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

REPORT OF INVESTIGATIONS NO. 62

GEOHYDROLOGIC FRAMEWORK, GROUND-WATER QUALITY AND FLOW, AND BRACKISH-WATER INTRUSION IN EAST-CENTRAL ANNE ARUNDEL COUNTY, MARYLAND

by
William B. Fleck
and
David C. Andreasen

With a section on

SIMULATION OF BRACKISH-WATER INTRUSION IN THE AQUIA AQUIFER IN THE ANNAPOLIS AREA USING A SOLUTE-TRANSPORT MODEL

by
Barry S. Smith

Prepared in cooperation with the
United States Department of the Interior
Geological Survey
and
The Anne Arundel County
Office of Planning and Zoning

1996

CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

ENGLISH TO METRIC CONVERSION FACTORS

Multiply	by	To obtain
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
pound, avoirdupois (lb)	0.4536	kilogram
foot squared per day (ft^2/d)	0.09290	meter squared per day
square mile (mi^2)	2.590	square kilometer
gallon (gal)	3.785	liter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per day (ft/d)	0.3048	meter per day
inch per year (in/yr)	25.4	millimeter per year
million gallons per day (Mgal/d)	0.04381	cubic meter per second
cubic foot per day (ft^3/d)	0.02832	cubic meter per day
gallon per day (gal/d)	0.003785	cubic meter per day
gallon per minute (gal/min)	0.06309	liter per second
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter

Chemical concentrations are expressed in milligrams per liter (mg/L) or micrograms per liter (μg/L). Temperature in degrees Celsius (C) can be converted to degrees Fahrenheit (F) using the following linear equation:

$$F=1.8\ (C) + 32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929--a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Metric units are used in this report in reference to solute transport. Researchers generally find that the use of metric units facilitates simulation and understanding of solute transport in porous media. Inch-pound units are provided in addition to metric units where appropriate for readers unfamiliar with the metric system. Direct conversions to inch-pound units can also be made with the following table; however, some units in this report that express two-dimensional model values should not be converted directly into three-dimensional units. Such conversions are generally explained in more detail within the text.

METRIC TO ENGLISH CONVERSION FACTORS

Multiply	by	To obtain
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
kilogram (kg)	2.205	pound, avoirdupois (lb)
	0.0685	slug
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
cubic meter (m^3)	264.2	gallon (gal)
liter (l)	0.2642	gallon (gal)
meter per second (m/s)	3.281	foot per second (ft/s)
meter per year (m/yr)	39.37	inch per year (in/yr)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
cubic meter per day (m^3/d)	264.2	gallon per day (gal/d)
kilogram per cubic meter (kg/m^3)	0.00194	slug per cubic foot ($slug/ft^3$)
kilopascal (kPa)	0.1450	pound per square inch (lb/in^2)
kilogram per meter-second (kg/m-s)	67.2	pound per foot-second (lb/ft-s)
meter per square second (m/s^2)	3.281	foot per squared second (ft/s^2)
kilogram per second (kg/s)	2.205	pound per second (lb/s)
square meter per second (m^2/s)	10.76	square foot per second (ft^2/s)
pascal (Pa)	0.0001450	pound per square inch (lb/in^2)

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ABSTRACT

This report focuses on the results of a study of the geohydrology of the geologic section that stratigraphically includes the Patapsco, Magothy, Matawan, Severn, Aquia, and Talbot Formations in east-central Anne Arundel County, Maryland. The principal aquifers within this Coastal Plain sequence of Holocene to Cretaceous sediments are the Aquia, Magothy, and Upper Patapsco. Results of aquifer tests at the Quiet Waters Park test site indicate that the horizontal hydraulic conductivity and the specific storage for the Aquia aquifer are about 4 feet per day and 4 x 10^{-6} $foot^{-1}$, respectively. An average horizontal hydraulic conductivity of about 40 feet per day for the Magothy aquifer was calculated from specific-capacity measurements. The Upper Patapsco aquifer, which is about 200 to 300 feet thick, is equivalent to the uppermost sand unit in the Patapsco Formation.

Acidic precipitation that recharges the Aquia aquifer produces pH values as low as 4.4. This low-pH water, which also contains high dissolved-oxygen concentrations, reacts with the glauconitic and goethitic sand and weathered shell material of the Aquia aquifer to produce high dissolved iron and dissolved calcium and magnesium concentrations. The result is a calcium and magnesium bicarbonate-type water. The Magothy and Upper Patapsco aquifers lack significant quantities of shell material and, in contrast to the Aquia aquifer, contain an acidic iron sulfate-type water.

Brackish water that underlies freshwater within the Aquia and Monmouth aquifers wedges 200 to 500 feet inland along the shores of Annapolis Neck and the Mayo Peninsula. Four of eight test wells located along the shore and screened in the Aquia and Monmouth aquifers had chloride concentrations exceeding 5,900 milligrams per liter, indicating the presence of the brackish-water wedge. The nearshore brackish-water/freshwater interface is relatively sharp and steeply inclined; however, elevated chloride concentrations may indicate sources other than brackish-water intrusion. Three criteria were used to differentiate sources of elevated chloride concentrations: (1) the bromide:chloride ratio, (2) nitrogen concentrations, and (3) the theoretical location of the Ghyben-Herzberg interface. The water chemistry of the brackish-water wedge is affected by: (1) a chemically reducing, anoxic environment below the bottom of the Chesapeake Bay; (2) brackish-water dilution, and (3) cation exchange. These processes produce concentrations of iron and manganese as high as 240,000 and 2,500 micrograms per liter, respectively; increase concentrations of calcium, magnesium, sodium, potassium, and sulfate; and produce higher than predicted concentrations of calcium due to cation exchange with sodium.

A quasi-three-dimensional ground-water-flow model simulated hydraulic head changes for the transient time period 1900-90. The model, which simulated the water-table and the Aquia, Monmouth, Magothy, and Upper Patapsco aquifers, was calibrated by matching hydrographs of 176 observation wells with simulated water levels. Analyses of rates of ground-water flow indicated that water that recharges the Magothy aquifer where the aquifer crops out under Round Bay requires about 300 to 1,700 years to travel to the point of discharge in the Upper Patapsco aquifer at the Arnold well field.

A two-dimensional solute-transport model for the Quiet Waters Park test site on Annapolis Neck simulated hydraulic heads and dissolved-solids concentrations as measured in 1990. Simulated equilibrium with respect to the 1990 conditions was approached after 600 years. Simulation results indicate that a small difference in well-screen depth with respect to the interface of the brackish-water wedge makes a substantial difference in the freshwater life of a well. The extent of brackish-water intrusion is a function of the severity of the water-level declines in and near the site, which, in turn, is a function of the amount of freshwater diverted landward of the site and the proximity of pumped wells.

INTRODUCTION

Aquifers underlying shoreline areas of east-central Anne Arundel County, Maryland, are particularly vulnerable to brackish-water intrusion from the Chesapeake Bay and its tributaries. The Aquia and Monmouth aquifers in parts of the county where it crops out near the bay or its tributaries are pumped by domestic and small commercial users who presently are unserved by central water-supply systems. Although individually small, the cumulative effect of this pumpage has lowered water levels locally in the Aquia and Monmouth aquifers to near sea level from an estimated prepumping level of 5 or more feet above sea level.

The Magothy and Upper Patapsco aquifers are pumped by large and small users in parts of the county where the Magothy aquifer crops out near the bay or its estuaries. As a result, water levels in the Magothy aquifer as deep as 15 ft below sea level are present in, for example, the Broadneck area.

Reduction of water levels in shallow coastal aquifers can result in the landward intrusion of brackish water. Evidence is accumulating that this process is underway, both on Annapolis Neck and the Mayo Peninsula where chloride concentrations of as much as 1,000 mg/L have been reported. Increased pumpage from the Aquia aquifer in these areas could result in further intrusion of brackish water and could cause chloride concentrations over extensive areas to exceed the U.S. Environmental Protection Agency's (USEPA)(1986) Secondary Maximum Contaminant Level of 250 mg/L in drinking water.

PURPOSE AND SCOPE

The purpose of this report, which was prepared by the Maryland Geological Survey and the U.S. Geological Survey (USGS) in cooperation with the Anne Arundel County Office of Planning and Zoning, is to provide elected officials, government planners, business leaders, and individual citizens with information on the present extent and future potential of brackish-water intrusion into the ground-water-flow system of east-central Anne Arundel County. In this report, brackish water is defined as water having a dissolved-solids concentration of 1,000 to 10,000 mg/L. Freshwater is defined as water having a dissolved-solids concentration of less than 1,000 mg/L. Several ground-water samples had dissolved-solids concentrations above 10,000 mg/L. Water having a dissolved-solids concentration of 10,000 to 35,000 mg/L is classified as saltwater.

The first part of this report discusses the geologic and hydrologic aspects of the ground-water-flow system in the upper part of the unconsolidated sediments of east-central Anne Arundel County. This discussion includes the geology of the sedimentary sequence from the Patapsco Formation upward through the Talbot Formation. This section includes a series of maps and geohydrologic sections that indicate the area of outcrop and the altitude of the top of each sedimentary unit. A discussion of the hydrology deals with the distribution of aquifers and confining units, aquifer hydraulic properties, and the configurations and altitudes of potentiometric surfaces.

The middle part of this report deals with several aspects of ground water in the study area; it includes a discussion of the chemistry of ground water of the aquifers under natural conditions and under conditions in which the chemistry is affected by brackish-water intrusion. This part also includes a discussion of a digital ground-water-flow model that was constructed to simulate various pumpage alternatives.

The last section of the report deals with the subject of brackish-water intrusion; it includes discussion of the sources and the present distribution of chloride in the ground water. Also included is a discussion of a model used to simulate solute transport in ground water in an area near Annapolis, Maryland.

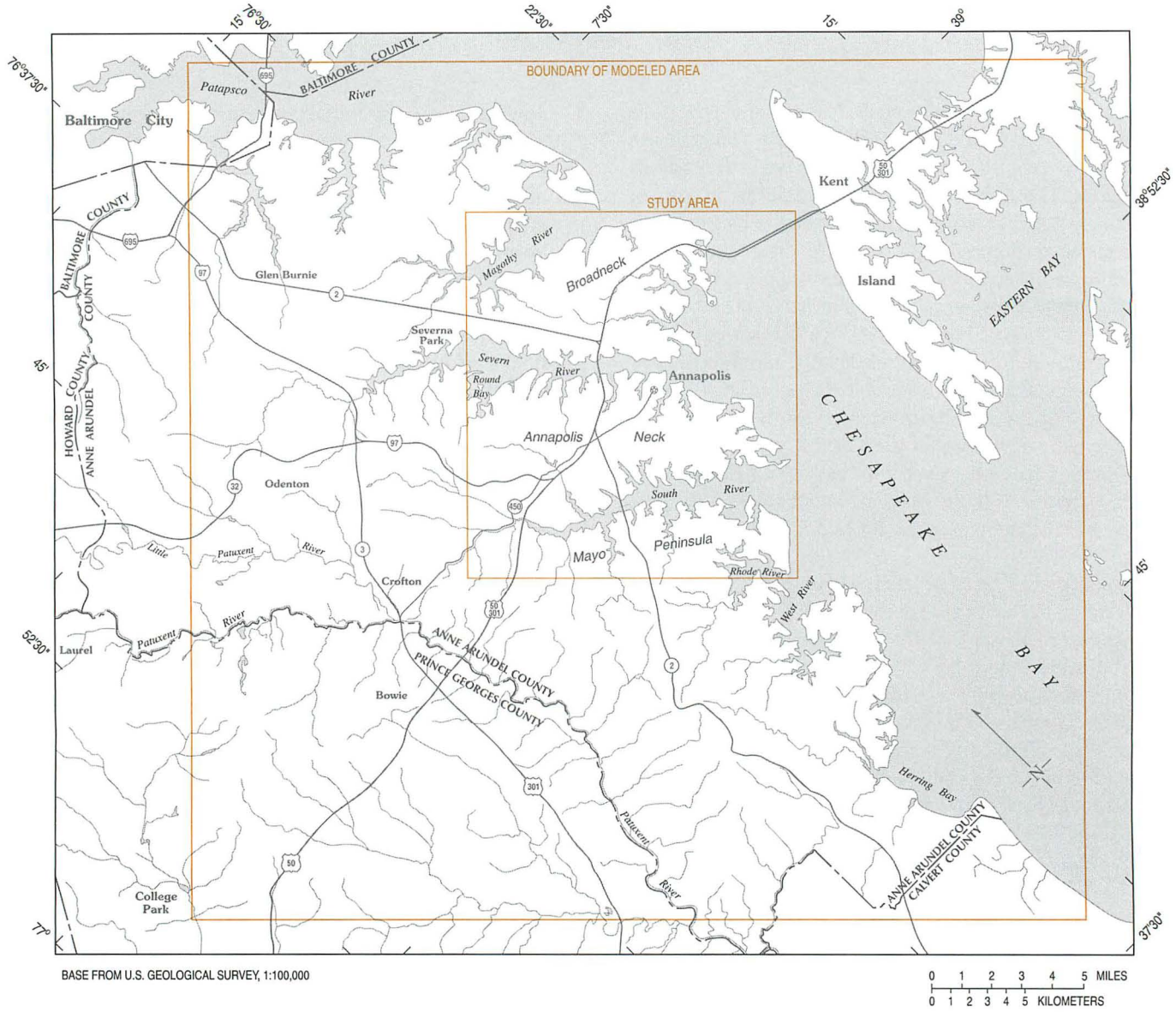
LOCATION OF STUDY AREA

The location of the study area, as indicated in figure 1, is the east-central part of Anne Arundel County. This area encompasses Broadneck, Annapolis Neck, and the Mayo Peninsula. The area within the model boundary (fig. 1) is considerably larger than the study area in order to simulate distant boundaries.

The study area is located wholly within the Atlantic Coastal Plain Physiographic Province. The Atlantic Coastal Plain is underlain by gently eastward dipping unconsolidated sediments of silt, clay, sand, and gravel. The age of these sediments ranges from Cretaceous to Holocene.

PREVIOUS INVESTIGATIONS

The geologic and hydrologic characteristics of the Coastal Plain sediments located in Anne Arundel County have been described in some detail by numerous authors. The early work of Darton (1896), Clark, Bibbins, and Berry (1911), and Clark, Mathews, and Berry (1918) described in detail the stratigraphy and the water resources of the sediments underlying the Maryland Coastal Plain. Otton (1955) authored a report that presented a general overview of the ground-water resources of southern Maryland, and Mack (1962), similarly, described the water resources of Anne Arundel County. Hansen (1968) correlated Cretaceous for-



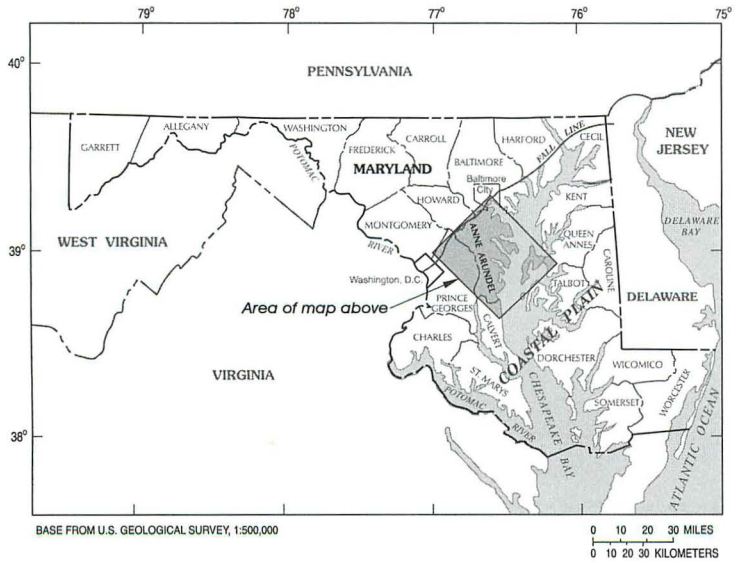


Figure 1. Location of study area and model boundary.

mations using a series of cross sections based on geophysical logs. The hydrologic properties of aquifers are discussed further by Hansen (1971, 1972). Reports using digital models to investigate the ground-water-flow system include Kapple and Hansen (1976), Mack and Mandle (1977), Chapelle (1985, 1986), Mack and Achmad (1986), Drummond (1988), Fleck and Wilson (1990), Achmad (1991), and Fleck and Vroblesky (1996). More recent studies of the geohydrologic framework include Vroblesky and Fleck (1991) and Mack and Andreasen (1991). Reports discussing the extent of water use include those by Wheeler and Wilde (1989) and Wheeler (1991).

METHODS OF INVESTIGATION

The principal thrust of the study was to refine the geohydrologic framework of the uppermost aquifers, to determine the extent of high chloride concentrations in the ground water, and finally, to use digital techniques to simulate potential effects of increased pumping on water levels and brackish-water intrusion within the ground-water-flow system. Initially, literature and unpublished data on file at the Maryland Geological Survey and the U.S. Geological Survey were reviewed to obtain information concerning geologic, hydrologic, and geochemical characteristics of the sediments underlying the study area.

The data-collection phase of the study lasted from October 1987 to November 1990. Under private contract with Branham Contractors, Inc. of Pasadena, Maryland, a total of 18 test wells were drilled between 1988 and 1989. A second contract with the Maryland Water Resources Administration (WRA) resulted in the completion of another eight test wells between 1989 and 1990. To aid in determining hydraulic and geohydrologic properties, well cuttings were collected, geophysical logs were obtained, and pumping tests were conducted at each test well. The suite of geophysical logs included gamma and single- and multi-point electric types. These logs were used to define the vertical extent of the aquifers and confining units and to define zones of brackish water. The pumping tests were used to determine transmissivities and, where possible, storativities. Also during each of the pumping tests, ground-water samples were collected for both onsite and laboratory analyses of selected chemical constituents.

Part of the work done by the WRA included five test wells drilled at Quiet Waters Park in 1990. This group of wells was drilled along a transect extending from Harness Creek inland a distance of about 300 ft. Geophysical logs collected from these five test wells help define the inward-sloping interface between freshwater and brackish water underlying the study area. Pumping tests provided information on hydraulic properties of the Brightseat confining unit as well as the Aquia and Monmouth aquifers.

Data collection included a well inventory and collection of water samples for analysis of chloride concentrations for 106 wells. A network of 105 wells were surveyed to determine the altitude of water levels related to sea level. Synoptic water-level and chloride-concentration measurements were made in 80 and 75 of the network wells, respectively, during the fall of 1988 and the spring of 1989. Continuous water-level recorders were installed on 15 test wells. These recorders were maintained for about 1 year from September 1989 through September 1990. The data collected from the inventory were entered into the U.S. Geological Survey's Ground-Water Site Inventory (GWSI) data base. Locations of these wells are shown on plate 1.

Two digital models were constructed. One model was a representation of the ground-water-flow system within the sediments underlying the study area down to and including the Upper Patapsco aquifer. A series of potentiometric-surface and structural maps were constructed and used to define input data sets for the model. The model was calibrated to transient conditions for 1900-90. Hydrographs of 52 wells screened in the Aquia aquifer, 75 wells screened in the Magothy aquifer, and 47 wells screened in the Upper Patapsco aquifer were compared to model results. A second model was constructed to simulate conditions at Quiet Waters Park. This was a cross-sectional, two-dimensional, solute-transport model that was calibrated to the measured chloride concentrations in water from the five test wells.

WELL-NUMBERING SYSTEM

Wells in this report are numbered according to a numbering system established by the Maryland Geological Survey. The first two letters of the well number are the county prefix (for example, AA for Anne Arundel County). The second part of the well number consists of two letters that designate a 5-minute quadrangle within the county; the first letter (a capital letter) 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 wells are numbered sequentially within each 5-minute quadrangle.

ACKNOWLEDGMENTS

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the staff of the Maryland Geological Survey and in particular special thanks to both Fred Mack and Harry Hansen for sharing their extensive understanding of the hydrology and geology of the area. Core samples were analyzed for microfossils by Gilbert J. Brenner, State University of New York, at New Paltz.

GEOHYDROLOGIC FRAMEWORK

REGIONAL SETTING

Anne Arundel County is located within Maryland's Coastal Plain Physiographic Province—a relatively flat, low-lying plain extending eastward from the Fall Line or line of contact with the consolidated rocks of the Piedmont Province (fig. 1). Sediments within the Coastal Plain Province form a thick wedge of interstratified layers of chiefly unconsolidated sand, gravel, silt, and clay. These sediments extend beneath the Atlantic Ocean and form part of the Continental Shelf. During geologic time, changes in sea level created a variety of sedimentary environments that resulted in deposits of varying lithology and thickness. These sedimentary environments include nonmarine (fluvio-deltaic), fluviomarine, and marine. The age of the sediments range from Early Cretaceous to Holocene. The Coastal Plain sediments increase in thickness from the Fall Line eastward. At Ocean City, Maryland, the total sediment thickness exceeds 7,700 ft (Hansen and Edwards, 1986). In Anne Arundel County, the Coastal Plain sediments range in thickness from a few tens of feet in the northern part of the county to more than 2,500 ft in the southern part (Mack and Andreasen, 1991). Beds are generally planar and dip gently to the southeast at about 40 ft/mi.

The Coastal Plain sediments lie unconformably on a basement rock complex, which consists of consolidated rocks such as shale, sandstone, gneiss, and granite. The age of the basement rocks ranges from Precambrian to Triassic.

