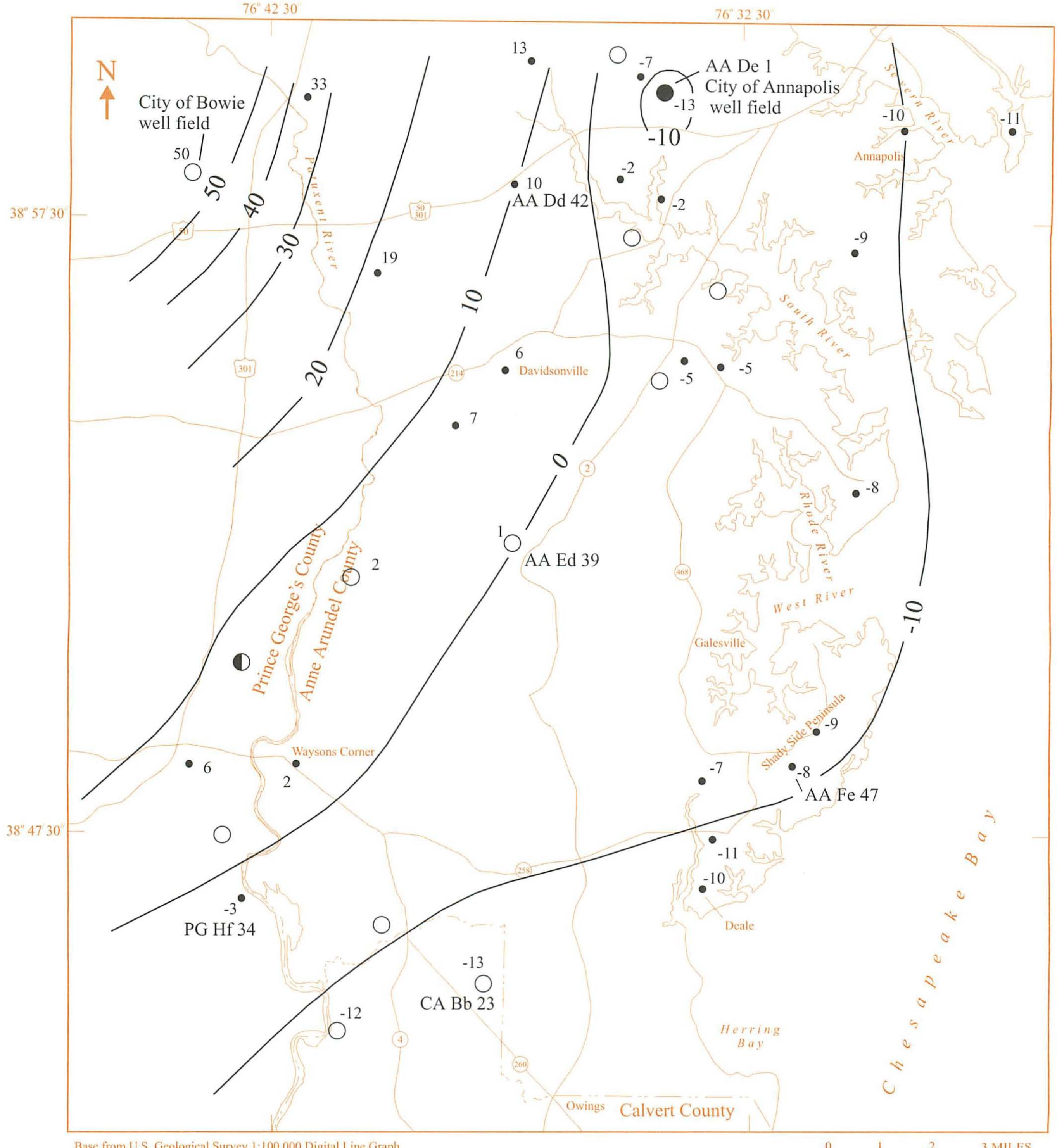


Figure 15. Water-level trends in the Magothy aquifer, 1970-2001.

Water levels in the Aquia aquifer at Davidsonville were stable during the period of record in AA Ed 45. This site is near the recharge area of the Aquia aquifer. Prior to about 1980, the Aquia aquifer at this location was an artesian aquifer, but since that time, water levels have fallen below the top of the aquifer, resulting in water-table conditions. Water levels in the Aquia aquifer at Deale and Franklin Point Park showed a gradual rise during the spring of 2001 and a decline extending from early summer to fall of 2001. These changes are probably caused by seasonal fluctuations in withdrawals. Water levels in the early part of 2002 did not fully recover to the levels of the prior year. The water-level trend in the Aquia aquifer at Waysons Corner was flat during the period of record. Water levels in the Magothy aquifer show a downward trend during the second half of 2001. This decline is likely a result of the regional lowering of water levels caused by withdrawals in central Anne Arundel and northern Charles Counties. Local pumping also causes water levels to decline. For instance, water-level declines of approximately 2 ft in wells AA Fe 51 (Franklin Point Park) and AA Fe 56 ("Safeway site" at Deale) were a result of pumping a Magothy production well at Shady Oaks Sod Farm during the late fall of 2002.



EXPLANATION

-10 POTENTIOMETRIC SURFACE -- Shows approximate altitude of water level, in feet related to sea level. Contour interval 10 feet.

•-3 OBSERVATION WELL -- Number is water level in feet related to sea level

PRODUCTION WELL

25 ○ 10,000 to 100,000 gallons per day ◐ 100,000 to 1,000,000 gallons per day ● Greater than 1,000,000 gallons per day

AA Ed 39 -- Observation well with hydrograph shown in figure 15.

Figure 16. Altitude of the potentiometric surface of the Magothy aquifer during the fall, 2000.

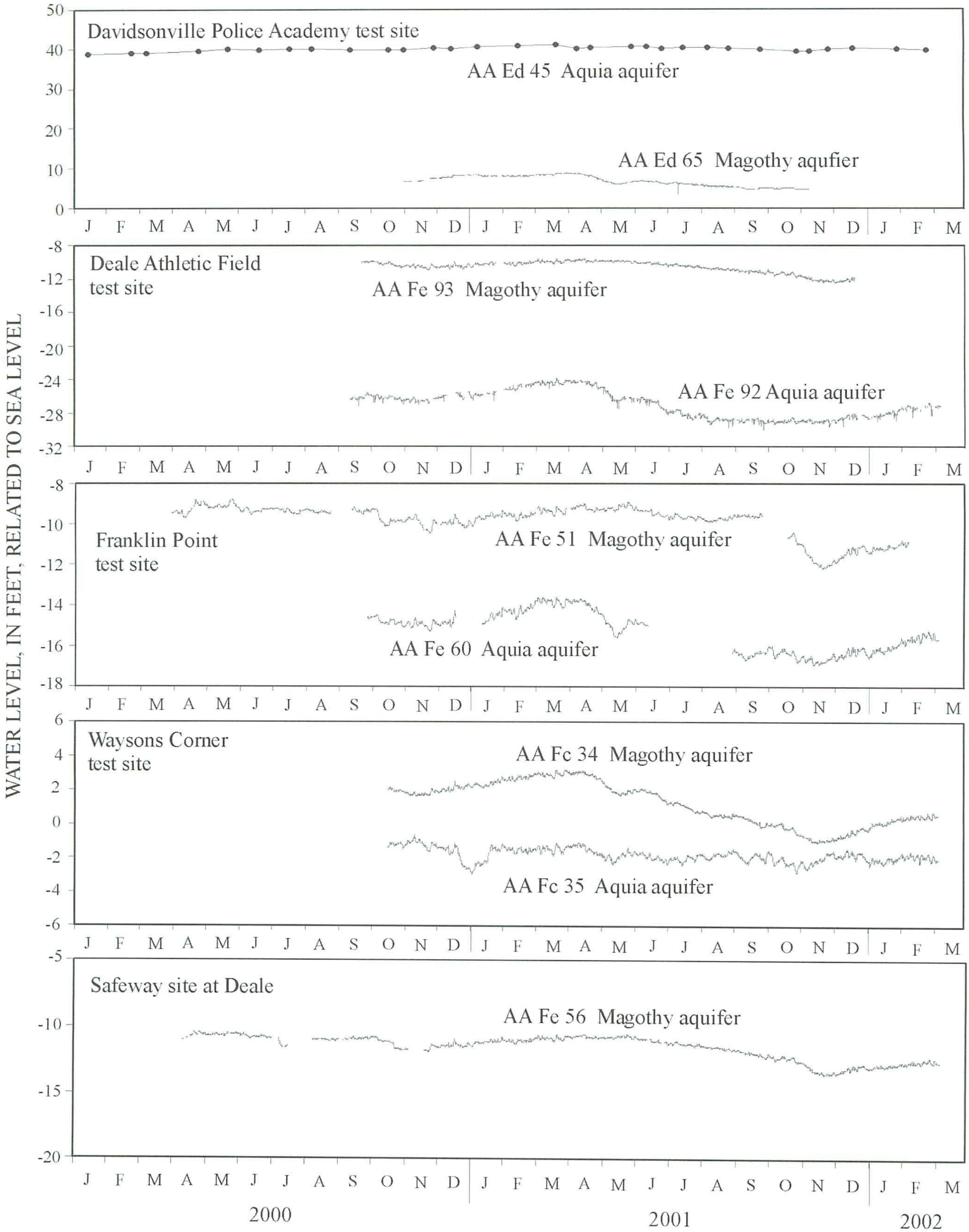


Figure 17. Water levels in the Aquia and Magothy aquifers in Southern Anne Arundel County, 2000-2002.

EFFECTS OF WITHDRAWALS FROM IRRIGATION WELLS

The effect of withdrawals from irrigation wells on water levels in the Aquia and Magothy aquifers was determined at two sites—Central Sod Farm near Deale and Shady Oaks Sod Farm near Galesville. Although water use at those sites has accounted for less than 5 percent of the total water pumped in Southern Anne Arundel County, the relatively high short-term pumping rates occurring during the growing season has caused concern to local residents with private wells. Water levels were monitored during the 2000-01 period. Rainfall during the growing season within that period was about normal.

Central Sod Farm is supplied by one well screened in the Aquia aquifer (AA Fe 61). Another supply well (AA Fe 54) screened in the Magothy aquifer has not been used since 2001. The first reported pumpage from the Aquia aquifer was 0.039 Mgal/d in 1993. Pumpage since that time has varied from 0 to 0.033 Mgal/d. Water levels were monitored in the Aquia production well (AA Fe 61), Magothy production well (AA Fe 54), and a nearby farm well (AA Fe 95) from July 2000 to October 2001. Well AA Fe 95, which is approximately 1,200 ft from the Aquia production well, was equipped with a continuous water-level recorder (fig. 18). During the period of observation, the irrigation well cycled on and off from October through November 2000 and from May through August 2001. The well pumped at a reported rate of approximately 100 gal/min. Water levels in the Aquia aquifer at AA Fe 95 declined approximately 4 ft due to pumping at the production well. After each pumping period, water levels in the observation well recovered nearly to levels measured prior to pumping. Pumping from the production well during May 2001 caused water levels to decline in the Aquia aquifer approximately 1 ft at observation wells in Deale (AA Fe 92) and Franklin Point Park (AA Fe 60), located approximately 2 mi from the production well (fig. 17). Water levels in the Aquia aquifer did not respond to pumpage from the Magothy aquifer. The frequent downward spikes in water levels in AA Fe 95 were caused by cycling of the pump in that well. During the observation period the Magothy production well was not pumped. Water levels in the Magothy aquifer are not affected by pumpage from the Aquia aquifer. The overall water-level trends in both the Aquia and Magothy aquifers are similar to water-level trends observed at other locations in the study area.

The effect of pumping the Magothy aquifer at Shady Oaks Sod Farm was observed for a 20-month period (fig. 19). An irrigation well (AA Fe 55) screened in the Magothy aquifer was pumped twice during the observation period at approximately 120 gal/min for a total withdrawal of approximately 6 million gallons. Water levels were measured periodically in the production well and in a residential well (AA Ee 96) screened in the Aquia aquifer located at a distance of 900 ft from the production well. Water levels in the production well ranged from about 3 ft above sea level to 55 ft below sea level. Water levels measured in pumping wells are typically lower than the water level in the aquifer immediately outside the well due to inefficiency of the well. Pumpage at this site caused water levels to decline in the Magothy aquifer approximately 2 ft at observation wells in Deale and Shady Side, located approximately 4 and 3.5 mi from the production well, respectively. Water levels in the Aquia aquifer did not respond to pumpage from the Magothy aquifer during the period of record (fig. 19).

AVAILABLE DRAWDOWN

Regulatory guidelines established by the Maryland Department of the Environment to protect aquifers from overpumping limit the drawdown caused by appropriated ground-water use. Although this department does not issue water appropriation permits for individual domestic use, permits are required for new subdivisions of 10 homes or more. Under the regulatory guidelines, drawdown resulting from appropriated ground-water use cannot exceed a prescribed management level (Code of Maryland Regulations, 1997). The management level is defined as 80 percent of the difference between the estimated pre-pumping potentiometric surface and the top of the aquifer (fig. 20). The available drawdown at any point in time at a specific location is the difference between the 80-percent management level and the water level measured at that time. The 80-percent management rule is applied to the regional water level in an aquifer (Cynthia Latham, written communication, 2002). "Regional" is defined as "an area in which water is appropriated or used from multiple wells located in a common source, or that location which, as a result

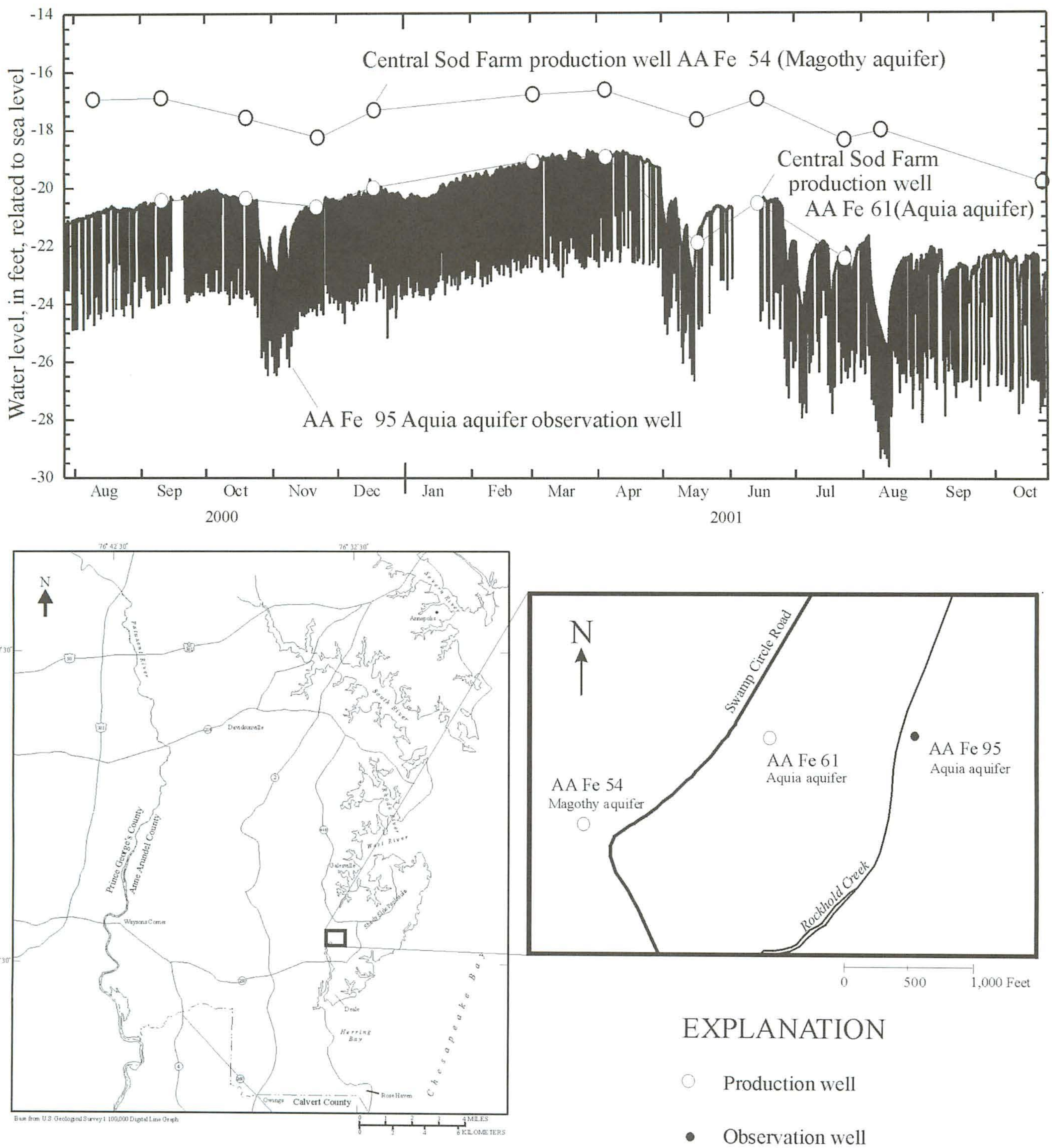


Figure 18. Water levels in the Aquia and Magothy aquifers at Central Sod Farm.

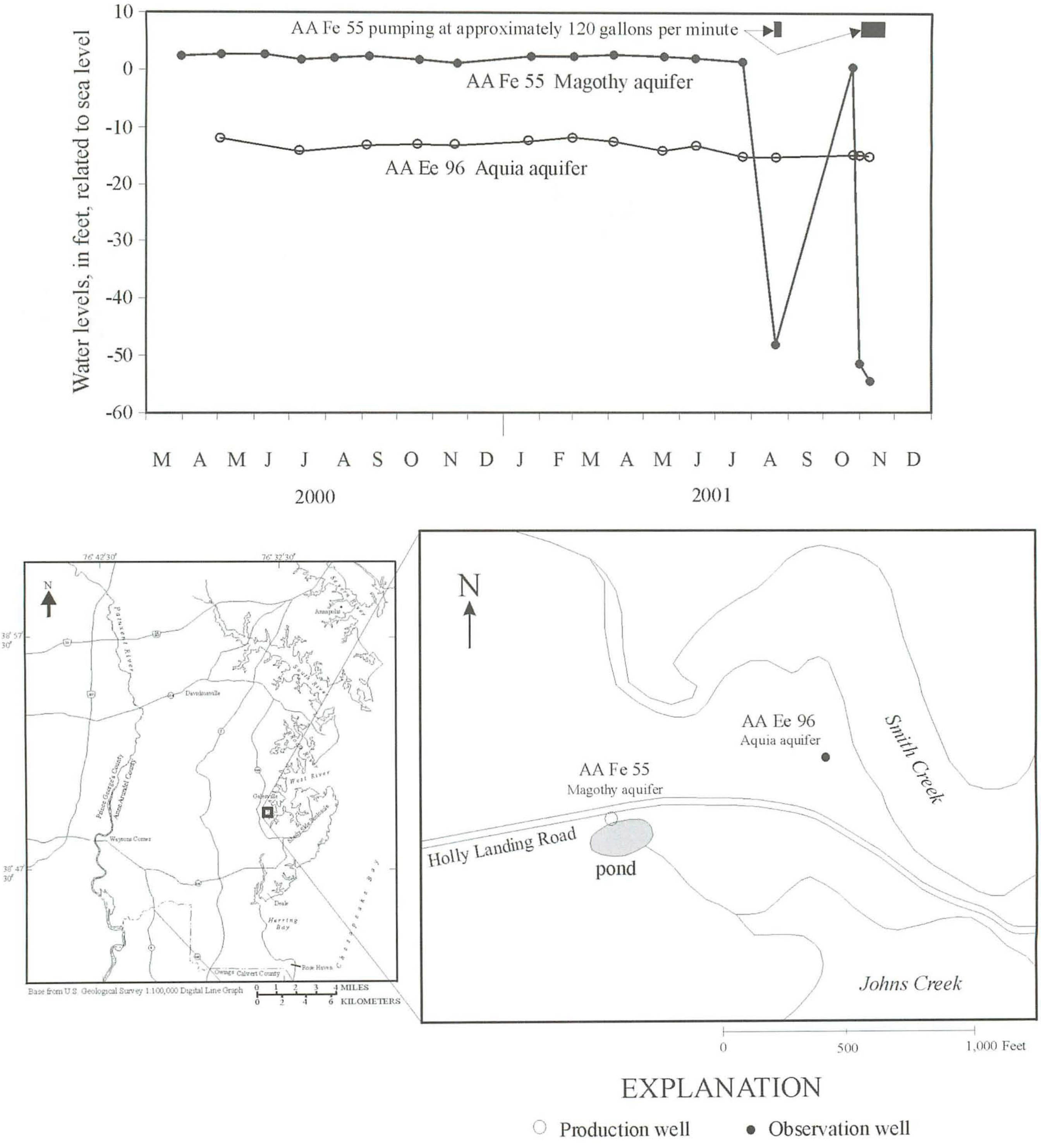


Figure 19. Water levels in the Aquia and Magothy aquifers at Shady Oaks Sod Farm.

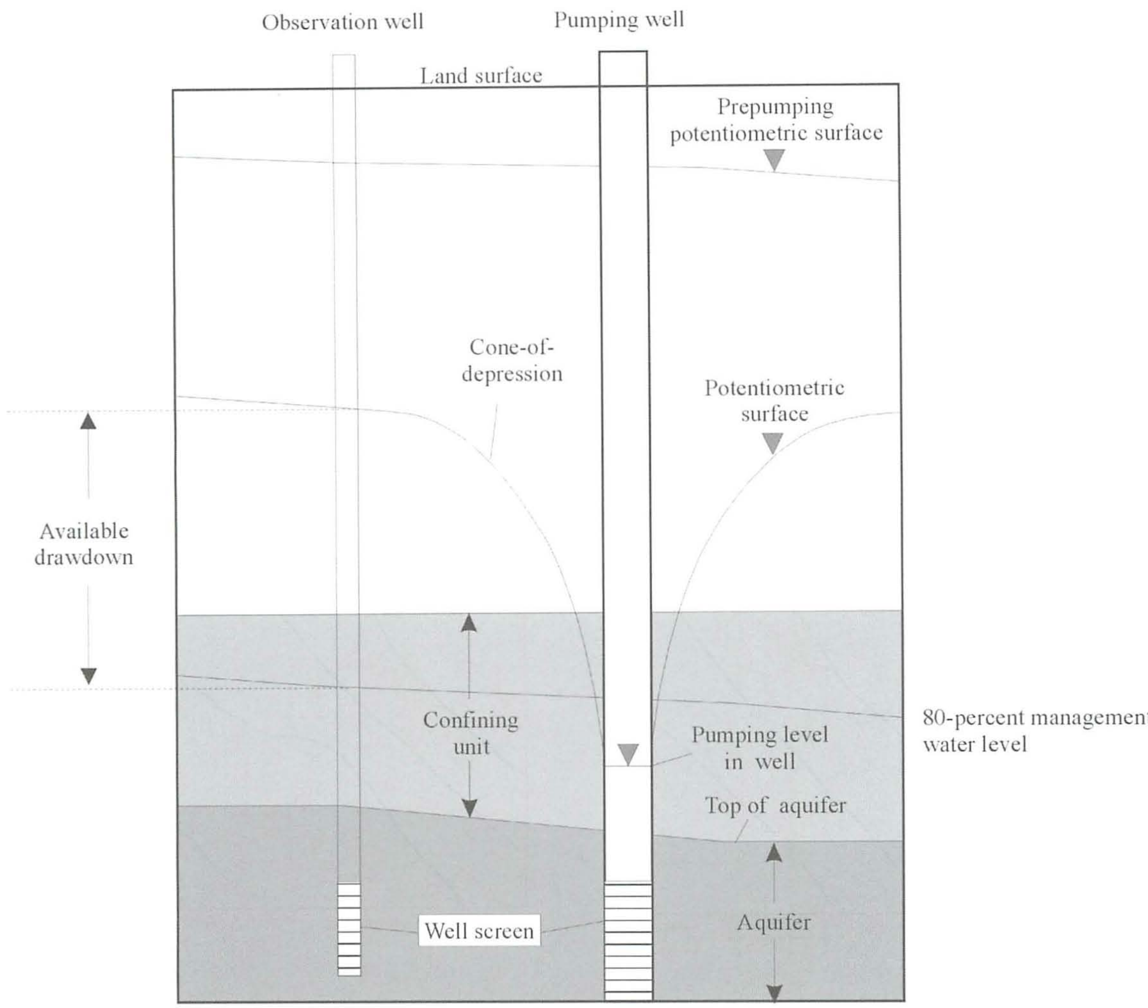
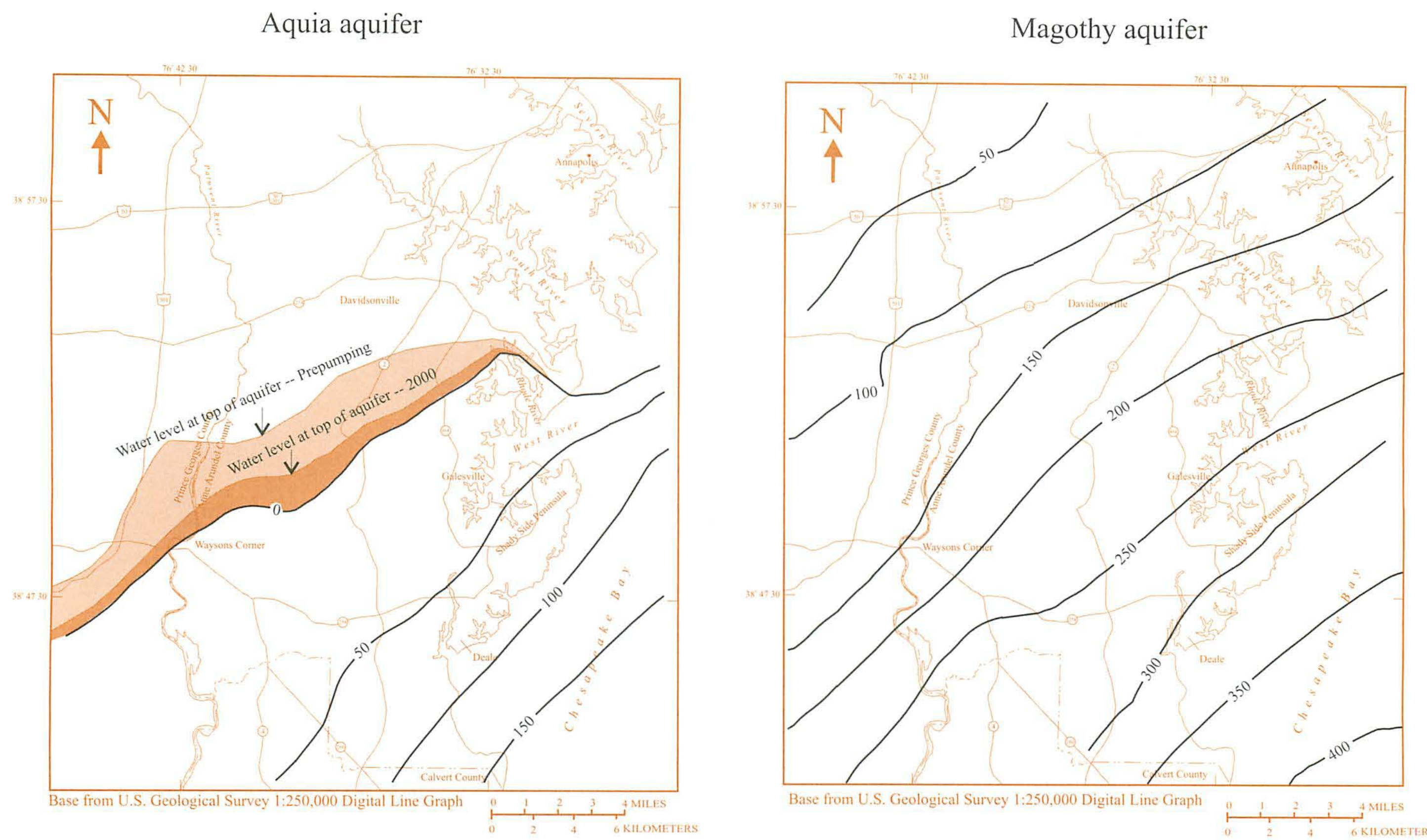


Figure 20. Schematic defining available drawdown and 80-percent management water level.

of the appropriation, is 50 percent of the distance from a single well to a point where the potentiometric surface is lowered one foot, and has stabilized" (Code of Maryland Regulations, 1977). It is possible, therefore, that water levels may decline below the 80-percent management level in the immediate vicinity of a pumping well (fig. 20) without the rule being invoked. In cases where the regional water level exceeds the 80-percent management level, the Maryland Department of the Environment may establish a water-management zone in which no new wells may be drilled to the aquifer being protected.

Available drawdown in the Aquia aquifer under pre-pumping conditions ranged from 0 ft in the Davidsonville area where the aquifer is under water-table conditions to as much as 200 ft at Rose Haven. In the Deale-Shady Side area, available drawdown ranged from 75 to 100 ft. The available drawdown in the Aquia aquifer in 2000 ranged from 0 ft in the central part of Southern Anne Arundel County to 150 ft at Rose Haven (fig. 21). Available drawdown in the Deale-Shady Side area ranged from about 50 to 90 ft. Since pumping began in the Aquia aquifer, water levels exceeded the 80-percent management level within a 2-mi-wide band in the central part of Southern Anne Arundel County (fig. 21). Water levels within more than half of that area were below the top of the aquifer.

Figure 22 shows a cross-sectional view of water levels in the Aquia aquifer through Southern Anne Arundel County based on an estimated pre-pumping



EXPLANATION

150 — Available drawdown, in feet. Contour interval is 50 feet.

Area where water level fell below the top of aquifer by 2000.

Area where drawdown exceeded the 80-percent management level in 2000.

Figure 21. Available drawdown in the Aquia and Magothy aquifers in 2000.

potentiometric surface, and the measured 1980 (Chapelle and Drummond, 1983) and 2000 (Curtin and others, 2002) potentiometric surfaces. The figure illustrates the amount of drawdown that has occurred since pumping began and its relation to the top of the Aquia aquifer. Near the recharge area water levels declined below the top of the aquifer between 1980 and 2000.

Available drawdown in the Magothy aquifer under pre-pumping conditions ranged from about 150 ft in the Davidsonville area to 400 ft at Rose Haven. In the Deale-Shady Side area, available drawdown was approximately 300 to 350 ft. In 2000, available drawdown in the Magothy aquifer had been reduced by approximately 20 to 40 ft since pre-pumping conditions. Available drawdown in 2000 ranged from approximately 125 ft in the Davidsonville area to 360 ft at Rose Haven (fig. 21).

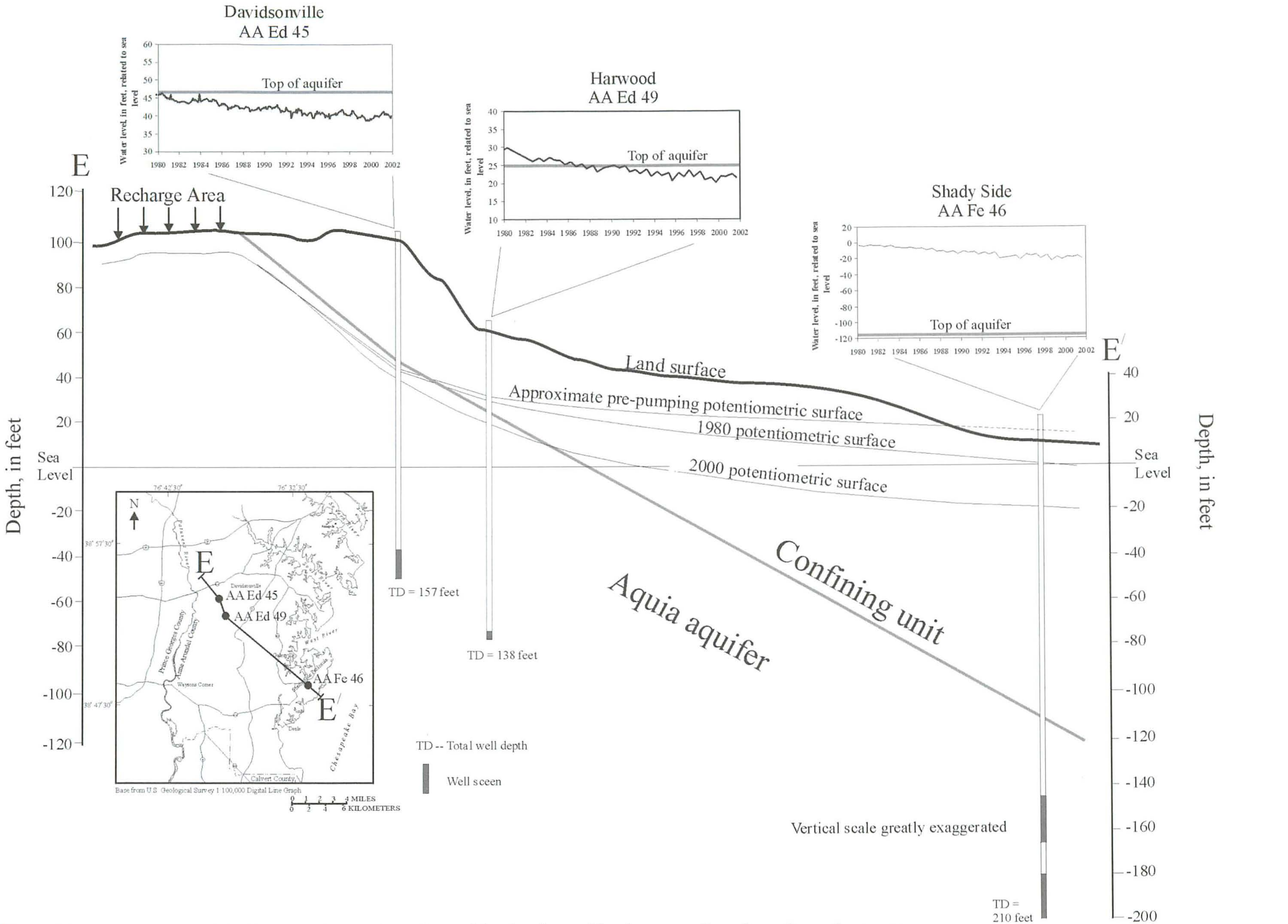


Figure 22. Downward trend in the potentiometric surface of the Aquia aquifer down-gradient from the recharge area.

WATER QUALITY

Water samples collected from 18 residential wells, 3 Aquia test wells, and 3 Magothy test wells were analyzed for: (1) major inorganic constituents; (2) gross alpha- and beta-particle activity; (3) arsenic; and (4) nitrate (app. H.). The purpose of sampling was to characterize the natural water quality. Natural water types were identified using a trilinear diagram. On this diagram, the percent composition of cations and anions for multiple samples is plotted on the sides of the two triangles. The intersection of these points on the diamond grid represents the water type defined by the dominant ions. Bicarbonate concentrations were computed for samples without direct laboratory determinations by multiplying the alkalinity (acid neutralizing capacity) by a factor of 1.22.

AQUIA AQUIFER

Water produced from the Aquia aquifer is predominantly a calcium bicarbonate type. A trilinear diagram of the dominant ionic constituents illustrates the water type (fig. 23). Generally, water produced from the Aquia aquifer is acceptable for domestic use with the possible exceptions of hardness, elevated iron and manganese concentrations, and hydrogen sulfide. These constituents do not pose health risks, but are aesthetically undesirable, as they affect both taste and appearance of the water. The pH of water produced from the Aquia aquifer ranged from 7.3 to 8.0.

The Aquia aquifer commonly contains layers of weathered shell. Dissolution of the shell material by interaction with the ground water releases calcium, magnesium, and carbonate ions. These ions are the main contributors to hardness. The term "hardness" refers to the ability of water to inhibit the formation of soap lather and to promote the formation of a white insoluble scale resulting from the heating of water. The range of hardness can be classified as soft (0-17 milligrams per liter [mg/L]), slightly hard (17-60 mg/L), moderately hard (60-120 mg/L), hard (120-180 mg/L), and very hard (greater than 180 mg/L) (Lehr, and others, 1988, p. 64). Hardness is expressed in terms of equivalent calcium carbonate. The range of hardness of water sampled from the Aquia aquifer was 112 to 275 mg/L, with a median value of 133 mg/L. Hardness was estimated by multiplying the combined calcium and magnesium concentrations by a factor of 2.6. The conversion factor was derived from the ratio of hardness to calcium plus magnesium concentration in water produced from the Aquia aquifer on Annapolis Neck and Mayo Peninsula (Fleck and Andreasen, 1996). Water with hardness values greater than 100 mg/L generally requires treatment for domestic use. Treatment typically involves exchanging calcium and magnesium for sodium in an ion-exchange water softener.