GEOLOGY

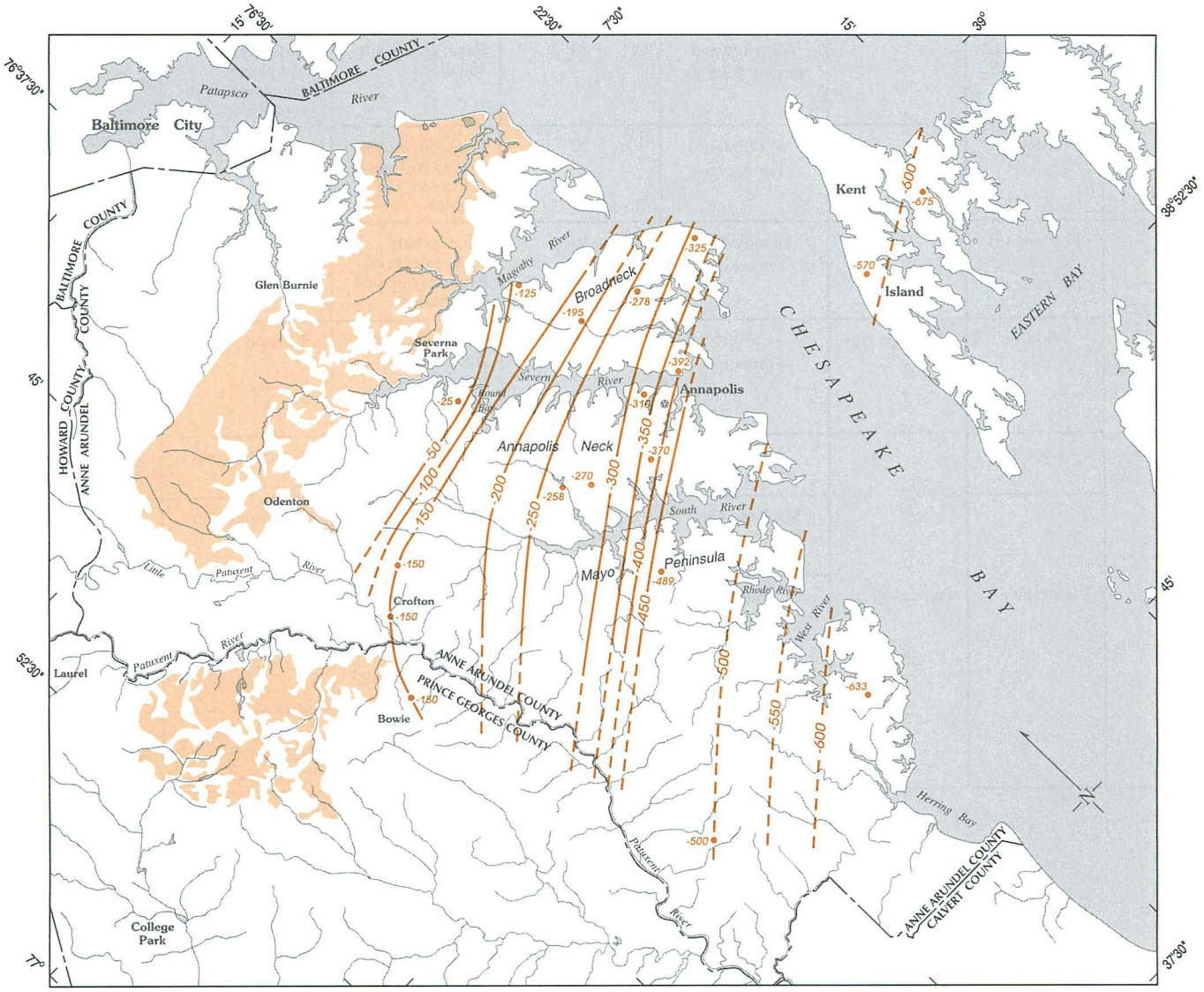
The geologic formations in the Coastal Plain of Anne Arundel County are shown on a stratigraphic section (table 1). The geologic units discussed in this report include the Patapsco, Magothy, Matawan, and Severn Formations of Cretaceous age; the Brightseat, Aquia, Marlboro Clay, Nanjemoy and Calvert Formations of Tertiary age ; and the Talbot Formation of Pleistocene age. A series of cross sections (pls. 2, 3, and 4) were drawn to define more clearly the geologic and geohydrologic framework within the study area. Geophysical and lithologic logs were used to identify formation and aquifer boundaries. Descriptive lithologic logs from wells drilled during this study are given in appendix E. In some cases, microfossils were used to date formations and to help identify geologic contacts. Selected palynological analyses (plant microfossils) are given in appendix F. Maps showing depth to top of aquifers and confining units were also prepared. These maps are shown in figures 2 - 7. Depths to top of aquifers and confining units correspond to depths to top of formations on all maps except the map of the Upper Patapsco aquifer (fig. 2).

Patapsco Formation

The Patapsco Formation of Early Cretaceous age is the oldest unit discussed in this report. In Anne Arundel County, the Patapsco Formation crops out as an irregular band in the northern part of the county (Glaser, 1976). This formation is a fluvio-deltaic deposit consisting of medium- to coarse-grained sand and dense, mottled clay. Thin beds of gravel and siderite-cemented sandstone also are present. Fining-upward sequences of sand, silt, and clay are typical of the Patapsco Formation. This depositional pattern was created by a network of laterally migrating river channels. Individual sand, silt, or clay layers are generally less than 10 to 20 ft thick but can be as much as 200 ft thick. A distinguishing characteristic of these sediments is the discontinuous nature of individual layers. It is quite common for a particular layer, present in one well, to be absent in an adjacent well only tens of feet away. This characteristic makes correlating individual layers difficult, even on a local scale.

The areal distribution of sand and clay in the Patapsco Formation, as in the entire Potomac Group, suggests that the axial portion of a fluvio-deltaic system occurred in the vicinity of Baltimore City (Hansen, 1971). As a result, thick, permeable sand beds were deposited in northern and central Anne Arundel County. North and south of the Anne Arundel County-Baltimore City area, fringing deltaic marshes and swamps dominate, causing Patapsco Formation sand percentages to decrease in these areas (Hansen, 1971).

Geohydrologic section A-A′ (pl. 2) extends downdip from well AA Bd 98, near Glen Burnie, to well AA Cg 22, at Sandy Point State Park. In this section the upper part of the Patapsco Formation (equivalent to the Upper Patapsco aquifer) crops out between Glen Burnie and Severndale (well AA Ce 117). Most of the Patapsco Formation in this section consists of medium- to coarse-grained sand. At well AA Bd 98, nearly the entire thickness (about 220 ft) of the Patapsco Formation is composed of sand, with the exception of a thin clay layer occurring near the surface. The thickness of this clay layer increases downdip and divides the Patapsco Formation into two distinct sand layers.



BASE FROM U.S. GEOLOGICAL SURVEY, 1:100,000

0 1 2 3 4 5 MILES
0 1 2 3 4 5 KILOMETERS

EXPLANATION

GENERALIZED OUTCROP AREA OF THE UPPER PATAPSCO AQUIFER -- Modified from Glaser (1976), Cooke and Cloos (1951).

-50 LINE OF EQUAL ALTITUDE OF THE TOP OF THE AQUIFER -- Dashed where approximately located. Interval 50 feet. Datum is sea level.

-270 WELL-DATA POINT -- Number is altitude of the top of the aquifer in feet. Datum is sea level.

Figure 2. Location of outcrop area and altitude of the top of the Upper Patapsco aquifer.

Table 1. Generalized stratigraphic, lithologic, and hydrologic characteristics of geologic formations underlying Anne Arundel County, Maryland (modified from Mack and Andreasen, 1991, table 1)

SYSTEM	SERIES	GROUP	FORMATION	AVERAGE THICKNESS (FEET)	GENERAL LITHOLOGY	HYDROLOGIC CHARACTER	GEOHYDRO-LOGIC UNIT
Quaternary	Holocene and Pleistocene		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	Pliocene (?) or Miocene (?)		Brandywine Formation	30	Sand, pebbly sand, and gravel; extremely limited distribution.	Aquifer	Not recognized
	Miocene	Chesapeake	Calvert Formation	75	Sandy clay and fine sand, fossiliferous, diatomaceous earth.	Limited aquifer	Not recognized
	Eocene	Pamunkey	Nanjemoy Formation	50	Glauconitic sand, silt, and clay.	Confining unit	Not recognized
	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	Brightseat confining unit

Magothy Formation

The Magothy Formation of Late Cretaceous age rests unconformably on the Patapsco Formation and marks the start of the first major sea-level rise associated with Maryland's inner Coastal Plain stratigraphy. The Magothy Formation is a fluviomarine deposit consisting of medium-to-coarse sand and black-to-gray, lignitic clay. Thick beds of lignite are common. Pyrite, associated with lignite, commonly occurs throughout the Magothy Formation.

A major regional unconformity marks the contact between the Patapsco Formation and the overlying Magothy Formation. Because the contact may occur between sand beds, it is difficult to determine accurately using only geophysical logs or driller's logs. Representative drill cuttings (or cores) are needed. Often in the past the base of the Magothy Formation was defined by the first occurrence of a reddish, mottled clay. However, this method results in lumping the uppermost Patapsco sand into the Magothy Formation and places the contact too low in some areas. The thickness of the Magothy Formation on section A-A′ (pl. 2) is relatively uniform at about 90 ft. On Broadneck, the formation is composed chiefly of sand, with an intervening, discontinuous clay layer approximately 20 ft thick. Geohydrologic section B-B′ (pl. 3) shows a general thickening of the formation from the Magothy River toward Shadyside. The thickness of the formation at the northern end of the section (well AA Ce 126) is about 80 ft, whereas at Shadyside (well AA Fe 47) the thickness is about 200 ft. The base of the formation at Shadyside is about 600 ft deep.

Matawan Formation

The Matawan Formation of Late Cretaceous age rests on the Magothy Formation. The contact is typically marked by an abrupt change of lithology from a medium-to-coarse, white and gray sand of the Magothy Formation, to a dark-green to black, glauconitic and slightly micaceous, tough clay of the Matawan Formation. The Matawan Formation

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

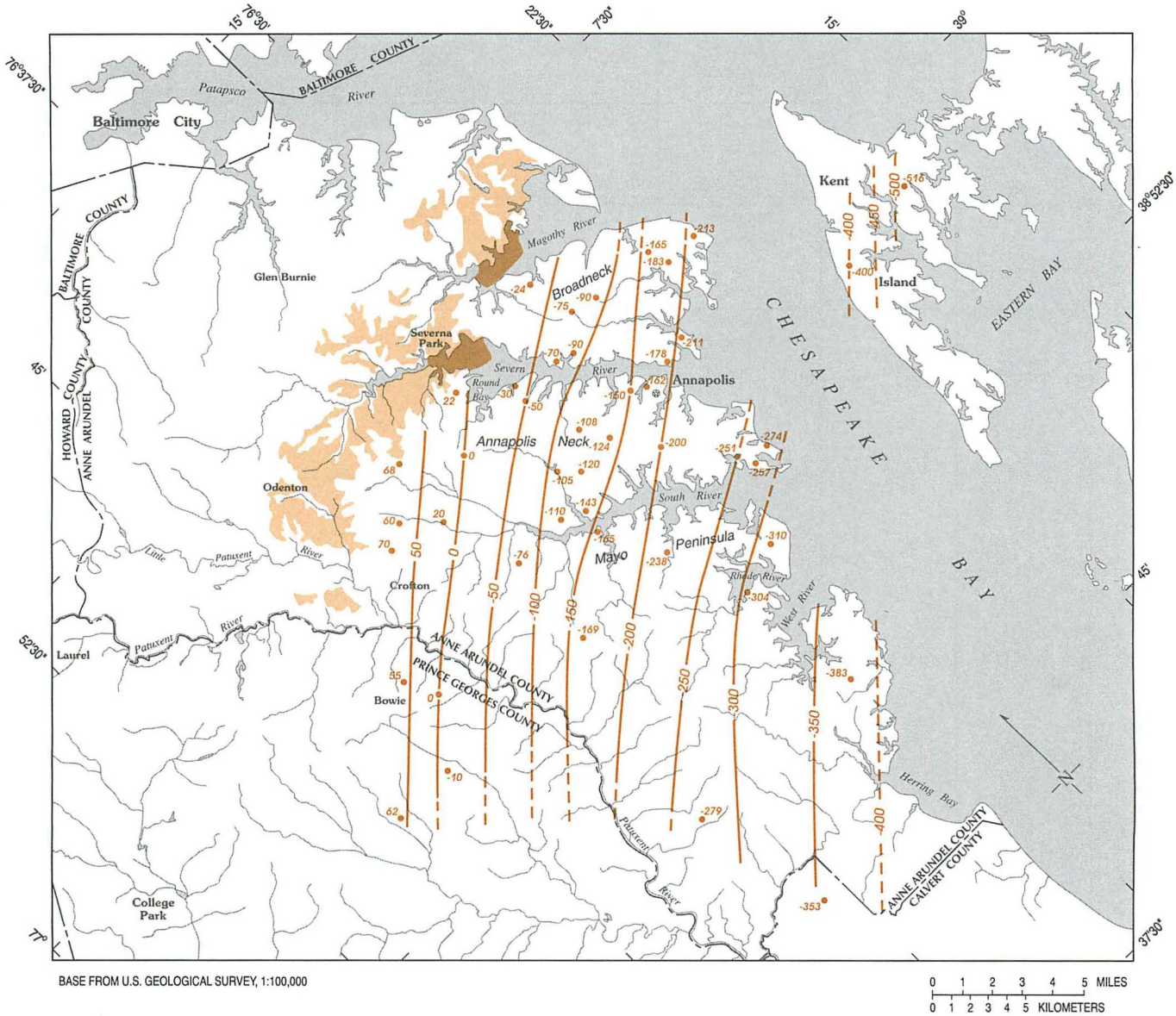
SYSTEM	SERIES	GROUP	FORMATION	AVERAGE THICKNESS (FEET)	GENERAL LITHOLOGY	HYDROLOGIC CHARACTER	GEOHYDRO-LOGIC UNIT
Cretaceous	Upper Cretaceous		Severn Formation	45	Sand, silty to fine, with some glauconite.	Limited aquifer	Monmouth aquifer
			Matawan Formation	60	Silt and fine sand, clayey, dark-green to black, glauconitic.	Confining unit	Matawan confining unit
			Magothy Formation	120	Sand, light-gray to white, with interbedded thin layers of organic black clay.	Aquifer	Magothy aquifer
	Lower Cretaceous	Potomac	Patapsco Formation	25	Clay, tough, variegated.	Confining unit	Confining unit
				750	Sand, fine to coarse, brown, and tough, variegated clay.	Multiple-layer aquifer	Upper Patapsco aquifer
					Clay, tough, variegated.	Confining unit	Confining unit
					Sand, fine to coarse, brown, and tough variegated clay.	Multiple-layer Aquifer	Lower Patapsco aquifer
			Arundel Clay	250	Clay, red, brown, and gray, contains some ironstone nodules, plant remains, and thin sandy layers.	Confining unit	Arundel confining unit
			Patuxent Formation	300	Sand, gray and yellow, with interbedded clay; kaolinized feldspar, pyrite, and lignite common; locally clay layers predominate.	Multiple-layer aquifer	Patuxent aquifer
Triassic (?) and/or Paleozoic (?) to Precambrian			Basement complex	Unknown	Shale, sandstone, gneiss, or granite.	Confining unit	Not recognized

marks the first occurrence of glauconite in inner Coastal Plain sediments. Within the study area the Matawan Formation is a marine deposit consisting of two glauconitic clay layers (as much as 30 ft thick) and separated by silty, dark-green, glauconitic quartz sand.

The top of the Matawan Formation (equivalent to the Matawan confining unit in plate 3) approaches 500 ft below sea level in the northeast corner of Calvert County. On Annapolis Neck and the Mayo Peninsula, the top of the Matawan Formation ranges from near sea level to more than 200 ft below sea level (pls. 3 and 4). The dip of the formation ranges from 20 to 50 ft/mi except in a 3-mi-wide band trending in a northeast direction across the Mayo Peninsula and Annapolis Neck. In that area the dip decreases to about 14 ft/mi.

Severn Formation

The Severn Formation of Late Cretaceous age rests disconformably on the Matawan Formation. The depositional environment of the Severn Formation is mostly inner shelf (Minard, 1980). The name Severn Formation was suggested by Minard, Sohl, and Owens (1977) for beds previously designated as the Monmouth Formation on the western shore



EXPLANATION

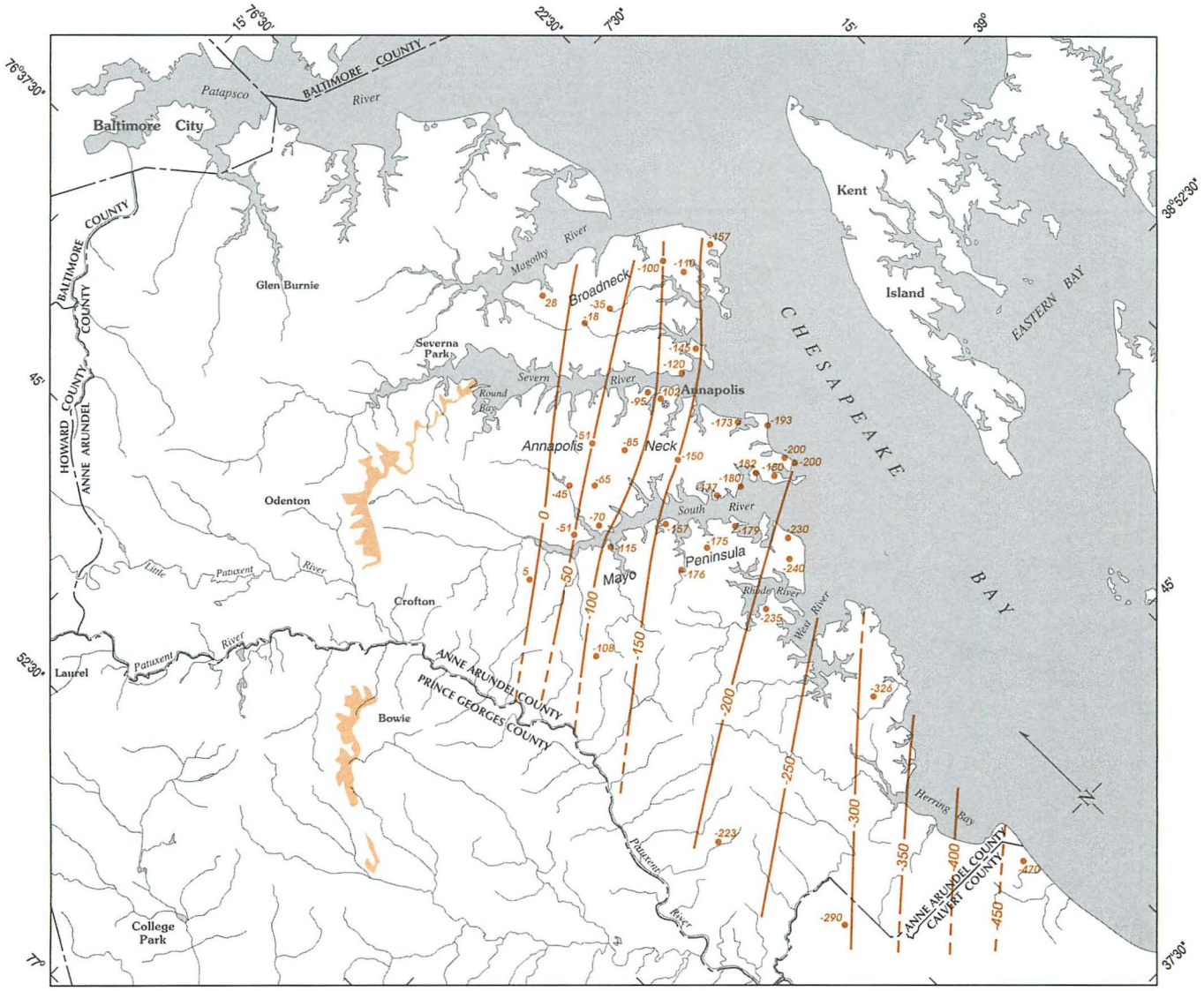
GENERALIZED OUTCROP AREA OF THE MAGOTHY AQUIFER -- Modified from Glaser (1976).

SUBCROP AREA OF THE MAGOTHY AQUIFER BENEATH THE MAGOTHY AND SEVERN RIVERS.

-50 LINE OF EQUAL ALTITUDE OF THE TOP OF THE AQUIFER -- Dashed where approximately located. Interval 50 feet. Datum is sea level.

-200 WELL-DATA POINT -- Number is altitude of the top of the aquifer in feet. Datum is sea level.

Figure 3. Location of outcrop area and altitude of the top of the Magothy aquifer.



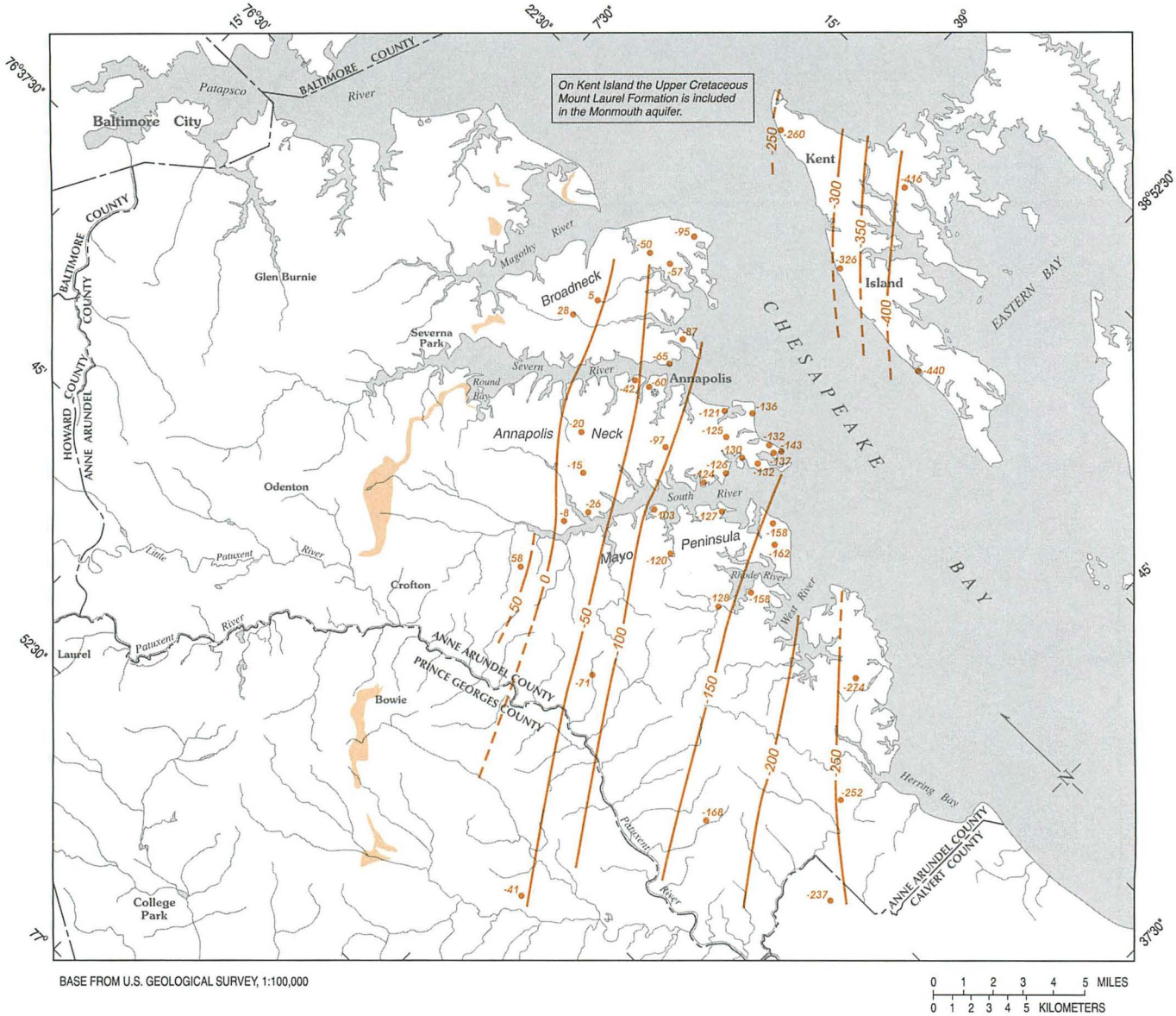
EXPLANATION

GENERALIZED OUTCROP AREA OF THE MATAWAN CONFINING UNIT -- Modified from Glaser (1976), Cooke and Cloos (1951).

-50 LINE OF EQUAL ALTITUDE OF THE TOP OF THE CONFINING UNIT -- Dashed where approximately located. Interval 50 feet. Datum is sea level.

-240 WELL-DATA POINT -- Number is altitude of the top of the confining unit in feet. Datum is sea level.

Figure 4. Location of outcrop area and altitude of the top of the Matawan confining unit.



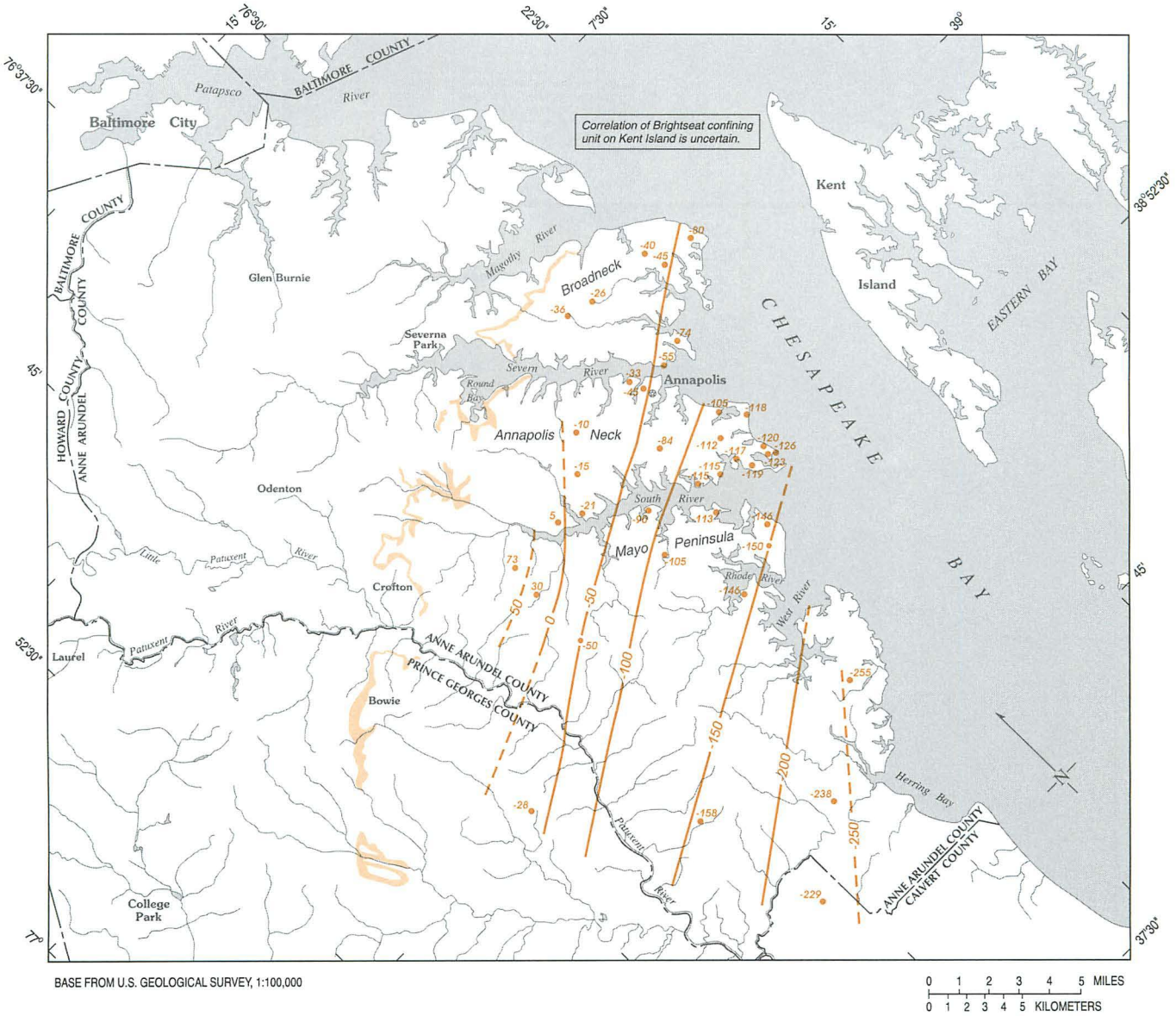
EXPLANATION

GENERALIZED OUTCROP AREA OF THE MONMOUTH AQUIFER -- Modified from Glaser (1976), Cooke and Cloos (1951).

-50 LINE OF EQUAL ALTITUDE OF THE TOP OF THE AQUIFER -- Dashed where approximately located. Interval 50 feet. Datum is sea level.

-120 WELL-DATA POINT -- Number is altitude of the top of the aquifer in feet. Datum is sea level.

Figure 5. Location of outcrop area and altitude of the top of the Monmouth aquifer.



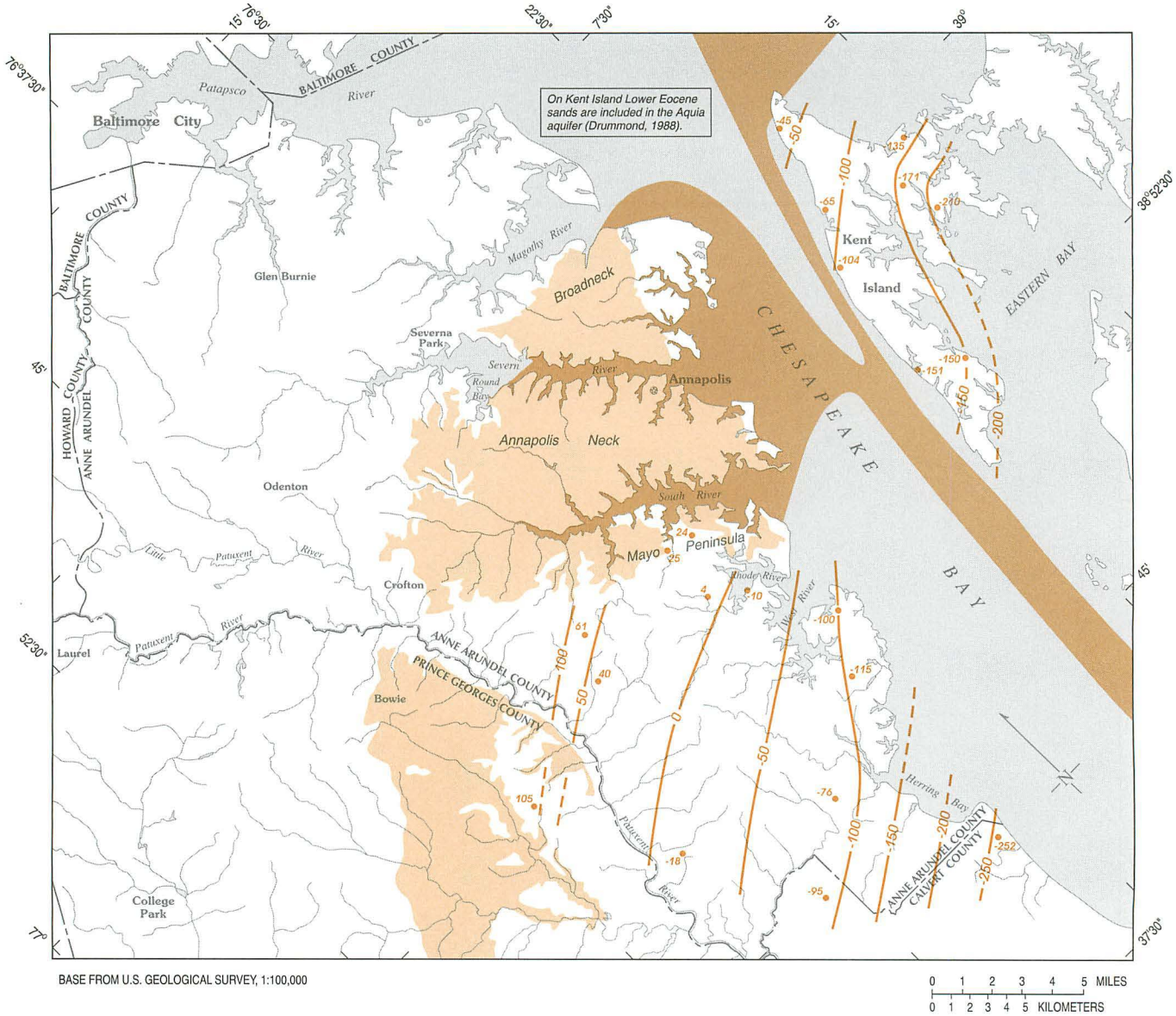
EXPLANATION

GENERALIZED OUTCROP AREA OF THE BRIGHTSEAT CONFINING UNIT -- Modified from Glaser (1976), Cooke and Cloos (1951).

-50 LINE OF EQUAL ALTITUDE OF THE TOP OF THE CONFINING UNIT -- Dashed where approximately located. Interval 50 feet. Datum is sea level.

-150 WELL-DATA POINT -- Number is altitude of the top of the confining unit in feet. Datum is sea level.

Figure 6. Location of outcrop area and altitude of the top of the Brightseat confining unit.



EXPLANATION

GENERALIZED OUTCROP AREA OF THE AQUIA AQUIFER -- Modified from Glaser (1976), Cooke and Cloos (1951).

SUBCROP AREA OF THE AQUIA AQUIFER BENEATH THE CHESAPEAKE BAY AND ITS TRIBUTARIES -- Modified from Chapelle and Drummond (1983).

-50 LINE OF EQUAL ALTITUDE OF THE TOP OF THE AQUIFER -- Dashed where approximately located. Interval 50 feet. Datum is sea level.

-115 WELL-DATA POINT -- Number is altitude of the top of the aquifer in feet. Datum is sea level.

Figure 7. Location of outcrop area and altitude of the top of the Aquia aquifer.

of the Chesapeake Bay and for correlative units on the Eastern Shore. The type locality for the Severn Formation is designated as the east bank of the Severn River at Round Bay (Minard, 1980). The lithology at that location is described by Minard (1980) as a dark- to medium-gray, clayey and silty, poorly sorted, mostly fine- to medium-grained, sparsely glauconitic quartz sand with an admixture of very fine and coarse to very coarse quartz grains and granules. Minard (1980) also indicates colorless mica and carbonaceous matter. The Severn Formation in the subsurface is primarily a silty, glauconitic quartz sand that grades upward to a fine-grained sand. Glauconite in the Severn Formation is generally unweathered (dark-green to black) and more abundant than it is in the overlying Aquia Formation; however, this might be attributed in part to a reduction in glauconite content in the Aquia Formation by weathering. Thin lenses of light-gray clay appear throughout the formation. The Severn Formation contains moderate amounts of weathered shell material and thin, hard, indurated layers.

The Severn Formation was identified by palynological age dating of a core sample from 102 ft below sea level at well AA De 100 (sections E-E′ and G-G′; pl. 4). The thickness of the Severn Formation is generally about 45 ft; however, the formation thins updip to about 25 ft (section G-G′; pl. 4).

Brightseat Formation

Above the Severn Formation lies the Brightseat Formation of Early Paleocene age. The outcropping Brightseat Formation in the Round Bay area is a dark-gray, silty and clayey, fine, quartz sand (Minard, 1980). The subtle changes in lithology among the Severn, Brightseat, and Aquia Formations make it virtually impossible to identify the relatively thin Brightseat Formation in the subsurface based solely on descriptions of drill cuttings. However, the Brightseat Formation often is identifiable on gamma-radiation logs as a subdued clay deflection.

Palynological age dating of cores identified the Brightseat Formation at wells AA De 100 (Mack, 1974), 144, 155, and 159 (appendix F). The location of these analyses are shown on geohydrologic sections E-E′ and G-G′ (pl. 4).

Hydrogeologic sections C-C′ to G-G′ (pl. 4) show the distribution of the Brightseat Formation (equivalent to the Brightseat confining unit) on Annapolis Neck and the Mayo Peninsula. On these sections the Brightseat Formation is generally well defined with the exception of the northwestern part of the Mayo Peninsula (sections E-E′ and F-F′) and at well AA Df 79 (section E-E′).

The top of the Brightseat Formation (fig. 6) slopes from an altitude of 75 ft above sea level near the area of outcrop to more than 250 ft below sea level at Shadyside. The dip of the formation ranges from about 15 to 30 ft/mi in Anne Arundel County. Correlation of the Brightseat Formation on Kent Island is uncertain.

Aquia Formation

The Aquia Formation of Late Paleocene age rests on the Brightseat Formation. This formation crops out over much of Broadneck, Annapolis Neck, and the Mayo Peninsula (Clark, 1916). The total thickness of the Aquia Formation exposed in bluffs along the Severn River at Round Bay is about 105 ft (Minard, 1980). On Annapolis Neck and the Mayo Peninsula, the thickness of the Aquia Formation ranges from about 100 to 135 ft (section C-C′; pl. 4). The base of the formation ranges from about sea level, near the Annapolis Shopping Mall (well AA De 113, section G-G′), to about 125 ft below sea level, at the southern end of the Mayo Peninsula (well AA Ef 29, section G-G′, pl. 4).

An 11-inch-long core sample from the Aquia Formation was collected at well AA De 200 (Quiet Waters Park, pl. 5). The sample consisted of a silty, micaceous, dark-green clay. Palynological analysis of the core identified two species that range in age no earlier than Late Paleocene (appendix F.).

The Aquia Formation probably was deposited in an inner-shelf to nearshore depositional environment (Minard, 1980). The lithology consists of medium- to coarse-grained, glauconitic quartz sand interbedded with thin layers of silt and limonite- or siderite(?)-cemented sandstone. Hard beds of calcareous sandstone are also common. The glauconite content is less than in the Severn and Brightseat Formations. Coloration of the sediment varies from dark green (unweathered) to reddish brown (weathered). Irregular bands of weathered strata, consisting of iron-stained quartz grains and glauconite altered to limonite and goethite(?), occur throughout the Aquia Formation. Hansen (1974) determined that the amount of goethite, as a percentage of goethite plus glauconite, exceeds 25 percent in southeast Anne Arundel County. In some layers, intense weathering has formed a loose, crusty material, probably consisting of iron hydroxide ($Fe(OH)_3$). These layers typically form along contacts separating permeable sediments from less-permeable sediments. Weathered horizons do not seem to correspond to any particular stratigraphic position; however, the upper part of the Aquia Formation is generally more weathered than the lower part. Oxidized zones occur both above and below the present-day water table.

The Aquia Formation is typically very fossiliferous, with calcareous shell material (calcium and magnesium carbonate) comprising as much as 20 percent of the aquifer material in southern Maryland (Chapelle and Drummond, 1983). In the study area, however, most of the fossil material has been leached out by acidic recharge water from precipitation. A white, chalky, calcareous silt was commonly observed in the drill cuttings from the Aquia Formation, as was cal-

careous sandstone. Both materials effervesced in a dilute hydrochloric acid solution. Deposits of calcareous silt and sandstone are generally more abundant in deeper, less weathered sections of the formation. This could be caused by downgradient transport of calcium, magnesium, and bicarbonate ions (products of shell dissolution) by ground-water flow. Calcite-cemented beds tend to form along bedding planes, similar to iron-cemented layers.

Marlboro Clay and Nanjemoy and Calvert Formations

South of the Mayo Peninsula, in Anne Arundel County and northern Calvert County, the Aquia Formation is overlain by, in successive order, the Upper Paleocene Marlboro Clay, the Eocene Nanjemoy Formation, and the Miocene Calvert Formation. The Calvert and part of the Nanjemoy Formations are eroded away in the areas of lower topographic relief. The Marlboro Clay, an estuarine to marine deposit, consists of tough, pink to silvery gray clay. The formation is relatively thin (generally less than 20 ft), yet laterally extensive, occurring throughout southern Maryland and in parts of adjacent Virginia (Darton, 1951).

The Nanjemoy and Calvert Formations are marine deposits primarily composed of silty sand and clay. Glaser (1976) describes the lithology of the Nanjemoy in the outcrop as a glauconitic sand, silt, and silty clay with interbedded layers of dark-gray, silty clay. The lithology of the Calvert Formation in the outcrop consists of fine-grained sand, silt, and diatomaceous silt (Glaser, 1976). The Nanjemoy and Calvert Formations are shown on section B-B′ (pl. 3) south of Shadyside and on section D-D′ (pl. 4).

Talbot Formation

The Aquia Formation on Annapolis Neck and the Mayo Peninsula is irregularly capped by Pleistocene-age deposits, most notably the Talbot Formation (Clark, 1916). The Talbot Formation, occurring almost entirely above sea level, is predominantly a silty, brown and gray clay with interbedded glauconitic sand. Pebbly sand or gravel and organic-rich beds are also common (Glaser, 1976). The formation was deposited in both estuarine and fluvial sedimentary environments. The thickness of the formation ranges from a thin veneer to as much as 35 ft (pl. 4).

HYDROLOGY

Geologic conditions play a major role in the presence and movement of water in the subsurface. The quantity of water stored in the sediments and the ability to transmit water are dependent primarily on the effective porosity and permeability of the sediments, respectively. Other important factors include sediment thickness and areal extent, surface-water and ground-water interactions, and ground-water-flow boundaries. Sand and gravel layers are relatively permeable and thus are capable of transmitting water. In contrast, clay and silt layers are relatively impermeable and tend to impede the flow of water; however, clay layers are capable of storing substantial quantities of water that, under suitable hydraulic conditions, can be important sources of recharge to aquifers. Saturated layers of sand and gravel that yield sufficient quantities of water to wells are called aquifers. Clay and silt layers form less-permeable boundaries to ground-water flow and are called confining units. Collectively, aquifers and confining units are termed geohydrologic units. The boundaries of geohydrologic units typically, but not necessarily, coincide with geologic formational boundaries. The geohydrologic units discussed in this report include the Aquia, Monmouth, Magothy, and Upper Patapsco aquifers, and the Talbot, Marlboro, Brightseat, Matawan, and Upper Patapsco confining units. The hydrology of the Calvert and Nanjemoy Formations are briefly discussed. The average thickness, general lithology, and hydrologic character of the geologic formations are given in table 1.