Iron concentrations in water from the Aquia aquifer in Southern Anne Arundel County ranged from 0.15 to 4.5 mg/L with a median value of 0.4 mg/L. The distribution of iron in Southern Anne Arundel County is shown on the map in figure 24. Both dissolved and total iron concentrations are shown on the map. The map includes sites sampled during this study and 10 additional sites sampled in earlier investigations, some located north of the study area. Water-quality data for these sites are stored in the U.S. Geological Survey's NWIS. In the outcrop area north of the study area, iron concentrations are as high as 41 mg/L, which Rabenhorst and Fanning (1989) attribute to acidic conditions caused by pyrite (FeS_2) oxidation. Concentrations are generally less than 0.5 mg/L throughout most of Southern Anne Arundel County with the exception of the Deale-Shady Side area and the Davidsonville-Harwood area, where levels exceed 1 mg/L. Eight of the 30 wells in Southern Anne Arundel County contain iron concentrations at levels less than the U.S. Environmental Protection Agency's (USEPA) Secondary Maximum Contaminant Level (SMCL) of 0.3 mg/L (U.S. Environmental Protection Agency, 1992). Elevated manganese concentrations are often associated with elevated iron concentrations. Dissolved manganese concentrations ranged from 0.002 to 0.057 mg/L. The federal recommended limit is 0.05 mg/L. Elevated iron and manganese concentrations cause red and black staining, respectively, on plumbing fixtures and clothing.

A common complaint of water produced from the Aquia aquifer is the presence of a "rotten-egg" or "swampy" odor emitted by hydrogen sulfide gas. Hydrogen sulfide can be produced naturally in aquifers by decomposition of organic matter by

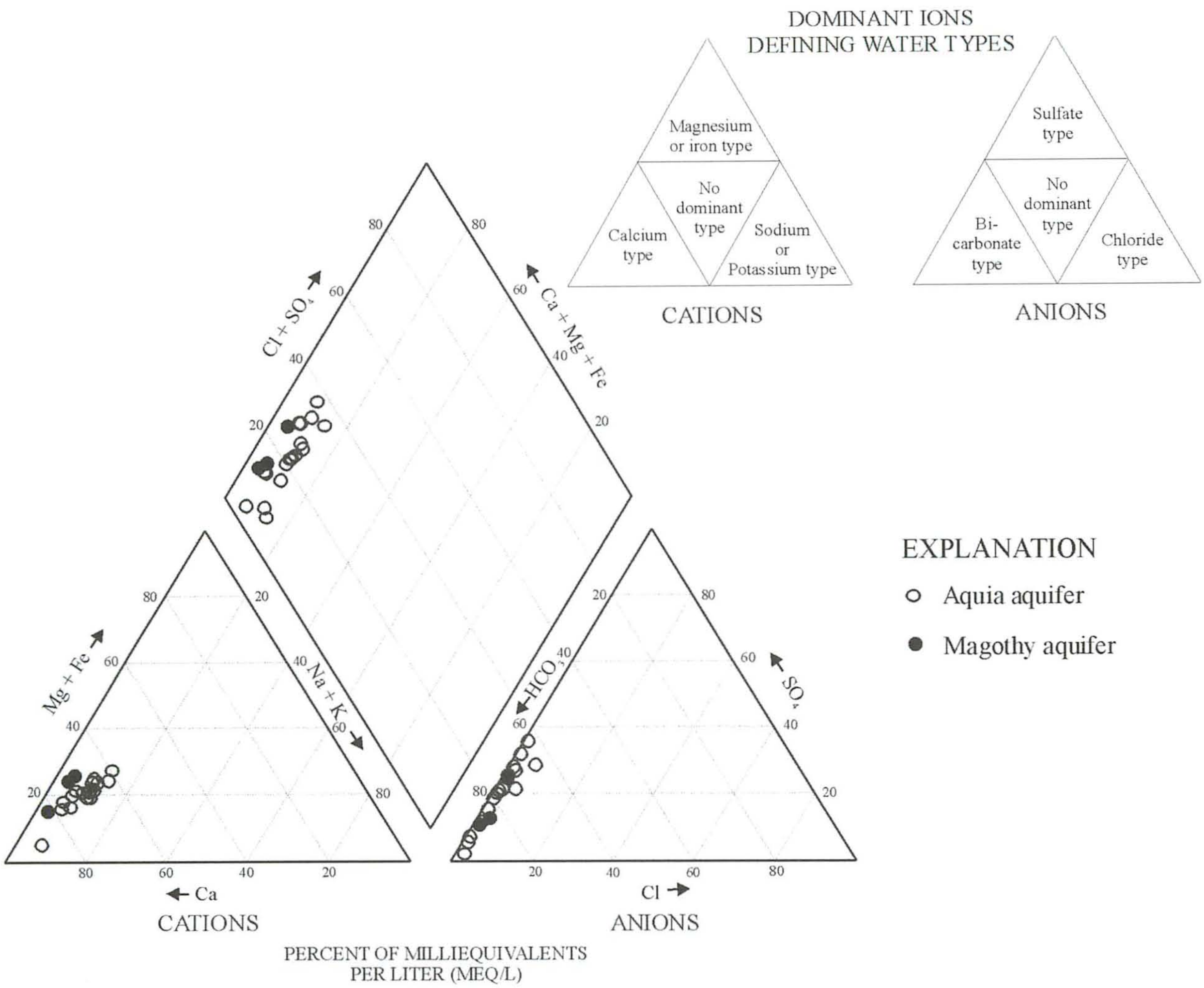
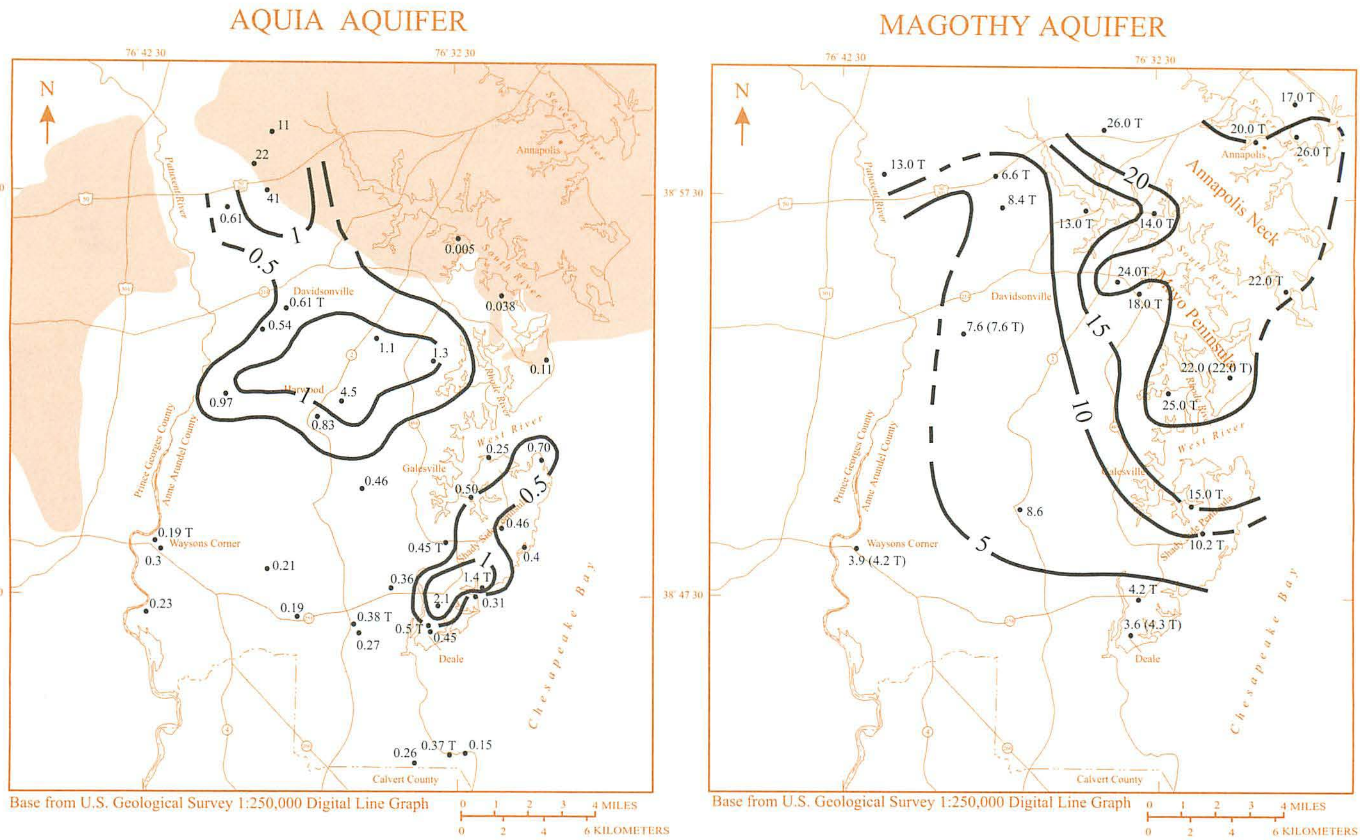


Figure 23. Trilinear diagram showing dominant inorganic chemical constituents in water from the Aquia and Magothy aquifers in Southern Anne Arundel County.

sulfate-reducing bacteria (Langmuir, 1997, p. 451). Anaerobic chemical environments within the well and plumbing systems may also provide favorable conditions for production of hydrogen sulfide (Lin, 1977, p.12). The magnitude and distribution of hydrogen sulfide in the Aquia aquifer varies widely, based on anecdotal evidence from homeowners supplied by individual wells. The most common means of reducing hydrogen sulfide is through filtration with activated carbon and periodic well chlorination (Lehr and others, 1988).

Residential water-treatment systems are commonly used to reduce hardness, and elevated iron and manganese concentrations. Treated water samples were collected from three residential wells—AA Dd 61, AA Ee 95, and AA Fd 60—screened in the Aquia aquifer, for comparison with the natural water-quality of the Aquia aquifer (app. H.). The treatment system at each site consisted of an ion-exchange water softener. The concentrations of calcium, iron, and manganese in the treated water are significantly lower than concentrations in untreated water sampled in other wells. During the treatment process calcium, iron, and manganese are replaced with sodium on the ion exchange media. This results in a corresponding increase in sodium concentrations in the treated water. Sodium concentrations in the sampled wells were one- to two-orders-of-magnitude greater than the average ambient concentrations. Elevated sodium concentrations may be of concern to people on sodium-restricted diets (Lehr and others, 1988).

Radiation scans of water samples collected during the project were made because elevated



EXPLANATION

3.9 (4.2 T) • Dissolved iron concentration, in milligrams per liter. Letter T indicates total iron concentration.

— 5 — Line of equal iron concentration, in milligrams per liter. Dashed where uncertain. Contour intervals 0.5 and 5 mg/L.

Outcrop area of the Aquia aquifer -- modified from Glaser (1976).

Figure 24. Iron concentrations in the Aquia and Magothy aquifers in Southern Anne Arundel County and surrounding areas.

concentrations of naturally occurring radium have been detected in ground water from the Magothy and Potomac Group aquifers in the northern part of Anne Arundel County (Bolton, 2000). During radioactive decay, alpha and beta particles are emitted. These particles can be used to screen for the presence of radium. Gross alpha-particle activity (GAPA) for the Aquia water sampled at the Waysons Corner, Franklin Point Park, and Deale Athletic Field test sites analyzed 6 to 7 days after collection was less than 3 picoCuries per liter (pCi/L) (app. H.). The USEPA Maximum Contaminant Level (MCL) for GAPA is 15 pCi/L. Present regulations for public-water supply systems require analyzing for radium-226 only when GAPA exceeds 5 pCi/L, and for radium-228 when radium-226 exceeds 3 pCi/L (Federal Register, 1976). The combined radium-226/228 MCL is 5 pCi/L (U.S. Environmental Protection Agency, 2001a).

Gross beta particle (GBPA) activity in Aquia water from three wells sampled during this project was less than 7 pCi/L (app. H.). When GBPA exceeds 50 pCi/L (minus naturally occurring potassium-40), USEPA requires analyses of specific beta-emitting isotopes, such as tritium and strontium-90. The relatively low concentrations of

GAPA and GBPA sampled during this project are consistent with Aquia samples from Southern Anne Arundel County reported previously by Bolton and Hayes (1999).

Nitrate can contaminate ground water from fertilizer application on farms and lawns or from septic tanks. Nitrate concentrations (as nitrogen) greater than approximately 3 mg/L may indicate contamination from one or more of these sources (Bachman and Wilson, 1984). The federal limit for nitrate plus nitrite as nitrogen is 10 mg/L (U.S. Environmental Protection Agency, 2001b). Concentrations in the Aquia aquifer were less than the detection limit of 0.05 mg/L.

Arsenic can occur in ground water from both natural (dissolution of certain rock types) and man-made (such as industrial processes, and pesticide production and application) sources. The USEPA MCL is 10 micrograms per liter (µg/L) (U.S. Environmental Protection Agency, 2001b). Detectable concentrations in the Aquia aquifer were 1 µg/L or less.

The Aquia aquifer in Southern Anne Arundel County is generally not susceptible to brackish-water intrusion from Chesapeake Bay or its tributaries because of the overlying low-permeability Marlboro Clay and clay layers of the Nanjemoy Formation. However, brackish water could enter the Aquia aquifer in the upper reaches of Rhode River where the aquifer is unconfined (Fleck and Andreasen, 1996). Since the direction of ground-water flow is to the southeast, brackish water could eventually reach the northern end of the Shady Side Peninsula. The threat to wells screened in the Aquia aquifer on the Shady Side peninsula, however, is low, considering the distance that the brackish water must travel (approximately 2 mi) and the relatively slow rate of ground-water flow (less than 0.5 ft/yr at the 2000 head gradient). A field survey was conducted July 18, 2000 to determine the presence of brackish-water intrusion in this area. Water from six residential wells screened in the Aquia aquifer was tested in the field for chloride. Elevated chloride concentrations can indicate the possible presence of brackish-water intrusion. The wells were located along the shoreline in the communities of West Shady Side and Idlewilde. Chloride concentrations in water sampled from the wells were less than 4 mg/L. The ambient chloride concentrations in ground water are typically less than 10 mg/L; therefore, the wells sampled are not affected by brackish-water intrusion.

Individual wells in low-lying areas near tidal water bodies may also be susceptible to contamination from brackish water if the annular space between well casing and borehole is not properly grouted during well construction.

MAGOTHY AQUIFER

Water sampled in the three test wells screened in the Magothy aquifer is a calcium bicarbonate type (fig. 23). Water from the Magothy aquifer typically is an iron sulfate type north of the study area (Knobel and Phillips, 1988; Fleck and Andreasen, 1996). However, from about the central part of the study area south, the Magothy aquifer contains predominantly calcium bicarbonate-type water. Back (1966) and Knobel and Phillips (1988) suggested that the change in the dominant ions is a function of recharge from the more alkaline water of the Aquia aquifer in southwestern Prince George's County. The pH of water produced from the Magothy aquifer is about neutral (pH=7).

The Magothy aquifer typically contains elevated concentrations of iron and manganese (Barnes and Back, 1964). Dissolved iron concentrations sampled in the three test wells ranged from 3.6 to 7.6 mg/L, well above the 0.3 mg/L SMCL set by the USEPA for public-water supply systems. The distribution of iron in the Magothy aquifer in Southern Anne Arundel County and surrounding areas is shown in figure 24. Both dissolved and total iron concentrations are shown on the map. The map includes sites sampled during this study and 18 additional sites sampled in earlier investigations. Iron concentrations ranged from 3.6 to 26.0 mg/L. The highest concentrations were near the Annapolis Neck and Mayo Peninsula northeast of the study area. Concentrations in those areas ranged from 14.0 to 26.0 mg/L. In Southern Anne Arundel County, iron concentrations are generally less than 10 mg/L, although all of the Magothy values presented on figure 24 exceed the SMCL of 0.3 mg/L.

The Magothy aquifer typically contains excessive amounts of hydrogen sulfide. Municipal users of the Magothy aquifer, such as the City of Annapolis, remove the odor through aeration, filtration, and chlorination.

GAPA and GBPA analyzed in water pumped from the three test wells screened in the Magothy aquifer were less than 3.5 and 11 pCi/L, respectively

(app. H.). Elevated radium concentrations cause high alpha-particle activity (greater than 15 pCi/L) in parts of the Magothy aquifer in northern Anne Arundel County, but concentrations tend to decrease with depth and with distance from the outcrop area (Bolton, 2000).

In the Magothy sample concentrations of nitrate plus nitrite (as nitrogen) and arsenic were less than detection levels (0.05 mg/L and 1 μg/L, respectively).

WATER-SUPPLY POTENTIAL OF THE AQUIA AND MAGOTHY AQUIFERS

SIMULATION OF GROUND-WATER FLOW IN THE AQUIA AND MAGOTHY AQUIFERS

Ground-water flow in the Aquia and Magothy aquifers was simulated using the quasi-three-dimensional, finite-difference, ground-water-flow modeling code MODFLOW (McDonald and Harbaugh, 1988). The ground-water-flow model simulated the response of water levels to varying pumping conditions over the period 1900-2000. The model was calibrated by using historical water-level records and was subsequently used as a tool to estimate the water-supply potential of the Aquia and Magothy aquifers and to predict the response of water levels to future pumping conditions. The ground-water-flow model was based on a conceptual model of flow developed from the hydrogeologic framework that was presented earlier in this report. The model area included central and southern Anne Arundel County, the northernmost part of Calvert County, and the easternmost part of Prince George's County (fig. 1). Ground-water flow in the Aquia aquifer in central Anne Arundel County, consisting chiefly of Annapolis Neck, was not simulated because it is hydraulically isolated from Southern Anne Arundel County by the South River (Fleck and Andreasen, 1996, p. 39). MODFLOW input data arrays were constructed using the pre- and post-processor Processing Modflow[1] (Chiang and Kinzelbach, 1993).

Conceptual Model

The ground-water-flow model was developed from a conceptual model of the ground-water-flow system. The conceptual model describes, in general terms, the geometry of the hydrogeologic units, direction of ground-water flow, natural flow boundaries, and temporal changes in water levels. The hydrogeologic units included in the conceptual model consist of the Calvert and Nanjemoy Formations, the Marlboro Clay, the Aquia aquifer, the Matawan confining unit, the Magothy aquifer (combined upper and lower sands), and the Patapsco Formation confining unit (fig. 25).

Water recharges the Aquia and Magothy aquifers primarily as precipitation falling on their outcrop areas. The outcrop area of the Aquia aquifer occurs just north of the study area in central Anne Arundel County and eastern Prince George's County (fig. 14). The outcrop area of the Magothy aquifer occurs immediately northwest of the model area (Mack, 1974). Most of the precipitation that infiltrates within the outcrop areas either is removed by evapotranspiration or is captured by surface-water bodies after traveling relatively short distances. The remainder of the water enters the confined (artesian) part of the aquifers. Clay layers above and below the aquifers can also supply some recharge to the aquifers through slow drainage from water contained in storage. Since the amount of water entering the aquifers from this source is probably low, it was not included in the conceptual model. Exchange of water between the aquifers is constrained by the intervening confining units. The relatively low vertical hydraulic conductivities of the Marlboro Clay and Matawan confining unit inhibit the interchange of water between the Calvert and Nanjemoy Formations, Aquia aquifer, and Magothy aquifer in Southern Anne Arundel County. The Magothy aquifer, composed of upper and lower sands in Southern Anne Arundel County, is assumed to function as a single aquifer. The low-permeability clays of the Patapsco confining unit form an effective confining unit separating the Magothy and Upper Patapsco aquifers and, therefore, were assumed to form a no-flow boundary. Representing the aquifer system in this manner, however, means that the Aquia aquifer is the only source of vertical flow to the Magothy aquifer. The implications of this assumption on simulated water levels are

[1] The use of brand names in this report is for identification purposes only and does not constitute endorsement by the Maryland Geological Survey.

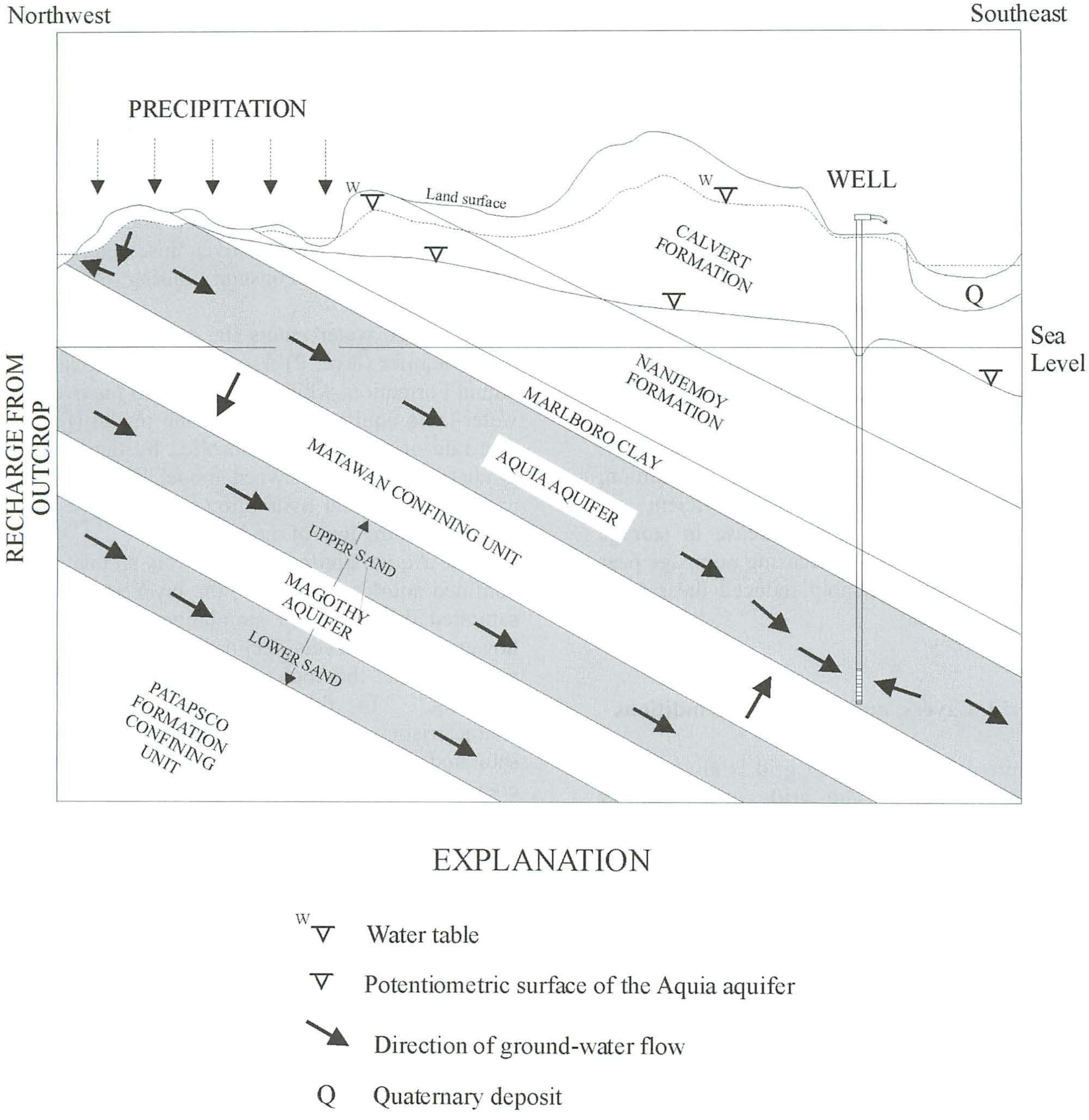


Figure 25. Conceptual model of the ground-water-flow system modeled in Southern Anne Arundel County and surrounding areas.

discussed in more detail later in the report in the section titled Pumping Scenario 4.

The South River forms a natural constant-head boundary in the Aquia aquifer in the northeastern part of the model area. Hydraulically, it separates Annapolis Neck from Southern Anne Arundel County.

Prior to pumping, water probably flowed in a southeastwardly direction until it discharged to shallower aquifers southeast of the model area. Under those conditions, water levels were maintained above sea level throughout Southern Anne Arundel County in both the Aquia and Magothy aquifers. The introduction of pumping wells, however, gradually lowered water levels below sea level in both aquifers. In the Aquia aquifer, pumpage lowered water levels to the top of the aquifer in a narrow area bordering the outcrop by 2000 (figs. 21 and 22). The aquifer in that area changed from an artesian condition, characterized by low storage coefficient and constant transmissivity, to an unconfined (water-table) condition, characterized by a higher storage coefficient and variable transmissivity. The increase in storage coefficient, combined with decreasing pumpage near the outcrop area, has probably reduced the rate of drawdown in that area.

Model Grid, Layers, and Boundary Conditions

The finite-difference model grid is aligned in a north-south orientation. The grid consists of 99 columns and 111 rows, with each model cell measuring 996 by 996 ft (fig. 26). The model area covers 392 square miles (mi^2) and includes the southern half of Anne Arundel County, the northern part of Calvert County, and the eastern part of Prince George's County.

The model consists of three layers representing, from top to bottom: (1) the water-table aquifer; (2) the confined part of the Aquia aquifer; and (3) the Magothy aquifer (combined upper and lower sands) (fig. 27). The confining units separating the water-table aquifer from the Aquia aquifer and the Aquia aquifer from the Magothy aquifer were represented in the model by a vertical conductance (or "vertical leakance") term between the model layers. Modeling the confining unit in this manner is referred to as the "quasi-three-dimensional" approach. The water-table aquifer includes the shallow parts of several geologic formations depending on the location. In the northwestern part of the model, the water-table aquifer consists chiefly of the Aquia aquifer, whereas in the central and southern parts of the model area it consists of the Nanjemoy and Calvert Formations, respectively. Model layer 1 is simulated as a constant-head boundary using a water-level array estimated from land surface and streambed altitudes (fig. 28). Records from water-table observation wells in Southern Maryland indicate that aside from seasonal fluctuations on the order of several feet, the long-term average water level is relatively constant (Smigaj and Davis, 1987; Curtin and Dine, 1995; Smigaj and others, 2001). Given this, water levels in layer 1 are held constant during the model simulations.

Recharge water enters the confined part of the Aquia aquifer (layer 2) from the outcrop area of the Aquia Formation, which is assigned to the overlying water-table aquifer (layer 1) in the model (fig. 27). The rate of recharge is controlled by the hydraulic gradient developed between model layers 1 and 2, and by the vertical hydraulic conductivity assigned to the confining unit of model layer 1.

The Aquia aquifer (layer 2) was simulated as a confined aquifer. As such, the layer remains fully saturated during model simulations. In the field, however, water levels decline below the top of the aquifer near the outcrop area in response to pumping. In those instances, the hydraulic characteristics of the aquifer change from a fully saturated condition of relatively low storage coefficient and constant transmissivity to a partially-saturated condition of relatively high storage coefficient and variable transmissivity. The increased storage coefficient would result in a reduced rate of drawdown. Representing the Aquia aquifer strictly as a confined aquifer may overestimate drawdown in those areas.

Natural flow boundaries were used in the model where possible. These boundaries include, for the Aquia aquifer, the South River as a constant head and the recharge area as a head-dependant flux boundary. Natural flow boundaries for the remainder of the Aquia aquifer, and for the Magothy aquifer, are too distant to model effectively. The size of the model area was, therefore, selected to satisfy the study objectives while minimizing potentially unrealistic boundary effects on the flow system. The model edges are located far enough from the main pumpage centers in the study area to minimize adverse boundary effects. The down-

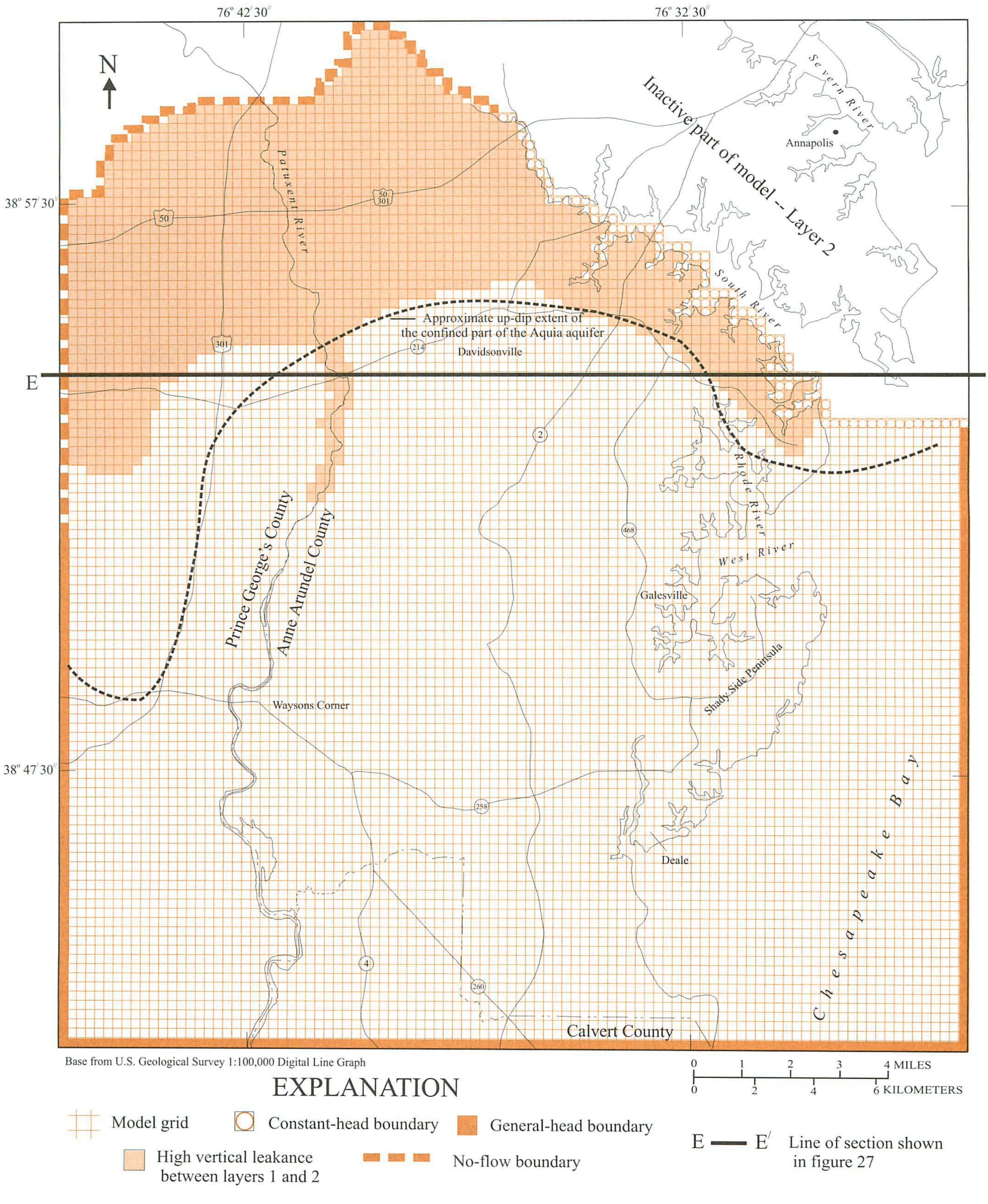


Figure 26. Finite-difference grid of the ground-water-flow model, and boundary conditions for layer 2 (Aquia aquifer).

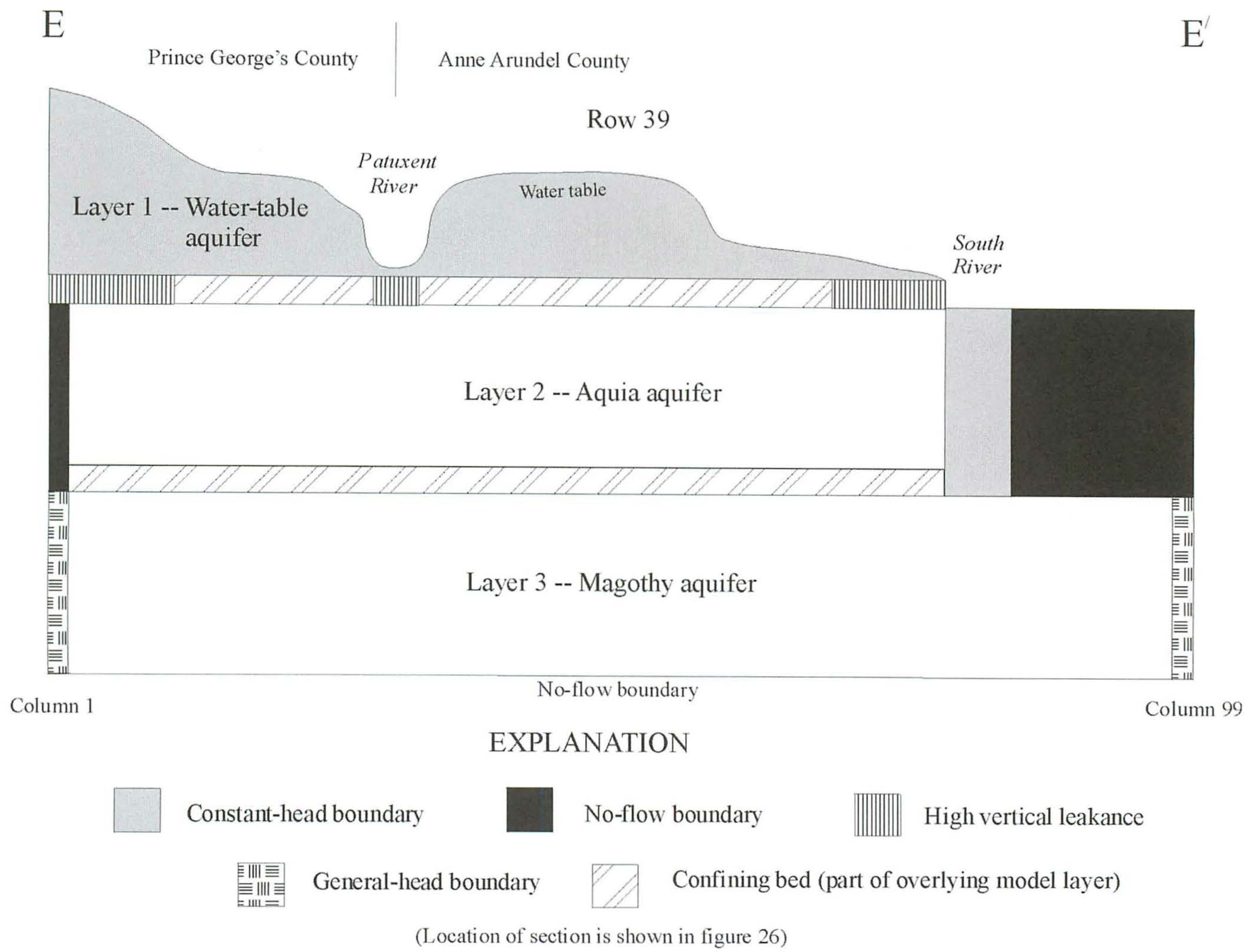
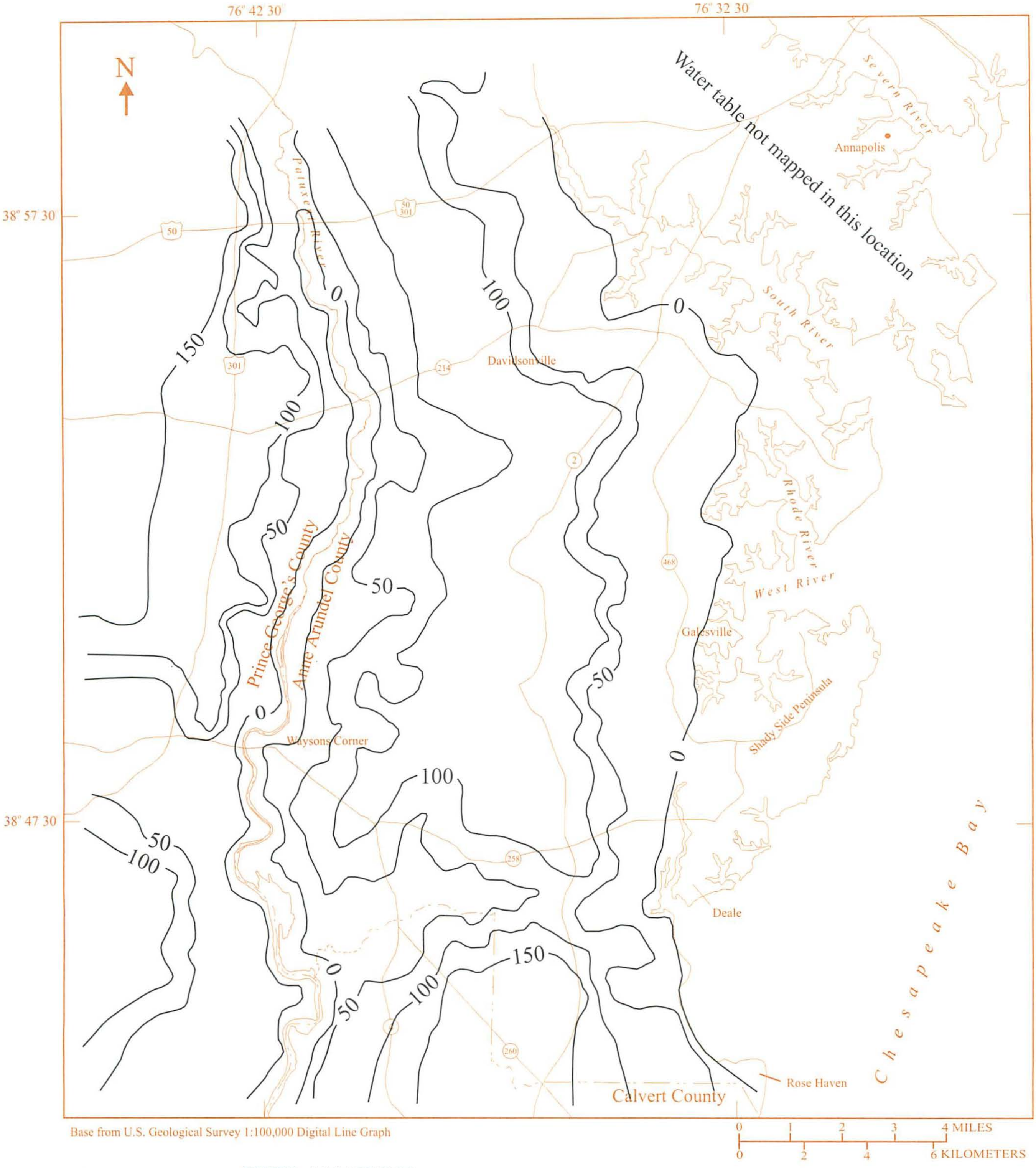


Figure 27. Cross section along model row 39 showing model layers and boundaries.

gradient model boundaries on the southern and eastern sides of model layer 2 (Aquia aquifer) are represented with general-head boundaries. In the general-head boundary, flow across a boundary cell is proportional to the head gradient between the active part of the model and the boundary cell and the horizontal hydraulic conductance at the boundary cell. Water levels assigned to the general-head boundaries were specified during the historic flow simulation (1900-2000) to represent temporal changes in water levels outside the model area. Sources of water-level data used at the general-head boundaries for selected stress periods are given in table 3. A no-flow boundary was assigned to the western side of the model in layer 2 where the Aquia aquifer outcrops. It was assumed, based on potentiometric surface maps for the Aquia aquifer, that ground-water flow at this location is parallel to the model boundary (Mack and others, 1992a; Curtin and others, 1996a, 1999a, 2001a). The South River is simulated as a constant-head boundary, which hydraulically separates the Aquia aquifer in Southern Anne Arundel County from the Annapolis Neck.