Distribution of Aquifers and Confining Units

The Talbot confining unit rests irregularly on the Aquia aquifer on Annapolis Neck and the Mayo Peninsula. The upper part of the unit, consisting chiefly of silt, clay, and peaty layers, forms a confining layer. Geohydrologic sections B-B′ (pl. 3) and C-C′ through G-G′ (pl. 4) indicate the location of the Talbot confining unit. The Talbot confining unit overlies a relatively small area of the Aquia aquifer on Annapolis Neck and the Mayo Peninsula (Glaser, 1976). In areas where the Aquia aquifer is overlain by the Talbot confining unit, recharge to the aquifer from precipitation could be substantially less.

The Marlboro Clay consists of plastic, dense clay and forms a confining unit in the southern part of the study area (pl. 3). In areas south of the West River, where the unit lies beneath the bottom of the Chesapeake Bay, the Marlboro confining unit effectively seals the Aquia aquifer from brackish-water intrusion.

The Aquia aquifer in this report is defined as the water-yielding part of the Aquia Formation. The Aquia aquifer crops out on Broadneck, Annapolis Neck, and the Mayo Peninsula. The Aquia aquifer is unconfined in the central part of Broadneck, on Annapolis Neck, and along the South River on the Mayo Peninsula. South of the Mayo Peninsula the aquifer is confined. The lower boundary of the aquifer is the Brightseat Formation, a leaky confining unit, which allows water to flow between the Aquia aquifer and the underlying Monmouth aquifer. Because of this hydraulic interconnection, the Aquia aquifer in southern Maryland has commonly included sand of the Severn Formation. On a re-

gional scale this hydrologic definition may be adequate; however, to evaluate the effects of the less-permeable Brightseat confining unit on ground-water flow and brackish-water intrusion in the study area, the units have been separated in this report.

The top of the Aquia aquifer (fig. 7) slopes from about 100 ft above sea level in the topographically high areas of central Anne Arundel and Prince Georges Counties to more than 250 ft below sea level in the northeast corner of Calvert County. The aquifer subcrops beneath the South and Severn Rivers and beneath Chesapeake Bay between the Annapolis area and Kent Island. The full thickness of the Aquia aquifer in Anne Arundel County and in the extreme northern part of Calvert County averages about 130 ft (sections B-B′, C-C′, D-D′, and E-E′, pls. 3 and 4). On Kent Island, however, the aquifer thickness is much greater (about 225 ft) because it includes an overlying lower Eocene sand as well as the underlying Lower Paleocene Hornerstown Formation (Drummond, 1988); the typical clayey facies of the Marlboro confining unit is absent beneath Kent Island.

The Brightseat Formation consists chiefly of silty clay and forms a leaky confining unit between the Aquia and Monmouth aquifers in most areas. The thickness of the confining unit averages about 15 ft; however, the effective thickness of the confining unit is dependent on the percentage of clay in the formation. In some areas the vertical hydraulic conductivity of the Brightseat confining unit is greater than in other areas because of a low clay content. Reduced clay content is evidenced on gamma radiation logs in sections E-E′ and F-F′ (pl. 4).

The Monmouth aquifer is present throughout the study area as a relatively thin (as much as 45 ft) unit (pls. 3 and 4). The geohydrologic name Monmouth aquifer is retained in this report for water-bearing sand in the Severn Formation. The aquifer is bounded above and below by the Brightseat leaky confining unit and the Matawan confining unit, respectively. The strike and dip of the aquifer (fig. 5) is similar to the underlying Matawan confining unit. The dip is somewhat reduced over an area trending northeast across Annapolis Neck and the Mayo Peninsula. On Kent Island, sand of the Mount Laurel Formation of Late Cretaceous age is included in the Monmouth aquifer. Geohydrologic sections C-C′ to G-G′ (pl. 4) show the distribution of the Monmouth aquifer. The top of the aquifer on Annapolis Neck and the Mayo Peninsula ranges from near sea level to more than 150 ft below sea level at the southern end of the Mayo Peninsula (fig. 5).

The Matawan Formation forms a confining unit throughout the study area and separates the Magothy aquifer from the overlying Monmouth and Aquia aquifers. Where the Matawan confining unit underlies the Chesapeake Bay and its tributaries, an effective seal from brackish-water intrusion to the Magothy aquifer is formed (Mack, 1974). The total thickness of the confining unit is about 60 ft.

The Magothy aquifer within the study area is bounded above by the clayey Matawan confining unit and below by tough clay in the Upper Patapsco confining unit. The Magothy aquifer, in most locations within the study area, is about 120 ft thick. On section B-B′ (pl. 3), the Magothy aquifer bifurcates into two sand layers south of Annapolis Neck. Total sand thickness decreases southward. Updip on section B-B′, near the Magothy River, the Magothy aquifer thins to about 30 ft. A relatively thick (35 ft) clay layer within the Magothy Formation overlies the Magothy aquifer at this location.

The top of the Magothy aquifer (fig. 3) slopes from an altitude of 70 ft above sea level near the outcrop to more than 400 ft below sea level in southern Anne Arundel County. The dip of the aquifer is fairly uniform across the study area at about 35 ft/mi.

Two prominent sand units within the Patapsco Formation form the Upper and Lower Patapsco aquifers. Thick beds of clay separate the aquifers. The thickness of the Upper Patapsco aquifer increases downdip from about 200 ft at Severndale to about 300 ft at Sandy Point (section A-A′; pl. 2). Relatively thin, laterally discontinuous clay lenses are common throughout the aquifer. A clay layer, referred to in this report as the "Upper Patapsco confining unit", occurs near the top of the Patapsco Formation and generally marks the upper boundary of the Upper Patapsco aquifer. This clay layer is of sufficient thickness and lateral extent to hydraulically separate the Upper Patapsco aquifer from the overlying Magothy aquifer. However, in some areas, most noticeably Broadneck, the clay layer is discontinuous and the Magothy and Upper Patapsco aquifers are interconnected (Mack and Andreasen, 1991).

At the north end of section B-B′ (pl. 3), which extends from northern Calvert County to Broadneck, the upper contact of the Upper Patapsco aquifer occurs at about 130 ft below sea level (well AA Ce 126). The altitude of the top of the aquifer decreases to about 630 ft below sea level at Shadyside (well AA Fe 47). Well data from below the Magothy aquifer in southeasternmost Anne Arundel County and northern Calvert County are presently unavailable.

The top of the Upper Patapsco aquifer (fig. 2) lies below sea level in much of central Anne Arundel County and increases in depth to more than 600 ft below sea level in southern Anne Arundel County. The dip of the aquifer ranges from 20 to 125 ft/mi and is steepest near the outcrop zone and beneath Annapolis Neck and Broadneck.

Hydraulic Properties of Aquifers and Confining Units

The two basic hydraulic properties that need to be known are specific storage (L^{-1}) and hydraulic conductivity (LT^{-1}). These two properties are necessary to solve the flow equation that is used to calculate hydraulic-head changes and fluxes. Both terms are a function of certain properties of water as well as certain properties of the geologic matrix. Transmissivity (L^2T^{-1}) and storativity (dimensionless) are

derived terms and for the confined aquifers in the study area are equal to the full thickness of the aquifer times its horizontal hydraulic conductivity and specific storage, respectively.

To provide information on hydraulic properties of the Aquia aquifer, Brightseat confining unit, and Monmouth aquifer, tests were performed on each of five test wells located at Quiet Waters Park on Annapolis Neck (fig. 8). For each aquifer test, the other test wells were used as observation wells, and the corrected drawdown and recovery data were plotted and analyzed to calculate aquifer and confining-unit properties.

Aquifer tests assume the isolation of one component of the flow system, in this case pumpage, in order to make use of the principle of superposition. However, because of the proximity of the South River and Harness Creek, water levels in the aquifer fluctuate due to tidal stresses. To correct for tidal-driven water-level trends, all five wells were equipped with continuous water-level recorders. These records were compared to the continuous tidal-driven water-level trends at observation well AA Df 154 (pl. 1) located 0.8 mi southeast of the park. The mathematical relation between water levels at observation well AA Df 154 and each of the five test wells at Quiet Waters Park was used to extrapolate water-level trends during each of the aquifer tests. Thus, the apparent drawdowns were corrected to account for tidal stresses.

The analysis of aquifer properties for the five pumping tests made use of the type-curve method devised by C.V. Theis (Wenzel, 1942, p. 88). The assumptions were as follows:

1. well discharges at constant rate,
2. well is of infinitesimal diameter and is screened in only part of the aquifer,
3. aquifer has a radial-vertical anisotropy,
4. aquifer is confined by a unit of uniform hydraulic conductivity and thickness,
5. confining unit is overlain or underlain by an infinite constant-head plane source,
6. hydraulic gradient across confining unit changes instantaneously with a change in hydraulic head in the aquifer,
7. flow is vertical in the confining unit, and
8. vertical flow in the aquifer is caused by partial penetration of the pumping well and not by leakage from the confining unit.

The differential equation describing nonsteady radial and vertical flow in a homogeneous aquifer with radial-vertical anisotropy and leakage proportional to drawdown is:

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r}\frac{\partial s}{\partial r} + \frac{a^2 \partial^2 s}{\partial z^2} - \frac{sK'}{Tb'} = \frac{S\partial s}{T\partial r} \qquad (1)$$

where

s = drawdown in head (L),
r = radial distance from center of pumping (L),
a = $(K_z/K_r)^{.5}$, where
K_z = hydraulic conductivity of the aquifer in the vertical direction (LT^{-1}), and
K_r = hydraulic conductivity of the aquifer in the radial direction (LT^{-1}),
K′= hydraulic conductivity of confining bed (LT^{-1}),
T = transmissivity (L^2T^{-1}),
b′= thickness of confining unit (L),
t = time (T); and
S = storativity, dimensionless.

The solution of the differential equation for an observation well (Hantush, 1964, p. 350) is:

$$s = \frac{Q}{4\pi T\left\{w(u,\beta) + \bar{f}(u, \frac{ar}{b}, \beta, \frac{d}{b}, \frac{c}{b}, \frac{d'}{b}, \frac{c'}{b})\right\}} \qquad (2)$$

where

Q = discharge rate (L^3T^{-1}),
b = aquifer thickness (L),
d = depth from top of aquifer to top of pumped well screen (L),
c = depth from top of aquifer to bottom of pumped well screen (L),
d′= depth from top of aquifer to top of observation well screen (L), and
c′= depth from top of aquifer to bottom of observation well screen (L).

$u = \frac{r^2 S}{4Tt}$ (dimensionless),

$\beta = r(K'/Tb')^{.5}$ (dimensionless),

$a = (K_z/K_r)^{.5}$ (dimensionless),

$$\bar{f}(u, \frac{ar}{b}, \beta, \frac{d}{b}, \frac{c}{b}, \frac{d'}{b}, \frac{c'}{b}) = 2b^2/\pi^2(c-d)(c'-d') \sum_{n=1}^{\infty} 1/n^2 (\sin n\pi c/b - \sin n\pi d/b)(\sin n\pi c'/b - \sin n\pi d'/b)\, W\{u, [\beta^2 + (n\pi ar/b)^2]^{.5}\}$$

(dimensionless),

$$W(u,\beta) = \int_u^{\infty} \frac{e^{-y-\frac{\beta^2}{4y^2}}}{y}\, dy \quad \text{(dimensionless).}$$

A computer program (Reed, 1980, p. 75-83) plots families of type curves for a given K_z/K_r value. Input to the program includes all the variables listed in equation 2. The output is a family of r/β type curves for values of 1/u and $W(u,\beta)$+ f (u,ar/b,β,d/b,c/b,d′/b,c′/b).

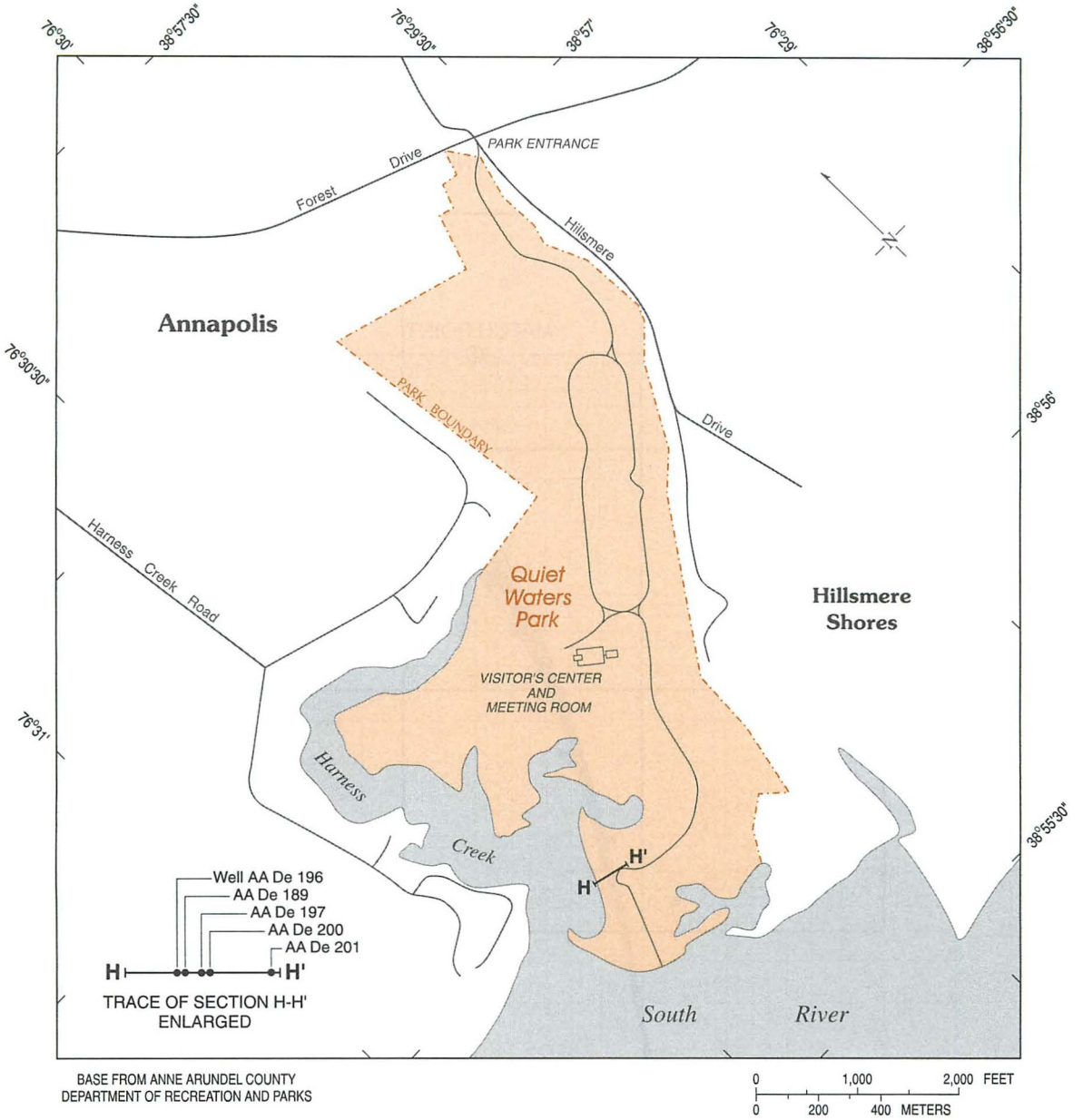


Figure 8. Location of test wells in Quiet Waters Park near Annapolis, Maryland.

An example is the analysis of the aquifer test for pumped test well AA De 200 and observed test well AA De 201 (figs. 52-53). The drawdown data as corrected for tidal fluctuations are plotted as a function of time from start of pumping test and overlain on a r/B family of curves as shown in figure 9. The input values were:

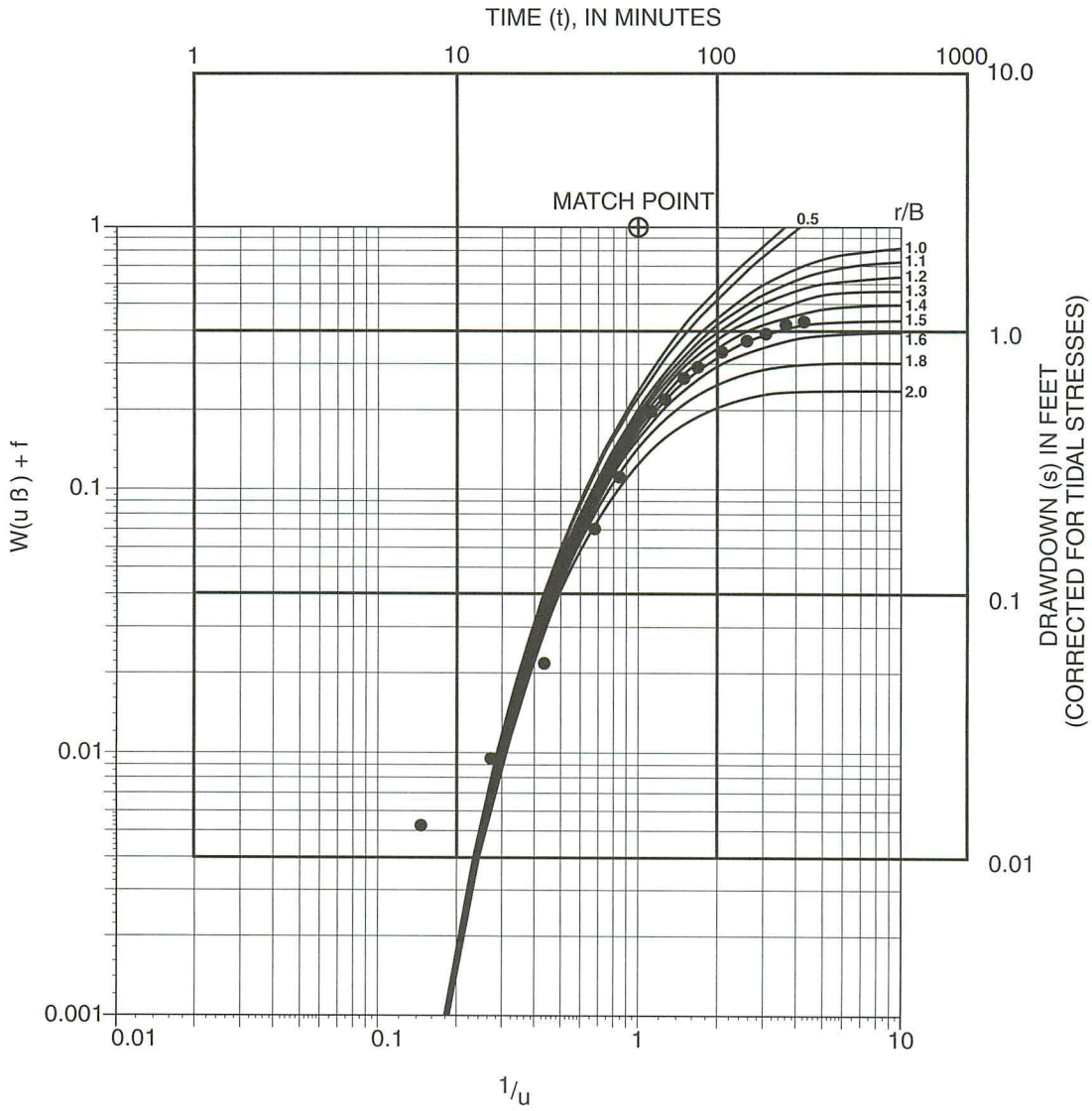
b = 52 ft,
d = 20 ft,
c = 30 ft,
d′= 15 ft,
c′= 25 ft, and
K_z/K_r= 0.1

The plotted drawdown is best matched to an r/β of 1.5. The match-point values are indicated in figure 9. The following equations were used to calculate the appropriate properties.

$$T = \frac{Q\{W(u,\beta)+f\}}{4\pi s}, \quad (3)$$

$$S = \frac{4Ttu}{r^2}, \quad (4)$$

$$K_r = \frac{T}{b}, \text{ and} \quad (5)$$



EXPLANATION

r/B =1.5

s = 2.6 FEET

t = 5.5 MINUTES

W(u,ß) + f = 1

1/u = 1

$K_z/K_r = 0.1$

Figure 9. Graph showing drawdown for observed test well AA De 201 as a function of time from start of pumping test for test well AA De 200 matched to type curves.

$$K' = \frac{Tb'(r/B)^2}{r^2} \quad . \qquad (6)$$

This procedure was repeated for the recovery data. The whole process then was repeated such that families of type curves for different K_z/K_r ratios were matched, and aquifer properties were calculated. Thus several sets of values were obtained. The values that fit best with the other tests were selected as the best estimates of the aquifer properties for each test.

Aquia aquifer

Nonequilibrium type curves (Reed, 1980, p. 29-33) were used to calculate horizontal and vertical hydraulic conductivities and storativities in the Aquia aquifer at Quiet Waters Park using the method described above. For the Aquia aquifer six separate analyses indicate a range of transmissivities from 168 to 1,120 ft^2/d. The thickness of the aquifer at this location is about 140 ft, and thus the horizontal hydraulic conductivity is about 4 ft/d. The vertical hydraulic conductivity was assumed to be about one order of magnitude less than the horizontal hydraulic conductivity.

The specific storage (also referred to as the "elastic storage coefficient") equals the storativity divided by the aquifer thickness. The specific storage of the Aquia aquifer ranged from about 7×10^{-6} to 4×10^{-6} ft^{-1} as determined from the Quiet Waters pumping tests and aquifer thickness at that site. The expected range of specific storage for a sandy aquifer is 3×10^{-4} to 3×10^{-6} ft^{-1} (Freeze and Cherry, 1979, p. 55). The Aquia aquifer is composed of silty sand, and the expected specific storage would be at the upper end of this range. Kapple and Hansen (1976, p. 20) used a value of about 3×10^{-6} ft^{-1} for the Aquia aquifer in southern Maryland where the aquifer tends to be somewhat coarser. Hansen (1972, p. 66) lists a storativity value for the Aquia aquifer in southern Maryland of 4×10^{-4} where the aquifer is about 200 ft thick, and, thus, specific storage is about 2×10^{-6} ft^{-1}.