Model layer 3 (Magothy aquifer) is a confined aquifer throughout the model area, with no natural flow boundaries. The degree of hydraulic connection between the upper and lower sands of the Magothy aquifer is unknown. In the model they are treated as a single discrete aquifer. The edges of model layer 3 are represented with general-head boundaries. Water levels assigned to the general-head boundaries were specified similar to layer 2. The sources of water-level data are given in table 3.

The base of model layer 3 (corresponding to the top of the Patapsco confining unit) is represented as a no-flow boundary.



EXPLANATION

100 — Water-table contour, in feet above sea level. Contour interval is 50 feet.

Figure 28. Water-table altitude of model layer 1.

Table 3. Source of water-level data used for general-head boundaries in the Aquia and Magothy aquifers

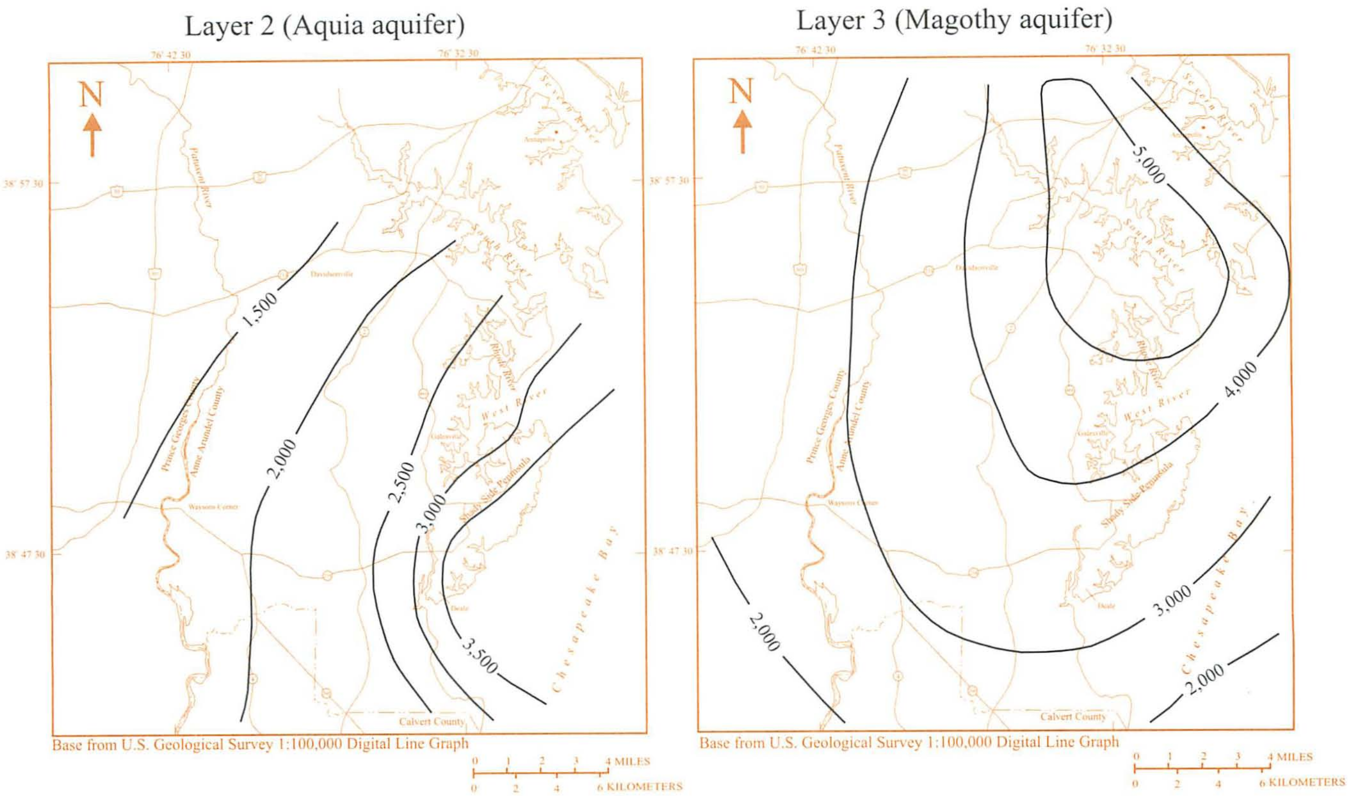
Stress period	Simulation period	Source of water-level data	
		Aquia aquifer	Magothy aquifer
1	1900-09	Chapelle and Drummond, 1983	Mack, 1974
7	1960-69	Otton, 1955	Mack, 1974
19	1980	Chapelle and Drummond, 1983	Mack and others, 1981
24	1982	Mack and others, 1984a	Mack and others, 1984b
29	1985	Mack and others, 1987a	Mack and others, 1987b
34	1987	Mack and others, 1989a	Mack and others, 1989b
39	1990	Mack and others, 1992a	Mack and others, 1992b
44	1992	Interpolated between 1990 and 1995 data	Interpolated between 1900 and 1995 data
49	1995	Curtin and others, 1996a	Curtin and others, 1996b
54	1997	Curtin and others, 1999a	Curtin and others, 1999b
59	1999	Curtin and others, 2001a	Curtin and others, 2001c

Hydraulic Parameters

Transmissivity arrays for model layers 2 and 3 were initially developed from contour maps of aquifer-test values but were adjusted during model calibration (fig. 29). Modeled transmissivity of layer 2 (Aquia aquifer) is up to 1.5 times higher than the measured transmissivity (fig. 10). The measured values probably underestimate the actual transmissivity because the entire thickness of the aquifer was not screened in the wells tested. Modeled transmissivity values for the Magothy aquifer is up to six times higher than measured values for similar reasons.

Storage coefficient, which was adjusted during model calibration, was 0.0007 for layer 2 (Aquia aquifer) and 0.0001 for layer 3 (Magothy aquifer). These values fall within the normal range for confined aquifers (Freeze and Cherry, 1979, p. 60) and are similar to values measured in central Anne Arundel County (Fleck and Andreasen, 1996).

Vertical leakance between model layers was calculated using the following equation (McDonald and Harbaugh, 1988, p. 5-16):



EXPLANATION

— 3,000 — Line of equal transmissivity, in feet squared per day. Contour interval is 500 and 1,000 feet squared per day.

Figure 29. Modeled transmissivity of layer 2 (Aquia aquifer) and layer 3 (Magothy aquifer) used in the ground-water-flow model.

$$L = \frac{1}{\dfrac{b_a/2}{K_a} + \dfrac{b_b}{K_b} + \dfrac{b_c/2}{K_c}},$$

where
L = vertical leakance, d^{-1},
K = vertical hydraulic conductivity, ft/d
b = thickness, ft
^{a} = upper aquifer
^{b} = confining unit
^{c} = lower aquifer.

The vertical leakance between the Aquia aquifer and the overlying water-table aquifer through the intervening Marlboro Clay was calculated at 1.1×10^{-6} cubic feet per day per cubic foot (1/d). This value was derived using average vertical hydraulic conductivities and layer thicknesses of: (1) 1.2 ft/d and 40 ft for the water-table aquifer; (2) 3.4×10^{-5} ft/d, and 30 ft for the Marlboro Clay; and (3) 1.3 ft/d and 150 ft for the Aquia aquifer. Vertical leakance assigned to the model was lowered to 5×10^{-8} 1/d during model calibration. The vertical hydraulic conductivity of the Marlboro Clay was taken from laboratory tests of sediment cores (Mack, 1974). In the absence of measured values, the vertical hydraulic conductivity of the water-table aquifer was estimated assuming: (1) a transmissivity of 500 ft^2/d based on a horizontal hydraulic conductivity of 5 ft/d for a fine-grained aquifer; and (2) an anisotropy ratio of 1:10 for layered sediments (Freeze and Cherry, 1979, p. 32). The same method was used to calculate vertical hydraulic conductivity of the Aquia aquifer. The area of the model that generally coincides with the

outcrop area of the Aquia aquifer (fig. 8) was assigned a vertical leakance of 0.1 1/d during model calibration. This relatively high value allows recharge water from model layer 1 (constant-head layer representing the water-table aquifer) to enter the Aquia aquifer.

Leakance between the Aquia and Magothy aquifers was calculated using average vertical hydraulic conductivities and layer thicknesses of: (1) 1.3 ft/d and 150 ft for the Aquia aquifer; (2) 2.1 x 10^{-4} ft/d and 60 ft for the Matawan confining unit; and (3) 17 ft/d and 40 ft for the upper sand in the Magothy aquifer. The vertical hydraulic conductivity of the Matawan confining unit was derived from permeability tests on core samples (Mack, 1974). Vertical hydraulic conductivity values for the Aquia and Magothy aquifers were calculated using average transmissivities determined from aquifer tests divided by the average aquifer thicknesses. The calculation assumed that the ratio between horizontal and vertical hydraulic conductivity is 10 to 1. The initial vertical leakance between the Aquia and Magothy aquifers assigned to the model was 3.5 x 10^{-6} 1/d. During model calibration, the value was reduced to 7.5 x 10^{-7} 1/d.

Pumpage

Pumpage assigned to model layer 2 (Aquia aquifer) included reported appropriated water use greater than 10,000 gal/d and estimated self-supplied, domestic water use. Appropriated use less than 10,000 gal/d was not represented in the model because it is relatively low, accounting for less than 5 percent of the total appropriated withdrawals. Domestic water use was assigned to the model based on population estimates for Assessment Districts 1, 7, and 8 (fig. 1) (Anne Arundel County Department of Planning and Code Enforcement, 2000). The population figures were multiplied by estimated rates of per-capita water use. The per-capita water-use rates ranged from 5 gal/d for 1900-19, 10 gal/d for 1920-29, 30 gal/d for 1930-41, 50 gal/d for 1950-59, and 60 gal/d for 1960-2000. The water-use rates, determined in part by model calibration, reflect the increase in water use that occurred as the percentage of the population served by running water increased. MacKichan (1957, p. 6) estimated that per-capita water use in homes without running water is 10 gal/d versus 50 to 60 gal/d in homes with running water. Cumulative self-supplied domestic pumpage in the calibrated model ranged from 0.04 Mgal/d for the period 1900-10 to 2.6 Mgal/d in 2000 (tab. 4). Appropriated pumpage in the Aquia aquifer assigned to the model ranged from 0.022 Mgal/d for the period 1920-29 to approximately 0.22 Mgal/d in 2000 (tab. 4; apps. D and E). Since production wells for North Beach and Paris Oaks in Calvert County are located on the southern model boundary, pumpage at those sites were simulated indirectly using the general-head boundary.

Appropriated pumpage assigned to the Magothy aquifer in the model ranged from 2.2 Mgal/d for the period 1940-49 to 2.6 Mgal/d in 2000 (apps. F and G). Self-supplied domestic pumpage in the Magothy aquifer was not represented in the model because relatively few wells are completed in the Magothy in Southern Anne Arundel County (Lucas, 1976).

Domestic pumpage in Prince George's County was not represented in the model because the amount is relatively low given the sparse distribution of wells in that area. Domestic pumpage in northern Calvert County is also not represented; however, the effect of that pumpage is indirectly represented in the model by the general-head boundary along the southern edge of the model.

STEADY-STATE FLOW SIMULATION

Prior to running the transient-flow model, a steady-state-flow simulation of pre-pumping conditions was made. Pumpage in the Aquia aquifer was relatively low in 1900; therefore, simulating the flow system in 1900 as non-pumping is a reasonable approximation of the 1900 flow regime. Water levels along the general-head boundary were taken from pre-pumping steady-state simulations of the Aquia (Chapelle and Drummond, 1983) and Magothy aquifers (Mack, 1974). Since measured water levels are generally absent for the early part of the 1900's, the steady-state-flow model was calibrated chiefly by comparing modeled water levels to the conceptual model of pre-pumping head conditions. Adjustments to transmissivity, vertical leakance, and general-head boundary conductance were made during the initial calibration of the steady-state model. The simulated water levels representing steady-state conditions in both the Aquia and Magothy aquifers were above sea level throughout the model area (fig. 30). In the low-

Table 4. Pumpage assigned to model layer 2 (Aquia aquifer) for entire model area, 1900-2000

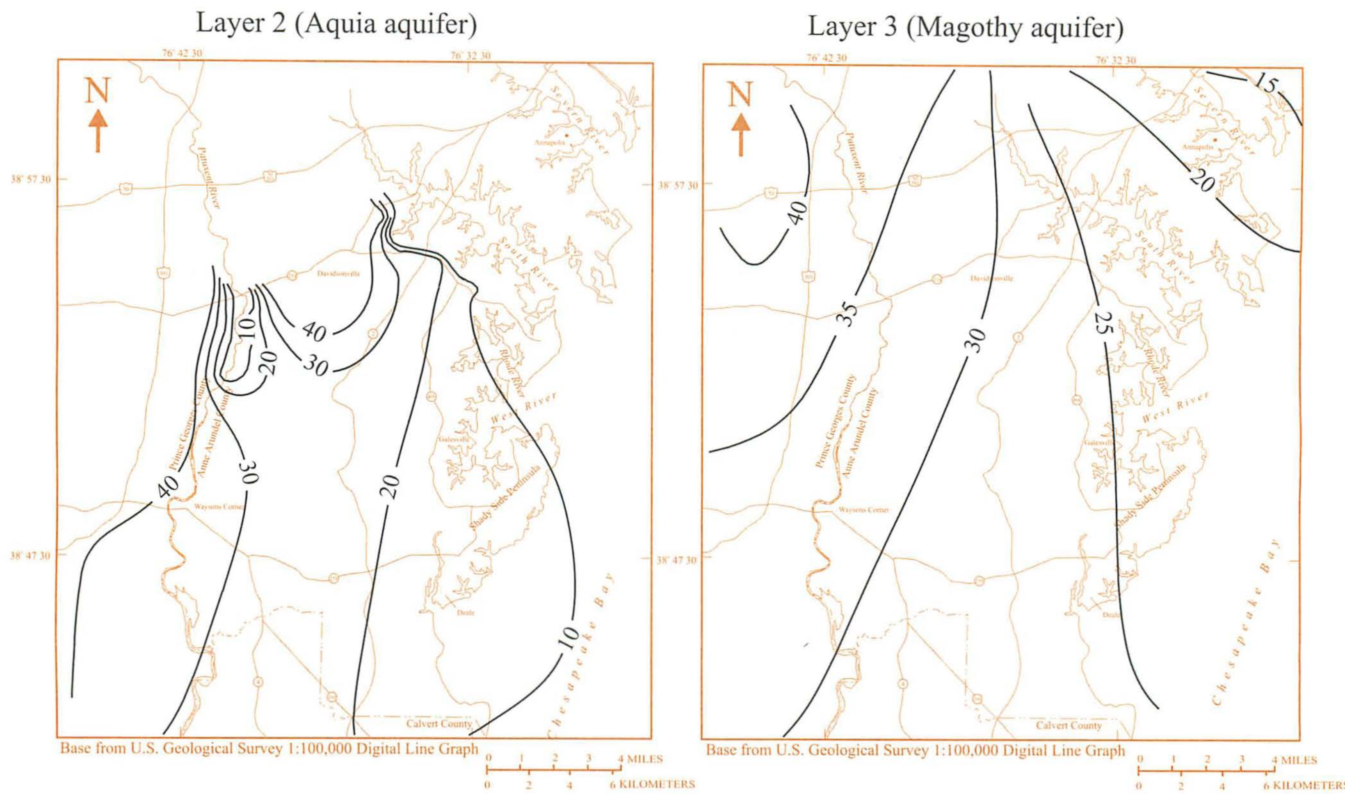
[gal/d = gallons per day; Mgal/d = million gallons per day]

Stress period(s)	Year(s)	Self-supplied residential pumpage (Mgal/d)	Appropriated pumpage greater than 10,000 gal/d (Mgal/d)	Total pumpage (Mgal/d)
1	1900-09	0.039	0	0.039
2	1910-19	.039	0	.039
3	1920-29	.077	.022	.099
4	1930-39	.22	.023	.243
5	1940-49	.256	.025	.281
6	1950-59	.677	.030	.707
7	1960-69	1.05	.088	1.14
8-18	1970-79	1.44	.1 – .188	1.54 – 1.63
19-38	1980-1989	1.93	.201 – .222	2.13 – 2.15
39-48	1990-1994	2.23	.254 – .199	2.48 – 2.43
49-50	1995	2.34	0.211	2.55
51-52	1996	2.35	.172	2.52
53-54	1997	2.38	.229	2.61
55-56	1998	2.43	.296	2.73
57-58	1999	2.49	.268	2.76
59-60	2000	2.60	.224	2.82

lying areas of Deale and Shady Side these water levels would have resulted in flowing wells. This is consistent with earlier reports of flowing wells in the Aquia aquifer in the Deale-Shady Side area (Clark and others, 1918). Test well AA Fe 47 completed in the Magothy aquifer in 1974 at the Broadcreek Waste-Water Treatment Plant flowed. That well had an initial head of approximately 8 ft above land surface or 14 ft above sea level (fig. 15).

TRANSIENT-FLOW SIMULATION

Transient-flow conditions were simulated for the period 1900-2000 in order to develop the model's ability to match the cause-and-effect relation between pumping and drawdown. Historical pumpage and water levels along boundaries were specified for the period of simulation. The model was then calibrated by



EXPLANATION

30 — Potentiometric contour of simulated water levels. Contour interval is 5 and 10 feet. Datum is sea level.

Figure 30. Simulated potentiometric surface of model layer 2 (Aquia aquifer) and model layer 3 (Magothy aquifer) for steady-state, pre-pumping conditions.

adjusting model input parameters until a reasonable match was obtained between simulated and observed water levels. The calibrated transient-flow model was then used to predict future water levels resulting from different pumping conditions.

Initial Conditions and Time Discretization

Water levels used at the start of the transient-flow simulation were derived from the steady-state-flow simulation (fig. 30). The initial water levels provided a starting place for the computation of simulated water levels for the period 1900-2000.

The simulation period was divided into selected time intervals of variable duration. For each time interval, or "stress period," water levels along the general-head boundary and pumpage were assigned to the model. The model computed water levels and inter-cell volumetric flow rates at specified intervals, or "time steps," within each stress period. Stress periods ranged in duration from 0.5 to 10 years and consisted of either two or four time steps (tab. 5).

Calibration and Sensitivity Analysis

Model calibration was an iterative process in which model input parameters were systematically adjusted until simulated water levels best matched observed water levels. Model parameters that were adjusted included transmissivity, vertical leakance, self-supplied domestic pumpage, horizontal hydraulic conductance at the general-head boundaries, and storage coefficient. The steady-state model, which simulated pre-pumping conditions, was periodically re-run to verify the results using the adjusted parameters.

Table 5. Time discretization used in the transient ground-water flow model

Stress periods	Duration of stress periods (days)	Time steps	Period simulated
1-7	3,652[1]	2	1900-1969
8	1,826	2	1970-1974
9-60	182.5[1]	4	1975-2000

[1] The modeled stress period duration was adjusted slightly to account for leap years.

Simulated water levels at the end of the simulation period 1900-2000 were compared to water levels measured during the Fall of 2000 at 65 observation wells in the Aquia aquifer and 13 wells in the Magothy aquifer (fig. 31). The slope of the first order linear regression (Y = mX + b) was 1.01. The root-mean-square error calculated using observed water levels from 65 wells in the Aquia aquifer and 13 wells in the Magothy aquifer was 4.3 ft. The model was considered calibrated when the lowest value of the root-mean-square error was obtained between simulated and observed water levels (Anderson and Woessner, 1992, p. 241).

Simulated water levels were plotted with observed water levels for 12 Aquia wells and 9 Magothy wells located within the model area (figs. 32, 33 and 34). Simulated water levels match the general water-level trends at most observation sites. The model is less able to match seasonal changes in water levels because seasonal changes in self-supplied, domestic water use are not simulated (tab. 4). Wells AA De 102 and AA Ef 17 are in the shallow water-table part of the Aquia aquifer, and are affected by short-term changes in recharge. Because the model simulated a constant-head water table, these short-term water-level fluctuations could not be simulated. Simulated drawdowns at many of the observation sites occur as a series of steps resulting from changes in water levels at the general-head boundaries.

The rate at which water recharges the confined part of the Aquia aquifer from its outcrop was calculated periodically during the model calibration process. Recharge was calculated by dividing the net vertical flux from the Aquia outcrop area within the model domain by the approximate outcrop surface area. The area of the outcrop within the model area was estimated at 1.1×10^9 feet squared (ft^2). The resulting linear recharge rate simulated by the steady-state pre-pumping model was 0.54 inches per year (in./yr). Pumping caused the rate to increase to 1.6 in./yr at the end of the transient model simulation period 1900-2000.

With respect to total yearly precipitation, the amount of water that recharges the confined aquifer is relatively low. The National Oceanic and Atmospheric Administration showed a yearly average precipitation of 43 in./yr at the Annapolis Police Barracks for the period 1951-97. The average was calculated using years with complete precipitation records. Precipitation falling on the land surface either enters the shallow ground-water system or runs off to streams. Part of the water entering the shallow ground-water system is removed by plants (transpiration), evaporates, or discharges to surface water. Some of the water may be captured by wells. The remainder of the water recharges the confined aquifer. Studies of the hydrologic budget in Maryland's Coastal Plain indicate that surface runoff, evapotranspiration, and ground-water discharge to streams account for approximately 46 to 50 percent, 12 to 14 percent, and 20 to 31 percent of precipitation, respectively (Rasmussen and Andreasen, 1959; Achmad, 1991). McFarland (1997), in a study of a basin within Virginia's Coastal Plain, calculated that flow to the confined aquifer from the outcrop area is approximately 1 percent of precipitation.

The sensitivity of the model to global changes in model input parameters was tested by running the calibrated model with each changed parameter and comparing results (fig. 35). The purpose of a sensitivity analysis is to determine the degree to which uncertainty in model input parameters affect simulated water levels. The model is sensitive to an order-of-magnitude increase in vertical leakance between model layers 1 and 2 (water-table aquifer and Aquia aquifer), and 2 and 3 (Aquia and Magothy aquifers). The model was also sensitive to a decrease in transmissivity of model layers 2 and 3

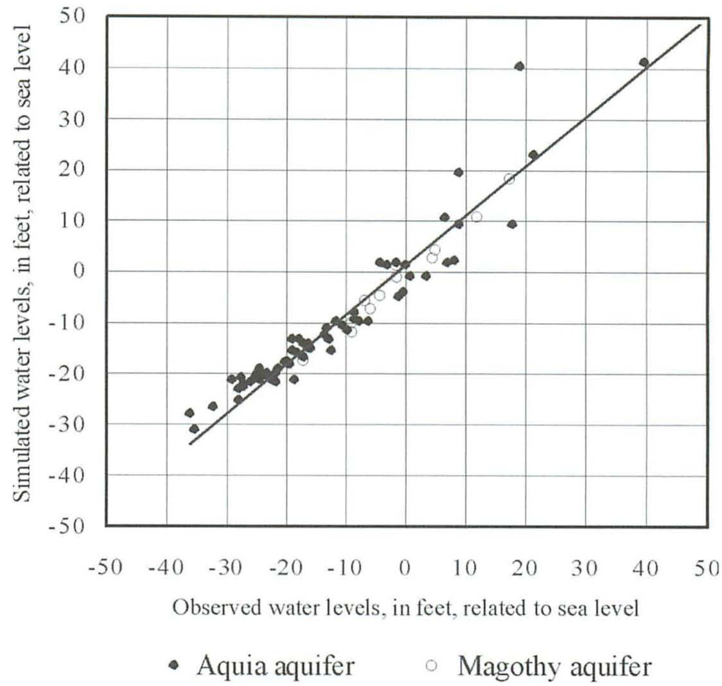


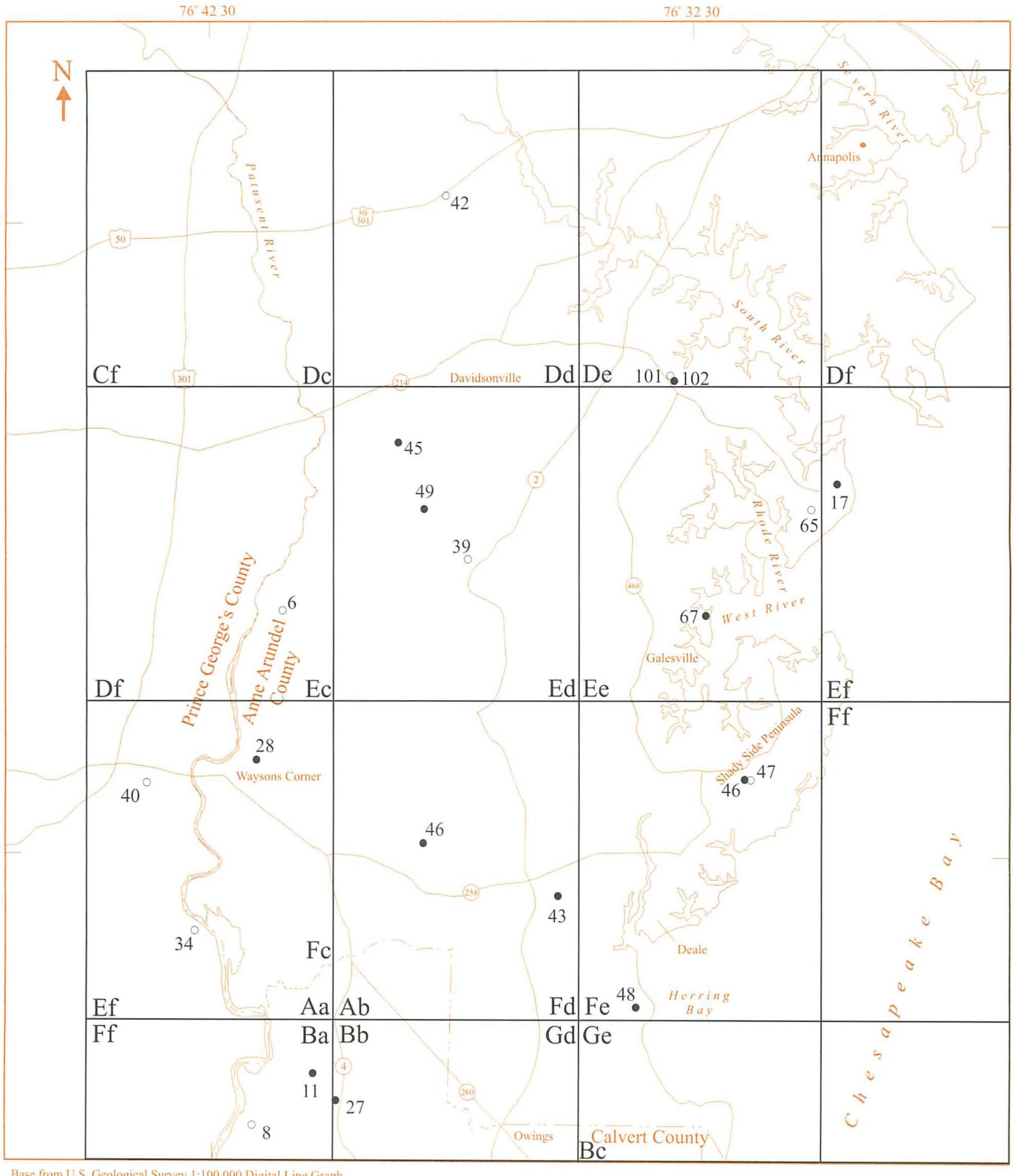
Figure 31. Relation between observed and simulated water levels in the Aquia and Magothy aquifers at the end of the transient simulation period 1900-2000.

(Aquia and Magothy aquifers). The model was somewhat sensitive to a change in self-supplied domestic pumpage in layer 2 (Aquia aquifer). The model showed little or no sensitivity to changes in the horizontal hydraulic conductivity at the general-head boundaries.

Volumetric Budget

The volumetric budget of model layer 2 representing the confined part of the Aquia aquifer was calculated at the conclusion of the transient simulation period 1900-2000 (fig. 36). Total inflow equaled 7.0 Mgal/d and was divided between: 6.0 Mgal/d or 85 percent from recharge entering through the outcrop area, 0.76 Mgal/d or 11 percent from the general-head boundaries, 0.19 Mgal/d or 2.6 percent from model layer 3 (Magothy aquifer), 0.10 Mgal/d or 1.4 percent from the constant-head boundary (South River), and 0.014 Mgal/d or 0.2 percent through the overlying confining unit from model layer 1 (water-table aquifer). Inflow to the Aquia aquifer was balanced by an equal amount of outflow. Outflow was divided between: 2.2 Mgal/d or 32 percent to the Patuxent River, 2.0 Mgal/d or 29 percent to wells, 1.8 Mgal/d or 26 percent to the general-head boundaries, 0.64 Mgal/d or 9.2 percent to the water-table part of the Aquia aquifer on Mayo Peninsula, 0.024 Mgal/d or 0.35 percent to the constant-head boundary (South River), 0.25 Mgal/d or 3.6 percent to model layer 3 (Magothy aquifer), and 0.01 Mgal/d or 0.14 percent from storage. There was neither flow upward through the confining unit to the water-table aquifer nor water returned to storage. In 2000, Aquia wells in Southern Anne Arundel County withdrew approximately 68 percent of the 1.6 in. of net recharge water entering the confined part of the aquifer from its outcrop. By comparison, pumping in 1950 captured approximately 20 percent of the 0.6 in. of net recharge water.

The volumetric budget for model layer 3 (Magothy aquifer) calculated at the end of the simulation period (2000) was divided evenly between inflow and outflow (fig. 36). Inflow consisted of 2.9 Mgal/d or 75 percent from general-head boundaries and 0.99 Mgal/d or 25 percent from the Aquia aquifer. Inflow from the Aquia aquifer includes flow from both the confined and outcrop parts of the Aquia aquifer. Outflow consisted of 1.1 Mgal/d or 27 percent to general-head boundaries,



EXPLANATION

11 ● Well screened in the Aquia aquifer. Number next to well symbol is well identification number. County prefixes "AA, CA, and PG" and 5-minute quad designations are omitted.

○ Well screened in the Magothy aquifer.

Ff Designation for Maryland 5-minute county grid system.

Figure 32. Location of wells with long-term water-level record used in model calibration.

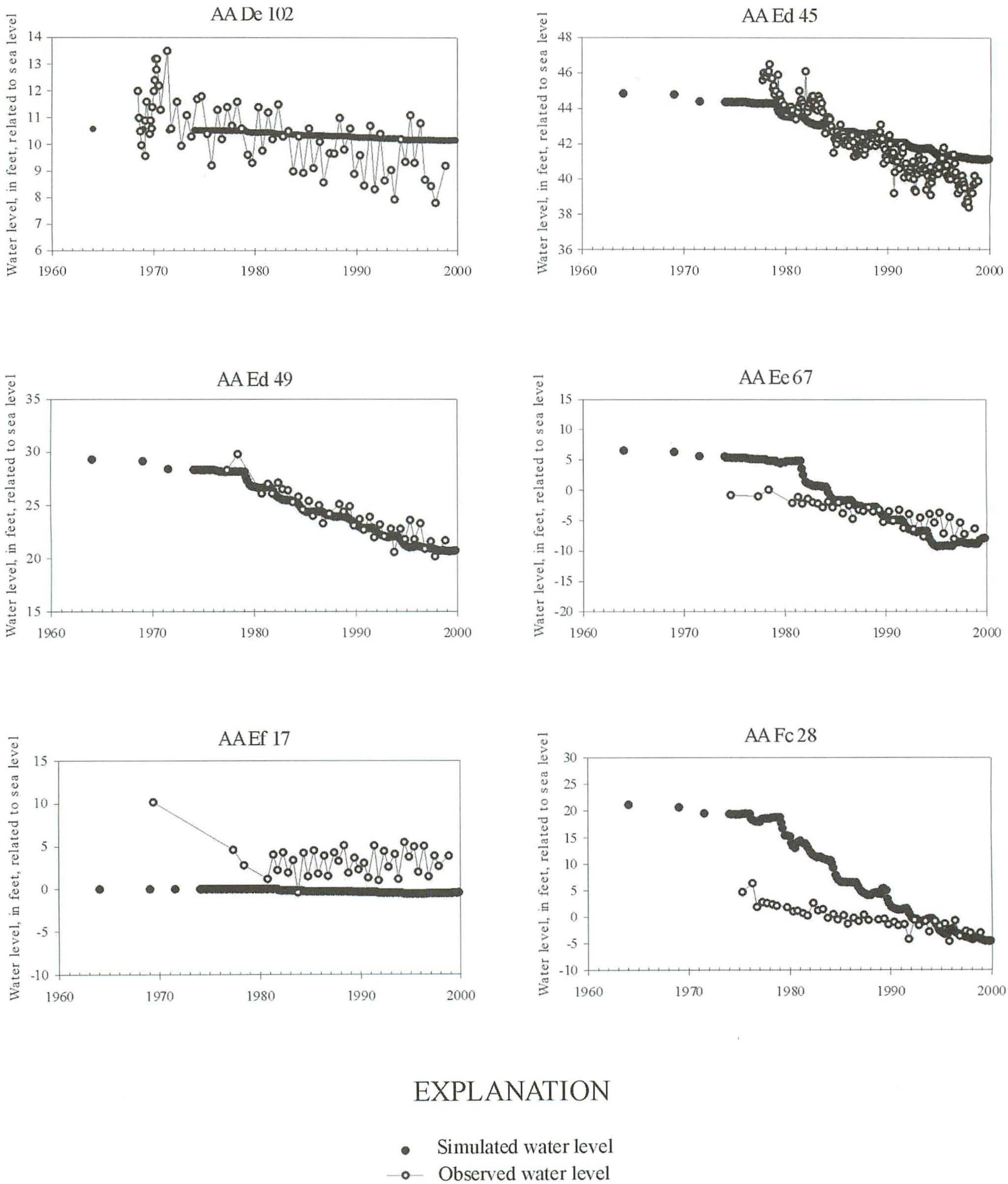


Figure 33. Hydrographs of observed and simulated water levels in wells screened in the Aquia aquifer, 1960-2000.

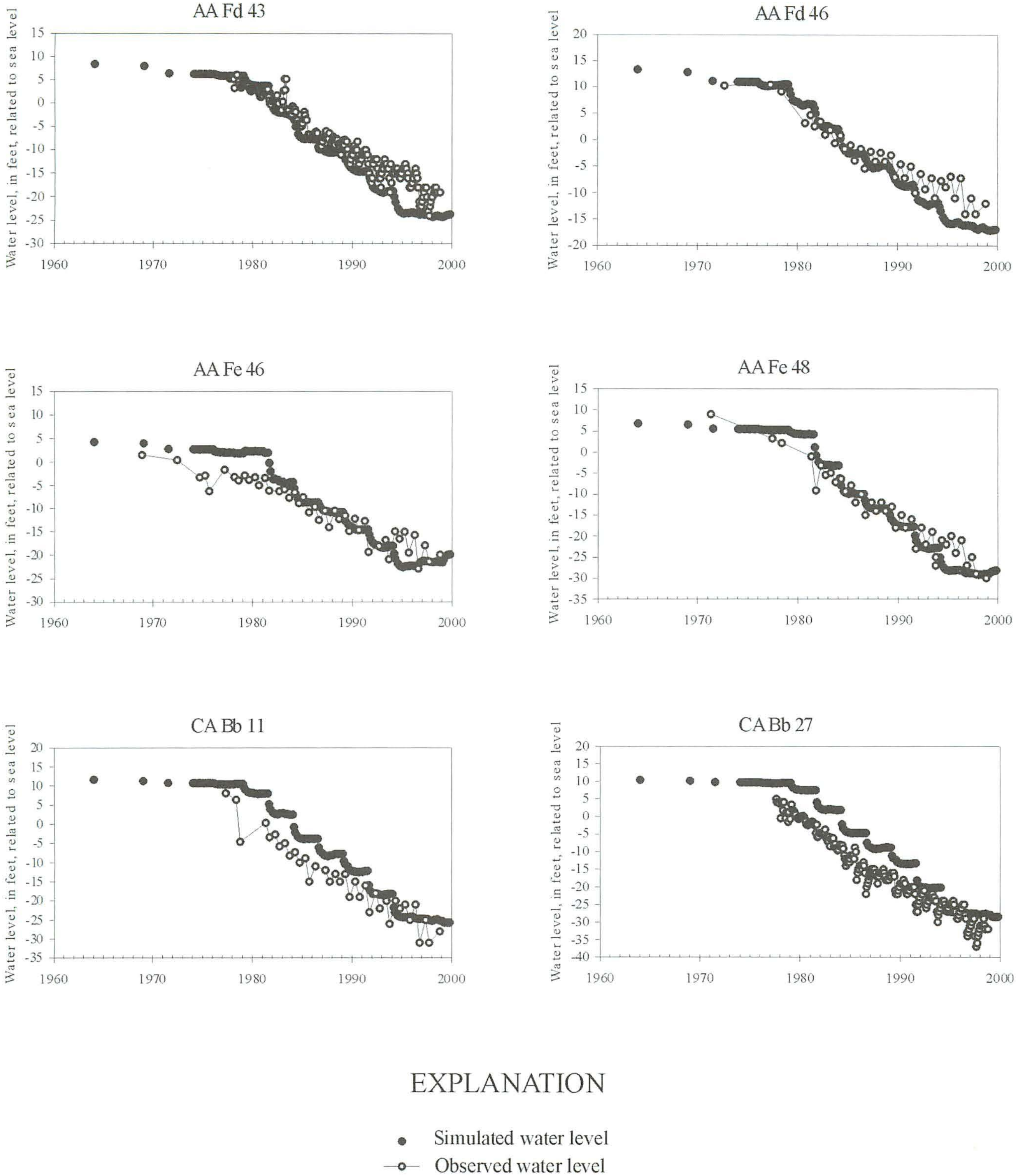


Figure 33. Continued.

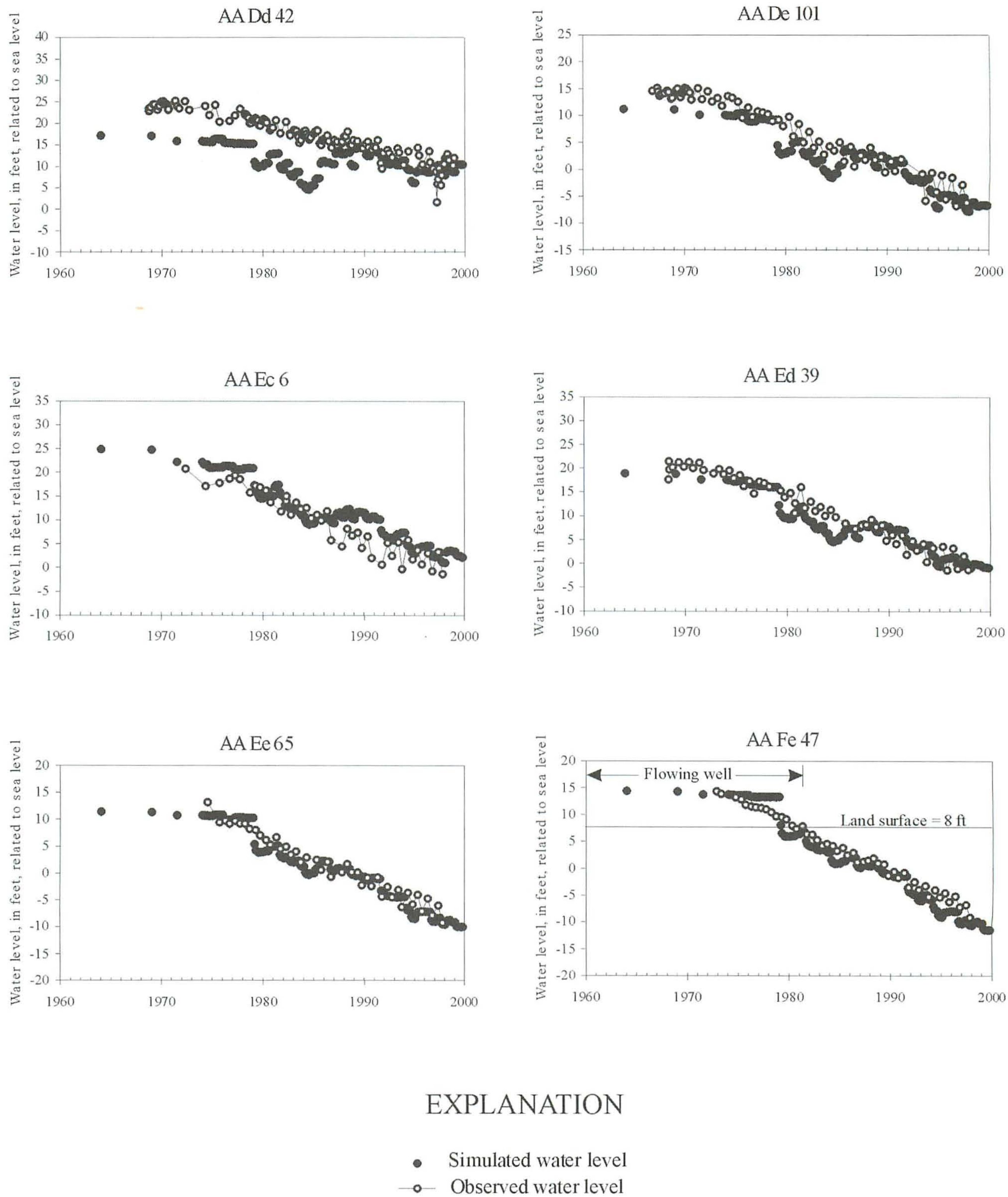


Figure 34. Hydrographs of observed and simulated water levels in wells screened in the Magothy aquifer, 1960-2000.

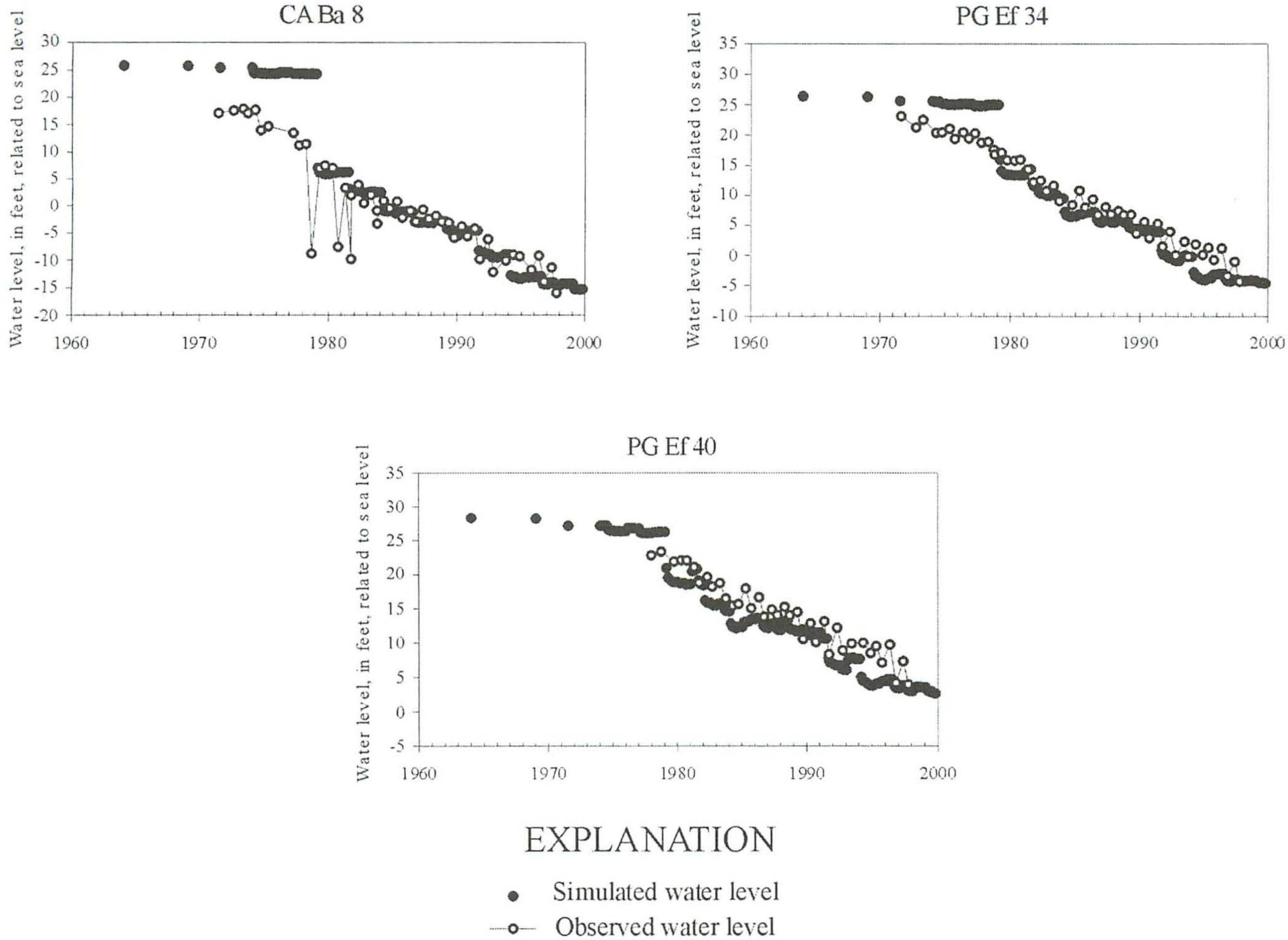


Figure 34. Continued.

2.7 Mgal/d or 69 percent to wells, and 0.19 Mgal/d or 5 percent to the Aquia aquifer. Water flowed upward to the confined part of the Aquia aquifer in areas where Aquia heads were lower than Magothy heads. Change in aquifer storage accounted for less than 1 percent of the budget. Discrepancies in percentages are caused by rounding.

PREDICTIVE MODEL SIMULATIONS

The calibrated transient flow model was used to predict future water levels in the Aquia and Magothy aquifers resulting from various projected pumping scenarios. Some of the pumping scenarios include multiple model simulations. A summary of pumping scenarios is given in table 6. The model simulated water-level changes for the period 2000 to 2020. Each simulation was divided into 20 stress periods, each of which was 1 year in duration. The model calculated water levels for each active model cell at four time steps within each stress period. Each time step was 3 months in duration. Water levels calculated at each active model cell are averages for the model cell area. Water levels along the general-head boundaries in layers 2 and 3 were specified at 5-year intervals.

Pumping Scenario 1: Projected 2020 Population Supplied by the Aquia Aquifer

Population in Southern Anne Arundel County is projected to increase to approximately 32,750 by 2020 while the population in the Mayo-Edgewater area is projected to increase to 20,930 by 2020 (Elizabeth Dixon, Anne Arundel County Land Use Officer, personal communication, 2001). This growth will cause water demand to increase to an estimated 2.6 Mgal/d in Southern Anne Arundel County and 1.7 Mgal/d in the Mayo-Edgewater area. These values include major appropriated pumpage at

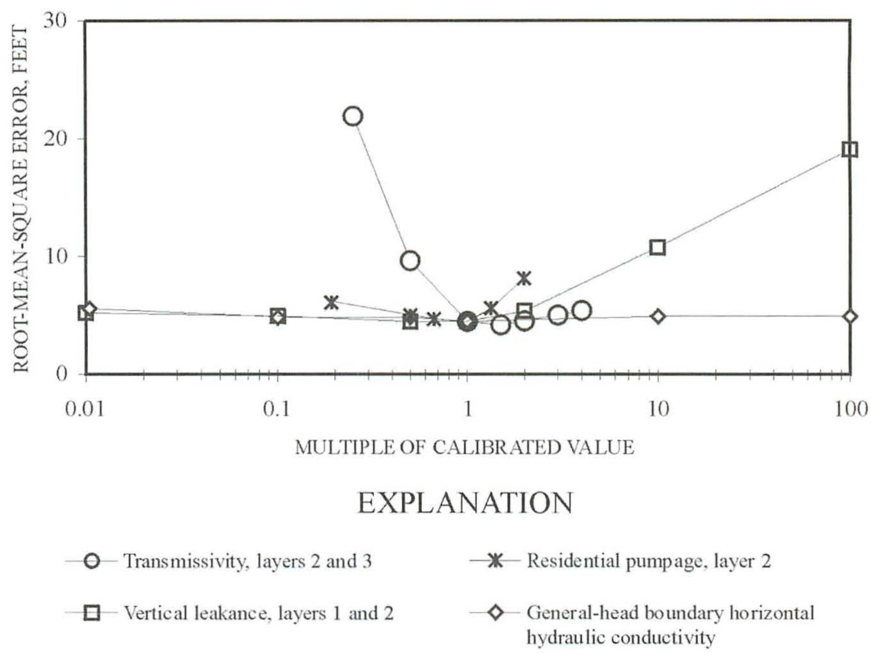


Figure 35. Effects of varying model parameters on simulated water-level match.

2000 levels. Total pumpage from the Aquia aquifer in 2000 was approximately 1.8 Mgal/d in Southern Anne Arundel County and 1.0 Mgal/d in the Mayo-Edgewater area. The Aquia aquifer is the most desirable source to supply future growth given its relatively shallow depth and generally acceptable water quality.

A model simulation (Scenario 1A) was made to determine the effect of pumping the Aquia aquifer to meet the projected 2020 water demand. Several alternative simulations were also made in which projected 2020 water demand was supplied in part by public-supply wells or by individual domestic wells with the pumpage amount lowered to reduce drawdown. Those simulations consisted of: (1) Scenario 1B—Part of the projected 2020 water demand supplied by public-supply wells; (2) Scenario 1C—50-percent reduction in the projected 2020 increase in water demand; (3) Scenario 1D—projected 2020 water demand and Aquia withdrawals in Calvert County based on low-growth projections; and (4) Scenario 1E—50-percent reduction in 2020 water demand and Aquia withdrawals in Calvert County based on low-growth projections.

In Scenario 1A, pumpage required to supply the projected increase in population through 2020 was entered as self-supplied domestic withdrawals in model layer 2 (Aquia aquifer) (app. I.). Starting in 2000, self-supplied domestic pumpage was increased at a linear rate to meet the projected demand. The pumpage was distributed in the model within Assessment Districts 1, 7, and 8 (fig. 1). The per capita water-use rate used to calculate pumpage based on population was increased incrementally from 60 gal/d derived from the calibrated 1900-2000 transient model simulation to an estimated 80 gal/d. A rate of 80 gal/d for per-capita water use is used by the Maryland Department of the Environment for planning purposes. Pumpage was assigned in the model using stress periods of 1 year. Seasonal changes in water levels caused by seasonal changes in water use, therefore, are not simulated. As a result, actual water levels during the spring and fall may be somewhat higher and lower, respectively, than simulated water levels. In 2000, approximately 2,600 residents in five mobile home parks located in the Waysons Corner area were served by central-supply wells appropriated for more than 10,000 gal/d and screened in the Aquia aquifer (Judith Wheeler, personal communication, 2001). Pumpage at those sites was held constant during the simulation at the reported 2000 rate (app. C.). The population served by public water was subtracted from the projected 2020 population. All other appropriated ground-water use in the Aquia aquifer in the model area was held constant at the 2000 rate of approximately 0.22 Mgal/d, which included 0.18

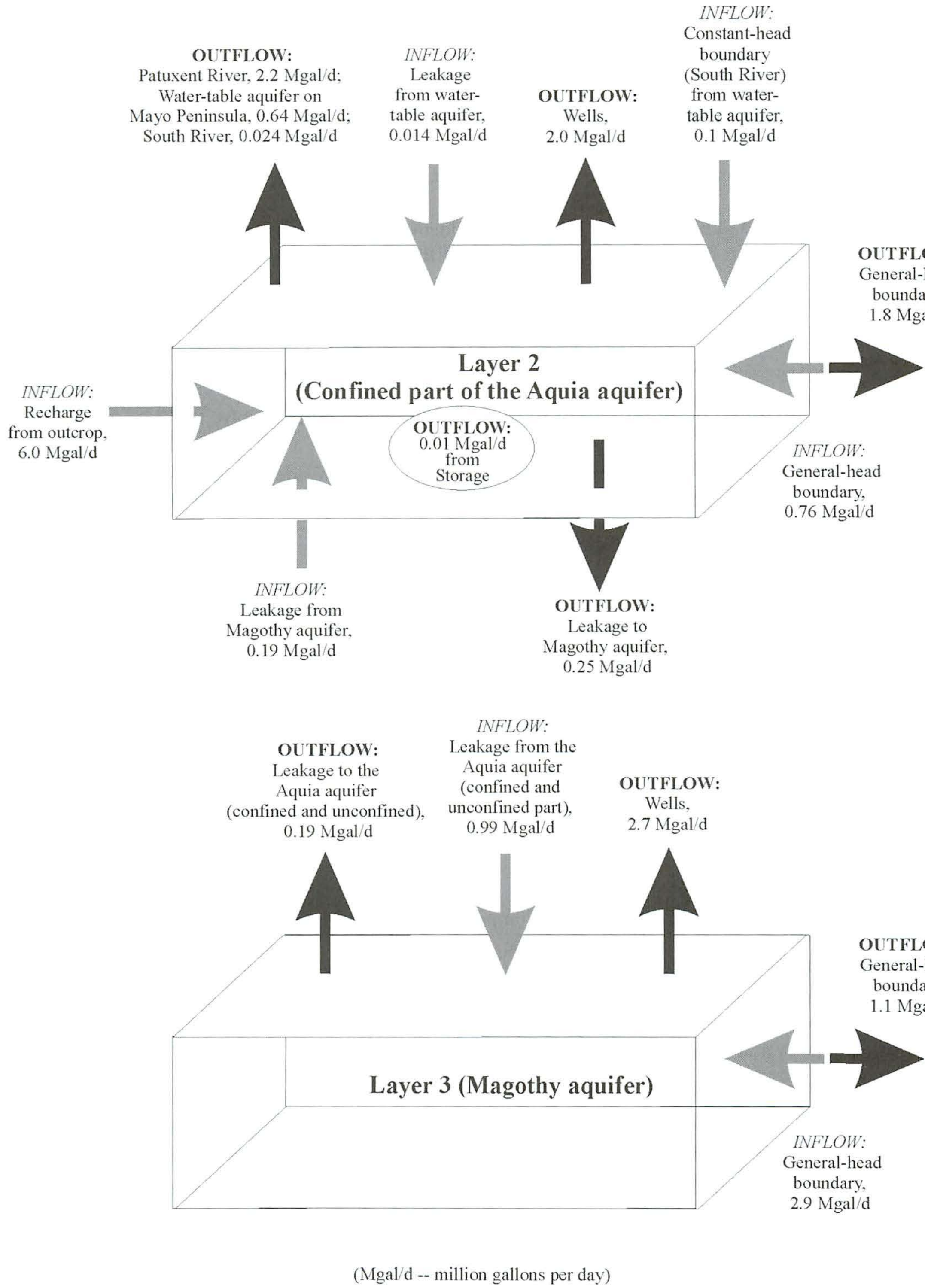


Figure 36. Water budget for model layer 2 representing the confined part of the Aquia aquifer and model layer 3 (Magothy aquifer) at the conclusion of the 1900-2000 transient simulation period.

Table 6. Pumping scenarios used in predictive model simulations in Southern Anne Arundel County

Pumping Scenario 1 – Projected 2020 population supplied by the Aquia aquifer. **1A** – Projected 2020 pumpage (2.6 Mgal/d) withdrawn by residential wells. **1B** – Part of the projected 2020 pumpage (1.25 Mgal/d) withdrawn by public-supply wells and the remainder (1.35 Mga/d) withdrawn by residential wells. **1C** – Projected 2000 to 2020 pumpage increase reduced 50 percent and withdrawn by residential wells (2.2 Mgal/d). **1D** – Projected 2020 pumpage (2.6 Mgal/d) withdrawn by residential wells. Pumpage in Calvert County reduced from 8.2 to 6.1 Mgal/d based on Calvert County Department of Planning and Zoning's population projection. **1E** – Projected 2000 to 2020 pumpage increase reduced 50 percent and withdrawn by residential wells (2.2 Mgal/d). Pumpage in Calvert County reduced from 8.2 to 6.1 Mgal/d based on Calvert County Department of Planning and Zoning's population projection.
Pumping Scenario 2 – Projected 2000 to 2020 population increase supplied by the Magothy aquifer. **2A** – Projected 2000 to 2020 pumpage increase (0.8 Mgal/d) withdrawn by residential wells. **2B** – Projected 2000 to 2020 pumpage increase (0.8 Mgal/d) withdrawn by public-supply wells.
Pumping Scenario 3 – Estimation of time required for water levels in the Aquia and Magothy aquifers to stabilize at 2000 pumping rates (1.8 Mgal/d from the Aquia aquifer and 0.22 Mgal/d from the Magothy aquifer).
Pumping Scenario 4 – Highest sustainable withdrawals in the Aquia and Magothy aquifers in Southern Anne Arundel County. Aquia aquifer The Aquia aquifer has reached its maximum allowable yield (1.8 Mgal/d) as defined by the 80-percent management level. Magothy aquifer **4A** – 38 Mgal/d pumped from the Magothy aquifer. Pumpage causes water levels in the Aquia aquifer to exceed the management level in a band as much as 2-miles wide. **4B** – 26 Mgal/d pumped from the Magothy aquifer. Reduces the area where water levels exceed the management level in the Aquia aquifer in Scenario 4A by 25 percent. **4C** – 14 Mgal/d pumped from the Magothy aquifer. Reduces the area where water levels exceed the management level in the Aquia aquifer in Scenario 4A by 50 percent. **4D** – 7 Mgal/d pumped from the Magothy aquifer. Drawdown in the Aquia aquifer resulting from the Magothy pumpage is less than 4 ft. **4E** – 7 Mgal/d pumped from the Magothy aquifer. Aquia pumpage reduced to 1.4 Mgal/d from the 2000 rate of 1.8 Mgal/d in Scenario 4D to compensate for drawdown caused by the Magothy pumpage.
Pumping Scenario 5 – Effect of projected 2020 withdrawals from the Aquia aquifer in Calvert and St. Mary's Counties on water levels in Southern Anne Arundel County. **5A** – Calvert County pumped at 8.2 Mgal/d and St. Mary's County pumped at 11.3 Mgal/d. **5B** – Calvert County pumped at 6.1 Mgal/d and St. Mary's County pumped at 11.3 Mgal/d.

Mgal/d in Southern Anne Arundel County. Total Aquia pumpage (self-supplied and major users) assigned to the model increased from 3.0 Mgal/d in 2000 to 4.4 Mgal/d in 2020. Withdrawals by major users of the Magothy aquifer within the model area were held constant at the 2000 level of 2.6 Mgal/d (0.22 Mgal/d in Southern Anne Arundel County).

Pumpage in the Aquia aquifer south of the model area was represented in the model indirectly through the general-head boundary. Water levels assigned to the general-head boundary in model layer 2 (Aquia aquifer) were obtained from a ground-water-flow model simulating projected pumpage in Calvert and St. Mary's Counties (Achmad and Hansen, 2001a). In that model, the Aquia aquifer was pumped at 8.2 Mgal/d in Calvert County and 11.3 Mgal/d in St. Mary's County. Pumpage values were derived from population projections made by the Maryland Office of Planning (1999) for Calvert County and the St. Mary's County Metropolitan Commission (written communication, 2000) for St. Mary's County. These values represent high growth estimates for each county. Water levels assigned to the general-head boundary in model layer 3 (Magothy aquifer) were derived by projecting the current drawdown trend of approximately 0.7 ft/yr out to 2020. Water levels at the general-head boundaries for both layers were assigned at 5-year increments.

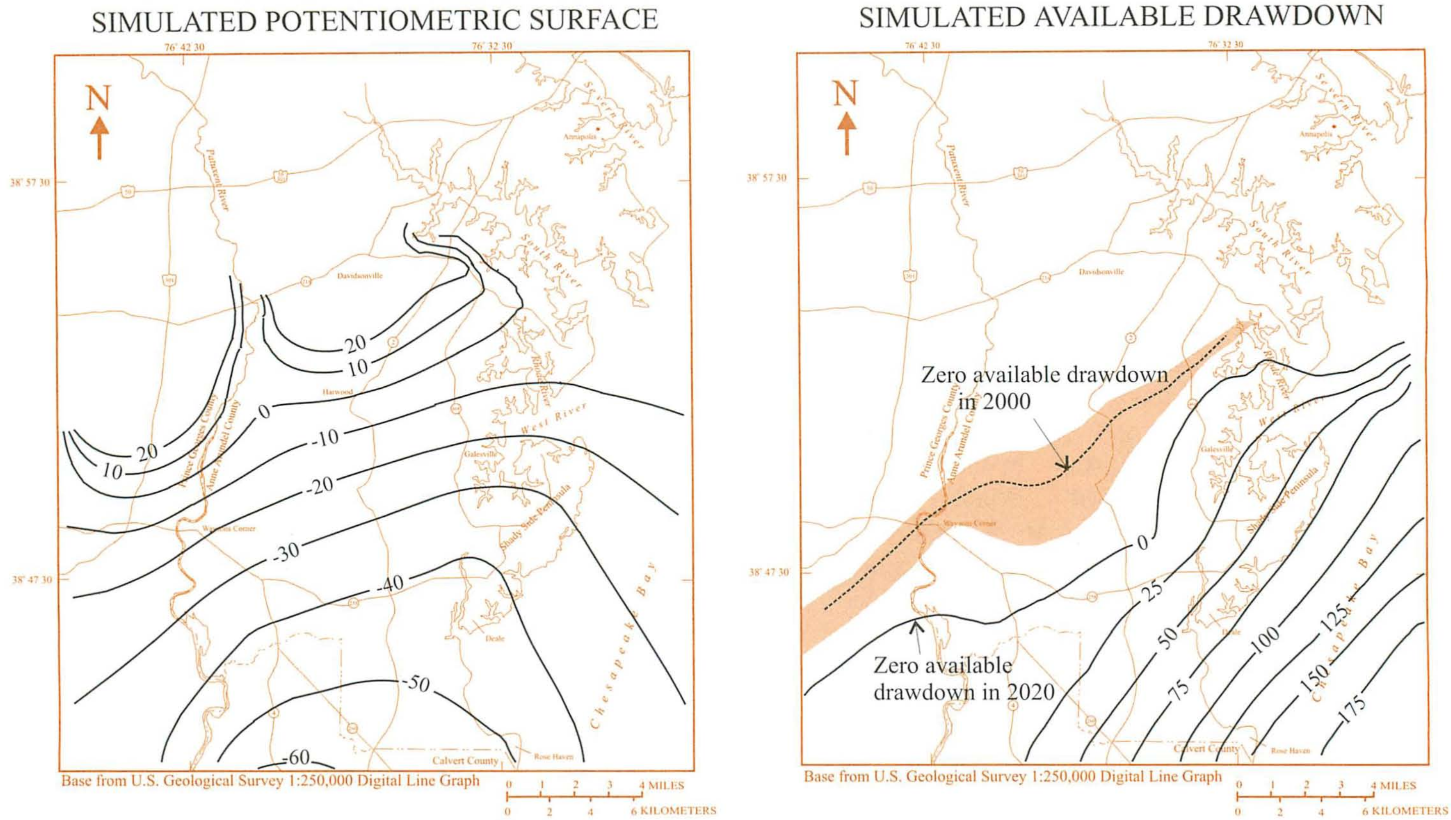
Results of the simulation of Scenario 1A indicate that water levels in the Aquia aquifer decline 2 to 22 ft across Southern Anne Arundel County by 2020. Simulated water levels range from sea level at Harwood to more than 50 ft below sea level near the Anne Arundel-Calvert County boundary (fig. 37). In the Deale-Shady Side area, water levels range from 20 to 45 ft below sea level. Available drawdown is reduced throughout Southern Anne Arundel County, but the reduction is most evident in the central part of the study area where the aquifer is shallower and had less initial available drawdown than farther to the south. Water levels exceed the 80-percent management water level in the central part of the study area in a band as much 3.5 mi wide extending from Waysons Corner to the Rhode River (fig. 37). Water levels fall below the top of the aquifer in an adjacent area approximately 1.5 mi wide. In as much as water levels in pumping wells are lower than water levels simulated by the model, wells screened in the upper part of the Aquia aquifer in this area could potentially fail.

The ground-water-flow model is limited in its ability to simulate water levels in model layer 2 (Aquia aquifer) in areas where water levels decline below the top of the aquifer. In the model, layer 2 is designated as a confined aquifer; therefore, unconfined (water-table) conditions cannot be simulated. Representing the Aquia aquifer strictly as a confined unit may simulate greater drawdown than would actually occur in those areas. In 2000, available drawdown in the central part of the study area ranged from about 0 to 15 ft (fig. 21). In the Deale-Shady Side area, available drawdown ranged from about 25 to 75 ft in 2020 compared to 50 to 90 ft in 2000 (fig. 21).

Water levels in the Magothy aquifer decline less than 2 ft resulting from the increased pumpage in the Aquia aquifer. Most of the drawdown in the Magothy aquifer is located in the southern part of the study area coinciding with the deepest water levels in the Aquia aquifer.

An alternative to individual residential wells to supply part of the projected water demand is the use of public-supply wells. The Aquia aquifer is capable of supplying as much as 200 gal/min to properly constructed production wells (Mack and Richardson, 1962, p. 27). A model simulation was made to illustrate the effect of supplying part of the projected population by public-supply wells screened in the Aquia aquifer. In Pumping Scenario 1B, 1.25 Mgal/d was pumped from five hypothetical wells, four located in the Deale-Shady Side area and one located at Tracys Landing. Pumping rates in those wells ranged from 0.18 to 0.27 Mgal/d. In this simulation, the entire projected 2020 population in the Deale-Shady Side Small Planning area and 2,000 of the population in the South County Small Planning area are served by public water. Simulated water levels and available drawdown by 2020 are the same as that produced when the projected population is served entirely by individual residential wells. Water levels calculated immediately outside the hypothetical pumping wells range from 7 to 8 ft deeper than the model-cell water levels, forming small cones-of-depression in the regional potentiometric surface. Estimated drawdown immediately outside the pumping wells was calculated from a modified version of the Thiem equation (Trescott and others, 1976, p. 10).

In order to reduce drawdown in the Aquia aquifer, pumpage must be reduced in Southern Anne Arundel County. A model simulation (Scenario 1C) was made with the increase in pumpage in Southern



EXPLANATION

-60 Potentiometric contour of simulated water levels. Contour interval is 10 feet. Datum is sea level.

EXPLANATION

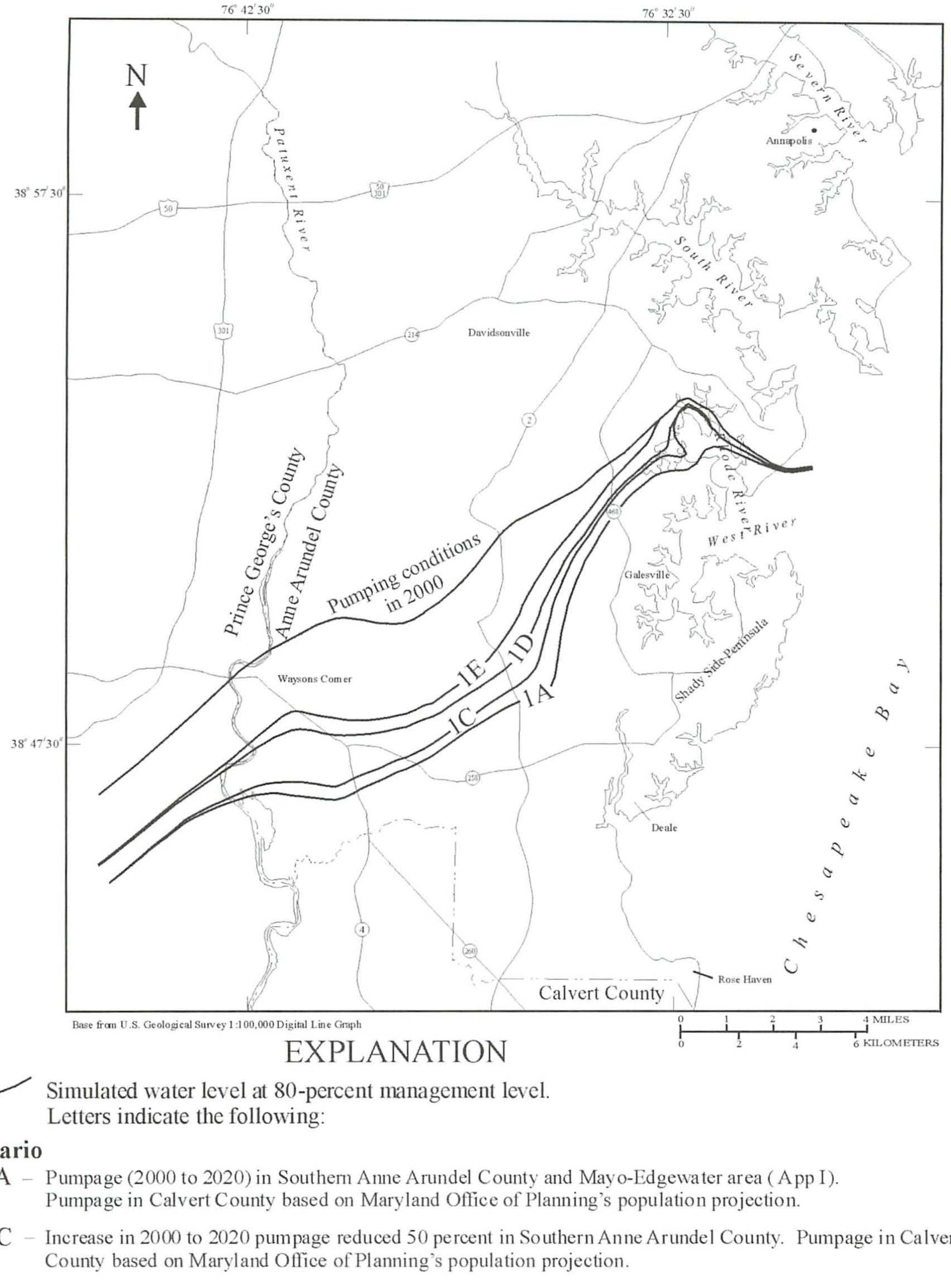
150 Available drawdown, in feet. Contour interval is 25 feet.