An aquifer test located near the southern end of Annapolis Neck at Southern Estates was completed in May 1988. The test included two wells screened in the Aquia aquifer and two wells screened in the deeper Monmouth aquifer. The results of the Aquia aquifer test were analyzed using the straight-line Jacob method. Transmissivity was calculated to be in the range of 1,800 to 5,600 ft^2/d. The thickness of the Aquia aquifer at this location is about 120 ft, thus, the hydraulic conductivity is in the range of 14 to 43 ft/d. The calculated storativity was 7×10^{-4}, and thus, the specific storage is about 6×10^{-6} ft^{-1}. This value is typical for a sandy aquifer.

Brightseat confining unit

Silt and clay in the Brightseat confining unit underlie the Aquia aquifer and serve as a thin leaky confining unit. An analysis of the drawdown curves for the aquifer test at Quiet Waters Park indicates a range of 0.3 to 0.03 ft/d for the vertical hydraulic conductivity of the Brightseat confining unit.

Monmouth aquifer

Two test wells were screened in the Monmouth aquifer at Quiet Waters Park. Aquifer tests were performed at both wells, and hydraulic heads were measured in the observation wells. The drawdown data were matched with type curves for nonequilibrium, partial penetration, and leaky aquifer conditions (Reed, 1980, p. 29-33). The radial hydraulic conductivities calculated for the two tests were 0.4 and 3.1 ft/d, and the vertical hydraulic conductivities were assumed to be about one-tenth of the horizontal conductivities. The elastic storage coefficient was calculated to be between 4×10^{-5} and 4×10^{-6} ft^{-1}. The aquifer thickness at this location is about 50 ft; thus, the transmissivity would be about 20 to 155 ft^2/d, and the storativity would be somewhere between 2×10^{-3} and 2×10^{-4}.

Transmissivities from an aquifer test conducted in May 1988 near the southern end of Annapolis Neck at Southern Estates ranged from about 400 to 1,600 ft^2/d. These values were calculated by use of the Jacob straight-line method for both an observation well and the pumped well. The storativity was calculated to be about 1×10^{-3}. The thickness of the Monmouth aquifer at this location is about 30 ft. Thus, the specific storage is about 3×10^{-4} ft^{-1}, which is typical of aquifers composed of fine sand and silt.

Matawan confining unit

The Matawan confining unit ranges in thickness from about 70 to 130 ft as indicated on the geohydrologic sections (pls. 3 and 4). The unit consists of a high percentage of glauconitic clay. Hydraulic conductivities for clay typically range from about 10^{-6} to 10^{-3} ft/d (Fetter, 1988, p. 80). It is assumed that the controlling vertical hydraulic conductivity for the Matawan is within this range. Thus, because of the large thickness and the low vertical conductivity, the Matawan is hydraulically a relatively impermeable confining unit.

Magothy aquifer

The Magothy aquifer, as previously indicated, is a sequence of medium to coarse sand of about 90 ft in thickness. Horizontal hydraulic conductivities of the Magothy aquifer were calculated from specific capacities (listed in appendix A) using the Theis equation and the Kozeny formula (Driscoll, 1986, p. 270) to account for the effects of partial penetration. The horizontal hydraulic conductivities thus obtained ranged from 1.5 to 83 ft/d and averaged about 40 ft/d. Wells AA Ce 128 and AA Ce 129 were also analyzed by the Jacob straight-line method (Fetter, 1988, p. 170)

and had hydraulic-conductivity values of 270 and 27 ft/d, respectively. As indicated earlier, the thickness of the Magothy aquifer is about 90 ft; thus, the transmissivity would range by an order of magnitude from about 2,400 to 24,000 ft^2/d. Previous studies (Hansen, 1972, p. 52; Mack and Mandle, 1977, p. 13) suggest that transmissivity for the Magothy aquifer in Anne Arundel County ranges from 1,000 to 12,000 ft^2/d.

The storativity (Hansen, 1972, p. 42; Mack and Mandle, 1977, p. 19) of the Magothy aquifer in the study area is about 10^{-4}, which means the specific storage is about $10^{-5}\ ft^{-1}$. This agrees with the typical specific storage for a sandy aquifer (Freeze and Cherry, 1979, p. 55).

Upper Patapsco confining unit

The Upper Patapsco confining unit, where present, has a thickness of as much as 40 ft (pl. 2). Similarly, the composition varies from silty clay to silty sand, and thus, the vertical hydraulic conductivity probably ranges from 10^{-2} to 10^{0} ft/d.

Upper Patapsco aquifer

Hansen (1972, p. 34) reports three values for transmissivities for that part of the Upper Patapsco aquifer that underlies Anne Arundel County. These transmissivity values (4,680; 5,350; and 6,680 ft^2/d) indicate a range of hydraulic conductivities of about 10 to 60 ft/d. Plate 2 indicates that the sandy part of the Upper Patapsco aquifer is as much as 200 ft thick. Assuming an average horizontal hydraulic conductivity of about 40 ft/d, the transmissivity of the Upper Patapsco aquifer may be as high as 8,000 ft^2/d.

The storativity for the Upper Patapsco aquifer ranges from about 5×10^{-5} to 1×10^{-4} (Hansen, 1972, p. 34), which is a specific storage of about 6×10^{-7} to $1 \times 10^{-6}\ ft^{-1}$. Typical values for specific storage of a sandy aquifer are about 10^{-6} to $10^{-4}\ ft^{-1}$ (Freeze and Cherry, 1979, p. 55) which suggests that the values reported by Hansen (1972) are low.

Potentiometric Surfaces

Aquia and Monmouth aquifers

The potentiometric surface of the Aquia aquifer within the study area, measured during the fall of 1988, is shown in figure 10. Water levels in 81 wells screened in the Aquia aquifer were used to construct the map. Also plotted on the map are five water levels from wells screened in the Monmouth aquifer. Water-level measurements were made in 4-in. inside-diameter domestic supply wells and in 4-in. inside-diameter test wells drilled during the study.

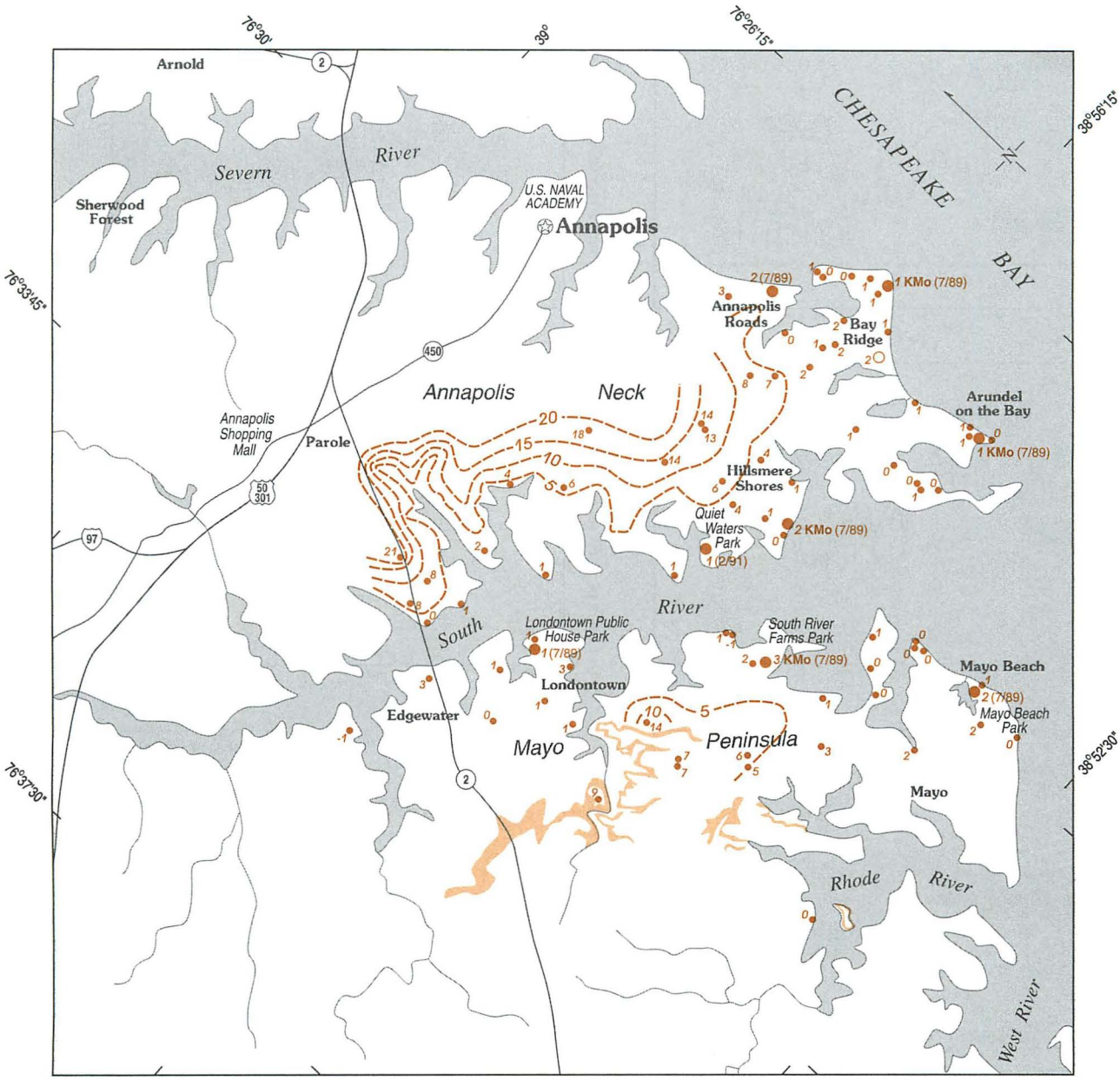
The Aquia aquifer crops out across Annapolis Neck and most of the Mayo Peninsula; the Marlboro confining unit overlies the Aquia aquifer south of the central part of the Mayo Peninsula. In the outcrop area, the Aquia aquifer probably is best described as a semiconfined aquifer. In general, the potentiometric surface is highest (as much as 21 ft above sea level on Annapolis Neck) in topographically high areas and lowest (at sea level) in topographically low areas. On Annapolis Neck, the direction of ground-water flow is from the interior area of the peninsula toward the South and Severn Rivers and Chesapeake Bay. The hydraulic gradient is relatively steep (about 50 ft/mi) in areas with high topographic relief and more gradual in flat-lying areas (most notably the southern end of Annapolis Neck and the Mayo Peninsula). On the Mayo Peninsula, the highest water levels measured (14 ft above sea level) occur in a topographically high area in the center of the peninsula; water levels decline away from that point toward the South River. Two water levels in the Aquia aquifer on the Mayo Peninsula measured 1 ft below sea level; however, the levels could have been affected by recent pumping in the wells.

The Aquia and Monmouth aquifers are hydraulically separated by the leaky Brightseat confining unit. As a result, the difference in water levels between the aquifers is generally slight.

Most of the wells that tap the Aquia aquifer within the study area are for domestic use and generally withdraw less than 300 gal/d; therefore, deep and areally extensive cones of depression do not occur. The Monmouth aquifer is relatively unproductive, and its use is limited to a small number of domestic supply wells.

Continuous water-level recorders were installed in eight Aquia aquifer wells and seven Monmouth aquifer wells at seven sites on Annapolis Neck and the Mayo Peninsula to determine water-level fluctuations and vertical potentiometric-surface distributions. Hydrographs of the water levels are shown in figure 11. The location of the well sites is shown in figure 10 and plate 1. Water levels, recorded from September 1989 through February 1990, responded to discharge, recharge, barometric, and semidiurnal tidal fluctuations. These fluctuations altered the external load on the Aquia and Monmouth aquifers causing an increase or decrease in pressure and a subsequent rise and fall in water levels.

Water levels in wells that tap the brackish-water part of the Aquia and Monmouth aquifers are slightly lower (caused by the greater density water) than water levels in wells in the same aquifer containing freshwater. Brackish-water head can be converted to equivalent freshwater head by multiplying the brackish-water head by the brackish-water:freshwater density ratio (Cooper, 1964). For example, consider a well tapping a zone of brackish water with approximately one-half the density of seawater (1,012 grams per cubic meter, gm/cm^3) and having a water level of 1.00 ft above sea level. The equivalent freshwater head would equal the brackish-water head multiplied by the ratio of brackish-water density to freshwater density ($1{,}012\ gm/cm^3 / 1{,}000\ gm/cm^3 = 1.012$) or 1.01 ft above sea level. The brackish-water content in each well, represented by the chloride concentration (in mil-



EXPLANATION

GENERALIZED OUTCROP AREA OF THE MARLBORO CONFINING UNIT -- Modified from Glaser (1976).

15 POTENTIOMETRIC CONTOUR -- Shows altitude at which water level would have stood in a tightly cased well screened in the Aquia aquifer. Dashed where approximately located. Contour interval 5 feet. Datum is sea level.

2 KMo (7/89) TEST WELL DRILLED DURING THIS STUDY -- Number shows altitude of Aquia water level in feet, except where KMo indicates that well is screened in the Cretaceous Monmouth aquifer. Date of water-level measurement is shown in parentheses.

PUMPING WELL -- Number is altitude of Aquia water level in feet. Symbol indicates average yield from well or well field in gallons per day:

1 *Less than 10,000*

2 *10,000 to 100,000*

Figure 10. Potentiometric surface of the Aquia aquifer in wells inventoried during the fall of 1988 on Annapolis Neck and Mayo Peninsula and location of test wells drilled during the study along with measured water levels and dates.

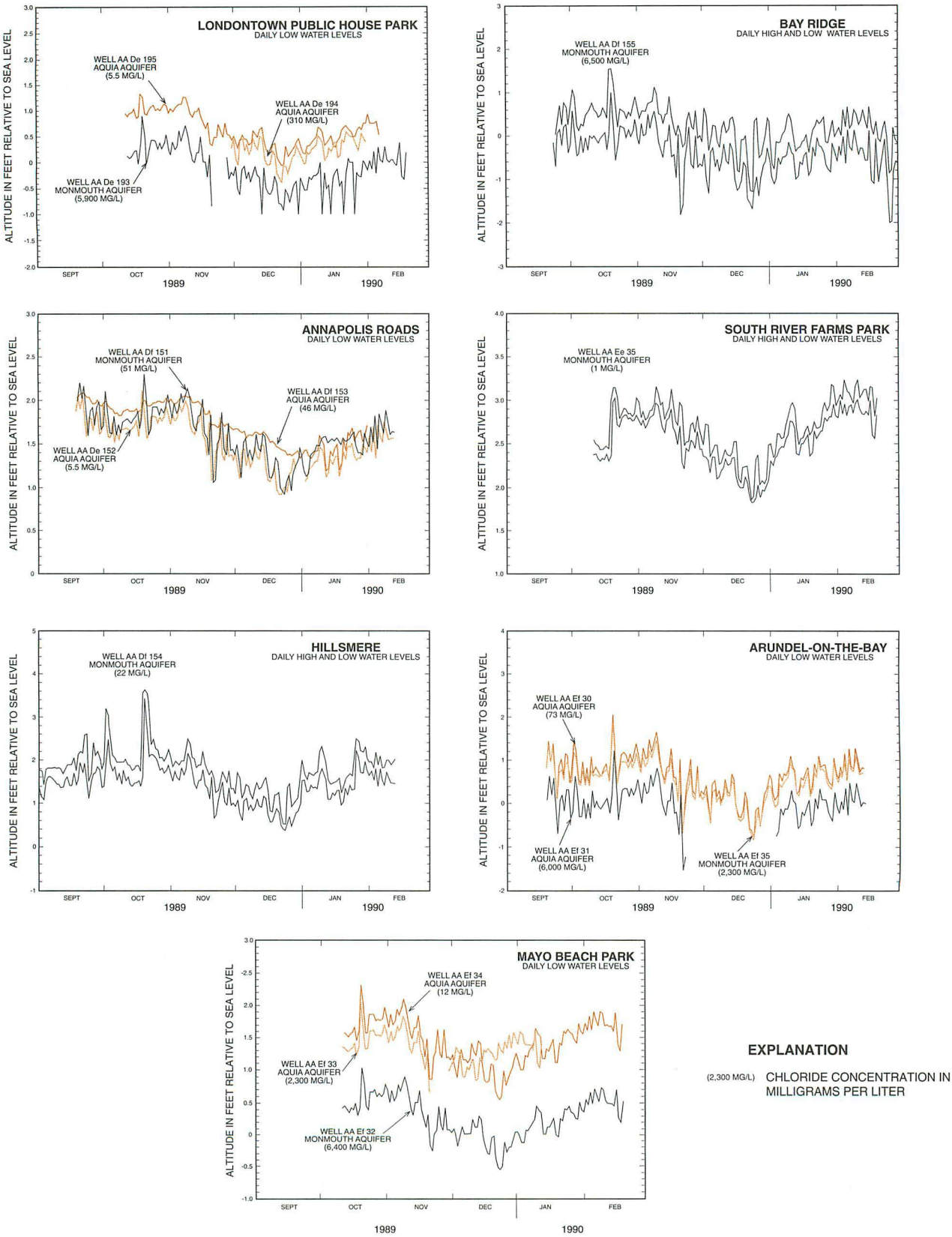


Figure 11. Hydrographs of water-level fluctuations in selected wells completed in the Aquia and Monmouth aquifers within the study area, September 1989 through February 1990, and chloride concentrations in water samples collected at time of aquifer tests.

ligrams per liter) of a water sample collected during aquifer tests, is shown in the hydrographs. Adjustment of brackish-water heads to equivalent freshwater heads was not made, however, because the difference is negligible.

The potentiometric surface of the Aquia aquifer for September 1990 south of the Mayo Peninsula is shown in figure 12. Water levels measured in wells range in altitude from 32 ft above sea level to 22 ft below sea level. The approximate direction of ground-water flow is to the southeast. The Aquia aquifer is confined in southern Anne Arundel County.

Magothy and Upper Patapsco aquifers

The potentiometric surface of the Magothy aquifer for September 1990 within the study area is shown in figure 13. Water levels greater than 80 ft above sea level occur in the central part of Anne Arundel County near the outcrop area and decrease in a east-southeastward direction. A shallow cone of depression has formed on Broadneck caused by downward leakage to the Upper Patapsco aquifer.

The correlation of water-level decline in the Magothy aquifer with pumpage from the Upper Patapsco aquifer on Broadneck is illustrated in figure 14. This figure shows declining water levels in the Magothy aquifer from 1976 to 1987, measured in well AA Cf 99, caused by pumpage in the Upper Patapsco aquifer at Anne Arundel County's water-treatment plant at Arnold 0.95 mi away. Between 1969 and 1976, levels were fairly constant, ranging between sea level and 3 ft above sea level. A downward trend, beginning in 1977, corresponds to the start of pumping from the Upper Patapsco aquifer at the Arnold plant. Water levels continued to decline until the fall of 1987 when a low of about 20 ft below sea level was reached. Since that time, water levels have risen corresponding to a shift of pumpage at Arnold from the Upper Patapsco aquifer to the Lower Patapsco aquifer. Water-level data from the fall of 1992 indicate that the cone of depression in the Magothy aquifer on Broadneck has dissipated.

The potentiometric surface of the Upper Patapsco aquifer measured during September 1990 is shown in figure 15. The highest water level (more than 70 ft above sea level) occurred in the western part of Anne Arundel County, and water levels declined toward the east-southeast. Three cones of depression have formed around the Arnold water-treatment plant on Broadneck, the U.S. Naval Academy well field, and the Broadcreek well field on Annapolis Neck.