Area where simulated water levels have declined below the top of the Aquia aquifer between 2000 and 2020.

Figure 37. Simulated 2020 potentiometric surface and available drawdown for model layer 2 (Aquia aquifer) based on projected population growth in Southern Anne Arundel County and Edgewater-Mayo area and Maryland Office of Planning projected population in Calvert County (Pumping Scenario 1A).

Anne Arundel County simulated in Scenario 1A reduced by 50 percent. During the simulation, model layer 2 (Aquia aquifer) was pumped at approximately 2.2 Mgal/d in Southern Anne Arundel County. Model results indicate that drawdown between 2000 and 2020 is reduced by less than 4 ft in Southern Anne Arundel County. This represents approximately half the drawdown that resulted from the full projected pumpage amount (Scenario 1A). The area for which water levels have reached the 80-percent management level is reduced by less than one-half mile from Scenario 1A (fig. 38, lines 1A and 1C).

Reduction of future pumpage from the Aquia aquifer in Calvert County provides another option for reducing drawdown in Southern Anne Arundel County. Model simulation Scenario 1D represents a reduction in Aquia pumpage in Calvert County based on population projections made by the Calvert County Department of Planning and Zoning (written communication, 2000), which assumes a slower growth rate than the Maryland Office of Planning (1999). The amount of pumpage from the Aquia aquifer required for the lower growth estimate in Calvert County totals 6.1 Mgal/d as opposed to 8.2 Mgal/d for the Maryland Department of Planning's



EXPLANATION

Simulated water level at 80-percent management level. Letters indicate the following:

Scenario

1A – Pumpage (2000 to 2020) in Southern Anne Arundel County and Mayo-Edgewater area (App I). Pumpage in Calvert County based on Maryland Office of Planning's population projection.

1C – Increase in 2000 to 2020 pumpage reduced 50 percent in Southern Anne Arundel County. Pumpage in Calvert County based on Maryland Office of Planning's population projection.

1D – Scenario 1A pumpage (2000 to 2020) in Southern Anne Arundel County and Mayo-Edgewater area. Pumpage in Calvert County based on Calvert County Department of Planning and Zoning's population projection.

1E – Increase in 2000 to 2020 pumpage reduced 50 percent in Southern Anne Arundel County. Pumpage in Calvert County based on Calvert County Department of Planning and Zoning's population projection.

Figure 38. Effect of reduced projected pumpage in Southern Arundel County and Calvert County on simulated water levels related to the 80-percent management level (Aquia aquifer).

population projection (Achmad and Hansen, 2001a). Pumping the Aquia aquifer at the lower rate in Calvert County while maintaining the full projected pumping rate in Southern Anne Arundel County, reduces drawdown in Southern Anne Arundel County as much as 15 ft. The benefit of lower pumpage in Calvert County is most apparent in the southern part of the study area near the Anne Arundel-Calvert County boundary. The area in which water levels have reached the 80-percent management level is shifted northwestward by as much as 1.5 mi (fig. 38, line 1D) from the simulation of Scenario 1A with full projected pumpage (fig. 38, line 1A).

Drawdown can be further reduced by combining a 50-percent reduction in projected 2020 pumpage increase in Southern Anne Arundel County with the lower estimate of projected pumpage in Calvert County (Scenario 1E). Under this scenario the area in which water levels reach the 80-percent management level by 2020 is reduced by as much as 2 mi (fig. 38, line 1E) from the simulation of full projected pumpage (Scenario 1A) (fig. 38, line 1A).

Increasing pumpage in model layer 2 (Aquia aquifer) to support the full projected population (Scenario 1A) causes an increase in recharge from the outcrop area of the Aquia aquifer. In 2000, the simulated recharge rate was 1.6 in./yr. This rate increased to 2.1 in./yr by 2020.

In conclusion, Scenario 1A indicates that the Aquia aquifer can sustain the projected 2020 water demand for Southern Anne Arundel County of 2.6 Mgal/d (4.3 Mgal/d including the Mayo-Edgewater area) without depleting the available drawdown in most areas. Water levels will, however, decline below the 80-percent management level in the central part of the study area (fig. 38). Withdrawing part of the water by public-supply wells (Scenario 1B) causes similar reductions in available drawdown. Scenarios 1C, 1D, and 1E demonstrate that drawdown and size of the exceedance area could be reduced by limiting future withdrawals from the Aquia aquifer in either Southern Anne Arundel County, northern Calvert County, or both. All of the simulations, however, result in an expansion of the area in which water levels have reached the 80-percent management water level compared to the 2000 pumping conditions.

Pumping Scenario 2: Projected 2020 Population Increase Supplied by the Magothy Aquifer

The Magothy aquifer, underlying the Aquia aquifer, is a potential source of potable water to supply the projected population growth in Southern Anne Arundel County. Historically, use of the Magothy aquifer in Southern Anne Arundel County consisted chiefly of public-supply wells serving mobile home parks. Since the late 1980's, the Magothy aquifer has also been utilized as a source for several irrigation wells. Wells completed in the Magothy aquifer in Southern Anne Arundel County for domestic supply are relatively uncommon because of the greater drilling depths required. Model simulations were made to determine the effect of pumping the Magothy aquifer to meet the projected 2020 demand using dispersed residential wells (Scenario 2A) and using public-supply wells (Scenario 2B). In both simulations, model layer 3 (Magothy aquifer) was pumped an additional 0.8 Mgal/d in Southern Anne Arundel County (1.5 Mgal/d including the Mayo-Edgewater area) to meet the projected 2020 population increase of approximately 3,800 in Southern Anne Arundel County (7,800 including the Mayo-Edgewater area). The increase in population represents the difference between the projected 2020 population for the Deale-Shady Side, South County, and Mayo-Edgewater Small Planning areas, and the 2000 population based on 2000 U.S. Census figures. Pumpage was increased gradually over the 20-year period. Pumpage from major users was maintained at the 2000 levels of approximately 2.6 Mgal/d for the model area (0.22 Mgal/d in Southern Anne Arundel County). Water levels assigned to the general-head boundary in model layer 3 were derived by projecting the current drawdown trend of approximately 0.7 ft/yr out to 2020. Water levels at the general-head boundary were assigned at 5-year increments. Pumpage in the Aquia aquifer was held at 2000 levels.

In the first model simulation (Scenario 2A), projected pumpage assigned to the model was dispersed to represent withdrawals by individual residential wells. The projected pumpage was assigned to model layer 3 (Magothy aquifer) evenly within the Deale-Shady Side, South County, and

Mayo-Edgewater Small Planning areas at rates of 0.45, 0.38, and 0.66 Mgal/d, respectively (fig. 39). Results of the simulation indicate that by 2020, water levels decline as much as 20 ft from the 2000 water levels. Most of the drawdown occurs in the Mayo-Edgewater and Deale-Shady Side areas. As much as 6 ft of drawdown is caused by the increased pumpage above 2000 levels while the remaining drawdown is a result of declining regional water levels represented at the general-head boundary. Water levels in 2020 range from 10 to 20 ft below sea level in the Davidsonville and Harwood areas and 25 to 35 ft below sea level in the Deale-Shady Side area (fig. 39). Available drawdown in 2020 ranges from about 100 ft at Davidsonville to 350 ft at Rose Haven. Water levels in the Magothy aquifer stabilize with respect to pumpage within 2 years after the simulation period 2000-2020. This was determined by extending the simulation period to 2025 and holding pumpage constant after 2020. Water levels in the Aquia aquifer are unaffected by the increased pumpage in the Magothy aquifer.

In the second simulation (Scenario 2B), the projected pumpage was assigned to seven model cells representing withdrawals from public-supply wells (fig. 39). Pumping rates for the individual wells ranged from 0.16 to 0.23 Mgal/d. Results of the simulation indicate that by 2020, water levels decline by as much as 20 ft from the 2000 water levels. Drawdown caused by pumping the public-supply wells ranges from 8 to 10 ft from 2000 water levels. The remaining drawdown is a result of declining regional water levels at the general-head boundary. Water levels in 2020 are similar with the exception of a few shallow cones-of-depression that form around simulated public-supply wells (fig. 39). Available drawdown in 2020 is nearly equal to the previous simulation. Water levels in the Magothy aquifer stabilize with respect to pumpage within 2 years after the simulation period 2000-2020. Water levels in the Aquia aquifer are unaffected by increased pumpage in the Magothy aquifer.

The Magothy aquifer can supply the projected increase in water demand of 0.8 Mgal/d in Southern Anne Arundel County (1.5 Mgal/d including the Mayo-Edgewater area) with either residential wells or public-supply wells without causing significant reduction of available drawdown. Treatment costs for reducing iron concentrations and the practicality and expense of centralized public-water systems are, however, important considerations related to the use of the Magothy aquifer as an alternative to the Aquia aquifer.

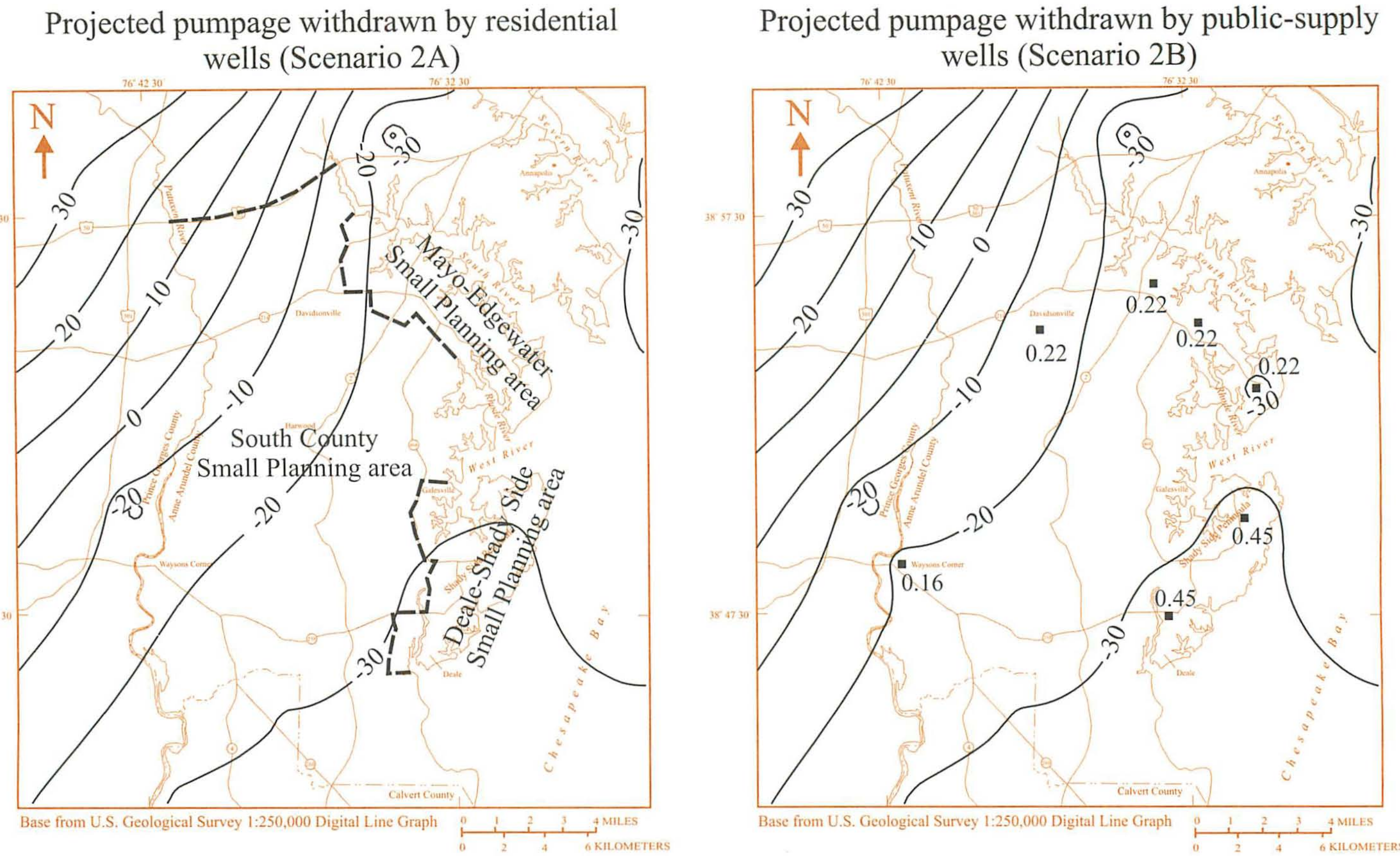
Pumping Scenario 3: Estimation of Time Required for Water Levels in the Aquia and Magothy Aquifers to Stabilize at 2000 Pumping Rates

When withdrawals in model layer 2 (Aquia aquifer) are held constant at 2000 levels, water levels stabilize with respect to those withdrawals in less than 1 year. A model simulation was made in which model layer 2 (Aquia aquifer) was pumped at the 2000 level of 1.8 Mgal/d in Southern Anne Arundel County (2.8 Mgal/d including the Mayo-Edgewater area) for the period 2000 to 2020. This rate includes both self-supplied domestic use and major appropriated users. Pumpage in Calvert County was indirectly held constant in the model at 2000 levels by holding water levels along the general-head boundaries constant at 2000 levels. Hydrographs of simulated water levels at seven observation wells in model layer 2 are shown in figure 40. The locations of the observation wells are shown in figure 32. Water levels stabilize after about 6 months.

In the same model simulation, model layer 3 (Magothy aquifer) was pumped continuously at the 2000 amount. In Southern Anne Arundel County, this amount was 0.22 Mgal/d. Pumpage outside the model area was indirectly held constant by holding water levels along the general-head boundary constant at the 2000 levels. In response to these pumping conditions, simulated water levels in model layer 3 stabilize within about 3 months in Southern Anne Arundel County.

Pumping Scenario 4: Highest Sustainable Withdrawals in the Aquia and Magothy Aquifers in Southern Anne Arundel County

The maximum yield of the Aquia aquifer in Southern Anne Arundel County is controlled by the amount of water available from the recharge area and by the available drawdown in the aquifer. A pumping well causes a reduction in pressure head as represented by the water level immediately surrounding the well. The lower pressure at the well creates a gradient within the aquifer causing water



EXPLANATION

-30 — Potentiometric contour of simulated water levels. Contour interval is 10 feet. Datum is sea level.

0.16 ■ Simulated public-supply well. Number next to symbol is the pumping rate in million gallons per day.

Anne Arundel County Small Planning Area boundary.

Figure 39. Simulated 2020 potentiometric surfaces for model layer 3 (Magothy aquifer) based on projected growth in Southern Anne Arundel County and Edgewater-Mayo area (Pumping Scenario 2).

to flow toward the well. The declining water level forms a cone-of-depression surrounding the well that expands outward from the well as pumping continues. The cone-of-depression stabilizes when the rate of withdrawal is balanced by an equal amount of recharge. The Aquia aquifer in Southern Anne Arundel County receives recharge from its outcrop area in Anne Arundel County and eastern Prince George's County. Previous studies (Chapelle, 1985; Harsh and Laczniak, 1990; and McFarland, 1997) indicate recharge rates of 1.1 to 3.8 in./yr to artesian Coastal Plain aquifers, dependent on pumping conditions. The rate of recharge can be increased through induced flow to wells. Available recharge to model layer 2 (Aquia aquifer) from the outcrop area was estimated by multiplying the area of the Aquia outcrop by a range of linear recharge rates. The outcrop area is approximately 1.1 x 109 ft^2. Assuming linear recharge rates of 1.1 to 3.8 in./yr, the recharge available from the outcrop area varies from 1.9 to 7.1 Mgal/d. Provided drawdown does not exceed the management level, pumpage could be increased to take advantage of the potential available recharge. However, utilizing this recharge would result in a reduction in evapotranspiration and in ground-water discharge (baseflow) to streams in the outcrop area (Achmad, 1991). The potentially adverse effects of

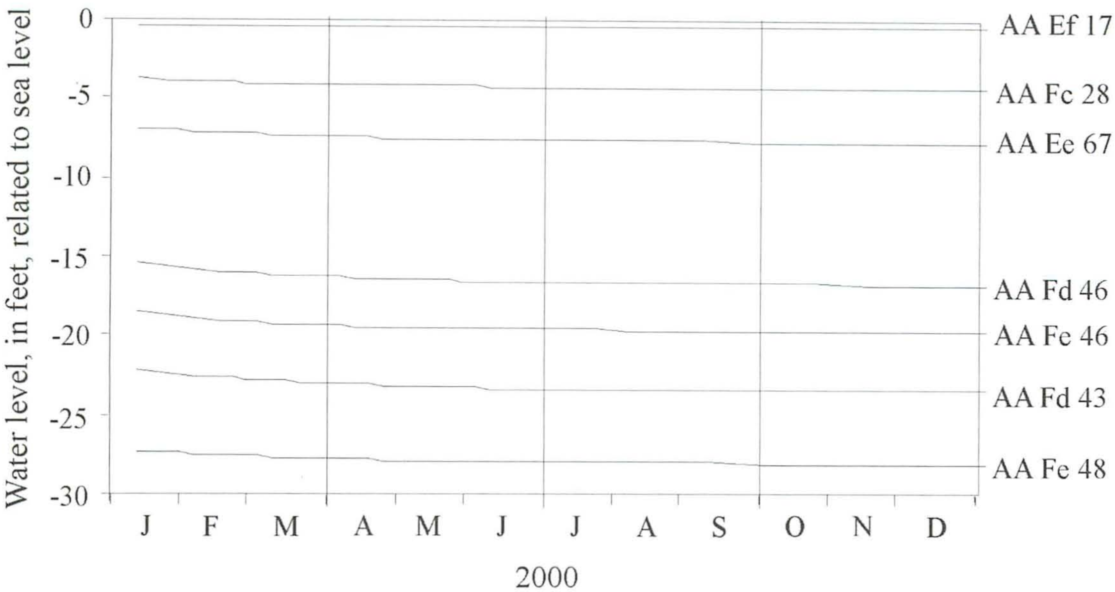


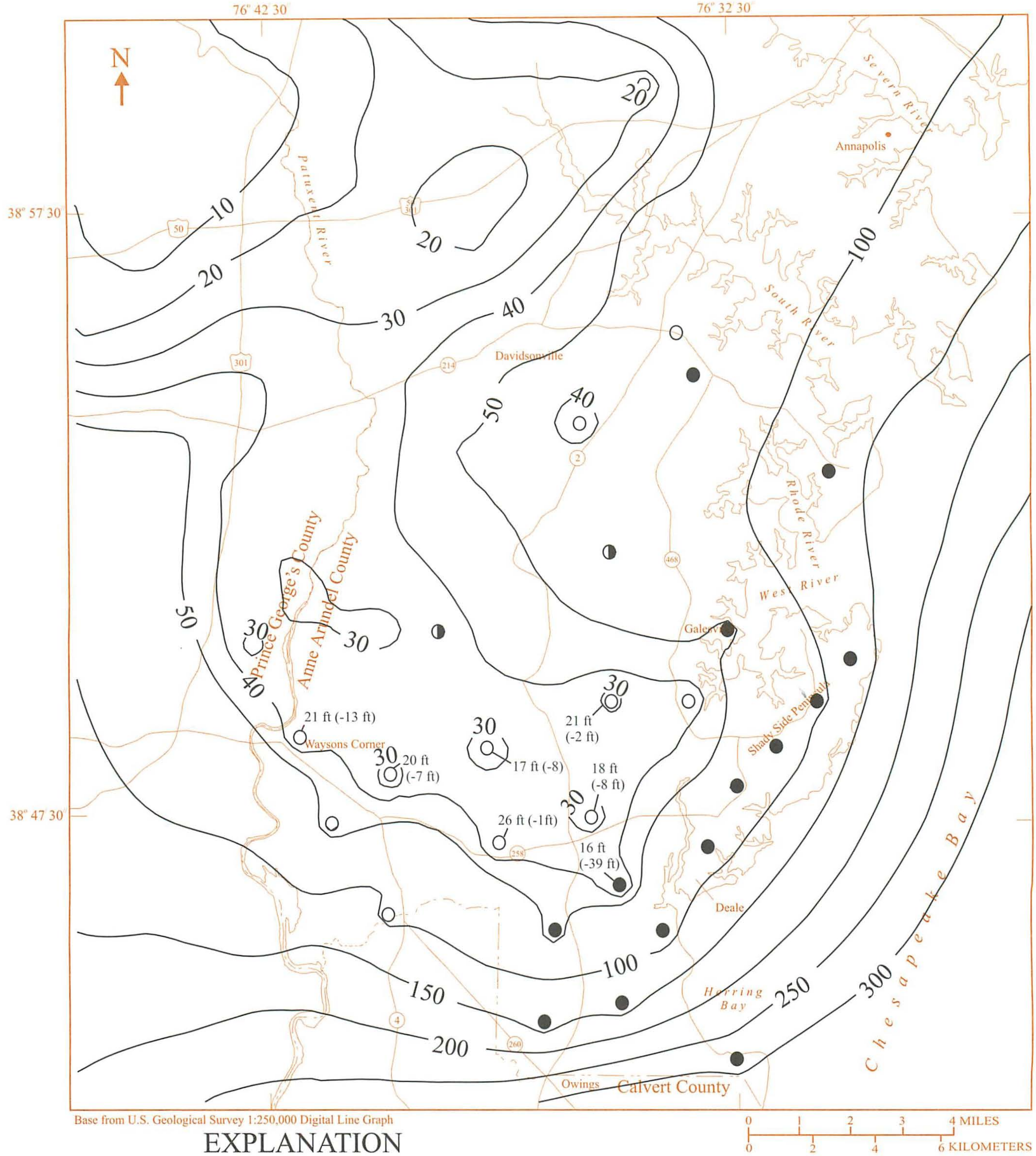
Figure 40. Hydrograph showing simulated water levels in model layer 2 (Aquia aquifer) at selected observation wells when pumpage and water levels at the general-head boundary are held constant at 2000 levels (Pumping Scenario 3).

reduced baseflow on stream ecology could constrain the amount of water pumped from the Aquia aquifer. Determining the potential impact of reduced baseflow to streams is beyond the scope of this study.

While additional recharge from the outcrop area is available to the confined part of the Aquia aquifer, obtaining that additional recharge would require further drawdown in the aquifer. As of 2000, water levels in the Aquia aquifer have exceeded the 80-percent management water level within a 2-mi-wide band in the central part of Southern Anne Arundel County (figs. 21 and 22). Increasing pumpage from the Aquia aquifer will result in an expansion of this area. Therefore, as defined by the present management guideline (Code of Maryland Regulations, 1997), the Aquia aquifer in Southern Anne Arundel County has reached its maximum allowable yield.

The simulated maximum yield of the Magothy aquifer based solely on the available drawdown in Southern Anne Arundel County is approximately 38 Mgal/d. In a model simulation (Scenario 4A), 26 hypothetical wells were pumped continuously from model layer 3 (Magothy aquifer) for the 20-year period 2000 to 2020, at rates of 0.5, 1, or 2 Mgal/d (fig. 41). Pumpage from existing major users was maintained at the 2000 level of approximately 2.6 Mgal/d for the model area. During the model simulation, model layer 2 (Aquia aquifer) was pumped at the 2000 rate of 2.8 Mgal/d. The simulated hypothetical wells in layer 3 were located mostly in the southern part of the study area where there is a greater amount of available drawdown. Model results indicate that simulated available drawdown in 2020 in layer 3 ranged from less than 16 ft in the Tracys Landing-Lothian area to 300 ft at Rose Haven (fig. 41). The deepest simulated water level in layer 3 is approximately 280 ft below sea level and occurs at Tracys Landing (fig. 42). Water levels decline up to 270 ft from the 2000 Magothy potentiometric surface. Water levels stabilize after about 1 year of pumping.

The model simulates average water levels within the model-cell area. Deeper water levels occur immediately surrounding pumping wells. Water levels immediately outside the hypothetical pumping wells range from 23 to 55 ft deeper than the model-cell water levels. The additional drawdown was calculated from a modified version of the Thiem equation (Trescott and others, 1976, p. 10). As a result, water levels immediately outside 7 of the 26 hypothetical wells exceed the 80-percent management level by 1 to 39 ft (fig. 41). Reducing pumpage by 1.4 Mgal/d in the 7 wells, for a total of approximately 37 Mgal/d pumped in Southern Anne



EXPLANATION

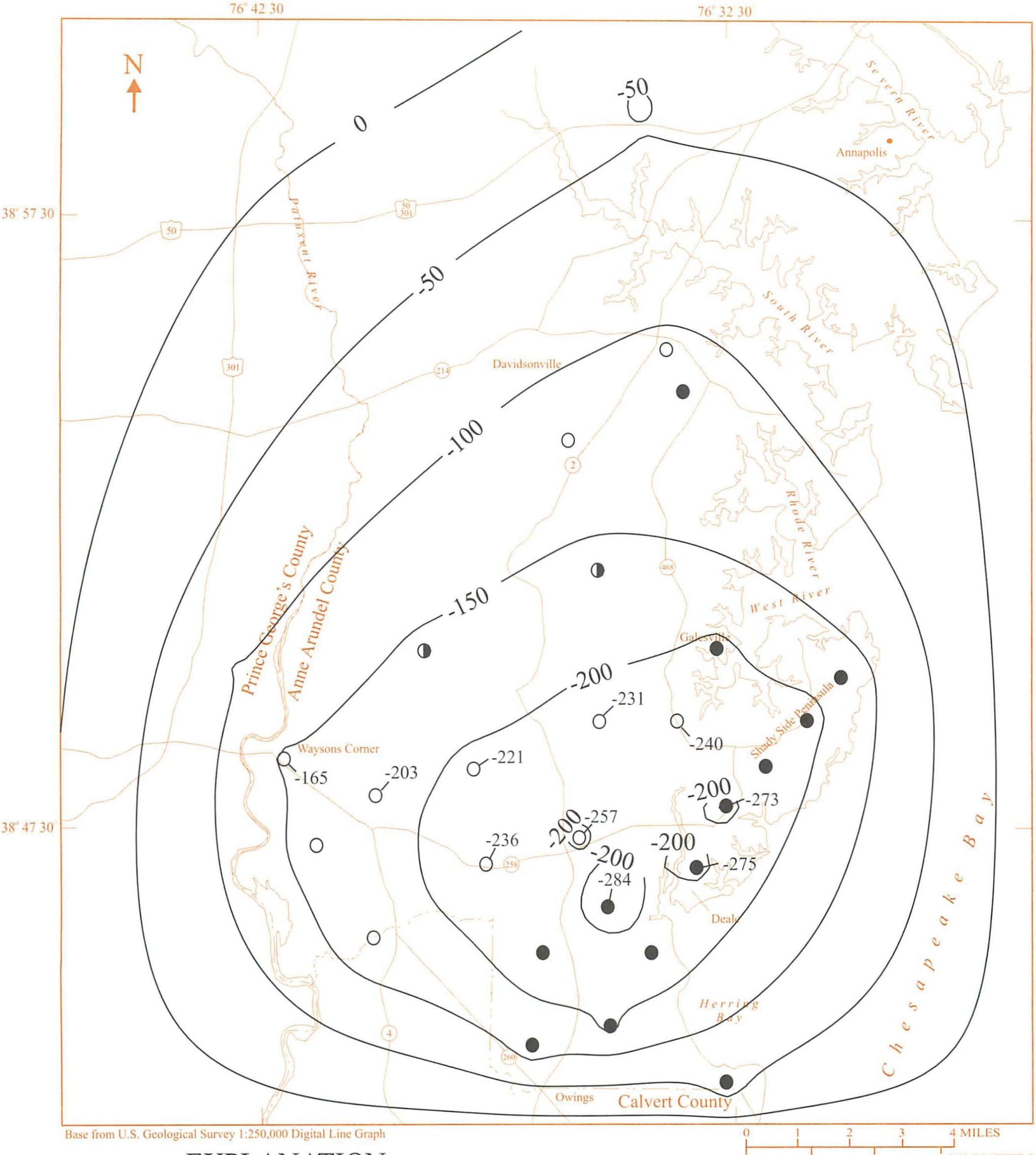
— 250 — Simulated available drawdown, in feet. Contour interval is variable.

Hypothetical wells pumped during model simulation:

- ◑ 0.5 million gallons per day
- 26 ft (-1 ft) ○ 1 million gallons per day
- ● 2 million gallons per day

Numbers next to well symbol are available drawdown in model cell and immediately surrounding pumping well (in parenthesis).

Figure 41. Simulated available drawdown in the Magothy aquifer in 2020 when pumped at 38 million gallons per day in Southern Anne Arundel County (Pumping Scenario 4A).



EXPLANATION

-50 — Potentiometric contour of simulated water levels, in feet. Contour interval is 50 feet. Datum is sea level.

Hypothetical wells pumped during model simulation:

- ◑ 0.5 million gallons per day
- -236○ 1 million gallons per day
- ● 2 million gallons per day

Number next to well symbol is the simulated water level in the model cell containing the pumping well.

Figure 42. Simulated 2020 potentiometric surface for model layer 3 (Magothy aquifer) when pumped at 38 million gallons per day in Southern Anne Arundel County (Pumping Scenario 4A).

Arundel County, raises water levels immediately outside the pumping wells above the management water level.

The modeled maximum yield of the Magothy aquifer in Southern Anne Arundel County is based on one set of hypothetical pumping wells. However, many different pumping-well locations and rates are possible, which could alter the simulated maximum yield. Optimum well locations and pumping rates of future production wells, which maximize withdrawals while satisfying the management-level drawdown constraint, could be determined if the Magothy aquifer is developed as a major source of water in Southern Anne Arundel County.

The Matawan confining unit separating the Aquia and Magothy aquifers has a relatively low permeability. The confining unit was represented in the model using a vertical leakance of 7.5×10^{-7} 1/d. The relatively low vertical leakance restricts the movement of water between the two aquifers. However, when the Magothy aquifer is pumped continuously for 20 years at the relatively high rate of 38 Mgal/d (Scenario 4A) in Southern Anne Arundel County, the vertical hydraulic gradient that develops between the two aquifers causes some leakage of water from the Aquia aquifer downward to the Magothy aquifer. Simulated water levels in model layer 2 (Aquia aquifer) decline by as much as 22 ft from 2000 levels. As a result, water levels exceed the 80-percent management water level in the central part of the study area in a band as much as 2 mi wide, extending from Waysons Corner to Rhode River. The maximum yield of the Magothy aquifer is, therefore, controlled, in part, by the amount of available drawdown in the Aquia aquifer. A series of model simulations based on Scenario 4A was made in which pumpage in the Magothy aquifer was lowered to reduce the impact on available drawdown in the Aquia aquifer. In the first simulation (Scenario 4B), hypothetical wells located in the central and northern part of Southern Anne Arundel County were removed. This lowered Magothy pumpage in Southern Anne Arundel County to approximately 26 Mgal/d from the remaining hypothetical wells. Eliminating the central and northern wells reduces the area in which the 80-percent management water level is exceeded in the Aquia aquifer by approximately 25 percent. Lowering the total pumpage in the remaining wells to 14 Mgal/d (Scenario 4C) reduces the area by about one-half. Further lowering pumpage to 7 Mgal/d (Scenario 4D) reduces the area where the 80-percent management water level is exceeded in the Aquia aquifer by approximately 75 percent. Water levels in the Magothy aquifer, when pumped continuously at 7 Mgal/d for the period 2000 to 2020, range from about 10 to 70 ft below sea level in Southern Anne Arundel County (fig. 43). Available drawdown ranges from 100 to 350 ft (fig. 43). Drawdown in the Aquia aquifer resulting from the Magothy pumpage is less than 4 ft. Reducing pumpage in the Aquia aquifer (Scenario 4E) to a rate 25 percent below the 2000 level (or approximately 1.4 Mgal/d in Southern Anne Arundel County and Mayo-Edgewater area) fully compensates for the drawdown caused by pumping the Magothy aquifer at 7 Mgal/d. Reducing pumpage in the Aquia aquifer further will allow a greater amount to be pumped from the Magothy aquifer.

The ground-water-flow model consisted of three layers representing the water-table aquifer, the Aquia aquifer, and the Magothy aquifer. The deeper Upper Patapsco aquifer was not modeled because it was assumed that the confining unit separating the Upper Patapsco aquifer from the Magothy aquifer forms a no-flow boundary. Therefore, vertical leakage to the Magothy aquifer is derived totally from the Aquia aquifer in the model. The validity of representing the base of model layer 3 (Magothy aquifer) as a no-flow boundary was tested by adding a fourth model layer representing the Upper Patapsco aquifer. The layer was simulated as a constant-head layer using the 1999 potentiometric surface (Curtin and others, 2001e). The confining unit separating the Magothy and Upper Patapsco aquifers, represented as a quasi-three dimensional layer, was assigned a leakance value of 2×10^{-8} 1/d. This value was calculated using an average vertical hydraulic conductivity and layer thickness of: (1) 17 ft/d and 65 ft for the Magothy aquifer; (2) 6×10^{-7} ft/d (Mack and Mandle, 1977) and 40 ft (Fleck and Andreasen, 1996) for the Patapsco Formation confining unit; and (3) 40 ft/d and 200 ft (Fleck and Andreasen, 1996) for the Upper Patapsco aquifer. Pumping Scenario 4A (38 Mgal/d withdrawn from the Magothy aquifer in Southern Anne Arundel County) was re-run using the modified model. Results of the simulation indicate the additional layer (Upper Patapsco aquifer) contributes approximately 4 percent of the total vertical leakage to the Magothy aquifer. Leakage from the Aquia aquifer was reduced from approximately 100 percent of total leakage to the Magothy aquifer in

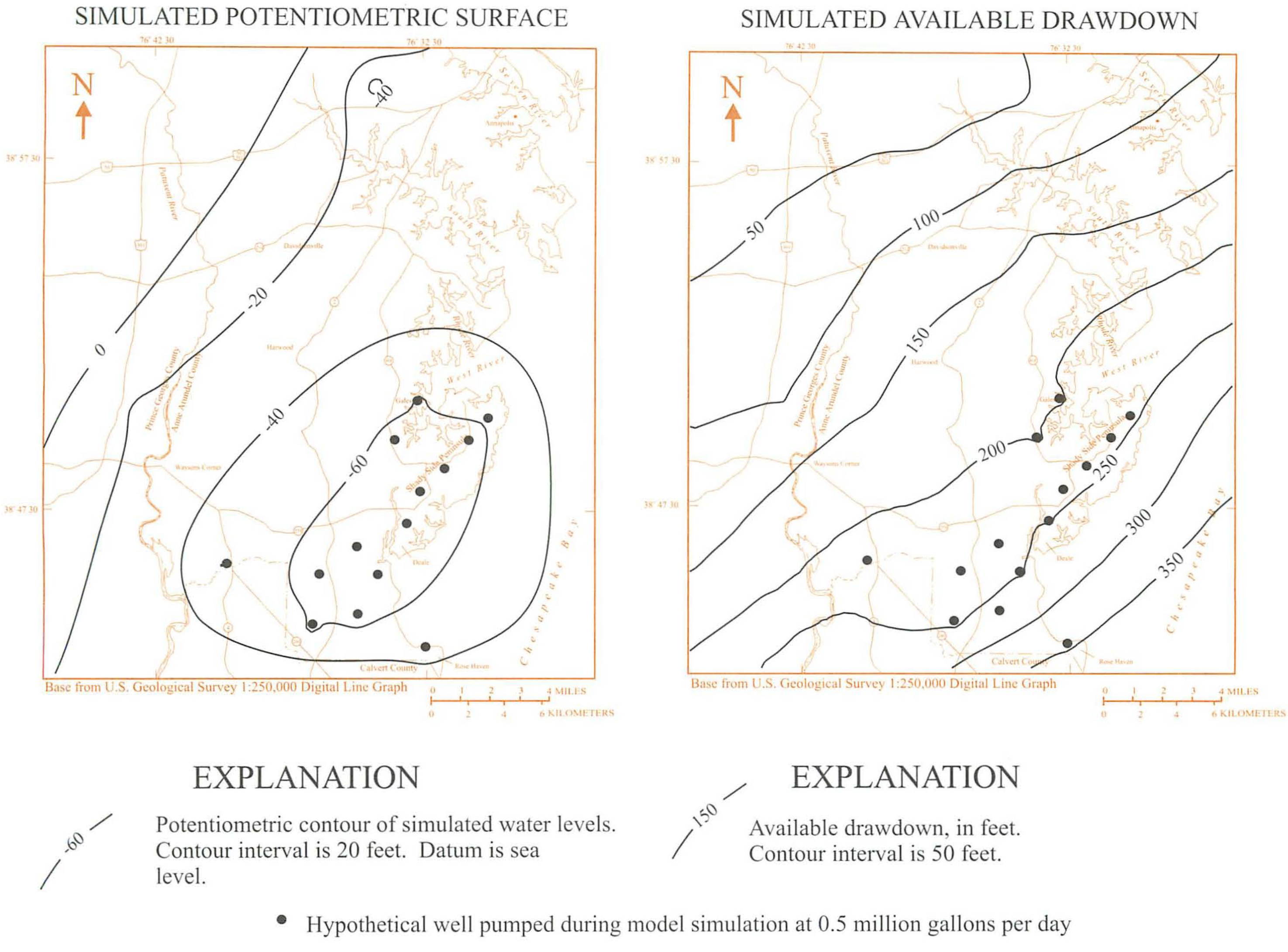


Figure 43. Simulated 2020 potentiometric surface and available drawdown for model layer 3 (Magothy aquifer) when pumped at 7 million gallons per day (Pumping Scenario 4D).

model simulation 4A (no-flow boundary at the base of the Magothy) to 96 percent in the modified model. The reduction in vertical flow from the Aquia aquifer, however, did not significantly reduce drawdown in either the Aquia or Magothy aquifer associated with the increased pumpage in the Magothy aquifer. Increasing the leakance value between the Magothy and Upper Patapsco aquifers from 2×10^{-8} to 5×10^{-7} 1/d, based on a vertical hydraulic conductivity of 1×10^{-5} ft/d for the Patapsco Formation confining unit (Mack, 1974), reduced leakage from the Aquia aquifer to 59 percent and increased to 41 percent the leakage from the Upper Patapsco aquifer. Drawdown in the Aquia aquifer in Pumping Scenario 4A was reduced approximately 2 ft, while water levels in the Magothy aquifer were not affected significantly by the changes in leakage.

If present, areally extensive gaps in the intervening confining unit between the Magothy and Upper Patapsco aquifers in Southern Anne Arundel County could increase the amount of leakage from the Upper Patapsco aquifer and affect drawdown in the Magothy aquifer and, in turn, the Aquia aquifer. At present there is no evidence of a direct hydraulic connection of regional extent between the Magothy and Upper Patapsco aquifers in Southern Anne Arundel County.

Pumping Scenario 5: Effect of Projected 2020 Withdrawals From the Aquia Aquifer in Calvert and St. Mary's Counties on Water Levels in Southern Anne Arundel County

Water-level decline in the Aquia aquifer in Southern Anne Arundel County is only partly a result of pumpage in that area. Water levels also decline because of pumpage south of the study area in Calvert and St. Mary's Counties. The magnitude of drawdown associated with this pumpage is an important consideration in water allocation for Southern Anne Arundel County. The Aquia aquifer is a major source of water for both self-supplied domestic use and public supply in the southern counties. Total withdrawals from the Aquia aquifer in Calvert and St. Mary's Counties in 2000 were approximately 4.5 and 6.0 Mgal/d, respectively (Judith Wheeler, personal communication, 2002). Model simulations were made to determine the amount of drawdown by 2020 in Southern Anne Arundel County resulting from the regional water-level decline. The regional head decline was derived from a ground-water-flow model simulating projected water use based on various population estimates for Calvert and St. Mary's Counties (Achmad and Hansen, 2001a). To isolate the effect of the regional drawdown, pumpage within Southern Anne Arundel County and the Mayo-Edgewater area was held constant at 2000 levels of approximately 2.8 Mgal/d (1.8 Mgal/d in Southern Anne Arundel County and 1 Mgal/d in the Mayo-Edgewater area). Pumpage in the Magothy aquifer was held constant at the 2000 rate of approximately 2.6 Mgal/d for the model area (0.22 Mgal/d in Southern Anne Arundel County).

In the first model simulation (Scenario 5A), a regional head decline in the Aquia aquifer representing projected pumpage amounts in 2020 of 8.2 Mgal/d (Calvert County) and 11.3 Mgal/d (St. Mary's County) was simulated. Pumpage values were derived from population projections made by the Maryland Office of Planning (1999) for Calvert County and the St. Mary's County Metropolitan Commission (written communication, 2000) for St. Mary's County. These values represent high growth estimates for each county. Pumpage occurring in those areas was represented in the model as specified water levels along the southern model boundary (general-head boundary). Water levels along the boundary were specified at 5-year increments. The projected pumpage causes water levels to decline by as much as 22 ft in Southern Anne Arundel County from 2000 levels. The greatest drawdown occurs along the Anne Arundel-Calvert County boundary. Water levels decline approximately 6 to 14 ft in the Deale-Shady Side area. Approximately 1 to 2 ft of the total drawdown by 2020 is attributed to stabilization of water levels with respect to pumpage within the model area. Simulated 2020 water levels range from sea level in the central part of Southern Anne County to more than 50 ft below sea level near the southernmost boundary with Calvert County. Available drawdown ranges from 0 ft along a line extending from Bristol through Lothian to Rhode River to about 25 ft at Galesville and 150 ft at Rose Haven. Over the simulation period 2000 to 2020, the 80-percent management level is exceeded in a band as much as 3 mi wide extending from Waysons Corner to Rhode River. Figure 44 shows the simulated drawdown trend at three observation wells in Southern Anne Arundel County. The simulated drawdown continues at the observed water-level trend for the period of record for AA Fe 46 at Shady Side. The simulated drawdown trend is steeper than the observed trend for AA Fc 28 at Waysons Corner and shallower for AA Ed 49 at Davidsonville.

A second model simulation (Scenario 5B) was made in which projected pumpage from the Aquia aquifer in Calvert County was reduced to 6.1 Mgal/d based on a population projection by the Calvert County Department of Planning and Zoning (written communication, 2000). An alternate growth projection was not available for St. Mary's County. The projected pumpage causes water levels to decline by as much as 10 ft in Southern Anne Arundel County from 2000 levels. The greatest amount of drawdown occurs along the Anne Arundel-Calvert County boundary. Water levels decline approximately 5 ft in the Deale-Shady Side area. Simulated 2020 water levels range from sea level in the central part of Southern Anne Arundel County to more than 30 ft below sea level near the southernmost boundary with Calvert County. Available drawdown ranges from 0 ft along a line extending from Waysons Corner through Lothian to Rhode River to about 25 ft at Galesville and 150 ft at Rose Haven. Over the simulation period 2000 to 2020, the 80-percent management level is exceeded in a band as much as 2 mi wide extending from Waysons Corner to Rhode River. The simulated drawdown continues at the observed water-level trend for the period of record for AA Fc 28 at

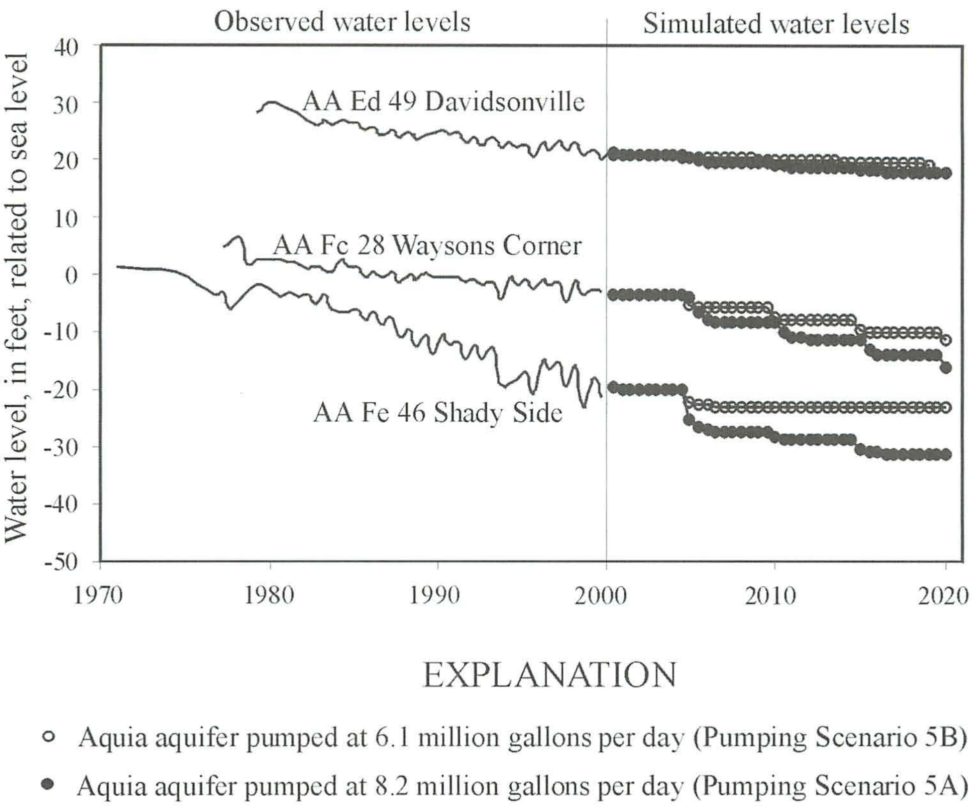


Figure 44. Hydrograph showing observed and simulated water levels when the Aquia aquifer is pumped at 6.1 and 8.2 million gallons per day in Calvert County (Pumping Scenarios 5A and 5B).

Waysons Corner (fig. 44). The simulated drawdown trend is shallower than the observed trend for wells AA Ed 49 at Davidsonville and AA Fe 46 at Shady Side (fig. 44).

MODEL ACCURACY

Model accuracy depends on a valid conceptualization of the hydrogeologic framework controlling the ground-water-flow system and on the assignment of representative values of input parameters such as aquifer transmissivity, confining unit leakance, and pumpage. The accuracy of ground-water-flow models simulating historical conditions can be determined by comparing observed water levels to simulated water levels. The accuracy of the same model to predict future conditions, however, can only be verified by comparing observed conditions to simulated conditions at the end of the simulation period. Model performance can be evaluated and improved at intermediate steps as more data on hydrogeologic characteristics, water-level trends, and domestic and appropriated pumpage become available. Collection and analysis of these data in Southern Anne Arundel County should be continued in the future.

CONCLUSIONS

Southern Anne Arundel County is supplied almost entirely by ground water from two aquifers, the Aquia and the Magothy. In 2000, a total of approximately 1.8 Mgal/d was pumped from the Aquia: 1.62 Mgal/d by domestic wells; 0.17 by privately owned public-supply wells; and 0.012 by commercial, sod-farm irrigation, and public-utility use. Use of the Magothy aquifer in 2000 totaled 0.22 Mgal/d: about 0.16 Mgal/d for public supply at mobile-home parks and 0.06 Mgal/d for sod-farm and golf-course irrigation. Almost no water from the Magothy is used for domestic purposes in Southern Anne Arundel County.

The Aquia and Magothy aquifers are part of the sequence of unconsolidated sediments in Maryland's Coastal Plain province. The coastal plain sediments, consisting of gravel, sand, silt, and clay, overlie consolidated basement rock. The total sediment thickness in Southern Anne Arundel County ranges from 1,600 ft at Davidsonville to 2,500 ft at Rose Haven. The major water-bearing formations underlying Southern Anne Arundel County include from deepest to shallowest, the Patuxent, Lower Patapsco, Upper Patapsco, Magothy, and Aquia aquifers. The Aquia aquifer consists of medium to coarse sand composed of clear to white quartz and dark-green, brown, and black glauconite. Hard layers of iron or calcareous-cemented sandstone are common. The top of the aquifer ranges from 100 ft above sea level in the outcrop area to 250 ft below sea level at Rose Haven. Total thickness of the Aquia aquifer ranges from 110 to 180 ft. South of its outcrop area in Southern Anne Arundel County, the Aquia aquifer is confined above and below by the low-permeability Marlboro Clay and Matawan Formations, respectively. The Magothy aquifer consists of medium to coarse, white, gray, and clear quartz sand, with interbedded black and gray, lignitic clay. The aquifer is divided into two sand layers in Southern Anne Arundel County. The thickness of the individual sand layers ranges from 15 to 90 ft. The top of the Magothy aquifer ranges from about 150 ft below sea level at Davidsonville to 500 ft below sea level at Rose Haven. The Magothy aquifer is confined above by low-permeability clays of the Matawan Formation and below by the dense clays of the Patapsco Formation.

Generally, the Magothy aquifer is more productive than the Aquia aquifer. Transmissivity of the Aquia aquifer ranges from about 1,000 to 3,400 ft^2/d. The transmissivity of the Magothy aquifer ranges from 450 to 12,000 ft^2/d.

Wells screened in the Aquia aquifer flowed in topographically low areas (less than about 10 ft above sea level) as recently as 1962. Since then, water levels have declined at rates ranging from 0.2 ft/yr at Waysons Corner to 1.4 ft/yr at Tracys Landing. Water levels declined at a rate of approximately 1 ft/yr in the Deale-Shady Side area and about 0.3 ft/yr at Davidsonville near the outcrop area. The water-level trend on Mayo Peninsula was flat during the 20-year period because the Aquia aquifer is under water-table conditions in this area and is recharged rapidly from direct infiltration. The potentiometric surface of the Aquia aquifer in 2000 ranged from a high of 64 ft above sea level at Davidsonville to 35 ft below sea level at Rose Haven. Except for the area near the outcrop of the Aquia aquifer, water levels in the Magothy aquifer are generally higher than in the Aquia aquifer. A well screened in the Magothy aquifer at Shady Side flowed as recently as 1980. Since about 1980, water levels have declined at approximately 0.8 ft/yr. The potentiometric surface of the Magothy aquifer in 2000 ranged from 7 ft above to 10 ft below sea level in Southern Anne Arundel County.

The available drawdown in the Aquia aquifer in 2000 ranged from 0 ft in the central part of Southern Anne Arundel County to 150 ft at Rose Haven. Available drawdown in the Deale-Shady Side area ranged from about 50 to 90 ft. Water levels exceeded the 80-percent management level within a 2-mi-wide band located in the central part of Southern Anne Arundel County in 2000, and water levels within more than half of that area were below the top of the aquifer. In 2000, available drawdown in the Magothy aquifer has been reduced by approximately 20 to 40 ft from estimated pre-pumping levels. Available drawdown in 2000 ranged from approximately 125 ft in the Davidsonville area to 360 ft at Rose Haven.

Water from 18 wells screened in the Aquia aquifer is predominantly a calcium bicarbonate type. The pH ranges from 7.3 to 8.0 and hardness ranges from 112 to 275 mg/L, with a median value of 133 mg/L. Total and dissolved iron concentrations in the Aquia aquifer in Southern Anne Arundel County range from 0.15 to 4.5 mg/L with a median value of 0.43 mg/L. Dissolved manganese concentrations

range from 0.002 to 0.057 mg/L. Gross alpha-particle activity was less than 3 pCi/L. The U.S. Environmental Protection Agency Maximum Contaminant Level for gross alpha-particle activity is 15 pCi/L. Specific testing for radium-226 and radium-228 is recommended when gross alpha-particle activity exceeds 5 pCi/L.

Water from the three test wells screened in the Magothy aquifer is a calcium bicarbonate type. The pH of water produced from the Magothy water is about neutral (pH=7). Iron concentrations sampled in the three test wells range from 3.6 to 7.6 mg/L, well above the recommended federal limit of 0.3 mg/L. Gross alpha- and beta-particle activity analyzed in water pumped from the three test wells screened in the Magothy aquifer were less than 3.5 and 11 pCi/L, respectively.

A ground-water-flow model was developed to predict future water levels in the Aquia and Magothy aquifers in Southern Anne Arundel County with respect to projected changes in water use. The model consisted of three layers representing the water-table aquifer, the Aquia aquifer, and the Magothy aquifer. The model simulated steady-state, pre-pumping conditions and historic conditions for the period 1900 to 2000. The model was calibrated using water levels measured during 2000 and by comparing simulated and measured water levels for observation wells with long-term records.

A series of pumping scenarios was simulated using the calibrated ground-water-flow model. In the first simulation an additional 0.8 Mgal/d was pumped from the Aquia aquifer to support a projected 2020 population of 32,750 in Southern Anne Arundel County. Results of the simulation indicate that the increased pumpage combined with increased pumpage to the south would cause water levels in the Aquia aquifer to decline by as much as 22 ft. A significant part of the drawdown would result from pumping in Calvert County. The Aquia aquifer can supply the projected 2020 water demand without depleting the available drawdown in most of Southern Anne Arundel County. However, water levels exceeded the management level in a band about 3.5 mi wide extending from Waysons Corner to Rhode River. Constraining the use of the Aquia aquifer in Southern Anne Arundel County and Calvert County would reduce drawdown in Southern Anne Arundel County.

In a second pumping scenario, an additional 0.8 Mgal/d was withdrawn from the Magothy aquifer in Southern Anne Arundel County during the period 2000 to 2020. Results of that simulation indicate that the increased pumpage combined with regional pumpage will cause water levels in the Magothy aquifer to decline about 20 ft by 2020. Available drawdown ranges from 100 to 350 ft. Water levels in the Aquia aquifer are unaffected by the increased pumpage from the Magothy aquifer. The Magothy aquifer can supply the projected increase in water demand through either individual residential wells or public-supply wells without a significant difference of reduction in available drawdown. However, greater drilling depths, treatment costs for the removal of iron, and the practicality and expense of centralized public-water systems are important considerations related to its use.

In a third pumping scenario, pumpage was held constant at 2000 levels in both the Aquia and Magothy aquifers. Water levels in the Aquia aquifer stabilized in less than 1 year when pumpage in Southern Anne Arundel County was held constant at the 2000 level (1.8 Mgal/d). Water levels in the Magothy aquifer stabilize within about 3 months when pumpage in Southern Anne Arundel County is held constant at the 2000 level of 0.22 Mgal/d.

In a fourth scenario, the total water-supply potential of the Aquia and Magothy aquifers was estimated. Available drawdown in the Aquia aquifer in most areas can sustain an increase in pumpage. In addition, recharge from the outcrop area could be increased by the increase in pumpage. However, increasing pumpage from the Aquia aquifer would cause water levels to exceed the management level in the central part of Southern Anne Arundel County. As of 2000, water levels in the Aquia aquifer have exceeded the management level within a 2-mi-wide band located in the central part of Southern Anne Arundel County. Consequently, as defined by the present management guideline, the Aquia aquifer in Southern Anne Arundel County has exceeded its maximum allowable yield.

The maximum simulated yield of the Magothy aquifer is approximately 38 Mgal/d based solely on the available drawdown in the Magothy aquifer. Water levels in the Magothy aquifer, when pumped continuously at this rate at 26 hypothetical wells for the period 2000 to 2020, are as deep as 280 ft below sea level in Southern Anne Arundel County. The vertical hydraulic gradient that develops between the Magothy and Aquia aquifers under this pumping scenario causes some leakage of water from the Aquia aquifer downward to the Magothy aquifer.

Simulated water levels in the Aquia aquifer decline by as much as 22 ft from 2000 levels. Lowering pumpage in the Magothy aquifer to 7 Mgal/d significantly reduces the amount of drawdown in the Aquia aquifer. The drawdown caused by pumping the Magothy aquifer at 7 Mgal/d can be offset by reducing pumpage in the Aquia aquifer to a rate 25 percent below the 2000 level (or approximately 1.4 Mgal/d). Reducing pumpage in the Aquia aquifer further would allow a greater amount to be pumped from the Magothy aquifer.

In a final pumping scenario, the effect of projected 2020 pumpage from the Aquia aquifer in Calvert and St. Mary's Counties on water levels in Southern Anne Arundel County was evaluated. Pumpage from the Aquia aquifer is projected to increase to 8.2 Mgal/d in Calvert County and 11.3 Mgal/d in St. Mary's County by 2020. These pumpage values, which were derived from population projections made by the Maryland Office of Planning (1999) for Calvert County and the St. Mary's County Metropolitan Commission (written communication, 2000) for St. Mary's County, represent high growth estimates for each county. Pumpage in Calvert County and St. Mary's County would cause water levels in the Aquia aquifer to exceed the management level in a band as much as 3 mi wide extending from Waysons Corner to Rhode River. Decreasing pumpage in Calvert County to 6.1 Mgal/d based on a 2020 population projection by the Calvert County Department of Planning and Zoning (written communication, 2000) reduces the area where the management level would be exceeded by about 1 mile.

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APPENDIX

A. Selected well records
B. Descriptive logs of washed drill cuttings from test wells drilled during study
C. Appropriated ground-water use over 10,000 gallons per day in the Aquia and Magothy aquifers in the model area in 2000
D. Appropriated ground-water use over 10,000 gallons per day in the Aquia aquifer in the model area, 1920-79
E. Appropriated ground-water use over 10,000 gallons per day in the Aquia aquifer in the model area, 1980-2000
F. Appropriated ground-water use over 10,000 gallons per day in the Magothy aquifer in the model area, 1920-79
G. Appropriated ground-water use over 10,000 gallons per day in the Magothy aquifer in the model area, 1980-2000
H. Chemical analyses of water from test wells drilled during study and other selected wells
I. Pumpage assigned to model layer 2 (Aquia aquifer) for Pumping Scenario 1A

Appendix A. Selected well records

[AA = Anne Arundel County; ft = feet; in. = inches; gal/min = gallons per minute; [(gal/min)/ft] = gallons per minute per foot; see Well Driller's Key at end of Appendix A]

Well number (pl. 1)	State permit number	Owner	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)	Diameter of well (in.)		Depth to top of screen (ft)	Length of screen (ft)	Aquifer	Water levels below land surface (ft)		Date measured	Pumping rate (gal/min)	Hours pumped	Specific capacity [(gal/min)/ft]
							Casing	Screen				Static	Pumping				
AA Cd 93	AA-05-4254	Summer Hill Mobile Home Park	Leatherbury	- -1964	135	201	4	-	185	16	Magothy	120	127	01- -1964	20	6	2.9
AA Dc 21	AA-73-5189	Hams, Beverly	Frank	10-27-1975	64	185	4	2	180	5	Magothy	39	49	10-27-1975	40	2	4
AA Dc 22	AA-94-2433	Crofton Athletic Complex	Atwater	06-25-1998	165	320	10, 8, 5	5	237, 254	10, 21	Magothy	134	220	06- -1998	210	8	2.4
AA Dc 23		Crofton Athletic Complex	Atwater	03-09-1998	170	400	4	3	259, 268	9, 9	Magothy	132	142	03- -1998	50	8	5.0
AA Dd 36	AA-04-1099	Davidsonville Elementary School	Layne-Atlantic	- -1960	145	344	6	-	339	5	Magothy	115	-	11- -1960	162	8	5.4
AA Dd 41	AA-71-0231	U.S. Geological Survey	East Coast	- -1970	105	372	2	-	360	12	Magothy	81	-	04- -1971	8	-	-
AA Dd 42	AA-71-0231	U.S. Geological Survey	East Cost	- -1970	105	275	4	-	190	30	Magothy	82	-	10- -1970	65	8	2.1
AA Dd 61	AA-81-7309	Morgan, Jenks	Greer	10-14-1986	122	105	4	2	100	5	Aquia	40	55	10-14-1986	20	2	1.33
AA De 2	--	City of Annapolis	Layne Atlantic	- -1939	14	258	18	-	-	45	Magothy	Flowing	181	02- -1943	700	-	10.0
AA De 38	--	South Down Water Works	Purner	-	7	100	4	-	-	-	Aquia	3	-	-	-	-	-
AA De 45	AA-00-1627	City of Annapolis	Layne-Atlantic	- -1947	28	242	20	-	192	52	Magothy	8	110	08- -1947	1,000	48	9.8
AA De 46	AA-00-1628	City of Annapolis	Layne-Atlantic	- -1947	24	248	20	-	199	49	Magothy	12	110	07- -1947	1,000	24	10.2
AA De 68	AA-03-0856	South Down Water Works	Bunker	- -1958	30	60	6	-	-	-	Aquia	20	40	05- -1958	25	3	1.3
AA De 69	AA-02-2000	Sylvan Shores	Bunker	- -1956	65	325	6	-	312	12	Magothy	42	110	04- -1956	240	24	3.5
AA De 88	AA-01-7076	City of Annapolis	Shannahan	- -1955	120	345	20	-	287	58	Magothy	120	145	03- -1955	600	24	24.0
AA De 100	-	U.S. Geological Survey	Ideal	- -1968	41	350	2	-	340	10	Magothy	-	-	-	-	-	-
AA De 101	AA-69-0332	U.S. Geological Survey	Ideal	- -1968	50	450	2	-	410	40	Magothy	35	-	- -1971	15	-	-
AA De 102	AA-69-0332	U.S. Geological Survey	Delmarva	- -1968	50	96	2	-	70	26	Aquia	40	-	- -1971	-	-	-
AA De 103	AA-69-0332	U.S. Geological Survey	Delmarva	- -1968	50	338	2	-	298	40	Magothy	34	-	- -1971	-	-	-
AA De 119	AA-04-8199	South Down Water Works	Bunker	- -1962	5	52	6	-	42	10	Aquia	34	45	09- -1962	15	1	1.4
AA De 120	AA-66-0021	South Down Water Works	Bunker	- -1965	30	53	6	-	45	8	Aquia	2	24	07- -1965	15	5	0.7
AA De 121	AA-66-0468	South Down Water Works	Bunker	- -1965	35	83	6	-	63	20	Aquia	23	48	10- -1965	20	3	0.8
AA De 122	AA-73-1868	Sylvan Shores	Bunker	- -1973	60	324	6	-	314	10	Magothy	47	130	10- -1973	70	20	0.8
AA De 215	AA-83-9514	Silva, Kristen	Greer	09-08-1998	28	65	4	2	58	7	Aquia	15	25	09-08-1998	35	1	3.5
AA De 216	AA-94-0827	Pleasant Living Convalescent Center	Wolford's	09-12-1996	20	304	4	2	297	7	Magothy	34	60	09- -1996	50	2	1.9
AA De 217	AA-93-0812	South River Colony Golf Course	A C Schultes	06-29-1995	120	508	8	8	392, 402, 433	40, 21, 12	Magothy	90	150	06- -1995	1,000	8	16.7
AA Df 64	AA-00-2313	U.S. Navy, David Taylor R & D	American	- -1948	32	402	12	-	350	52	Magothy	32	-	04- -1969	500	-	-
AA Ec 6	AA-70-0726	Maryland Manor Mobile Home Estates	Leatherbury	- -1970	50	295	4	-	275	20	Magothy	140	155	06- -1970	55	5	3.7
AA Ec 7	AA-70-0727	Maryland Manor Mobile Home Estates	Leatherbury	- -1970	55	300	4	-	280	20	Magothy	140	150	06- -1970	65	4	6.5
AA Ec 8	AA-70-0728	Maryland Manor Mobile Home Estates	Leatherbury	- -1979	55	305	4	-	285	20	Magothy	120	140	06- -1970	60	5	3.0
AA Ec 13	AA-94-4608	Bayard Sand and Gravel	Allied Envir	10-01-1999	75	318	4	4	298	20	Magothy	75		10-01-1999	150	4	
AA Ec 14	AA-94-4609	Bayard Sand and Gravel	Allied Envir	11-04-1999	75	325	6	4	285	40	Magothy	75	210	11-09-1999	210	4	1.56

Well number (pl. 1)	State permit number	Owner	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)	Diameter of well (in.) Casing	Diameter of well (in.) Screen	Depth to top of screen (ft)	Length of screen (ft)	Aquifer	Water levels below land surface (ft) Static	Water levels below land surface (ft) Pumping	Date measured	Pumping rate (gal/min)	Hours pumped	Specific capacity [(gal/min)/ft]
AA Ed 39	AA-68-0209	Southern Senior High School	Layne-Atlantic	- -1967	175	480	12	-	455	25	Magothy	144	197	11- -1967	150	24	2.8
AA Ed 41	AA-67-0286	Southern Senior High School	Layne-Atlantic	- -1966	180	480	6	-	450	30	Magothy	130	200	09- -1966	80	8	1.1
AA Ed 45	AA-74-1005	U.S. Geological Survey	Kanarr	08-14-1979	100	157	4	2	147	10	Aquia	110	131	08-14-1978	15	3	0.7
AA Ed 49	AA-73-0618	Woodall, J.	Purner	12-08-1972	60	138	4	2	134	4	Aquia	60	134	12-08-1972	20	1	0.3
AA Ed 58	AA-88-5834	Chopp, Joseph	Arnette	04-01-1991	147	245	4	2	238	7	Aquia	190	230	04-01-1991	15	3	.38
AA Ed 59	AA-81-4313	Franklin, Spencer	Slater's	03-02-1985	153	270	4	2	260	10	Aquia	160	180	03-02-1985	20	8	1
AA Ed 60	AA-92-1586	Warren, Debbie	Arundel W & P	06-24-1994	100	225	4	4	215	10	Aquia	125	150	06-24-1994	30	1	1.2
AA Ed 61	AA-73-3772	Joyce, Kevin	Purner	10-28-1974	175	242	4	2	238	4	Aquia	148	238	10-28-1974	15	1	.17
AA Ed 62	AA-81-9667	Rosenson, Peter	Wolford's	11-11-1987	86	135	4	2	128	7	Aquia	70	90	11-11-1987	25	2	1.25
AA Ed 63	AA-73-4666	Black, Ray	Zittinger	07-31-1975	145	222	4		168	54	Aquia	101	133	07-13-1975	6	4	.19
AA Ed 65	AA-94-5387	Maryland Geological Survey, Davidsonville Police Academy	A C Schultes	09-28-2000	110	310	4.5	4.5	285	20	Magothy	103.28	130.91	10-10-2000	74	8	2.68
AA Ee 28	-	Woodfield Fish and Oyster Co.	Leatherbury	- -1936	5	180	2	-	-	-	Aquia	10	-	-	-	-	-
AA Ee 60	AA-70-0545	Shady Side Elementary School	Layne-Atlantic	- -1970	10	301	6	-	189	30	Aquia	9	80	03- -1970	271	8	3.8
AA Ee 61	AA-01-3578	Woodfield Fish and Oyster Co.	Purner	- -1954	5	159	4	-	115	44	Aquia	12	35	09- -1954	100	12	4.3
AA Ee 64	AA-73-5693	Chesapeake Bay Village	CZ Enterprises	- -1976	20	538	6	6	508	30	Magothy	9	174	07- -1976	80	48	0.5
AA Ee 65	AA-73-5694	Chesapeake Bay Village	CZ Enterprises	06-28-1976	20	530	2	2	525	5	Magothy	14	100	06- -1976	10	36	0.1
AA Ee 67	AA-73-6199	Heintz, Richard	Purner	07-27-1976	12	105	4	2	85	20	Aquia	12	24	07- -1976	10	2	0.8
AA Ee 87	AA-88-7903	Salem Avery House Museum	Purner	05-17-1992	9	150	4	2	143	7	Aquia	26	70	05-17-1992	30	2	.68
AA Ee 88	AA-94-0495	Anne Arundel County, Shady Side Park	Artesian	06-10-1996	8	185	4	2	178	7	Aquia	20	60	06-10-1996	60	2	1.5
AA Ee 89	AA-92-0192	Stearns, Caroline	Winslow	08-25-1993	11	250	4	2	220	20	Aquia	25	34	08-25-1993	80	3	8.89
AA Ee 90	AA-88-4085	Thomas, Julie	Estes	03-06-1990	10	130	4	3	121	9	Aquia	21	26	03-06-1990	10	3	2
AA Ee 91	AA-92-0008	Castro, John W.	Wolford's	07-29-1993	5	195	4	2	188	7	Aquia	16	50	07-29-1993	50	2	1.47
AA Ee 92	AA-88-9239	Marshall, Donald	Catterton	02-05-1993	9	150	4	3	141	9	Aquia	18	25	02-05-1993	12	3	1.71
AA Ee 93	AA-88-9981	Ammon, Michelle	Wolford's	07-20-1993	10	195	4	2	188	7	Aquia	15	45	07-20-1993	50	2	1.67
AA Ee 94	AA-92-0602	Thomas, Frances	Wolford's	11-11-1993	8	200	4	2	193	7	Aquia	16	50	11-11-1993	50	2	1.47
AA Ee 95	AA-94-0630	Hill, Ava	Purner	07-15-1996	10	132	4	2	125	7	Aquia	21	75	07-15-1996	25	2	.46
AA Ee 96	AA-81-0880	Moreland, Edward	Purner	09-17-1982	13	140	4	2	133	7	Aquia	10	133	09-17-1982	30	3	.24
AA Ee 97	AA-94-1817	Moreland, Joan	Purner	08-26-1997	22	138	6	4	128	10	Aquia	8	120	08-26-1997	50	3	.45
AA Ee 98	AA-93-1350	Smithsonian Institution	Gibble	01-22-1996	10	348	4.5	2	333	15	Magothy	25	49	01-22-1996	30	2	1.25
AA Ef 17	AA-71-0808	Fuller	Purner	05-03-1971	20	41	4	2	37	4	Aquia	10	37	05-03-1971	15	1	0.6
AA Ef 40	AA-94-0663	Renno, Ralph	Purner	07-24-1996	5	172	4	2	165	7	Aquia	20	85	07-24-1996	26	1	.4
AA Fc 20	AA-05-6639	Waysons Mobile Home Park	Columbia	- -1964	40	110	8	-	95	15	Aquia	50	100	03- -1964	30	8	0.6