GROUND-WATER QUALITY AND FLOW

WATER QUALITY

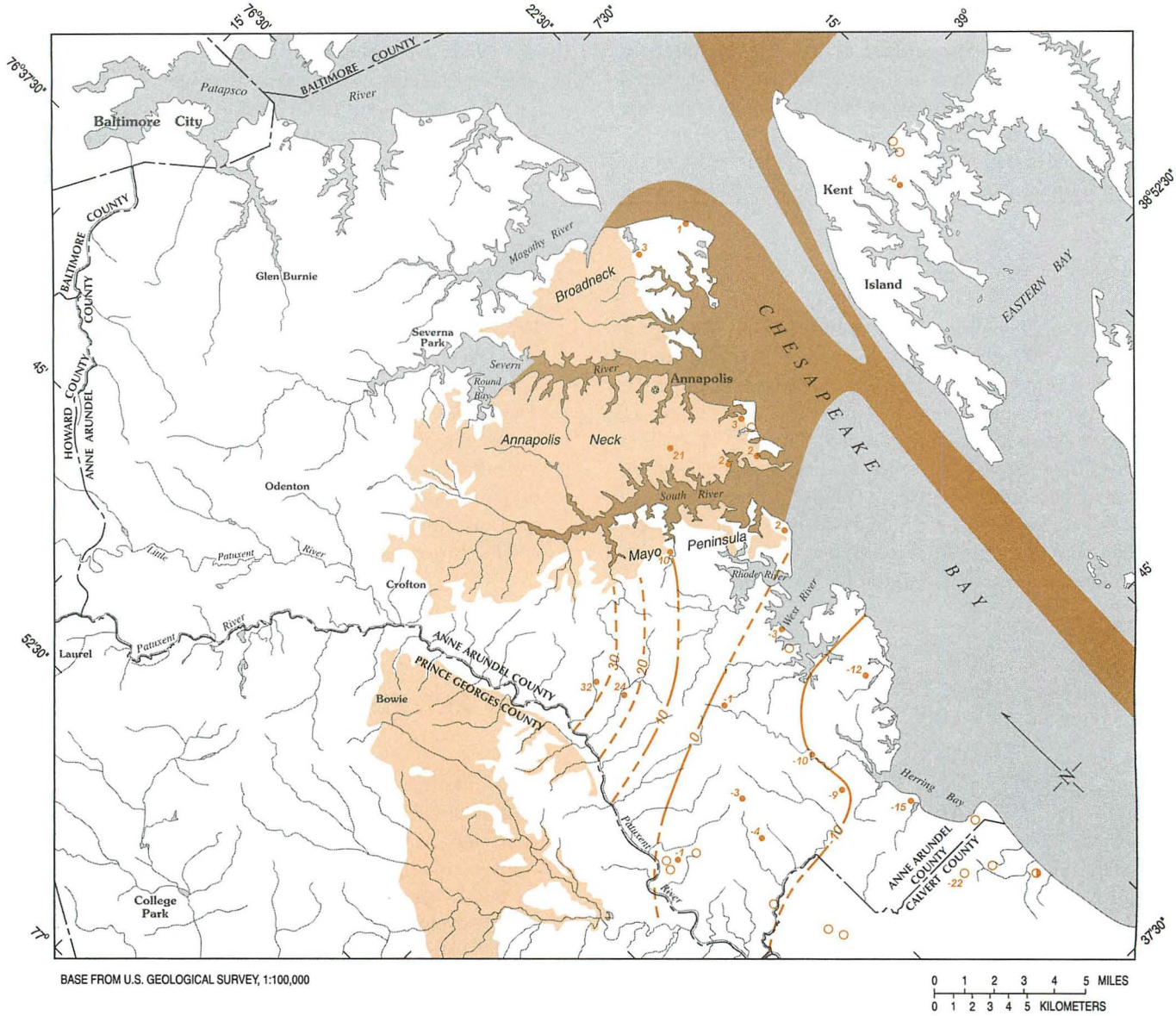
This section of the report describes in detail the methods of water-quality data collection and analysis as well as the type of water-quality data collected. The ambient water quality in the Aquia, Monmouth, Magothy, and Upper Patapsco aquifers was determined using the water-quality data gathered during this study along with data collected by previous investigators. A discussion of the ambient water quality of these aquifers is included in this section.

Collection and Analysis of Data

Ground-water-quality data collected during the study were used to define the ambient water quality of the Aquia, Monmouth, Magothy, and Upper Patapsco aquifers and to determine the effect on water quality of brackish-water intrusion. Additionally, limited chemical analyses of Chesapeake Bay water and bottom-sediment pore water were obtained to estimate the concentration of the major cations and anions in water from the bay that may enter the aquifer.

During the data-collection phase of the study, 27 test wells, consisting of 11 Aquia aquifer wells, 10 Monmouth aquifer wells, and 6 Magothy aquifer wells were sampled. Results of chemical analyses of water samples from these wells are given in appendix C. In addition, 75 residential wells, consisting of 74 Aquia wells and 1 Monmouth well were also sampled. Results of chemical analyses of water samples from these wells are given in appendix D. The residential well sampling was conducted in the fall of 1988 and the spring of 1989 to determine seasonal variations in chloride concentrations. The wells were selected to provide an even areal and vertical distribution of data points throughout the study area. Emphasis was placed on the Aquia aquifer in areas near the shoreline where concern for brackish-water intrusion is the greatest.

The procedure followed for collecting water samples from residential wells consisted of pumping the wells for a minimum of 15 minutes, or the equivalent of approximately three well-casing volumes, to allow for the removal of stagnant water stored in the casing. Water samples from test wells were collected using a submersible pump. The samples were collected after about 3 hours of pumping. For both residential and test wells the water was discharged into an open bucket where specific conductance, pH, and water temperature were measured periodically. After these physical properties stabilized, the water was collected in bottles provided by the U.S. Geological Survey National Water-Quality Laboratory (NWQL) in Arvada, Colorado. Samples were col-



EXPLANATION

GENERALIZED OUTCROP AREA OF THE AQUIA AQUIFER -- Modified from Glaser (1976), Cooke and Cloos (1951).

SUBCROP AREA OF THE AQUIA AQUIFER BENEATH THE CHESAPEAKE BAY AND ITS TRIBUTARIES -- Modified from Chapelle and Drummond (1983).

10 POTENTIOMETRIC CONTOUR -- Shows altitude at which water level would have stood in a tightly cased well. Dashed where approximately located. Contour interval 10 feet. Datum is sea level.

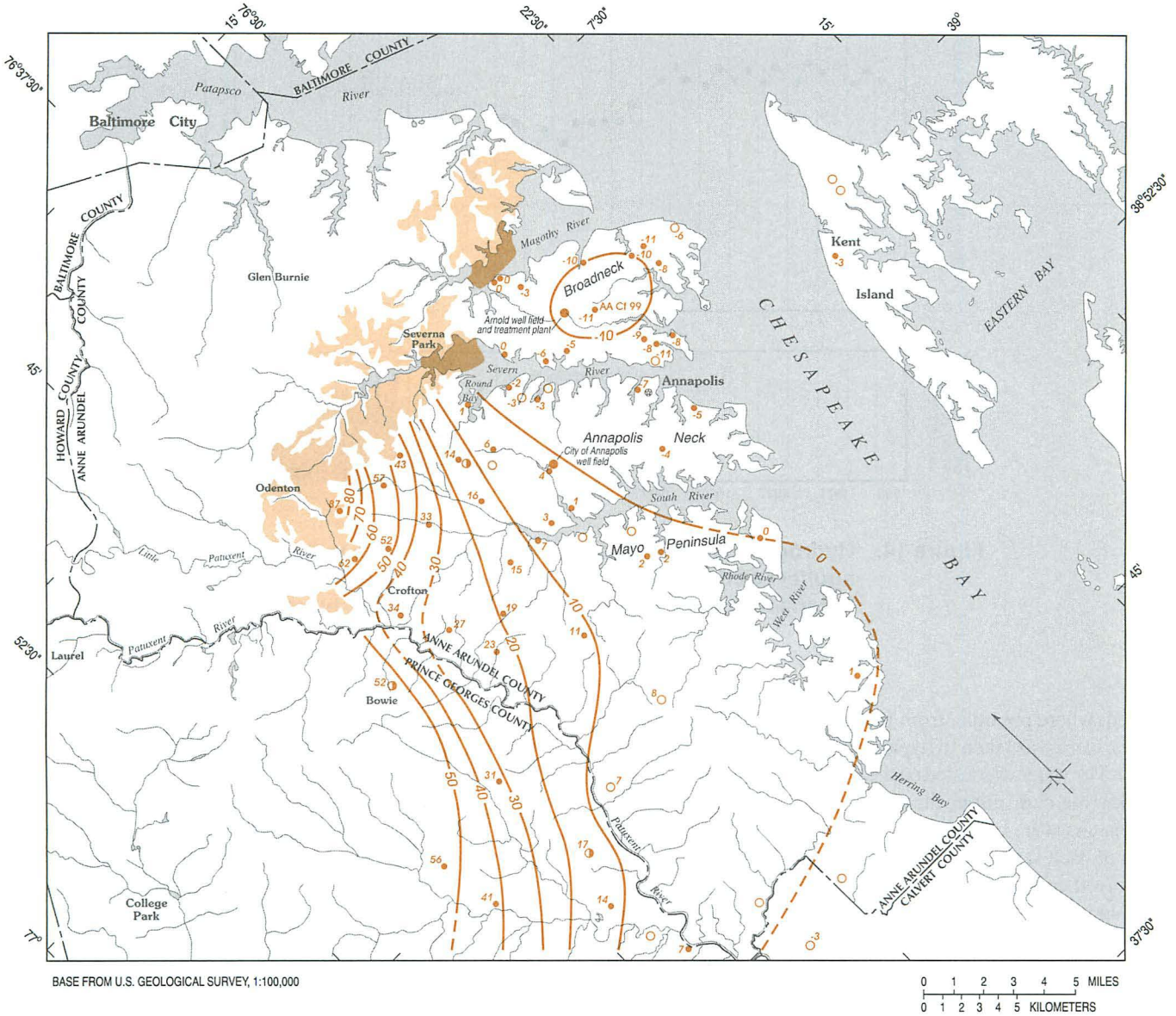
WELL-DATA POINT -- Number is altitude of water level in feet. Symbol indicates average yield from well or well field in gallons per day:

-3 *Less than 10,000*

-22 *10,000 to 100,000*

100,000 to 1,000,000

Figure 12. Potentiometric surface of the Aquia aquifer, September 1990 (modified from Mack and others, 1992a).



EXPLANATION

GENERALIZED OUTCROP AREA OF THE MAGOTHY AQUIFER -- Modified from Glaser (1976).

SUBCROP AREA OF THE MAGOTHY AQUIFER BENEATH THE MAGOTHY AND SEVERN RIVERS.

50 POTENTIOMETRIC CONTOUR -- Shows altitude at which water level would have stood in a tightly cased well. Dashed where approximately located. Contour interval 10 feet. Datum is sea level.

WELL-DATA POINT -- Number is altitude of water level in feet. Symbol indicates average yield from well or well field in gallons per day:

- 15 *Less than 10,000*
- 8 *10,000 to 100,000*
- 17 *100,000 to 1,000,000*
- *Greater than 1,000,000*

Figure 13. Potentiometric surface of the Magothy aquifer, September 1990 (modified from Mack and others, 1992b).

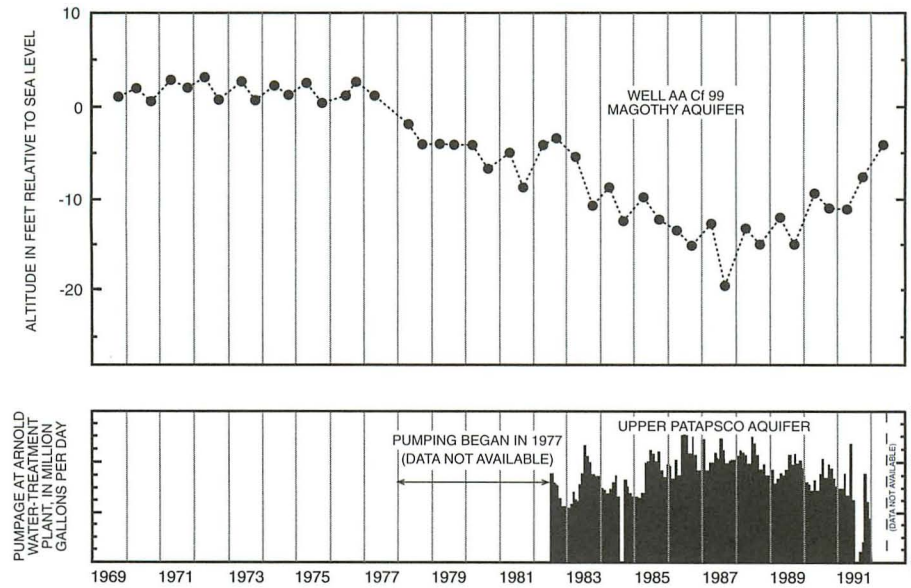


Figure 14. Hydrographs showing water-level fluctuations in the Magothy aquifer (well AA Cf 99), 1969-92, and pumpage from the Upper Patapsco aquifer at the Arnold water-treatment plant, 1982-91.

lected, where possible, from faucets located before storage tanks. Care was taken to bypass all water-conditioning systems. The water was tested onsite for chloride using a HACH[1] test kit (mercuric nitrate titration). Specific-conductance and pH meters were calibrated to standardized solutions at the start of each sample day. Samples collected for analysis of dissolved constituents were passed through a 0.45-micron membrane filter using a peristaltic pump. Unfiltered samples were collected for analysis of total ion (dissolved plus suspended) concentrations. Samples for nitrate analysis were preserved by treating with 1 milliliter of mercuric chloride. Samples collected for pH sensitive constituents, such as iron, were acidified by adding 1 milliliter of nitric acid to reduce mineral precipitation. The samples were labeled, packed in ice, and sent to the U.S. Geological Survey NWQL for analysis.

Water samples collected from the 24 test wells and from 3 residential wells were analyzed for major inorganic ions plus bromide. Water samples collected from the 75 residential wells were analyzed for specific conductance, pH, alkalinity, chloride, bromide, and nitrogen (as nitrite + nitrate). All analyses were done by the U.S. Geological Survey NWQL. The results of the analyses are given in appendixes C and D and are stored in the U.S. Geological Survey's WATSTORE data base.

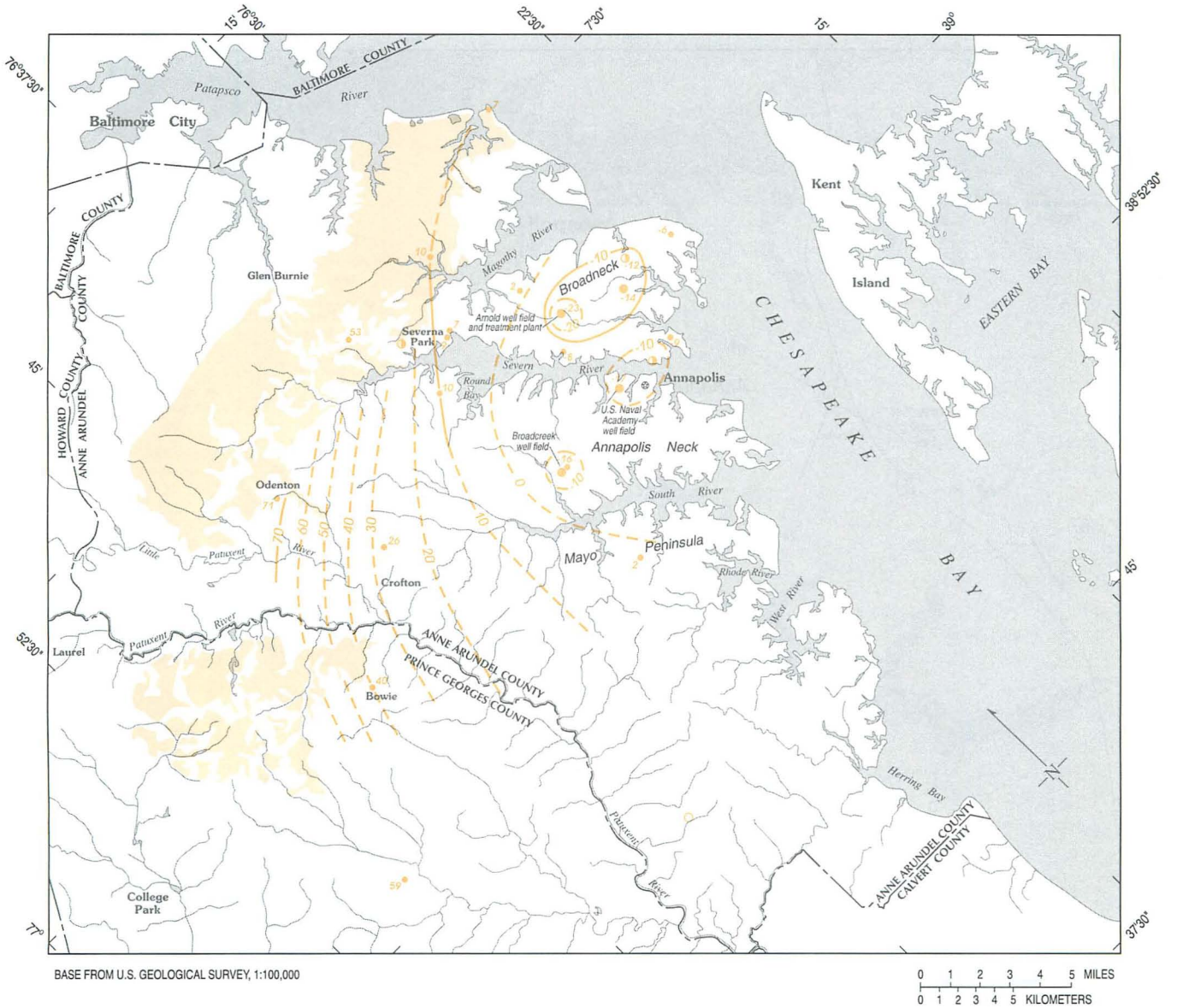
[1] The use of brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey or the Maryland Geological Survey.

Sediment pore fluid was collected by the Maryland Geological Survey between 1978 and 1981 and analyzed by the College of William and Mary (Tyree and others, 1981). These analyses are presented in table 11 later in this report.

The completeness and accuracy of an analysis of the major dissolved ions in water can be checked by examining the balance between cations and anions expressed in milliequivalents per liter (meq/L). If all ions have been correctly determined, then the total milliequivalents per liter of cations will equal the total milliequivalents per liter of anions. The percentage difference between cations and anions for the analyses made during this study was generally at an acceptable level (less than about 7 percent).

Interpretations of the water-quality data were made by utilizing a trilinear diagram, concentration plots relating major ions to chloride, and schematic cross sections. Chloride concentrations in water from the Aquia and Monmouth aquifers for 1988-90 were plotted in figure 16.

Under the Safe Drinking Water Act of 1986, the U.S. Environmental Protection Agency established Maximum Contaminant Levels (MCL's) for a variety of inorganic and organic substances in drinking water that are enforced for public water supplies (U.S. Environmental Protection Agency, 1986). Limits for nitrate in drinking water fall under this category. All other constituents discussed in this report fall under the Secondary Maximum Contaminant Level (SMCL) category. Levels set by these U.S. Environmental Protection Agency regulations are not enforced (U.S. Environmental Protection Agency, 1986).



EXPLANATION

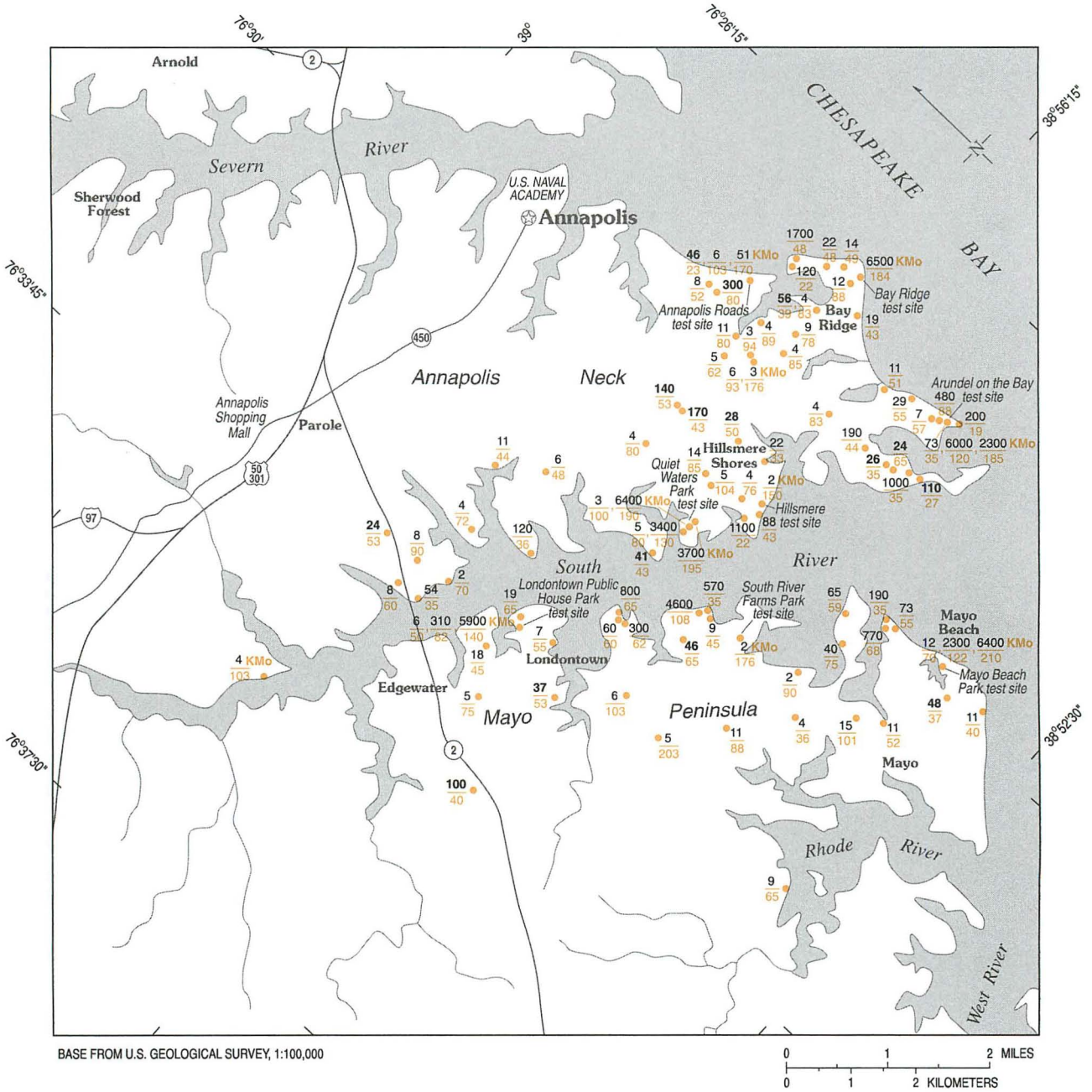
GENERALIZED OUTCROP AREA OF THE UPPER PATAPSCO AQUIFER -- Modified from Glaser (1976), Cooke and Cloos (1951).

POTENTIOMETRIC CONTOUR -- Shows altitude at which water level would have stood in a tightly cased well. Dashed where approximately located. Contour interval 10 feet. Datum is sea level.

WELL-DATA POINT -- Number is altitude of water level in feet. Symbol indicates average yield from well or well field in gallons per day:

- *Less than 10,000*
- *10,000 to 100,000*
- *100,000 to 1,000,000*
- *Greater than 1,000,000*

Figure 15. Potentiometric surface of the Upper Patapsco aquifer, September 1990 (modified from Mack and others, 1992c).



EXPLANATION

46 6 51 KMo
23 103 170

TEST OR RESIDENTIAL WELL -- Top number is chloride concentration in water from the Aquia aquifer, in milligrams per liter. A bold number indicates a chloride concentration probably associated with sources other than brackish water. Bottom number is depth to top of well screen, in feet below land surface. KMo indicates that sample is from a well screened in the Cretaceous Monmouth aquifer. More than one number indicates multiple wells at that site screened at different depths.

Figure 16. Areal distribution of chloride concentrations in water from the Aquia and Monmouth aquifers, 1988-90.

Ambient Conditions

Aquia and Monmouth aquifers

Water from the Aquia and Monmouth aquifers not affected by brackish-water intrusion is generally of acceptable quality for most uses within the study area. However, treatment is often required for the reduction of acidity, hardness, and iron (Fe). Chloride and nitrate concentrations exceeding the U.S. Environmental Protection Agency (USEPA) limits were observed in water from several locations in the Aquia and Monmouth aquifers. Contamination from sources such as road salt, septic systems, and lawn fertilizers, typically found in urban settings, are possible causes for these elevated concentrations. A list of ranges and median values for pH, hardness, chloride, nitrate, iron, and dissolved solids for selected Aquia and Monmouth water samples and possible sources of these constituents are given in table 2. Water from the Aquia and Monmouth aquifers is chemically indistinguishable.

The pH of water from the Aquia and Monmouth aquifers ranged from 4.4 to 8.0, with a median value of 7.1 calculated from 71 analyses. The recommended range of pH is between 6.5 and 8.5 (U.S. Environmental Protection Agency, 1986). Water with a pH greater than 7.0 is alkaline, whereas water with a pH less than 7.0 is acidic. Pure water, containing no solutes, has a neutral pH of 7.0 at 25°C. Acidic precipitation recharging the Aquia and Monmouth aquifers is the primary cause of low pH. Acidic water, with a pH less than 6.5, can lead to the corrosion of metal pipes and to green staining on porcelain plumbing fixtures. Also, corrosive water can release unacceptable levels of cadmium, copper, lead, and zinc from pipes and plumbing fixtures (Lehr and others, 1988). Acidity can be lowered through the application of soda ash (Na_2CO_3) and, in some cases, caustic soda (NaOH) to the water (Lehr and others, 1988).

Overall, low pH values in water from the Aquia and Monmouth aquifers within the study area did not correspond to any particular depth or location. However, a vertical variation in pH was observed at the Annapolis Roads test well site (fig. 16). Water from three wells at the site, completed at depths of 38, 118, and 178 ft, had a pH of 5.3, 7.8, and 7.2, respectively. The increase in pH from the shallowest well to the deeper wells was accompanied by an increase in

Table 2. Range in values of pH, hardness, dissolved chloride, nitrogen, dissolved iron, and dissolved solids in water from the Aquia and Monmouth aquifers not affected by brackish-water intrusion

[All values are in milligrams per liter except as noted]

Chemical constituent	Number of samples	Range of values	Median value	Recommended limit	Possible sources
pH	71	4.4 - 8.0	7.1	(2)6.5 - 8.5	Low pH may result from oxidation of organic material and sulfides (pyrite) and acidic precipitation.
Hardness	19	10 - 240	190	(1)0 -60 soft; 61 - 120 moderately hard; 121 - 180 hard; greater than 181 very hard	Shell material.
Dissolved chloride	62	2 - 300	6	(2)250	Road salt; sewage effluent; water softener recharge effluent; marine aerosols.
Nitrogen (NO_2+NO_3)	29	<0.1 - 15	0.1	(3)10	Sewage effluent; fertilizer.
Dissolved iron, in micrograms per liter	15	5 - 15,000	140	(2)300	Sediment-grain coatings; weathered glauconite; iron bacteria.
Dissolved solids	18	39 - 336	240	(2)500	Dissolution of minerals in aquifer material.

(1) Durfor and Becker (1964).

(2) Secondary Maximum Contaminant Level--not enforceable (U.S. Environmental Protection Agency, 1986).

(3) Maximum Contaminant Level, health related--enforceable (U.S. Environmental Protection Agency, 1986).

alkalinity of 7, 215, and 169 mg/L and an increase in dissolved calcium of 16, 83, and 82 mg/L. The increase in pH, alkalinity, and calcium can be related to the presence of carbonate material, which was logged in drill cuttings from the screened interval of the two deeper wells. Carbonate material was noticeably absent in drill cuttings from the shallow well.

Hardness of water from the Aquia and Monmouth aquifers is a common problem within the study area. The term "hardness" refers to the ability of water to inhibit the formation of soap lather and to promote the formation of a white scale resulting from the heating of water. Hardness is attributed mainly to the amount of dissolved calcium and magnesium ions in the water and is reported in terms of the equivalent concentration of calcium carbonate. The range of hardness can be classified as soft (0-60 mg/L), moderately hard (61-120 mg/L), hard (121-180 mg/L), and very hard (greater than 180 mg/L) (Durfor and Becker, 1964). In selected samples from the Aquia and Monmouth aquifers, hardness ranged from 10 (soft) to 240 mg/L (very hard) (table 2). The median value calculated from 19 samples analyzed was 190 mg/L. Hardness values greater than 100 mg/L generally require treatment for domestic use. Treatment typically involves exchanging calcium and magnesium for sodium in an ion-exchange water softener.

The primary source of hardness-producing calcium and magnesium ions is carbonate materials, including weathered shell composed of calcium carbonate (present as both calcite and aragonite), magnesium calcite, and secondary precipitated calcite. This is a common mineral assemblage in the Aquia and Monmouth aquifers. Acidic recharge water, formed by the reaction of dissolved carbon dioxide and water, dissolves the carbonate material and releases calcium, magnesium, and bicarbonate ions. Under appropriate pH conditions, this reaction can reverse itself when the solution becomes saturated with respect to these ions. Concentrations of dissolved calcium, magnesium, and bicarbonate ranged from 2.8 to 91 mg/L, 0.70 to 7.4 mg/L, and 1 to 340 mg/L, respectively. Bicarbonate was calculated from alkalinity for analyses that did not report bicarbonate.

Chloride is a naturally occurring substance in ground water. Concentrations of about 2 to 3 mg/L are typical for water in the Aquia and Monmouth aquifers (Chapelle and Drummond, 1983). However, concentrations are typically higher in the outcrop area near the Chesapeake Bay as a result of wind-driven marine aerosols. Background concentrations of chloride in this report are considered to be less than 10 mg/L. Chloride concentrations analyzed in 62 water samples (57 Aquia and 5 Monmouth) ranged from 2 to 300 mg/L, with a median value of 6 mg/L (table 2). Fourteen Aquia water samples had chloride concentrations greater than 10 mg/L. All of the Monmouth samples contained less than 10 mg/L chloride. Chloride concentrations greater than background may be attributed to road salt, sewage lines, or water-softener recharge effluent. In the routine operation of residential water softeners, a brine (NaCl) solution is flushed through the ion-exchange media. The potential for contamination exists in cases where the effluent brine is allowed to discharge on the ground close to well heads. The SMCL for chloride is 250 mg/L (U.S. Environmental Protection Agency, 1986). A salty taste can be detected in drinking water with chloride concentrations greater than 250 mg/L; however, the threshold of detection by taste for many individuals is generally around 500 mg/L. An elevated chloride concentration, in itself, does not constitute a health concern, although high levels of sodium can accompany chloride in water containing dissolved sodium chloride. The USEPA suggests that sodium concentrations in drinking water not exceed 20 mg/L to afford protection for that part of the population on a sodium-restricted diet (Federal Register, 1985). Ambient sodium concentrations analyzed in 14 samples with chloride concentrations less than 10 mg/L were less than 5 mg/L (appendix C).

Nitrogen (as $NO_2 + NO_3$) concentrations above 0.1 mg/L were observed in the Aquia aquifer. The MCL for nitrogen (as $NO_2 + NO_3$) is 10 mg/L (U.S. Environmental Protection Agency, 1986). Nitrogen (as $NO_2 + NO_3$) concentrations exceeded the MCL in two Aquia samples. The highest concentration detected was 15 mg/L in a sample collected in the fall of 1988 from well AA Df 147. This concentration decreased to approximately 1 mg/L in a sample collected in the fall of 1991 from the same well. The most common sources of nitrogen in ground water are sewage effluent and fertilizer. Nitrogen in sewage effluent is mostly in the form of ammonium ion (NH_4^+). Once it enters the ground-water system, NH_4^+ is converted to nitrate through a process known as nitrification ($NH_4^+ - NO_2^{-2} - NO_3^{-3}$). Nitrate is very mobile in oxygenated ground water because of its high solubility and anionic form and can migrate along ground-water flow paths for long distances (Canter and Knox, 1986). Nitrogen (as $NO_2 + NO_3$) concentrations greater than 10 mg/L can cause methemoglobinemia or "blue-baby syndrome" in infants. High concentrations of nitrogen have been associated with cancer. Nitrate converted to nitrite in the body can form N-nitroso compounds, which are classified as probable human carcinogens (Freshwater Foundation, 1988).

Concentrations of dissolved iron in the Aquia and Monmouth aquifers not affected by brackish-water intrusion ranged from 5 to 15,000 µg/L (micrograms per liter), with a median concentration of 140 µg/L calculated from 15 water analyses (table 2). Total-iron concentrations in 13 water analyses, representing dissolved and suspended-solid iron, ranged from 50 to 6,000 µg/L (appendix C.). In several samples total-iron concentrations were significantly higher than dissolved-iron concentrations. The differences in the total and dissolved concentrations are attributed to suspended colloidal iron particles unable to pass through the 0.45-micron filter used for collection of the dissolved sample. The SMCL for iron in drinking water is 300 µg/L (U.S. Environmental Protection Agency, 1986). Concentrations greater

than this value can stain clothing and plumbing fixtures and can impart a metallic taste to the water. Removal of iron is generally accomplished by a combination of increasing the pH of the water through the addition of a strong base (for example sodium hydroxide), application of oxidizing agents (for example chlorine and permanganate, MnO^{-4}), and passing the water through a sand or activated charcoal filter. Cation exchange also can be used to remove small quantities of iron (Lehr and others, 1988).

Dissolved iron in water from the Aquia and Monmouth aquifers originates from dissolution of iron oxyhydroxide sediment-grain coatings and authigenic iron-bearing minerals such as goethite, limonite, and iron hydroxide produced from the weathering of glauconite (iron-aluminum silicate). Approximately 30 to 40 percent of the total sand fraction of the Aquia Formation is composed of glauconite and goethite (FeOOH) (Hansen, 1974). In highly weathered zones, glauconite and goethite are altered to limonite $(FeOOH)\times nH_2O$ and iron hydroxide $Fe(OH)_3$, both of which are loose materials that can fill pore spaces and in some instances form sandstone. Weathered zones occur irregularly throughout the outcrop area in Anne Arundel County as discontinuous bands parallel to bedding. Weathering, caused by high concentrations of dissolved oxygen and low pH, is more pervasive in the outcrop area than in less aerated downdip sections of the Aquia aquifer. The reaction of iron in ground water is complex and depends on the amount of iron-bearing minerals in the sediment, the Eh (reduction-oxidation potential) of the water, the pH, and the availability of other ions and organic compounds that can bond with iron. Also, aqueous iron chemistry can be affected greatly by both iron-reducing and iron-oxidizing microorganisms.

Dissolved solids is a measure of the total concentration of dissolved constituents in solution and can be used as a gross indicator of water quality. In general, a low dissolved-solids concentration is preferred because there are fewer minerals in solution that might adversely affect water quality. A list of the major and minor dissolved, inorganic constituents commonly found in ground water is given in table 3.

Concentrations of dissolved solids in the Aquia and Monmouth aquifers ranged from 39 to 336 mg/L (table 2) and typically were between 200 and 300 mg/L. The median concentration calculated from 18 samples was 240 mg/L. The SMCL for public supply is 500 mg/L (U.S. Environmental Protection Agency, 1986).

The general chemical character of ground water can be classified according to the dominant ions present in the water. Complete and balanced chemical analyses of selected Aquia and Monmouth water samples were used to characterize the water type. Understanding the water type can help to determine if a sample is affected by brackish-water intrusion, to evaluate the water quality in regards to treatment, and to relate geochemical environments to the ground-water-flow system. A trilinear diagram (fig. 17) is used to graphically display the dominant ionic characteristics of the sampled aquifer water. On this diagram the percentage composition of cations and anions for multiple samples is plotted on the two triangles at the base. 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 sample alkalinity by a factor of 1.22. Samples from the Aquia and Monmouth aquifers affected by brackish-water intrusion and samples of pore fluid from Chesapeake Bay sediment cores are included on the diagram for comparison with freshwater samples. The water not affected by intrusion is a calcium and magnesium bicar-

Table 3. Major and minor inorganic constituents commonly found in ground water

Major constituents		Minor constituents	
Cations	Anions	Cations	Anions
Calcium, Ca	Chloride, Cl	Iron, Fe [1]	Fluoride, F
Potassium, K	Bicarbonate, HCO_3	Manganese, Mn [1]	Nitrate, NO_3
Magnesium, Mg	Carbonate, CO_3		Carbonate, CO_3
Sodium, Na	Sulfate, SO_3		
Silica, Si [2]			

[1] May be present as a major constituent in the Aquia and Monmouth aquifers.

[2] Silica in ground water is usually present as silicon (SiO_2).

bonate type. This water type is typical of the Aquia and Monmouth aquifers in the outcrop area where calcium magnesium carbonate shell material has been leached causing high levels of hardness. Chapelle and Drummond (1983) described the water from the Aquia aquifer as a calcium and magnesium bicarbonate type in the outcrop area, changing downgradient to a sodium bicarbonate type facies. The change from calcium and magnesium to sodium results in a "softening" of the water. The transition between the two water types becomes noticeable south of the study area in the northern part of Calvert County.

Magothy and Upper Patapsco aquifers

Water from the Magothy aquifer was analyzed in six test wells drilled for this study: wells AA Ce 127, 128, 130, 133, 134, and AA Cf 141 (appendix C). All the wells are located on Broadneck (pl. 1) with the exception of one well, AA Ce 130, which is located on Annapolis Neck at Sherwood Forest. The results of water-quality analyses indicate that water from the Magothy aquifer is an iron sulfate type high in acidity. The pH and alkalinity of water from the Magothy aquifer ranged from 3.6 to 5.4 standard units and 1 to 26 mg/L, respectively. Concentrations of iron ranged from 3,500 to 30,000 µg/L making the water, in the absence of treatment, generally unacceptable for public supply use. On Broadneck, Mack and Andreasen (1991, fig. 25) show concentrations of iron in the Magothy aquifer ranging from 8,700 to 30,000 µg/L in water along a cross section extending from the test well cluster at Lakeview to Sandy Point (pl. 1). Dissolved-solids concentrations in water from the Magothy aquifer were generally low. Concentrations ranged from 21 to 81 mg/L. Chloride concentrations were less than 3.5 mg/L. Chloride concentrations tested in the field in water from three residential supply wells (AA Cf 138, AA Cf 139, and AA Cf 140) screened in the Magothy aquifer showed levels less than 3 mg/L. These wells are located on the north shore of Broadneck Peninsula in an area potentially susceptible to brackish-water intrusion from the Magothy River.

Water from the Upper Patapsco aquifer was not tested during this study. A previous investigation showed that water from the Upper Patapsco aquifer is an iron sulfate type similar to that of the Magothy aquifer (Mack and Andreasen, 1991). Ranges in pH, iron concentration, and dissolved solids on Broadneck were 3.6 to 6.2 standard units, 1,600 to 38,000 µg/L, and 48 to 98 mg/L, respectively.

SIMULATION OF FLOW

A digital ground-water-flow model was designed for the study area to simulate the response of hydraulic heads to changes in various conditions. A simplified version of the ground-water-flow system was represented in digital form, and the U.S. Geological Survey modular three-dimensional, finite-difference, ground-water-flow computer code (McDonald and Harbaugh, 1984) was used to conduct the simulation. The theory and use of the model is fully discussed by McDonald and Harbaugh.

Conceptual Model of Ground-Water Flow

The computer code for ground-water-flow modeling (McDonald and Harbaugh, 1984) uses the general equation of ground-water flow to calculate hydraulic heads at any given time over a defined space. For the model used in this study, calculations were dependent on the following input parameters: aquifer transmissivity, leakage through confining units, leakage through streambeds, ground-water withdrawals, and recharge from precipitation. A conceptualized model of the actual ground-water-flow system (fig. 18) was used to estimate the input values for the ground-water-flow model. This figure indicates the layered structure of the system of aquifers and intervening confining units, and the general direction of ground-water flow within and between aquifers. As indicated in figures 18 and 19, flow is from recharge areas into either the shallow unconfined flow system discharging to streams or into the deeper confined flow system. The flow in the deeper confined system discharges upward through overlying confining units or horizontally out of the study area.

The geometry of the flow system describes the location and extent, both vertically and horizontally, of the aquifers and intervening confining units. Figure 18 depicts a two-dimensional slice of the geometry. Boundary types, as discussed later, include variable-head, constant-head, general-head, and no-flow conditions. Model discretization includes (1) the rectangular gridding of space both vertically and horizontally and (2) division of time into discrete periods of constant stress during which rates of recharge, withdrawal, and certain boundary conditions remain constant. Hydraulic properties specified for the flow system are transmissivities and storage coefficients for the aquifers and vertical hydraulic conductivities for the intervening confining units. Recharge was uniformly applied to all recharge areas and varied with the discretization of time. The interaction between streamflow and ground-water flow was specified from estimates of stream geometry and streambed conductance.

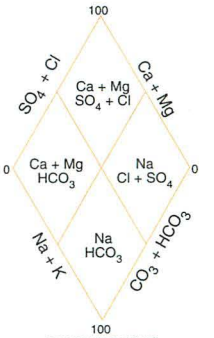
The model was used to estimate hydraulic-head changes during 1900-90. Model-estimated head changes compared to measured head changes indicated the accuracy of the model calibration. The model then was used to estimate head changes and flow patterns through the year 2020 for the study area.

Simulation of Ground-Water Flow

Modeling theory and data requirements

The movement of water through permeable sediments, such as those of which the Coastal Plain aquifers of Anne

PLOT NUMBER	WELL NUMBER (PLATE 1)	AQUIFER
1	AA Cg 25	Monmouth
2	AA De 35	Aquia
3	AA De 105	Aquia
4	AA De 159	Aquia
5	AA De 189	Aquia
6	AA De 193	Monmouth
7	AA De 195	Aquia
8	AA De 196	Aquia
9	AA De 197	Aquia
10	AA De 200	Monmouth
11	AA De 201	Monmouth
12	AA Df 32	Aquia
13	AA Df 131	Monmouth
14	AA Df 132	Aquia
15	AA Df 151	Monmouth
16	AA Df 152	Aquia
17	AA Df 154	Monmouth
18	AA Df 155	Monmouth
19	AA Ee 10	Aquia
20	AA Ee 81	Monmouth
21	AA Ef 2	Aquia
22	AA Ef 18	Aquia
23	AA Ef 31	Aquia
24	AA Ef 32	Monmouth
25	AA Ef 33	Aquia
26	AA Ef 34	Aquia
27	AA Ef 35	Monmouth
	SEDIMENT CORE NUMBER (SEE TABLE 4 FOR CHEMICAL ANALYSIS AND FIGURE 48 FOR SAMPLE LOCATIONS)	
28	1	
29	2	
30	3	
31	4	
32	5	



DOMINANT IONS DEFINING WATER TYPES

EXPLANATION

- ○ 3 GROUND WATER NOT AFFECTED BY BRACKISH-WATER INTRUSION.
- ● 15 GROUND WATER AFFECTED BY BRACKISH-WATER INTRUSION.
- □ 32 PORE WATER FROM SELECTED BOTTOM-SEDIMENT CORES LOCATED NEAR THE STUDY AREA.

NUMBER NEXT TO SYMBOL INDICATES PLOT NUMBER.