Appendix A. Selected well records--Continued

Well number (pl. 1)	State permit number	Owner	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)	Diameter of well (in.) Casing	Screen	Depth to top of screen (ft)	Length of screen (ft)	Aquifer	Water levels below land surface (ft) Static	Pumping	Date measured	Pumping rate (gal/min)	Hours pumped	Specific capacity [(gal/min)/ft]
AA Fc 22	AA-66-1582	Lyons Creek Mobile Home Estates	Columbia	- -1966	60	284	6	-	-	-	Aquia	120	260	06- -1966	42	8	0.3
AA Fc 23	AA-73-0144	Lyons Creek Mobile Home Estates	East Coast	- -1972	60	466	6	-	451	15	Magothy	38	147	09- -1972	150	12	1.4
AA Fc 24	AA-70-0490	Rio Vista Mobile Home Park	Bunker	- -1970	50	125	6	-	115	10	Aquia	55	110	01- -1970	25	5	0.5
AA Fc 25	-	Patuxent Mobile Home Park	-	-	50	200	6	-	180	-	Aquia	-	-	-	-	-	-
AA Fc 26	-	Patuxent Mobile Home Park	-	-	50	160	6	-	-	-	Aquia	-	-	-	-	-	-
AA Fc 28	AA-73-6836	Duncan Campground	Wolford's	04-05-1977	78	210	4	2	189	21	Aquia	77	109	04-05-1977	45	2	1.4
AA Fc 31	AA-81-3583	Boones Mobile Home Estates	East Coast	07-07-1985	78	223	4	4	160, 205	30, 15	Aquia	83	110	07- -1985	100	8	3.7
AA Fc 32	AA-86-3561	Anne Arundel County, Jug Bay	East Coast	09-13-1984	44	159	4	3	149	10	Aquia	40	61	09-13-1984	12	2	.57
AA Fc 33	AA-88-6450	Burris, Bill	Arnette	09-13-1991	95	222	4	2	215	7	Aquia	80	100	09-13-1991	25	3	1.25
AA Fc 34	AA-94-5390	Maryland Geological Survey, Waysons Corner	A C Schultes	09-22-2000	51	371	4.5	4.5	336	30	Magothy	25.34	74.46	10-06-2000	98	8	3.87
AA Fc 35	AA-94-5388	Maryland Geological Survey, Waysons Corner	A C Schultes	09-23-2000	51	177	4.5	4.5	142	30	Aquia	52.4	135.3	10-04-2000	75	8	0.9
AA Fc 36	AA-81-3948	Shepherd, Lila	Ford	11-02-1984	60	140	4, 2	2	130	10	Aquia	40	56	11- -1984	10	4	0.6
AA Fc 37	AA-73-6137	Boones Mobile Home Estates	East Coast	01-27-1977	130	249	6	4	218, 229	11, 20	Aquia	130	140	01- -1977	75	8	7.5
AA Fc 38	AA-94-3890	Rio Vista Mobile Home Park	Wolford's	04-07-1999	50	180	4	2	160	20	Aquia	58	80	04- -1999	35	2	1.6
AA Fc 39	AA-73-3368	Boones Mobile Home Estates	East Coast	10-04-1974	130	235	6	4	205	30	Aquia	137	180	10- -1974	80	24	1.9
AA Fd 43	AA-74-1004	U.S. Geological Survey	Kanarr	08-06-1979	140	280	4, 2	2	270	10	Aquia	110	133	08-06-1979	12	3	0.5
AA Fd 46	AA-73-3173	Chatlen	Bunker	08-30-1974	140	272	4, 2	2	267	5	Aquia	130	200	08- -1974	20	3	0.3
AA Fd 56	AA-94-4031	Eversfield, William	Atwater	11-11-1999	140	530	4.5, 2.5	2	520	10	Magothy	158	185	11- -1999	60	4	2.2
AA Fd 57	AA-73-9135	Hysan, Daniel	Branham	06-07-1978	97	290	4, 2	2	280	10	Aquia	105	150	06-07-1978	15	2	.33
AA Fd 58	AA-81-5245	Wormwood, Carrie	Ford	10-07-1985	110	340	4, 2	2	320	10	Aquia	125	135	10-07-1985	12	3	1.2
AA Fd 59	AA-88-5562	Robertson, Kristen	Purner	12-11-1990	150	290	4	2	283	7	Aquia	158	225	12-11-1990	20	3	.30
AA Fd 60	AA-88-7870	Moreland, John	Slater's	07-13-1992	170	350	4	4	340	10	Aquia	150	155	07-13-1992	50	2	10
AA Fe 46	AA-71-0526	Anne Arundel County Dept. of Public Works	Layne-Atlantic	- -1970	7	210	8	-	155	40	Aquia	7	61	12- -1970	300	24	5.6
AA Fe 47	AA-73-3408	U.S. Geological Survey	Delmarva	- -1974	6	590	4	-	580	10	Magothy	8	-	-	-	-	-
AA Fe 48	AA-73-0589	Broder	East Coast	04-10-1973	85	283	4	3	273	10	Aquia	76	93	04- -1973	20	8	1.2
AA Fe 51	AA-88-1276	Anne Arundel County, Franklin Point Park	CZ Enterprises	01-06-1989	8	432	4	4	368, 394, 414	15, 10, 15	Magothy	11	76	01-06-1989	91	24	1.4
AA Fe 54	AA-88-0719	Central Sod Farm	Branham	08-22-1988	10	453	6	4	433	20	Magothy	20	50	08-22-1998	200	3	6.67

Appendix A. Selected well records—Continued

Well number (pl. 1)	State permit number	Owner	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)	Diameter of well (in.) Casing	Diameter of well (in.) Screen	Depth to top of screen (ft)	Length of screen (ft)	Aquifer	Water levels below land surface (ft) Static	Water levels below land surface (ft) Pumping	Date measured	Pumping rate (gal/min)	Hours pumped	Specific capacity [(gal/min)/ft]
AA Fe 55	AA-88-1349	Shady Oaks Sod Farm	Purner	12-20-1988	20	401	6	4	296	105	Magothy	8	125	12-20-1988	200	2	1.7
AA Fe 56	AA-94-4137	Safeway, Inc.	Sydnor	09-07-1999	8	450	4	4	407	20	Magothy	22	28	09-13-1999	21	23	3
AA Fe 57	AA-92-0933	Tri State Marine, Inc.	Arundel W & P	01-15-1994	10	210	6	6	200	10	Aquia	21	27	01-15-1994	90	2	15
AA Fe 58	AA-88-2414	Dingivan, Terrence	Estes	05-01-1989	8	190	4	3	180	10	Aquia	22	28	05-01-1989	10	3	1.67
AA Fe 59	AA-88-3916	Andreasen, Jane	Branham	12-19-1989	5	130	4	2	120	10	Aquia	12	60	12-19-1989	40	3	.83
AA Fe 60	AA-94-5776	Maryland Geological Survey, Franklin Point Park	A C Schultes	08-25-2000	8	205	4.5	4.5	160, 185	15, 15	Aquia	23.5	63.4	09-07-2000	92	8	2.3
AA Fe 61	AA-81-6570	Central Sod Farm	Wolford's	07-12-1988	13	175	6	4	155	20	Aquia	23	45	07-12-1998	100	3	4.54
AA Fe 62	AA-88-2116	Kitzmiller, William	Wolford's	10-09-1989	100	338	4	2	331	7	Aquia	130	150	10-09-1989	40	2	2
AA Fe 63	AA-81-6965	Nutwell, Reginald	Purner	09-15-1986	30	187	4	2	180	7	Aquia	35	180	09-15-1986	20	2	.14
AA Fe 64	AA-88-0849	Maimone, John	Purner	08-22-1988	9	167	4	2	160	7	Aquia	20	75	08-22-1998	25	2	.45
AA Fe 65	AA-88-0807	Meletzke, Dorothy	Estes	08-22-1988	5	190	4	3	180	10	Aquia	26	30	08-22-1988	10	3	2.5
AA Fe 66	AA-88-8632	Nyep, James	Purner	12-14-1992	4	172	4	2	165	7	Aquia	20	70	08-22-1988	30	2	.6
AA Fe 67	AA-88-1220	Pumphrey, Kenneth	Estes	10-11-1988	9	190	4	3	180	10	Aquia	24	28	10-11-1988	10	3	2.5
AA Fe 68	AA-88-1429	Leonard, Barry	Purner	11-08-1988	8	172	4	2	165	7	Aquia	24	65	11-08-1988	20	2	.49
AA Fe 69	AA-81-9224	McMan, Elaine	Branham	08-27-1987	10	174	4	2	167	7	Aquia	15	60	08-27-1987	50	2	1.11
AA Fe 70	AA-81-0790	Jeffers, Joanne	Branham	08-28-1982	5	140	4	2	133	7	Aquia	40	55	08-28-1982	30	2	2
AA Fe 71	AA-88-3425	Miller, David	Purner	10-24-1989	6	172	4	2	165	7	Aquia	22	90	10-24-1989	30	2	.44
AA Fe 72	AA-88-1093	Lynch, Beverly	Branham	11-04-1988	9	140	4	2	133	7	Aquia	10	60	11-04-1988	40	3	.80
AA Fe 73	AA-81-9298	Rhody, Donna	Brucksch	09-13-1987	7	135	4	2	128	7	Aquia	15	40	09-13-1987	40	2	1.6
AA Fe 74	AA-88-0456	Liddy, Dennis	Brucksch	06-29-1988	7	130	4	2	123	7	Aquia	15	40	06-29-1988	20	2	.8
AA Fe 75	AA-86-0038	Blassi, Mike	Wolford's	01-22-1988	8	160	4	2	153	7	Aquia	110	130	01-22-1988	20	2	1
AA Fe 76	AA-81-3419	Hensley, John	Dennis	08-06-1984	4	210	4	2	190	20	Aquia	12		08-06-1984	20	3	
AA Fe 77	AA-74-1629	White, Janey	Slater's	02-25-1980	7	167	4	2	160	7	Aquia	6	16	02-25-1980	30	4	3
AA Fe 78	AA-81-7470	Baker, Marylin	Branham	11-17-1986	3	150	4	2	143	7	Aquia	15	50	11-17-1986	60	5	.71
AA Fe 79	AA-81-7505	Acquafresca, Nancy	Wolford's	07-14-1987	2	190	4	2	183	7	Aquia	10	30	07-14-1987	50	2	2.5
AA Fe 80	AA-88-4876	Newton, Ray	Arnette	07-24-1990	15	130	4	2	123	7	Aquia	15	65	07-24-1990	40	3	.80
AA Fe 81	AA-92-0025	Brandenburg, Arnold	Winslow	07-21-1993	7	230	4	2	200	20	Aquia	25	30	07-21-1993	100	3	20
AA Fe 82	AA-88-2946	Jackson, Gustav	Arundel W & P	08-10-1989	5	210	4	2	190	20	Aquia	20	29	08-10-1989	45	1	5
AA Fe 83	AA-88-0336	Burroughs, Henry	Bunker	06-29-1988	7	120	4	2	113	7	Aquia	21	35	06-29-1988	10	1	1.67
AA Fe 84	AA-88-9917	Dattore, Mary	Purner	07-23-1993	4	152	4	2	145	7	Aquia	20	60	07-23-1993	25	2	.63
AA Fe 85	AA-94-2274	Boucher, Ken	Wolford's	02-10-1998	6	167	4	2	160	7	Aquia	24	45	02-10-1998	40	2	1.67
AA Fe 86	AA-94-1380	Deale Aquaculture	Arundel W & P	06-24-1997	20	210	4	4	205	5	Aquia	22	31	06-24-1997	45	1	5
AA Fe 87	AA-88-0939	Sticknall, Lawrence	Branham	08-31-1988	8	145	4	2	138	7	Aquia	10	60	08-31-1988	40	3	.80
AA Fe 88	AA-81-1828	Johnson, Jan	Purner	06-14-1983	9	180	4	2	173	7	Aquia	15	173	06-14-1983	20	2	.13
AA Fe 89	AA-73-6585	White, Kelly	Wolford's	12-11-1976	7	146	4	2	141	5	Aquia	10	20	12-11-1976	20	2	2
AA Fe 90	AA-92-1406	Cane, Joe	Arnette	05-13-1994	5	170	4	2	163	7	Aquia	10	50	05-13-1994	30	4	.75
AA Fe 91	--	Maryland Geological Survey, Deale Athletic Field	A C Schultes	08-10-2000	9	--	--	--	--	--	--	--	--	--	--	--	--

Well number (pl. 1)	State permit number	Owner	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)	Diameter of well (in.)		Depth to top of screen (ft)	Length of screen (ft)	Aquifer	Water levels below land surface (ft)		Date measured	Pumping rate (gal/min)	Hours pumped	Specific capacity [(gal/min)/ft]
							Casing	Screen				Static	Pumping				
AA Fe 92	AA-94-5386	Maryland Geological Survey, Deale Athletic Field	A C Schultes	08-18-2000	9	205	4.5	4.5	170	30	Aquia	34.6	72.5	09-02-2000	90	8	2.4
AA Fe 93	AA-94-5391	Maryland Geological Survey, Deale Athletic Field	A C Schultes	08-23-2000	9	470	4.5	4.5	429, 454	20, 10	Magothy	19.3	60.6	08-29-2000	102	8	2.5
AA Fe 95	-	Duvall, Weems	-	-	9	160	4, 2	2	150	10	Aquia	-	-	-	-	-	-
AA Ff 1	AA-93-0697	Goodman, Nelson G.	Shockley	07-12-1995	4	140	4	2	130	10	Aquia	18	25	07-12-1995	60	2	8.57
AA Gd 8	AA-81-3977	Gordon, Howard, Jr.	W. Ward	11-20-1984	160	371	4	3	361	10	Aquia	150	170	11- -1984	25	8	1.2
AA Ge 13	AA-69-0843	Rose Haven (Herrington Harbor)	Shannahan	- -1969	5	348	8	-	306	42	Aquia	6	68	06- -1969	95	20	1.5
AA Ge 15	AA-73-4007	Copeland, Wesley	Branham	01-07-1975	10	290	4	2	280	10	Aquia	-	-	-	12	3	-
AA Ge 16	AA-81-0440	Rose Haven (Herrington Harbor)	Shannahan	12-02-1982	5	348	6, 4	4	307	41	Aquia	31	168	12- -1982	202	2	1.5
CA Ba 7	CA-73-0094	Shores of Calvert	East Coast	- -1973	51	473		6	25	25	Magothy	42	98	08-06-1973	150	24	2.7
CA Ba 8	CA-73-0095	Shores of Calvert		- -1973	51	473		6		21	Magothy	42	196	06-06-1973	300	24	1.9
CA Ba 11	CA-73-0670	Colter, James	W. Ward	- -1974	120	365		4		40	Aquia	108	115	04-12-1979	25	6	3.6
CA Bb 16	CA-04-7010	Regency Manor Mobile Home Park	W. Ward	07-01-1962	185	444		2.5		10	Aquia	153	195	07-07-1962	22	24	0.5
CA Bb 21	CA-03-7400	Regency Manor Mobile Home Park		- -1959	140	360		-		10	Aquia	126	-	- -1959	7	24	-
CA Bb 23	CA-71-0013	Calvert County	East Coast	- -1970	148	552		6		19	Magothy	135	145	08-11-1970	150	12	15.0
CA Bb 24	CA-71-0012	Calvert County	East Coast	- -1970	137	542		6		20	Magothy	120	156	08-20-1970	150	12	4.2
CA Bb 27	CA-73-3303	U.S. Geological Survey	Calvert	- -1974	140			2		10	Aquia	136	157	08-30-1979	12	-	0.6
CA Bb 30	CA-73-0196	Lakewood	W. Ward	- -1973	160	335	--	3	325	10	Aquia	154	186	06-28-1973	60	4	1.9
CA Bb 41	CA-66-0044	Lakewood	W. Ward	02-01-1966	155	355	--	4	345	10	Aquia	137	147	02-01-1966	60	8	6.0
CA Bb 43	CA-81-1573	Regency Manor Mobile Home Park	Calvert	07-02-1985	180	410		2	400	10	Aquia	70	130	07-02-1985	8	1	0.1
CA Bb 44	CA-94-1879	Regency Manor Mobile Home Park	Atwater	04-09-2000	20	390	6, 5	5	357	31	Aquia	-	-	-	70	8	-
CA Bb 45	CA-94-1098	Cross Point	A C Schultes	11-03-1998	95	394	4	4	372	22	Aquia	163	250	11-18-1998	60	24	0.7
CA Bb 46	CA-94-1099	Cross Point	A C Schultes	11-08-1998	95	398	4	4	376	20	Aquia	-	-	-	-	-	-
CA Bc 32	CA-73-0474	Calvert County, Paris Oaks	Williams	05-03-1974	130	413		4	388	25	Aquia	135	151	05-03-1974	60	6	0.5
CA Bc 44	CA-88-1829	North Beach	CZ Enterprises	02-05-1991	8	435	8	6	320	115	Aquia	29	100	02-05-1991	352	24	5.0
CA Bc 45	CA-88-1828	North Beach	CZ Enterprises	02-22-1991	12	435	8	8	320	115	Aquia	35	117	02-22-1991	352	24	4.3
CA Bc 50	CA-88-0715	Paris Oaks	Calvert	11-09-1989	150	450	4	2	440	10	Aquia	90	105	11-09-1989	40	5	2.7
PG Cf 33	PG-03-4997	City of Bowie	Lauman	- -1959	113	192	20, 12	12	110	82	Magothy	65	103	09- -1959	500	8	13.2
PG Cf 34	PG-04-0717	City of Bowie	Lauman	- -1960	112	114	6	6	98	116	Magothy	27	47	09- -1960	94	2	4.7
PG Df 34	PG-65-0098	Marlboro Meadows	Sydnor	- -1965	80	540	24, 12, 8	8	242, 270, 322, 369, 384, 409	20, 11, 16, 10, 10, 16	Magothy	45	94	07- -1965	1,016	12	20.6

Appendix A. Selected well records—Continued

Well number (pl. 1)	State permit number	Owner	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)	Diameter of well (in.) Casing	Diameter of well (in.) Screen	Depth to top of screen (ft)	Length of screen (ft)	Aquifer	Water levels below land surface (ft) Static	Water levels below land surface (ft) Pumping	Date measured	Pumping rate (gal/min)	Hours pumped	Specific capacity [(gal/min)/ft]
PG Df 36	PG-68-0043	Marlboro Meadows	Sydnor	- -1968	100	500	24, 10, 8	10	222, 236, 272, 320, 342, 362, 398	3, 8, 10, 12, 16, 10, 24	Magothy	29	-	05- -1968	1,200	72	
PG Df 39	PG-69-0046	Marlboro Meadows	Layne-Atlantic	- -1969	40	474	6, 4	4	350, 378	20, 54	Magothy	Flowing	50	05- -1969	250	24	1.0
PG Ef 34	PG-73-0092	Patuxent River Park	East Coast	- -1973	40	380	4	3	342	11	Magothy	16	50	07- -1973	35	8	1.5
PG Ef 37	PG-70-0009	Western Run Waste Water Treatment Plant	Layne-Atlantic	- -1969	20	464	26, 8	8 (?)	281	60	Magothy	Flowing	75	12- -1969	412	12	-
PG Ef 40	PG-73-1086	Bob Halls, Inc.	East Coast	- -1979	65	323	8, 6	6	285	27	Magothy	57	81	12- -1979	160	8	6.7

Well driller's abbreviation key

A C Schultes	= A C Schultes of Maryland	Caterton	= Chesapeake Well Drilling Co.	Frank	= Frank's Well Drilling, Inc.	Shannahan	= Shannahan Artesian Well Co.
Allied Envir	= Allied Environmental Services, Inc.	Calvert	= Calvert Well Drilling	Gibble	= Calvert Well Drilling Co.	Shockley	= Millineum Group
American	= American Drilling	Columbia	= Columbia Pump & Well Co.	Greer	= H.J. Greer & Sons Drilling Co.	Slater's	= Slater's Well Drilling, Inc.
Arnette	= Branham Well Drilling Contractors	CZ Enterprises	= CZ Enterprises	Ideal	= Ideal Well Drillers, Inc.	Sydnor	Sydnor Hydrodynamics, Inc.
Artesian	= Artesian Well & Pump Service, Inc.	Delmarva	= Delmarva Drilling Co.	Kanarr	= Paul E. Kanarr	W. Ward	= Willard S. Ward Co., Inc.
Arundel W & P	= Arundel Well & Pump Service, Inc.	Dennis	= Dennis Well Drilling	Lauman	= C. Lauman & Co., Inc.	Williams	= Ray Williams, Jr.
Atwater	= Atwater Drilling	East Coast	= East Coast Well & Pump, Inc.	Layne-Atlantic	= Layne-Atlantic Co.	Winslow	= Winslow Pump & Well, Inc
Branham	= Branham Well Drilling Contractors	Estes	= Chesapeake Well Drilling Co.	Leatherbury	= Robert M. Leatherbury	Wolford's	= Wolford's Well & Pump Service, Inc
Brucksch	= Branham Well Drilling Contractors	Ford	= Ford's Well Drilling	Purner	= Purner Well Drilling, Inc.	Zittinger	= CZ Enterprises
Bunker	= H.H. Bunker & Sons, Inc.						

Appendix B. Descriptive logs of washed drill cuttings from test wells drilled during study

[AA = Anne Arundel County; < = less than; > = greater than]

Descriptions by T. Brandon Fewster, Maryland Geological Survey

WELL AA Ed 65 – DAVIDSONVILLE POLICE ACADEMY

Altitude of land surface = 110 feet

Depth, feet below land surface	Description
CALVERT FORMATION	
0-13	Sand, fine, tan, quartzose, subangular; glauconite
13-23	Sand, fine, tan, quartzose, subangular; glauconite
NANJEMOY FORMATION	
23-33	Sand, medium, gray-green, quartzose, subangular to subrounded; iron-stained glauconite and limonite
33-43	Sand, medium to coarse, gray, quartzose; glauconite; 5 percent iron stained; <5 percent clay, pale yellow
MARLBORO CLAY	
43-53	Sand, as above; clay, silty, light tan; geophysical logs indicate clay
53-63	Clay, pink; sand, gray, very fine, quartzose; glauconite
AQUIA FORMATION	
63-73	As above, geophysical logs indicate a sand
73-83	Sand, tan, gray, fine to medium, quartzose; some glauconite; 1 percent iron stained; clay, pink, probably contamination from up-hole; geophysical logs indicate a sand
83-93	Sand, fine, tan, quartzose; clay, pink and tan
93-103	Sand, fine, gray, quartzose; glauconite; shell fragments; cemented layer indicated by rig chatter at 98 feet
103-113	Sand, medium to fine, gray, quartzose, glauconite; 15-20 percent shell fragments; <1 percent iron staining
113-123	Sand, medium to fine, gray, quartzose, glauconite; slightly less shell fragments; <1 percent iron staining
123-133	Sand, medium, gray, clear, lightly iron stained and <5 percent pink quartz, glauconite; shell fragments; calcareously-cemented sand and shell
133-143	Sand, medium to fine, gray, quartzose, glauconite; 5 percent shell fragments; 20 percent botryoidal glauconite
143-153	Sand, medium, tan, subrounded clear to opaque quartz; 15-20 percent botryoidal glauconite
153-163	Sand, medium, light tan, quartzose; 10-15 percent glauconite
BRIGHTSEAT FORMATION (?)	
163-173	Sand, medium to coarse, light tan, quartz grains are clear to opaque, <5 percent quartz has light iron staining; 10 percent glauconite; 1 percent shell
173-183	As above

AA Ed 65—Continued

Depth, feet below land surface	Description
SEVERN FORMATION (?)–Continued	
183-193	Sand, medium to coarse, light tan, quartz is clear to opaque; 5-10 percent glauconite; 5 percent shell fragments
193-203	Sand, medium to coarse, tan, quartzose; shell fragments; clay, red-tan (possible contamination). Rig chatter from 195 to 198 feet
MATAWAN FORMATION	
203-213	Sand, coarse, brown, quartzose; shell fragments; clay red-gray
213-223	Sand, medium, brown to gray; quartzose, glauconite; clay, gray and tan; shell
223-233	Clay, dark gray with some tan; sand, medium to fine, quartzose; <5 percent shell
233-243	Clay, gray to tan; sand, fine to very fine, tan, quartz; <1 percent mica; <1 percent shell
243-253	Clay, silty, dark gray with some red cuttings (possible contamination); sand, very fine, quartzose; <5 percent shell
253-263	Clay, silty, dark gray; less sand, very fine, quartz with 10 percent glauconite
263-273	Clay, gray; sand, fine, brown, quartzose. Faster drilling at 268 feet; possible sand layer
273-283	Clay, silty, dark gray
MAGOTHY FORMATION	
283-293	Clay, silty, dark gray; field description included sand, medium to coarse, mostly clear and occasional pale blue quartz; gamma-ray and resistivity logs indicate sand
293-303	Sand, coarse to medium, white quartz grains, well sorted
303-313	Sand, coarse to medium, white quartz grains, well sorted; <1 percent lignite. At 305 feet gamma-ray log indicates clay. Driller reported a possible clay layer at 308 feet.
313-323	Sand, coarse to fine, white, 1-5 percent pink quartz grains; clay, pink and gray; 1-5 percent lignite; geophysical logs indicate a clay.
323-333	Sand, coarse to medium, opaque pink and <1 percent pale green quartz; lignite
333-343	Sand, coarse, pale gray, opaque and 5 percent pink quartz grains; <5 percent lignite
343-353	Sand, medium to coarse, pale gray, opaque and <5 percent pink quartz grains, well sorted
353-363	As above
363-373	Sand, medium to fine with 5-10 percent coarse grains, pale gray, white quartz; field description includes some red clay and lignite
373-383	Sand, medium, opaque, clear, and white quartz grains
383-393	Sand, coarse to medium, opaque, clear, pink and white quartz grains; clay, gray to pink

Appendix B. Descriptive logs of washed drill cuttings from test wells drilled during study–Continued

WELL AA Fc 34 – WAYSONS CORNER

Altitude of land surface = 51 feet

Depth, feet below land surface	Description
UNDIFFERENTIATED PLEISTOCENE DEPOSITS	
0-23	Sand, medium to coarse, tan, quartzose, opaque to clear; 5-10 percent glauconite; 1 percent mica
23-33	As above with iron staining
NANJEMOY FORMATION (?)	
33-43	Sand, very coarse to gravelly, tan, quartzose, opaque, subrounded; 1 percent iron staining; driller reported gray clay at 36 feet
43-53	Clay, gray; sand, very coarse to gravelly, tan, quartzose, opaque, 5 percent gray-green; 5-10 percent with iron staining
MARLBORO CLAY	
53-63	Clay, pink and gray; sand, coarse to gravelly, quartzose, opaque (probably up-hole contamination)
63-73	Clay, pink with some gray; some coarse sand (probably up-hole contamination)
73-83	Clay, pink with gray
AQUIA FORMATION[2]	
83-93	Sand, fine to medium, gray, quartzose, clear; 30 percent glauconite; <1 percent shell; <1 percent mica
93-103	As above; heavy rig chatter at 100 feet; possible shell layer
103-113	Sand, medium, gray, quartzose, clear; glauconite; 10-20 percent shell
113-123	Sand, fine to medium, gray, quartzose, clear and opaque, occasional cemented grains; glauconite; shell; <1 percent mica
123-133	Sand, fine, light tan and gray, quartzose, clear, opaque, tan; glauconite; 5 percent shell
133-143	As above
143-153	As above with more glauconite; <1 percent shell
153-163	Sand, fine, tan to gray, quartzose with abundant dark-green to black glauconite; <1 percent mica
163-173	As above with trace shell (up-hole contamination)
173-183	Sand, fine to medium, light tan, quartzose, some grains are cemented; some fine glauconite
183-193	Sand, fine to medium, light tan, quartzose, iron-stained; fine glauconite; <5 percent shell; <1 percent mica
193-203	Sand, fine to medium, tan, quartzose, iron-stained; 15-20 percent glauconite; <1 percent shell; at 196 feet, rig chatter (possible shell layer)
203-213	Sand, fine, dark tan, quartzose, white; fine glauconite
213-223	Sand, fine to medium, gray, quartzose, clear to opaque, with very fine-grained glauconite; partially cemented

[2]Brightseat and Severn Formations were not distinguishable in the drill cuttings or on the geophysical logs.

Appendix B. Descriptive logs of washed drill cuttings from test wells drilled during study–Continued

AA Fc 34 –Continued

Depth, feet below land surface	Description
AQUIA FORMATION–Continued	
223-233	Sand, medium, gray, equal amounts of quartz and glauconite; partially cemented
MATAWAN FORMATION	
233-243	Sand, medium to fine, gray, quartz and glauconite; gray clay; at 238 feet driller reported clay; gamma-ray log indicates interbedded clays starting at 233 feet
243-253	Clay, gray; abundant shell; sand, fine, black glauconitic and partially cemented
253-263	Clay, gray; sand, fine, black, glauconite with clear quartz; shell
263-273	Clay, dark gray; sand, black, very fine, glauconite with 5-10 percent fine opaque quartz; shell
273-283	Clay, silty, gray and reddish-tan; shell; sand, very fine, black, glauconite with 5-10 percent fine to medium quartz
283-293	Clay, silty, gray and reddish; sand, very fine to fine, quartzose, opaque; shell
293-303	No sample taken; geophysical logs indicate a clay
MAGOTHY FORMATION	
303-313	Sand, medium to coarse, quartzose, clear, well sorted; 5 percent medium glauconite
313-323	Sand, coarse, quartzose, clear; <1 percent glauconite; <1 percent lignite
323-333	Sand, coarse, quartzose, clear with 10 percent pink; lignite; heavy rig chatter from 325 feet to 330 feet; driller reported clay; gamma-ray log indicates clay layer between 324 feet to 335 feet
333-343	Sand, coarse, quartzose, clear with 10-15 percent pink and bluish-purple grains; lignite; <1 percent pyrite
343-353	Sand, coarse, quartzose, clear with 15 percent pink and bluish-purple grains; abundant lignite
353-363	As above; less lignite
363-373	Sand, coarse to medium, quartzose, clear with 5-10 percent pink; some silty clay, reddish-pink; lignite
PATAPSCO FORMATION (?)	
373-383	Clay, silty, reddish; sand, fine to coarse, quartzose, poorly sorted
383-393	As above with trace pyrite
393-403	Clay, reddish-brown; sand, coarse to very coarse, quartz, clear and pink
403-413	Clay, reddish-brown; sand, medium to coarse, quartzose, white; abundant lignite

Appendix B. Descriptive logs of washed drill cuttings from test wells drilled during study–Continued

WELL AA Fe 60 – FRANKLIN POINT PARK

Altitude of land surface = 8 feet

Depth, feet below land surface	Description
TALBOT FORMATION	
0-10	Clay, light gray and white; sand, fine, quartzose, clear; 10 percent very fine glauconite
10-20	As above
CALVERT FORMATION (?)	
20-30	Clay, dark to light gray; sand, silty, light gray with 10 percent glauconite
NANJEMOY FORMATION (?)	
30-40	Sand, fine to very fine, quartzose, light gray; 10-15 percent glauconite, very fine
40-50	Sand, coarse, gray, quartzose with fine glauconite; clay, gray
50-60	Clay, silty, gray; sand, medium to fine, gray, quartzose, 5 percent with light iron staining; fine black glauconite
60-70	Clay, gray; sand, medium and 10 percent gravel-sized grains of quartz with 30 percent fine black glauconite; resistivity and gamma-ray logs indicate a sand grading downward to a clay
70-80	Clay, silty, gray to dark gray; sand, gravelly with 10 percent medium to fine grained quartz; fine black glauconite
80-90	As above
90-100	Sand, medium with some gravel, quartzose, opaque; 10-20 percent fine black glauconite; clay, silty, gray; 20-30 percent with iron staining; field description noted white, calcareously-cemented sand
MARLBORO CLAY	
100-110	Sand, fine to medium with 10 percent gravel (up-hole ?), quartz, clear to opaque; equal amount of fine-grained, green and black glauconite; gamma-ray log indicates a clay
110-120	As above with iron staining and broken shell; gamma-ray log indicates a clay
120-130	As above with less gravel noted; gamma-ray log indicates a clay between 120 feet to 125 feet
AQUIA FORMATION	
130-140	Sand, fine to medium, quartz with 5 percent calcareous cementation; 20-30 percent glauconite, fine, black; clay, gray
140-150	Sand, fine to medium, quartzose, white with fine, black glauconite; clay, gray; shell
150-160	Sand, fine to medium, dark gray, equal amounts of quartz and glauconite, 5 percent iron staining on quartz grains; <1 percent shell
160-170	Sand, medium to coarse, quartz with fine black glauconite; calcareously-cemented sandstone fragments; shell; trace amount of gravel
170-180	Sand, medium to coarse, quartz with fine black glauconite; calcareous-cemented sandstone; 10 percent gravel; shell
180-190	As above with a greater amount of gravel

Appendix B. Descriptive logs of washed drill cuttings from test wells drilled during study–Continued

AA Fe 60 – Continued

Depth, feet below land surface	Description
AQUIA FORMATION–Continued	
190-200	Sand, medium to coarse, quartz with fine black glauconite; calcareously-cemented sandstone fragments; 10 percent gravel; 5 percent coarse to very coarse, reddish-brown goethite (?); <1 percent shell
200-213	Sand, medium to coarse, quartz with fine, black glauconite; calcareously-cemented sandstone fragments; some gravel; <1 percent shell

Appendix B. Descriptive logs of washed drill cuttings from test wells drilled during study–Continued

WELL AA Fe 91 -- DEALE ATHLETIC FIELD

Altitude of land surface = 9 feet

Depth, feet below land surface	Description
TALBOT FORMATION (?)	
0-10	Clay, silty, light gray with some iron staining
10-20	Clay, silty, light gray with some iron staining; some sand, fine, quartzose. At 18 feet, driller reported fine, tan sand
CALVERT FORMATION (?)	
20-30	Clay, light gray and olive-green; sand, very fine, black, glauconite with some quartz; light iron staining
30-40	Sand, fine, black, glauconitic with fine to medium, clear quartz grains; <5 percent iron staining
NANJEMOY FORMATION (?)	
40-50	Sand, fine, black, glauconitic with fine to medium and a few coarse quartz grains; clay, olive-green
50-60	Sand, fine, black, glauconitic with fine to medium clear quartz grains; clay, light gray to olive-green; trace iron staining
60-70	As above with an increased amount of quartz
70-80	Sand, fine, black, glauconitic with fine, clear quartz grains; clay, gray
80-90	Clay, gray-green; sand, very fine, black glauconitic with fine, clear quartz
90-100	Clay, gray-green; sand, very fine to fine, black, glauconitic with fine quartz
100-110	Sand, medium to coarse, green-black glauconite with clear quartz; gray clay
110-120	Clay, olive-green; sand, very fine to fine black glauconite with fine clear quartz
120-130	Clay, olive-green and gray; sand, fine, green-black glauconitic with fine, clear quartz; geophysical logs indicate a sand
MARLBORO CLAY (?)	
130-140	Clay, olive-green with trace reddish silt; sand, fine, black glauconite with fine, clear quartz; trace shell
140-150	Sand, fine, green-black glauconite with fine to medium clear quartz; geophysical logs indicate a clay
AQUIA FORMATION[2]	
150-160	Sand, medium to fine, black glauconite and clear quartz; shell; gray clay; geophysical logs indicate a clay
160-170	No sample
170-180	Sand, tan, medium with some coarse grains, quartz with 25 percent glauconite; aggregates of calcareously-cemented grains; shell
180-190	Sand, medium to coarse, opaque quartz with some light iron staining and equal amount of black glauconite; aggregates of calcareously-cemented grains; <1 percent pyrite; <1 percent shell

[2] Brightseat and Severn Formations not distinguishable in the drill cuttings or on the geophysical logs.

Appendix B. Descriptive logs of washed drill cuttings from test wells drilled during study–Continued

AA Fe 91 – Continued

Depth, feet below land surface	Description
AQUIA FORMATION–Continued	
190-200	Sand, medium to coarse, opaque quartz with some light iron staining and equal amount of black glauconite; aggregates of calcareously-cemented grains; some shell
200-210	As above. Field description noted occurrence of goethite (?)
210-220	Sand, medium to coarse, quartzose, clear, opaque, pale green, and iron-stained; glauconite, medium, 60 percent green-black and 40 percent brown (goethite ?); shell; <1 percent pyrite
220-230	Sand, medium, quartzose, clear, opaque, and iron-stained; glauconite, medium, green-black, and brown (goethite ?); calcareously-cemented sand; <5 percent shell
230-240	Sand, medium, opaque quartz with iron staining and black glauconite; >60 percent calcareously-cemented sand; <5 percent shell
240-250	Sand, medium to coarse, quartzose, opaque with light iron staining; glauconite, medium, black, and brown (goethite ?); calcareously-cemented sand; shell
250-260	As above
260-270	Sand, medium to coarse, quartz with iron staining; glauconite, medium, black and coarse brown grains; calcareously-cemented sand; shell
270-280	Sand, coarse to medium, clear and opaque quartz and greenish-black glauconite; calcareously-cemented sand; shell
280-290	Sand, coarse to very coarse, quartz, opaque, and medium, black glauconite; calcareously-cemented sand; 40 percent shell; <1 percent pyrite
290-300	Sand, coarse to very coarse, opaque quartz and black glauconite; 40 percent shell; calcareously-cemented sand
300-310	Sand, coarse to very coarse, quartzose and glauconitic; calcareously-cemented sand; 50 percent shell; rig chatter throughout interval
310-320	As above
320-330	As above
330-340	Sandstone; calcareously-cemented sand grains consisting of coarse to very coarse, opaque quartz with iron staining and black glauconite; 50 percent shell
340-350	As above with <5 percent gray clay
350-360	As above with <5 percent gray clay
MATAWAN FORMATION	
360-370	Shell; sand, coarse to very coarse, well-rounded, quartzose, opaque and iron staining; calcareously-cemented sand, quartzose and glauconitic, coarse to medium grains; gray clay; gamma-ray log indicates clay layer; driller's log describes coarse sand with black clay
370-380	As above
380-390	Sand, very coarse to pebbles, quartzose, well-rounded with light iron-staining; calcareously-cemented sand consisting of medium quartz and black glauconite; shell; gray clay; trace pyrite
390-400	As above; gamma-ray log indicates thinly bedded clay layer
400-420	Sand, very coarse, quartzose, clear and 10 percent iron-stained; calcareously-cemented sand, aggregates consisting of clear quartz and black glauconite; shell; clay, olive-green
420-430	As above

Appendix B. Descriptive logs of washed drill cuttings from test wells drilled during study—Continued

AA Fe 91 – Continued

Depth, feet below land surface	Description
MAGOTHY FORMATION	
430-440	Sand, coarse, quartzose, clear, pink and pale-blue grains; 10 percent calcareously-cemented sand and <5 percent shell (from up-hole ?); driller reported lignite
440-450	Sand, coarse to very coarse, quartzose, clear and pink-purple grains; trace calcareously-cemented sand (from up-hole ?)
450-460	As above with 5 percent lignite
460-470	As above with 5 percent lignite
470-480	Sand, coarse to very coarse, quartzose with clear, pink and bluish-purple grains; 40 percent lignite; <1 percent pyrite; <5 percent calcareously-cemented sand (from up-hole ?); geophysical logs indicate a clay
480-490	As above
490-500	Sand, fine to coarse, quartzose with clear and pink-purple grains; some clay, silty, gray; lignite; <1 percent pyrite; geophysical logs indicate a clay
500-510	Sand, medium to coarse, quartzose with clear and pink-purple grains; lignite
510-520	Sand, fine to coarse, quartzose with clear and pink grains; lignite; clay, silty, gray (from up-hole ?)
520-530	As above
530-540	Sand, fine to medium with some coarse grains, quartzose, clear and pink-purple; lignite; clay, gray; <1 percent pyrite
540-550	Sand, fine to medium, quartz, clear; clay, gray; lignite; <1 percent pyrite
550-560	Clay, gray; sand, fine to medium, clear quartz; <5 percent lignite
560-570	As above
PATAPSCO FORMATION (?)	
570-610	Poor sample recovery; field description indicates a white and yellow clay
610	Clay, stiff, yellow and red (bit sample)

Appendix C. Appropriated ground-water use over 10,000 gallons per day in the Aquia and Magothy aquifers in the model area in 2000

Site number[A]	Owner or name	Ground-water Appropriation Permit (GAP)	U.S. Geological Survey number (see appendix A)	Average amount appropriated (1,000 gallons per day)	Average daily pumpage in 2000 (1,000 gallons per day)
		AQUIA AQUIFER			
1	Rose Haven (Herrington Harbor)	AA1948G001	AA Ge 13, 16	80	58[B]
2	Woodfield Fish and Oyster Co.	AA1954G003	AA Ee 28, 61	50	3.6
3	Southdown Water Works	AA1958G008	AA De 38, 68, 119, 120, 121	--[C]	--
4	Waysons Mobile Home Park	AA1960G008	AA Fc 20	47	52
5	Lyons Creek Mobile Home Estates	AA1966G055	AA Fc 22	38	0
6	Broadwater Waste-Water Treatment Plant	AA1971G020	AA Fe 46	20	1.4
7	Patuxent Mobile Home Park	AA1973G013	AA Fc 25, 26	40	33
8	Boones Mobile Home Estates	AA1976G014	AA Fc 31, 37, 39	75	20
9	Rio Vista Mobile Home Park	AA1986G045	AA Fc 24, 38	10.5	7.5
10	Central Sod Farms	AA1993G024	AA Fe 61	65.1	7.3
11	Regency Manor Mobile Home Park	CA1959G003	CA Bb 16, 21, 43, 44	20	15
12	Lakewood	CA1966G005	CA Bb 30, 41	15	19
13	Paris Oaks	CA1973G013	CA Bc 32, 50	29	25
14	North Beach	CA1988G009	CA Bc 44, 45	200	137

Appendix C. Appropriated ground-water use over 10,000 gallons per day in the Aquia and Magothy aquifers in the model area in 2000

Site number[A]	Owner or name	Ground-water Appropriation Permit (GAP)	U.S. Geological Survey number (see appendix A)	Average amount appropriated (1,000 gallons per day)	Average daily pumpage in 2000 (1,000 gallons per day)
		AQUIA AQUIFER			
15	Cross Point	CA1996G026	CA Bb 45, 46	37	7.2
		MAGOTHY AQUIFER			
16	U.S. Navy, David Taylor R & D	AA1932G001	AA Df 64	--[C]	--
17	Sylvan Shores	AA1956G002	AA De 69, 122	55	75
18	Summer Hill Mobile Home Park	AA1960G021	AA Cd 93	25	11
19	Maryland Manor Mobile Estates	AA1965G032	AA Ec 6, 7, 8	80	89
20	Southern High School	AA1968G011	AA Ed 39, 41	25	11
21	City of Annapolis	AA1972G009	AA De 2, 45, 46, 88	2,000	1,700
22	Pleasant Living Convalescent Center	AA1981G039	AA De 216	14	24[B]
23	Central Sod Farm	AA1988G044	AA Fe 54	126	8.7
24	Shady Oaks Sod Farm	AA1988G058	AA Fe 55	200	0
25	South River Colony Golf Course	AA1990G045	AA De 217	61	59[B]
26	Lyons Creek Mobile Home Estates	AA1992G022	AA Fc 23	38	57[D]
27	Bayard Sand and Gravel	AA1996G122	AA Ec 14	70	0

Appendix C. Appropriated ground-water use over 10,000 gallons per day in the Aquia and Magothy aquifers in the model area in 2000

Site number[A]	Owner or name	Ground-water Appropriation Permit (GAP)	U.S. Geological Survey number (see appendix A)	Average amount appropriated (1,000 gallons per day)	Average daily pumpage in 2000 (1,000 gallons per day)
		MAGOTHY AQUIFER			
28	Crofton Athletic Complex	AA1997G030	AA Dc 22, 23	16.2	0.1[B]
29	Safeway, Inc.	AA1998G028	AA Fe 56	13	0
30	Cavalier Country	CA1970G004	CA Bb 23, 24	55	56
31	Shores of Calvert	CA1972G002	CA Ba 7, 8	35	25
32	City of Bowie	PG1961G008	PG Cf 33, 34	200	73
33	Marlboro Meadows	PG1963G003	PG Df 34, 36, 39	600	370
34	Western Run Waste-Water Treatment Plant	PG1970G002	PG Ef 37	30	2.5

A – Sites are located on figure 12
B – Pumpage reported for January through June only
C – Inactive permit
D – Pumpage reported for July through December only

Appendix D. Appropriated ground-water use over 10,000 gallons per day in the Aquia aquifer in the model area, 1920-79

[AA = Anne Arundel; Data from Wheeler and Wilde, 1989]

Owner	Ground-water Appropriation Permit (GAP)	Average daily pumpage for period (1,000 gallons per day)														
		1920-29	1930-39	1940-49	1950-59	1960-69	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
Woodfield Fish and Oyster Co.	AA1954G003	22	23	25	28	39	41	55	55	48	48	55	43	32	35	40
South Down Water Works	AA1958G008	0	0	0	2	11	16	16	24	20	22	22	22	22	22	41
Waysons Mobile Home Park	AA1960G008	0	0	0	0	36	41	47	49	49	51	57	53	55	55	47
Lyons Creek Mobile Home Estates	AA1966G055	0	0	0	0	2.0	2.0	3.0	8.0	8.0	8.0	8.0	13	29	40	17
Broadwater Waste-Water Treatment Plant	AA1971G020	0	0	0	0	0	0	0	0	0	0	0	0	19	21	24
Boones Mobile Home Estates	AA1976G014	0	0	0	0	0	0	0	0	0	0	0	0	57	26	19

Appendix E. Appropriated ground-water use over 10,000 gallons per day in the Aquia aquifer in the model area, 1980-2000

[AA = Anne Arundel County; CA = Calvert County; -- = not reported; e = estimated]

Owner	Ground-water Appropriation Permit (GAP)	Period	Average daily pumpage for period (1,000 gallons per day)																				
			80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00
Rose Haven (Herrington Harbor)	AA1948G001	Jan-Jun	0	0	0	0	0	64.5	65.4	52.7	51.3	44.6	48.4	56.2	52.9	50.8	68.4	49.9	55.1	62.4	70.5	94.1	58.1
		Jul-Dec	0	0	0	0	0	62.9	54.0	65.9	55.0	53.1	59.6	60.3	54.5	67.9	54.6	60.8	59.4	64.5	106.5	64.4	--
Woodfield Fish and Oyster Co.	AA1954G003	Jan-Jun	56.4	11.6	9.36	34.4	27.1	29.1	29.0	32.0	29.2	38.9	23.1	33.6	27.3	4.56	4.05	3.25	2.11	2.34	0	0	3.21
		Jul-Dec	30.5	13.6	40.6	41.8	38.8	33.9	37.8	35.9	41.8	33.5	17.3	25.4	1.05	7.39	6.40	5.83	3.77	4.19	3.48	0	4.05
South Down Water Works	AA1958G008	Jan-Jun	25.3	35.6	33.6	42.0	29.3	32.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		Jul-Dec	35.6	32.8	42.9	29.5	33.2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Waysons Mobile Home Park	AA1960G008	Jan-Jun	4.65	51.4	53.2	55.3	42.9	33.8	34.3	34.6	32.0	42.2	41.4	40.7	39.6	39.3	34.3	38.7	59.8	51.3	68.7	53.4	53.2
		Jul-Dec	0	5.14	54.7	53.9	44.3	36.5	34.5	35.2	35.1	45.5	44.0	39.2	46.0	41.3	42.1	46.5	--	43.9	56.1	57.1	50.2
Lyons Creek Mobile Home Estates	AA1966G055	Jan-Jun	75.0	69.1	68.1	66.8	53.0e	54.0e	43.0e	43.0e	96.8	--	46.6	45.4	--	--	0	0	0	67.6	0	0	0
		Jul-Dec	73.4	68.5	74.7	--	53.0e	54.0e	43.0e	43.0e	46.0e	--	46.6	46.5	50.4	31.0e	0	--	--	0	63.4	64.3	0
Broadwater Waste-Water Treatment Plant	AA1971G020	Jan-Jun	12.1	12.6	28.3	0	48.6	6.94	5.95	5.95	2.13	8.17	8.06	8.75	5.18	8.35	15.6	11.9	7.14	5.70	5.80	1.44	1.26
		Jul-Dec	14.5	13.8	23.7	10.0	7.50	8.01	6.02	2.69	3.74	7.20	0	5.95	7.36	8.24	3.07	9.28	5.60	7.05	2.90	1.14	1.66
Patuxent Mobile Home Estates	AA1973G013	Jan-Jun	0	39.9	--	--	16.5	17.7	26.1	26.8	32.3	29.3	31.7	32.3	34.7	36.3	30.2	23.0	36.3	30.2	33.8	25.0	33.8
		Jul-Dec	0	27.3	--	--	17.1	27.7	29.8	32.2	31.0	32.3	32.3	32.1	27.1	35.8	25.6	30.5	31.8	27.3	28.0	27.3	31.67
Boones Mobile Home Estates	AA1976G014	Jan-Jun	24.4	22.8	21.8	20.6	28.6	28.0	24.4	20.1	19.7	19.0	20.1	19.5	19.3	19.1	18.4	19.1	19.3	13.6	19.4	19.8	19.71
		Jul-Dec	24.0	24.5	21.3	24.8	24.0	22.7	20.0	20.0	20.8	20.4	20.1	20.2	20.1	19.5	19.7	21.0	21.0	20.8	21.2	21.1	19.84
Rio Vista Mobile Home Park	AA1986G045	Jan-Jun	0	0	0	0	0	0	0	12.5	9.27	12.3	13.8	14.6	15.3	11.7	15.4	5.19	6.39	5.93	6.70	7.30	7.18
		Jul-Dec	0	0	0	0	0	0	0	12.7	13.8	15.3	12.4	17.0	22.5	14.2	5.56	8.84	1.61	6.54	9.23	10.5	7.86
Central Sod Farms	AA1993G024	Jan-Jun	0	0	0	0	0	0	0	--	--	--	--	--	--	--	4.36	9.83	0	1.08	17.6	19.0	0.84
		Jul-Dec	0	0	0	0	0	0	0	--	--	--	--	--	--	38.7	10.2	32.7	0	3.29	32.1	30.5	13.7
Regency Manor Mobile Home Park	CA1959G003	Jul-Jun	0	0.41	0.41	0.41	0.41	0	8.56	9.34	9.92	10.1	10.0	9.82	11.0	10.3	9.45	11.5	12.2	9.05	9.18	5.71	11.8
		Jul-Dec	0	0.41	0.41	0	0	7.9	10.5	10.6	10.1	10.6	9.7	12.3	0	10.8	10.5	12.2	0	9.25	9.34	9.34	18.7
Lakewood	CA1966G005	Jul-Jun	10.4	10.4	15.5	0	21.2	21.2	21.6	8.22	10.1	8.76	11.8	11.6	10.6	10.9	10.7	10.2	10.6	11.1	11.6	12.0	23.4
		Jul-Dec	16.5	16.5	16.4	23.8	22.8	19.6	27.6	8.74	11.8	11.8	11.5	11.9	10.6	12.5	9.98	11.5	11.2	11.3	16.1	12.9	14.5

Appendix F. Appropriated ground-water use over 10,000 gallons per day in the Magothy aquifer in the model area, 1920-79

[AA = Anne Arundel County; CA = Calvert County; PG = Prince George's County; data from Wheeler and Wilde, 1989]

Owner	Ground-water Appropriation Permit (GAP)	Average daily pumpage for period (1,000 gallons per day)														
		1920-29	1930-39	1940-49	1950-59	1960-69	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
U.S. Navy, David Taylor R & D	AA1932G001	0	0	150	188	190	180	200	200	200	200	164	168	137	161	143
Sylvan Shores	AA1956G002	0	0	0	35.0	38.0	41.0	43.0	52.0	47.0	43.0	34.0	38.0	44.0	41.0	42.0
Maryland Manor Mobile Home Park	AA1965G032	0	0	0	0	0	0	29.0	54.0	57.0	55.0	55.0	52.0	51.0	51.0	45.0
Lyons Creek Mobile Home Estates	AA1992G022	0	0	0	0	0	0	0	0	0	0	0.1	15.0	21.0	32.0	9.0
Southern High School	AA1968G011	0	0	0	0	0	0	0	0	0	0	0	0	14.0	20.0	32.0
Central Avenue School	AA1971G026	0	0	0	0	0	0	0	0	0	0	0	0	0	16.0	27.0
City of Annapolis	AA1972G009	0	0	2,046	2,684	2,582	2,822	3,014	3,348	2,775	2,795	3,063	2,739	3,992	3,173	3,233
Riva Development	AA1975G023	0	0	0	0	0	0	0	0	0	0	0	0	0	11.0	25.0
Cavalier Country	CA1970G004	0	0	0	0	0	0	38.0	41.0	44.0	47.0	47.0	49.0	53.0	38.0	42.0
Shores of Calvert	CA1972G002	0	0	0	0	0	4.0	4.0	4.0	4.0	4.0	30.0	30.0	25.0	28.0	32.0
City of Bowie	PG1962G008	0	0	0	0	184	268	478	353	195	171	254	230	152	175	121
Marlboro Meadows	PG1963G003	0	0	0	0	34	60	96	119	127	145	175	187	115	193	187

Appendix G. Appropriated ground-water use over 10,000 gallons per day in the Magothy aquifer in the model area, 1980-2000

[-- = not reported; AA = Anne Arundel Count; CA = Calvert County; PG = Prince George's County]

Owner	Ground-water Appropriation Permit (GAP)	Period	Average daily pumpage for period (1,000 gallons per day)																				
			80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00
U.S. Navy, David Taylor R & D	AA1932G001	Jan-Jun	140	--	164	174	142	453	7.5	83	--	--	155	--	--	--	434	--	0	0	0	0	0
		Jul-Dec	141	--	147	89	112	460	4.7	6.3	--	--	327	--	--	--	419	--	0	0	0	0	0
Sylvan Shores	AA1956G002	Jan-Jun	37.2	41.8	42.6	44.0	39.0	46.6	48.7	47.9	50.0	45.8	47.2	50.7	52.6	80.3	50.9	47.6	50.1	67.9	68.1	75.5	85.4
		Jul-Dec	42.1	41.5	44.1	45.6	44.2	46.6	47.9	50.0	53.6	48.4	46.2	57.3	92.6	55.8	50.6	54.7	66.5	69.7	111.6	77.1	65.3
Maryland Manor Mobile Estates	AA1965G032	Jan-Jun	63.9	61.2	67.8	55.7	50.5	38.0	42.0	79.4	80.5	67.9	72.6	84.8	80.7	95.3	103.9	105.4	99.1	104.4	110.2	85.7	74.3
		Jul-Dec	76.6	65.5	65.0	50.4	47.7	40.9	67.0	81.4	80.2	75.0	80.4	93.4	93.4	92.1	95.2	115.8	101.4	115.6	134.9	83.1	104.2
Southern High School	AA1968G011	Jan-Jun	29.1	30.4	22.4	20.7	22.3	22.4	22.1	23.1	16.3	9.6	10.9	17.6	15.2	16.2	16.4	16.7	23.1	11.8	14.2	16.0	12.0
		Jul-Dec	37.9	34.1	23.0	25.9	21.6	21.4	23.0	56.2	12.1	14.4	14.9	20.0	14.6	20.5	12.9	24.4	22.8	16.4	18.2	7.7	9.5
City of Annapolis	AA1972G009	Jan-Jun	3,407	2,932	2,068	2,196	3,034	3,938	2,718	1,257	1,514	1,800	1,249	2,221	1,904	1,944	2,083	1,560	1,598	1,719	1,414	1,622	1,731
		Jul-Dec	3,162	1,820	2,870	3,306	4,217	3,427	977	1,387	1,891	3,062	1,475	1,514	1,346	1,471	1,614	2,720	1,638	1,731	2,157	2,065	1,720
Pleasant Living Convalescent Center	AA1981G039	Jan-Jun	0	0	0	9.6	14.1	13.4	13.2	13.5	13.0	12.5	13.4	13.7	14.0	13.9	13.8	12.9	16.6	21.1	24.0	30.4	23.8
		Jul-Dec	0	0	0	10.8	13.5	13.3	14.4	13.9	13.4	13.3	13.7	13.9	13.9	13.8	14.3	11.6	19.1	24.8	23.6	33.5	--
Central Sod Farm	AA1988G044	Jan-Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.2	0	17.3	21.1	24.0	1.6
		Jun-Dec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24.7	9.2	28.3	67.7	29.3	15.8
Shady Oaks Sod Farm	AA1988G058	Jan-Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	6.5	0
		Jul-Dec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	30.2	0	51.0	0	31.2	0
South River Colony Golf Course	AA1990G045	Jan-Jun	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	60.3	51.2	93.0	133.1	59.0
		Jul-Dec	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	56.5	55.3	138.3	194.5	122.4	--
Lyons Creek Mobile Home Estates	AA1992G022	Jan-Jun	0.37	0	0	0	0	0	0	0	0	0	0	0	--	78.2	88.4	83.6	76.5	--	66.8	63.9	--
		Jul-Dec	0.37	0	0	0	0	0	0	0	0	0	0	0	50.4	81.9	85.8	82.7	--	67.4	--	55.1	57.3

Appendix G. Appropriated ground-water use over 10,000 gallons per day in the Magothy aquifer in the model area, 1980-2000–Continued

Owner	Ground-water Appropriation Permit (GAP)	Period	Average daily pumpage for period (1,000 gallons per day)																				
			80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	00
Cavalier Country	CA1970G004	Jan-Jun	51.2	45.0	48.8	42.1	45.2	51.3	63.5	46.9	53.8	41.1	43.7	51.3	40.0	45.3	48.6	40.6	42.8	52.6	57.0	74.2	62.5
		Jul-Dec	48.7	47.3	51.8	59.6	49.0	54.1	58.1	56.3	52.2	45.8	46.6	49.2	41.4	54.1	43.9	55.3	46.4	56.4	77.2	67.3	48.7
Shores of Calvert	CA1972G002	Jan-Jun	33.2	31.9	31.5	31.1	34.9	39.5	51.1	46.4	47.2	33.1	34.2	41.4	35.2	34.8	41.5	36.4	38.4	37.3	29.5	33.6	28.4
		Jul-Dec	38.2	27.9	34.4	40.4	34.3	38.8	42.5	47.0	49.0	40.2	36.1	40.0	28.0	47.4	35.8	40.9	41.3	37.4	42.5	34.7	28.3
City of Bowie	PG1961G008	Jan-Jun	2,430	2,385	2,370	2,235	2,314	2,291	2,548	2,285	232	158	164	189	0	164	133	149	66	186	71	58	67
		Jul-Dec	2,540	2,645	2,431	2,605	2,462	2,392	2,489	2,552	194	314	126	330	83	211	72	148	30	235	91	35	79
Marlboro Meadows	PG1963G003	Jan-Jun	180	223		316	300	425	312	290	356	330	427	454	524	494	351	360	376	328	326	344	356
		Jul-Dec	187	247		NR	400	397	304	347	462	435	385	406	505	546	370	356	367	346	399	351	394

Appendix H. Chemical analyses of water from test wells drilled during study and other selected wells

[mg/L = milligrams per liter; µg/L = micrograms per liter; µS/cm = microsiemens per centimeter at 25 degrees Celsius; deg C = degrees Celsius; E = estimated; < = less than]

Well number (pl. 1)	Aquifer	Date sampled	Acid neutralizing capacity (mg/L as $CaCO_3$)	Arsenic, dissolved (µg/L)	Bromide, dissolved (mg/L)	Calcium, dissolved (mg/L)	Chloride, dissolved (mg/L)	Fluoride, dissolved (mg/L)	Iron, total (µg/L)	Iron, dissolved (µg/L)	Magnesium, dissolved (mg/L)	Manganese, total (µg/L)
AA Ed 58	Aquia	08-16-00	217	<1	.027	83	3.9	.12	600	460	15	17
AA Ed 59	Aquia	08-01-00	178	<1	.026	59	1.9	<.10	920	830	8.2	10
AA Ed 60	Aquia	08-01-00	147	<1	.038	51	1.9	.12	1,300	1,100	5.9	11
AA Ed 62	Aquia	08-16-00	127	<1	<.010	46	1.7	<.10	1,200	970	1.3	16
AA Ed 65	Magothy	10-10-00	112	1 (E)	.025	41	2.3	.43	7,600	7,600	5.3	130
AA Ee 93	Aquia	08-23-00	98	<1	.016	45	.58	.16	280	250	5.9	45
AA Ef 40	Aquia	08-16-00	168	1 (E)	.015	59	2.5	.14	810	700	9.8	6
AA Fc 32	Aquia	08-01-00	140	1 (E)	.010	39	.66	.16	280	230	7.7	17
AA Fc 34	Magothy	10-06-00	152	<1	.022	58	2.0	.33	4,200	3,900	4.2	140
AA Fc 35	Aquia	10-04-00	121	<1	.020	49	1.4	.18	360	300	8.1	25
AA Fd 58	Aquia	08-04-00	128	1 (E)	.014	37	.94	.18	270	190	8.3	14
AA Fe 57	Aquia	08-23-00	232	1	.069	87	16	.13	2,100	2,100	20	59
AA Fe 59	Aquia	08-04-00	136	<1	.033	48	6.0	.17	580	500	8.0	15
AA Fe 60	Aquia	09-07-00	109	1	.029	44	.71	.17	490	460	7.8	19
AA Fe 63	Aquia	08-04-00	132	1 (E)	.019	42	1.2	.18	400	360	9.2	14
AA Fe 71	Aquia	08-04-00	121	<1	.014	40	.98	.24	380	310	7.6	2 (E)
AA Fe 82	Aquia	08-16-00	123	1	.019	44	.75	.19	520	400	8.2	12
AA Fe 92	Aquia	09-02-00	126	<1	.024	42	1.0	.27	450	450	9.6	6
AA Fe 93	Magothy	08-29-00	113	<1	.058	40	1.2	.22	4,300	3,600	6.4	63
AA Ge 15	Aquia	08-04-00	140	<1	.010	34	1.1	.28	200	150	9.5	<3
Samples which passed through residential water-treatment system												
AA Dd 61	Aquia	08-01-00	126	<1	.026	.051	2.7	.10	40	11	<.014	<3
AA Ee 95	Aquia	08-01-00	209	1 (E)	.11	.14	29	.11	<20	<10	.018	<3
AA Fd 60	Aquia	08-23-00	131	<1	.018	.067	1.4	.12	<20	<10	<.014	<3

Appendix H. Chemical analyses of water from test wells drilled during study and other selected wells—Continued

Well number (pl. 1)	Aquifer	Manganese, dissolved (µg/L)	Nitrogen, $NO_2 + NO_3$, dissolved (mg/L)	pH, field (standard units)	pH, lab (standard units)	Potassium, dissolved (mg/L)	Silica, dissolved (mg/L)	Specific con-ductance, lab (µS/cm)	Specific con-ductance, field (µS/cm)	Sodium, dissolved (mg/L)	Dissolved solids, residue at 180 deg C, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Tempera-ture, (deg C)
AA Ed 58	Aquia	16	<.050	7.5	7.6	7.5	23	564	515	4.4	364	81	17.3
AA Ed 59	Aquia	9.9	<.050	7.5	7.4	3.9	27	388	365	2.5	243	24	16.3
AA Ed 60	Aquia	10	<.050	7.3	7.2	3.0	41	327	313	2.7	221	20	16.2
AA Ed 62	Aquia	16	<.050	7.5	7.7	3.1	18	260	249	1.8	157	2.8	14.6
AA Ed 65	Magothy	140	<.047	7.2	6.8	3.1	23	261	262	1.6	171	16	14.6
AA Ee 93	Aquia	43	<.050	7.8	7.7	4.8	24	308	295	2.4	204	54	15.3
AA Ef 40	Aquia	5.3	<.050	7.7	7.7	6.6	25	414	384	6.1	265	46	15.7
AA Fc 32	Aquia	16	<.050	7.7	7.7	5.4	15	291	272	4.2	170	11	15.8
AA Fc 34	Magothy	141	<.047	7.1	7.3	2.9	12	335	318	1.8	199	19	15.8
AA Fc 35	Aquia	25	<.047	7.6	7.7	4.7	17	330	308	2.4	207	47	15.6
AA Fd 58	Aquia	16	<.050	8.0	7.8	5.6	15	296	290	3.7	175	23	16.5
AA Fe 57	Aquia	57	<.050	7.2	7.3	7.7	23	675	617	17	439	100	15.3
AA Fe 59	Aquia	14	<.050	7.9	7.7	5.4	20	358	345	6.0	223	39	15.9
AA Fe 60	Aquia	21	<.050	7.6	7.8	5.6	20	318	302	2.9	210	51	14.7
AA Fe 63	Aquia	14	<.050	7.9	7.8	5.8	17	325	313	3.5	195	33	16.2
AA Fe 71	Aquia	4.7	<.050	7.9	7.8	5.2	20	305	289	3.8	190	32	15.8
AA Fe 82	Aquia	10	<.050	7.8	7.9	5.7	21	326	306	3.9	204	42	15.6
AA Fe 92	Aquia	6.3	<.050	7.7	7.8	6.0	17	304	286	3.5	179	29	16.1
AA Fe 93	Magothy	55	<.050	7.1	7.2	2.3	9.3	301	300	1.7	184	37	18.1
AA Ge 15	Aquia	1.9 (E)	<.050	8.0	7.8	8.1	16	286	290	3.4	165	8.2	18.5
Samples which passed through residential water-treatment system													
AA Dd 61	Aquia	<2.2	<.050	7.6	7.6	0.14 (E)	49	288	274	65	214	18	16.2
AA Ee 95	Aquia	<2.2	<.050	7.6	7.7	2.4	24	555	514	120	342	28	16.4
AA Fd 60	Aquia	<2.2	<.050	7.7	7.7	.14 (E)	20	364	346	81	234	49	16.2

Gross alpha- and beta-particle activity in water samples collected from test wells

[pCi/L = picoCuries per liter; 2 sigma = total analytical error (2 standard deviations)]

Well number	Aquifer	Sample collection		Sample analysis		Gross alpha-particle activity (pCi/L)	Gross alpha 2 sigma (pCi/L)	Gross beta-particle activity (pCi/L)	Gross beta 2 sigma (pCi/L)
		Date	Time	Date	Time				
AA Ed 65	Magothy	10-10-00	1550	11-15-00	0429	2.8	3.2	2.0	4.4
AA Fc 34	Magothy	10-06-00	1515	10-11-00	1920	3.5	3.2	11	4.4
AA Fc 35	Aquia	10-04-00	1530	10-11-00	2121	<3.0	2.6	4.6	4.0
AA Fe 60	Aquia	09-07-00	1500	09-13-00	1528	<3.0	1.8	6.8	1.8
AA Fe 92	Aquia	09-02-00	1515	09-09-00	0232	<3.0	2.9	4.0	4.5
AA Fe 93	Magothy	08-29-00	1530	08-31-00	0059	3.0	3.1	<4.0	4.2

Appendix I. Pumpage assigned to model layer 2 (Aquia aquifer) for Pumping Scenario 1A

Stress period	Period		Small Planning area population[1]			Self-supplied pumpage (million gallons per day)[2]		
			Mayo-Edgewater	Southern Anne Arundel County		Mayo-Edgewater	Southern Anne Arundel County	
				Deale-Shady Side	South County		Deale-Shady Side	South County
1	2000	Jan-Jun	16,884	10,464	15,931	1.01	0.63	0.95
2		Jul-Dec	16,988	10,542	15,950	1.03	0.64	0.96
3	2001	Jan-Jun	17,091	10,619	15,968	1.04	0.65	0.97
4		Jul-Dec	17,195	10,697	15,987	1.06	0.66	0.98
5	2002	Jan-Jun	17,299	10,774	16,006	1.08	0.67	0.99
6		Jul-Dec	17,403	10,852	16,024	1.09	0.69	1.00
7	2003	Jan-Jun	17,506	10,929	16,043	1.11	0.70	1.01
8		Jul-Dec	17,610	11,007	16,062	1.13	0.71	1.02
9	2004	Jan-Jun	17,714	11,084	16,080	1.15	0.72	1.03
10		Jul-Dec	17,817	11,162	16,099	1.16	0.73	1.04
11	2005	Jan-Jun	17,921	11,239	16,118	1.18	0.74	1.05
12		Jul-Dec	18,025	11,317	16,136	1.20	0.76	1.06
13	2006	Jan-Jun	18,128	11,394	16,155	1.21	0.77	1.07
14		Jul-Dec	18,232	11,472	16,174	1.23	0.78	1.08
15	2007	Jan-Jun	18,336	11,550	16,192	1.25	0.79	1.09
16		Jul-Dec	18,440	11,627	16,211	1.26	0.80	1.10
17	2008	Jan-Jun	18,543	11,705	16,230	1.28	0.81	1.11
18		Jul-Dec	18,647	11,782	16,248	1.30	0.83	1.12
19	2009	Jan-Jun	18,751	11,860	16,267	1.31	0.84	1.13
20		Jul-Dec	18,854	11,937	16,286	1.33	0.85	1.14
21	2010	Jan-Jun	18,958	12,015	16,304	1.35	0.86	1.15
22		Jul-Dec	19,062	12,092	16,323	1.37	0.87	1.16
23	2011	Jan-Jun	19,165	12,170	16,342	1.38	0.88	1.17
24		Jul-Dec	19,269	12,247	16,360	1.40	0.89	1.18
25	2012	Jan-Jun	19,373	12,325	16,379	1.42	0.91	1.19
26		Jul-Dec	19,477	12,403	16,398	1.43	0.92	1.20

Appendix I. Pumpage assigned to model layer 2 (Aquia aquifer) for Pumping Scenario 1A–Continued

			Small Planning area population[1]			Self-supplied pumpage (million gallons per day)[2]		
			Mayo-Edgewater	Southern Anne Arundel County		Mayo-Edgewater	Southern Anne Arundel County	
Stress period	Period			Deale-Shadyside	South County		Deale-Shady Side	South County
27	2013	Jan-Jun	19,580	12,480	16,416	1.45	0.93	1.20
28		Jul-Dec	19,684	12,558	16,435	1.47	0.94	1.21
29	2014	Jan-Jun	19,788	12,635	16,453	1.48	0.95	1.22
30		Jul-Dec	19,891	12,713	16,472	1.50	0.96	1.23
31	2015	Jan-Jun	19,995	12,790	16,491	1.52	0.98	1.24
32		Jul-Dec	20,099	12,868	16,509	1.53	0.99	1.25
33	2016	Jan-Jun	20,202	12,945	16,528	1.55	1.00	1.26
34		Jul-Dec	20,306	13,023	16,547	1.57	1.01	1.27
35	2017	Jan-Jun	20,410	13,100	16,565	1.59	1.02	1.28
36		Jul-Dec	20,514	13,178	16,584	1.60	1.03	1.29
37	2018	Jan-Jun	20,617	13,255	16,603	1.62	1.05	1.30
38		Jul-Dec	20,721	13,333	16,621	1.64	1.06	1.31
39	2019	Jan-Jun	20,825	13,411	16,640	1.65	1.07	1.32
40		Jul-Dec	20,930	13,488	16,659	1.67	1.08	1.33

[1] See figure 39 for location of Small Planning areas.

[2] Pumpage calculated by multiplying population by per capita water-use rate. Per capita water-use rate was increased incrementally from 60 gallons per day per person in 2001 to 80 gallons per day per person in 2020.

Notes

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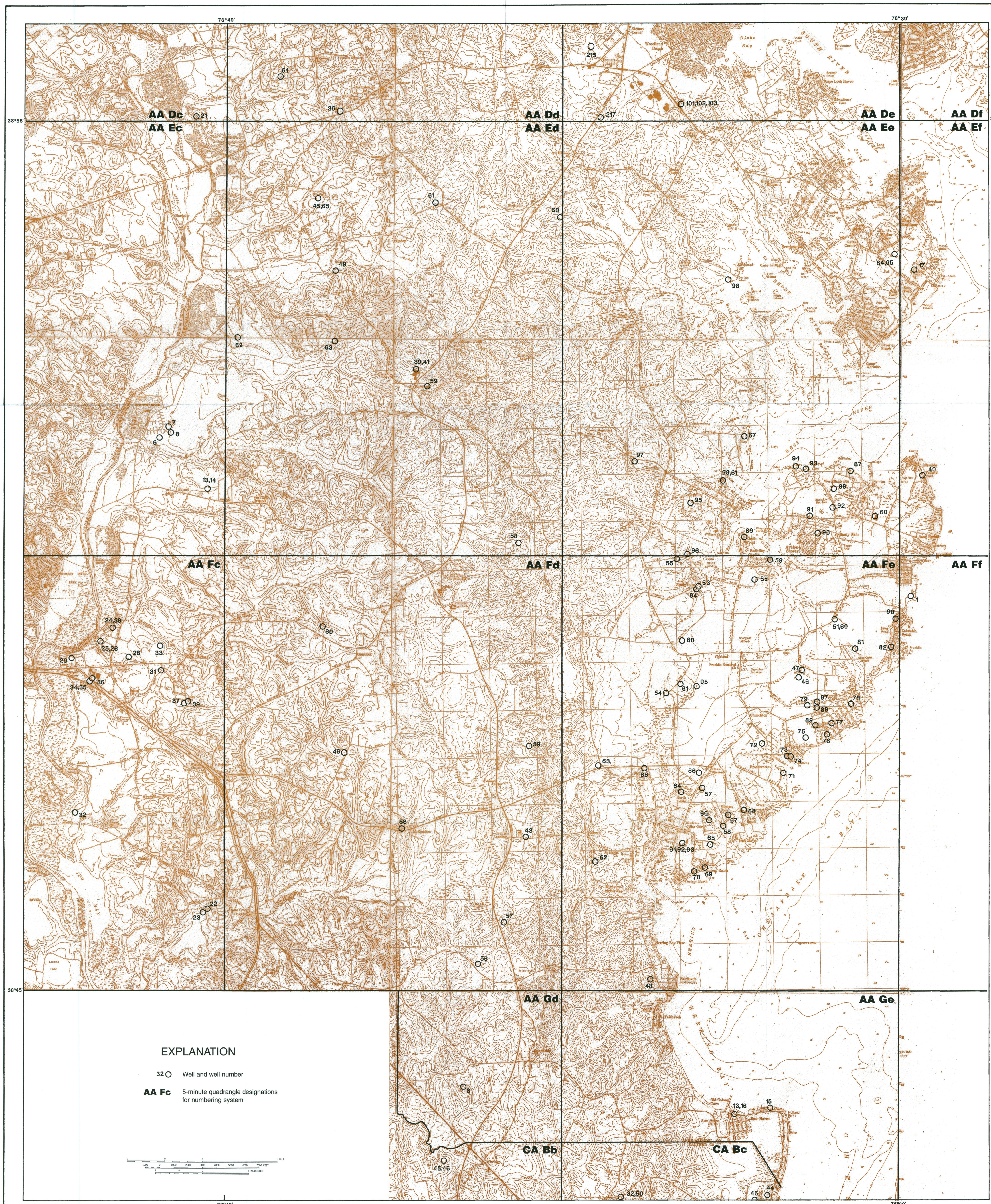

Base map from U.S. Geological Survey, 1:24,000 quadrangles

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