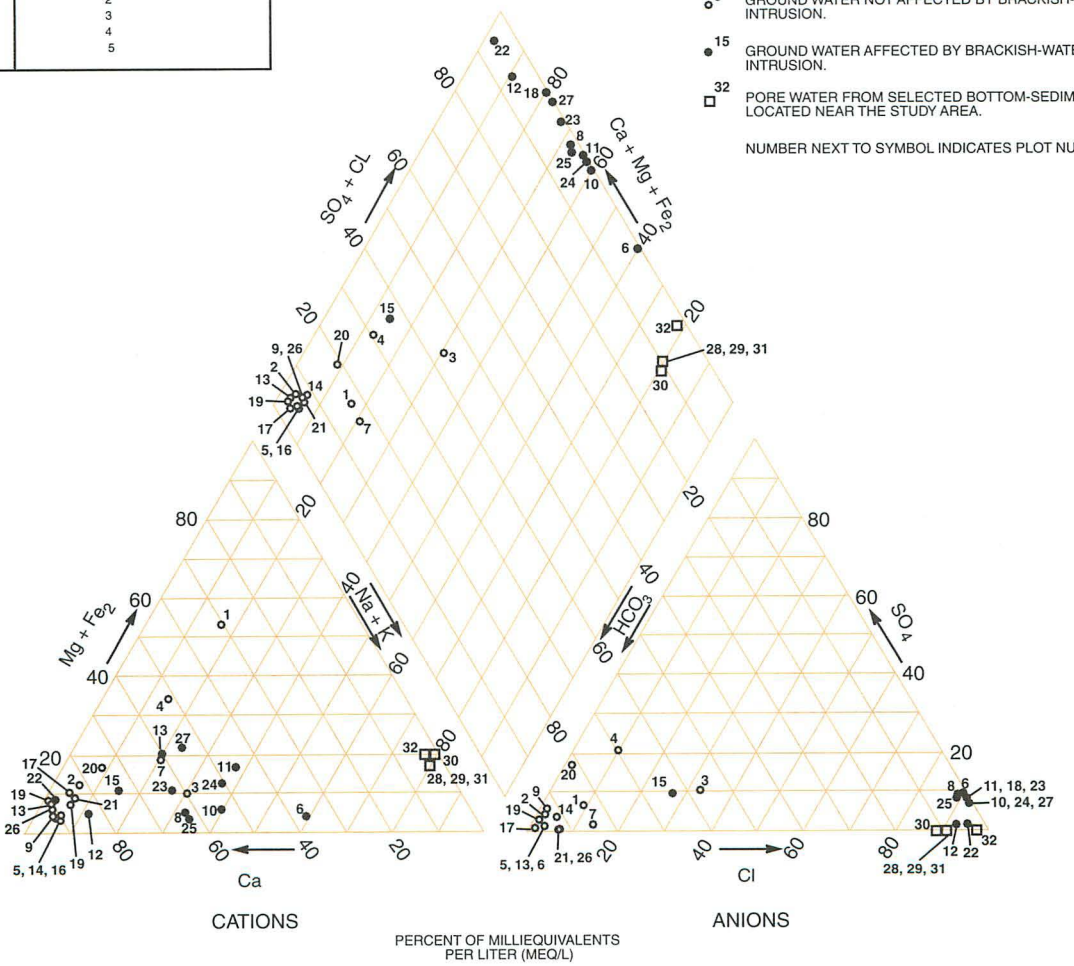


Figure 17. Trilinear diagram showing dominant inorganic chemical constituents in water from the Aquia and Monmouth aquifers and selected Chesapeake Bay bottom-sediment cores.

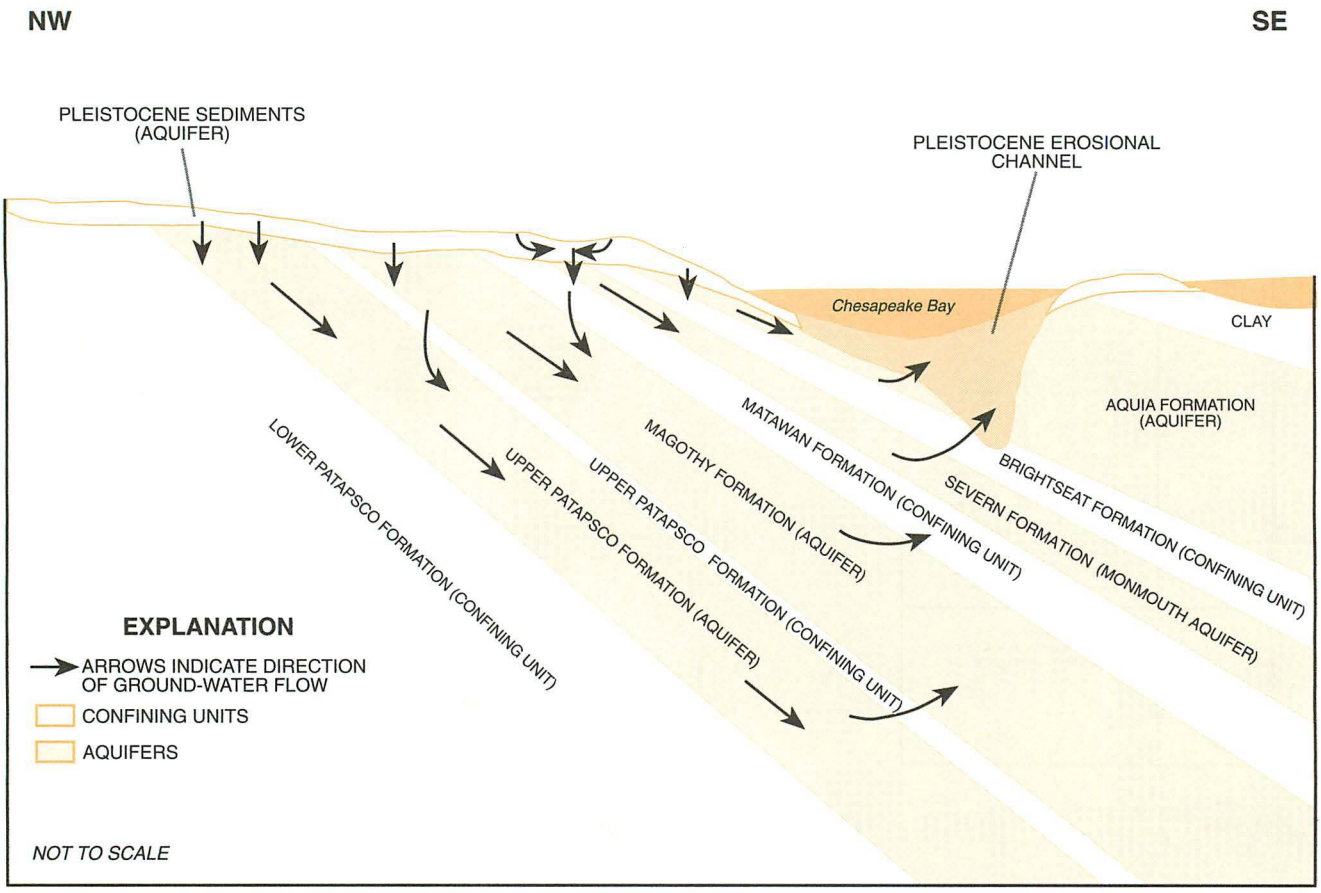


Figure 18. Generalized hydrologic section showing general ground-water-flow patterns along model row 11.

Arundel County are composed, can be described in two dimensions by the partial differential equation (Fetter, 1988, p. 135):

$$\frac{\partial^2 h}{\partial x^2} + \frac{\partial^2 h}{\partial y^2} + \frac{W}{T} = \frac{S}{T}\frac{\partial h}{\partial t} \qquad (7)$$

where

x,y = Cartesian coordinates [L],
h = potentiometric head [L],
W = rate of accumulation [LT^{-1}],
T = hydraulic transmissivity [L^2T^{-1}],
S = storage coefficient [dimensionless], and
t = time [T].

The rate of vertical movement of water through less permeable confining units can be described by Fetter (1988, p. 135):

$$q = K'\frac{(h_1 - h_2)}{b'} \qquad (8)$$

where

q = rate of vertical movement [LT^{-1}],
K′ = vertical hydraulic conductivity of the confining unit [LT^{-1}],
h_1,h_2 = potentiometric heads at top and bottom of confining unit [L], and
b′ = thickness of confining unit [L].

Equations 7 and 8, coupled with either hydraulic head or flow for boundary conditions and the initial hydraulic-head values, describe the head conditions at any point within the flow system at any time. However, because of the complexity of the flow system, the partial differential equation, equation 7, is difficult to solve and thus is replaced by sets of finite-difference numerical approximations.

Assumptions

The ground-water-flow model, as an approximation of the geometric, hydrologic, and hydraulic characteristics of the flow system, requires a number of simplifying assumptions. The principal assumptions for the model used in this study are:

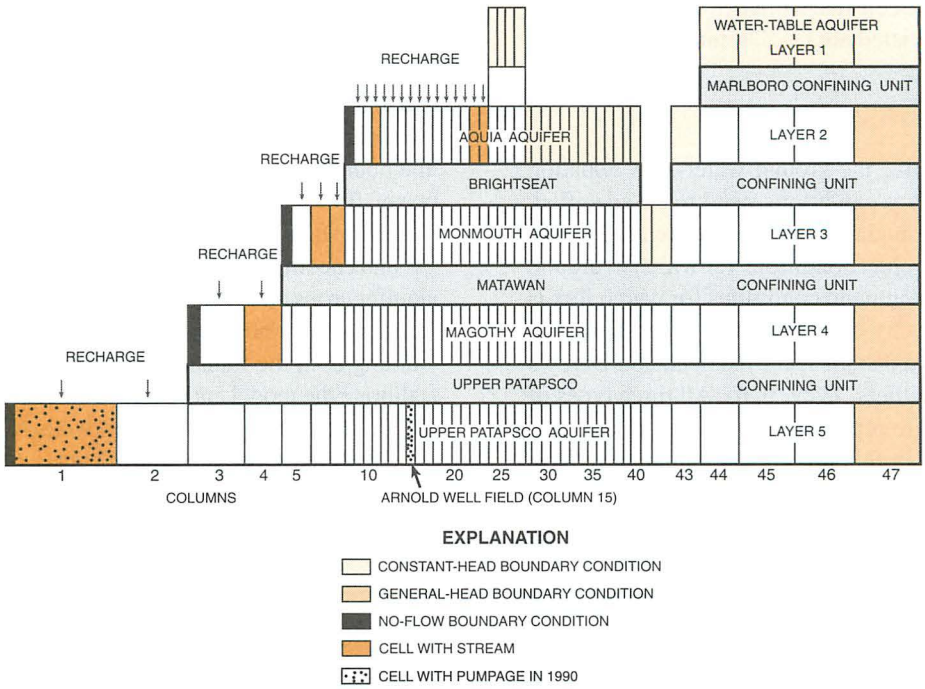


Figure 19. Diagram showing structure of ground-water-flow model along model row 11.

1. Both the measured and calculated hydraulic heads in each cell represent an average for the entire cell. This is a good approximation for the area encompassed by Annapolis Neck and most of Broadneck and the Mayo Peninsula where each cell is less than 0.1 mi^2. Around the perimeter of the model, however, the cells range in size from 0.6 to 10.8 mi^2, and thus here, the assumption is a gross approximation.

2. Hydraulic heads in model layer 1 represent water-table conditions. These heads are held constant in time but variable in space through all simulations and act either as sources of recharge or sinks of discharge with respect to the ground-water-flow system. This is a good assumption because the hydraulic heads tend to fluctuate above and below a common mean.

3. Horizontal hydraulic conductivity of the aquifers is assumed to be isotropic. Although there is no detailed information with respect to horizontal anisotropy within the aquifers, it is probably very small.

4. Flow within the aquifers is assumed to be horizontal. This assumes that there is little or no vertical hydraulic-head difference across each aquifer and that the vertical hydraulic conductivity is much less than the horizontal hydraulic conductivity. Both of these assumptions are probably good approximations of the actual conditions.

5. Flux in the confining units is only calculated in the vertical direction as leakage between aquifers and is based on the hydrologic properties of the confining unit. Because of the low hydraulic conductivities of the confining units compared to aquifers, this is a good assumption.

6. Recharge is uniform for each stress period throughout the entire model area. Recharge is a calculated average both areally and through time of each stress period. Because of the length of the stress periods, an average recharge is probably a good assumption.

7. For cells in which streams are modeled, the stream stage is set constant for the entire simulation. Because stress periods are no shorter than 1 year, setting stream stages constant is a good assumption.

8. Patapsco Formation clay underlying and along the western side of the Upper Patapsco aquifer is modeled as a no-flow boundary. This, because of the clay's low transmissivity, is a good assumption.

9. The Magothy Formation in Southern Maryland is an erosional truncation. This truncation is considered to be a no-flow boundary condition. This is a good assumption.

Grid design

The modeled area was divided into a three-dimensional array of 43 rows, 47 columns, and 5 layers, consisting of 2,021 cells per layer. The grid of rows and columns was oriented orthogonally to the principal direction of ground-water flow, which is generally to the southeast within the modeled area (fig. 20). The grid is designed to include the greatest detail in the area of principal interest for the purposes of this study. As shown in figure 20, this area (86.1 mi^2) is divided into the smallest model cells, each of which encompasses 0.09 mi^2. Extending outward toward the limits

of the modeled area, the cell size increases to a maximum of 10.8 mi^2. The total modeled area is 870 mi^2.

Boundary conditions

To numerically solve the ground-water-flow equation (eqs. 7 and 8), boundary conditions need to be specified. Three basic types of boundary conditions were used in this model analysis: (1) Dirchlet conditions for which hydraulic head is specified, (2) Neumann conditions for which flux is specified, and (3) Cauchy conditions for which head and flux are dependent on a distant specified head and Darcy's equation (Franke and others, 1987, p. 6). All three types of boundary conditions are represented in the ground-water-flow model described in this report. The boundary conditions represent constant heads, recharge, streams, general heads, and no flow situations. A constant-head boundary specifies a known hydraulic-head condition. Recharge, streams, general heads, and no flow specify a flux across a boundary. Figures 21 to 30 indicate the areal distribution of the boundary conditions for each layer used in the ground-water-flow model.

Model layer 1 represents the surficial water-table aquifer and encompasses the model area west of where the Aquia aquifer crops out. Hydraulic heads representing the surficial aquifer were held constant throughout each simulation, including both the transient simulations for 1900-90 used to calibrate the model and the predictive simulations for 1990-2020. There are no observation wells for layer 1 within the modeled area. Generally, water levels in the water-table aqui-

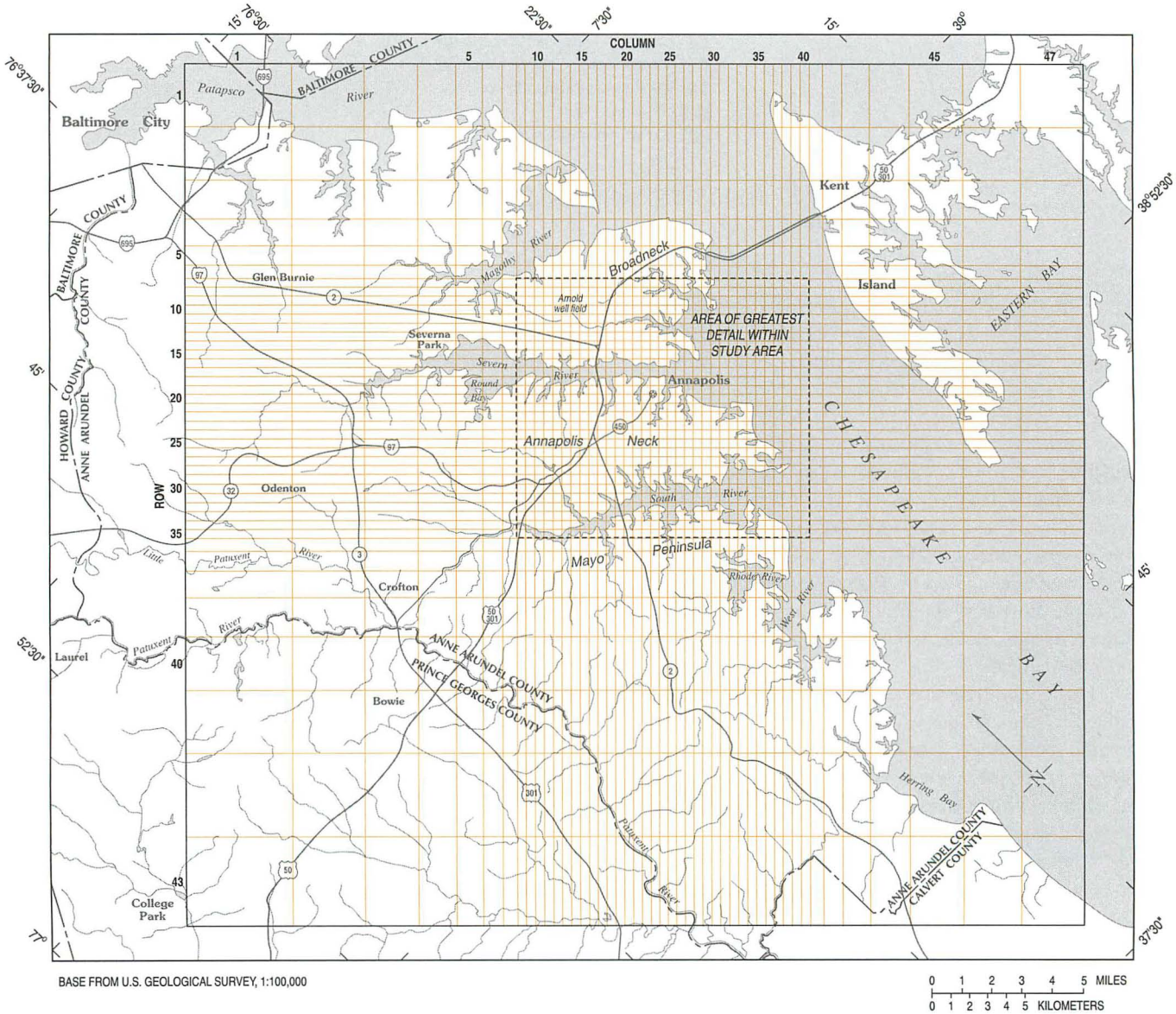


Figure 20. Location and design of finite-difference grid used in the ground-water-flow model.

fer of southern Maryland fluctuate on a yearly basis within a limited range of about 10 ft (Fleck and Wilson, 1990, p. 43). Three water-table observation wells in Calvert County a few tenths of a mile south of the modeled area with cumulative measurements from 1947 through 1990 indicate that during this period of record the maximum annual fluctuation was 15 ft, but that the average annual water level remained constant. For this study, the altitude of the water table was estimated from the altitude of perennial streams that intersect the water table. The constant-head boundary in the water-table aquifer acts as an infinite source of recharge to the underlying Aquia aquifer through the intervening Marlboro confining unit.

Boundary conditions for the Aquia aquifer, which is represented by layer 2 in the flow model, include constant head, general head, stream, recharge, and no flow and are shown in figures 22 and 23. Constant-head conditions, figure 22, for the flow model are specified for the Aquia aquifer where it subcrops beneath Chesapeake Bay and the estuarine parts of the Magothy and Severn Rivers. These constant heads were specified at altitudes slightly higher than sea level to account for density differences between the saltier water of the bay and the freshwater flow system. General-head boundary conditions, as indicated in figure 22, are located in cells along the flow-model boundary. The general-head condition assumes a hydraulic head that is specified for each stress period located some distance from the model boundary. Also specified is the hydraulic conductance between the specified head and the model boundary (McDonald and Harbaugh, 1984, p. 343). Thus, a general-head condition consists of either a source or sink of water located outside the modeled area. Another type of boundary condition for model layer 2 is a stream boundary. Stream boundaries are indicated in figure 22. A stream boundary specifies a constant stream head (stage) and a streambed conductance (McDonald and Harbaugh, 1984, p. 209). The rate and direction of flux between the stream boundary and the aquifer are determined by Darcy's law.

The location of recharge applied to model layer 2 is shown in figure 23. Recharge for the flow model is applied to all cells that represent the uppermost active layer. In the case where the uppermost active cell is specified as a constant head, no recharge is applied. Recharge for the flow model varied from stress period to stress period but remained constant over the duration of each stress period. The amount of recharge for each stress period was determined as follows:

(1) Base flow for 22 streamflow-gaging stations located in or near the modeled area was determined using three computerized methods (Pettyjohn and Henning, 1979).

(2) Average annual precipitation for 1933-90 was determined for 14 precipitation stations within or near the modeled area.

(3) Regression equations were calculated for each site for which base flow under unstressed conditions was the dependent variable and annual precipitation was the independent variable.

(4) A weighted-average base flow for unstressed conditions for each stress period was calculated by applying a weighted-average technique to the regression equations. This weighted-average base-flow value was applied to the model as recharge. Figure 24 indicates the average annual precipitation and the weighted-average base-flow value that was applied to the model as recharge. The average precipitation from 1933 to 1990 was about 43 in. and the average recharge was 11 in.

No-flow boundary conditions exist along the west side of the active area, as indicated in figure 23, and represent the updip pinch-out of the Aquia aquifer.

Boundary conditions specified for layer 3 of the flow model are shown in figures 25 and 26. Constant-head boundaries, as shown in figure 25, are located where the Monmouth aquifer subcrops beneath Chesapeake Bay and its estuaries. The perimeter of layer 3 is surrounded by either general-head or no-flow boundary conditions (figs. 25 and 26). Stream boundaries are located only where the Monmouth either subcrops or crops out within the model area, as shown in figure 25. The amount and distribution of applied recharge are indicated in figure 26. As with the other model layers, recharge is applied to cells that represent the area of outcrop.

The type and distribution of boundary conditions used in model layer 4 are shown in figures 27 and 28. About 35 constant-head cells are located where the Magothy aquifer subcrops beneath the sediments of Chesapeake Bay, the Magothy River, and Round Bay. Again, as with layers 2 and 3, the active cells of layer 4 generally are surrounded on three sides by general-head boundary cells and on the fourth side by a no-flow boundary. The location of stream and recharge boundaries are shown in figures 27 and 28.

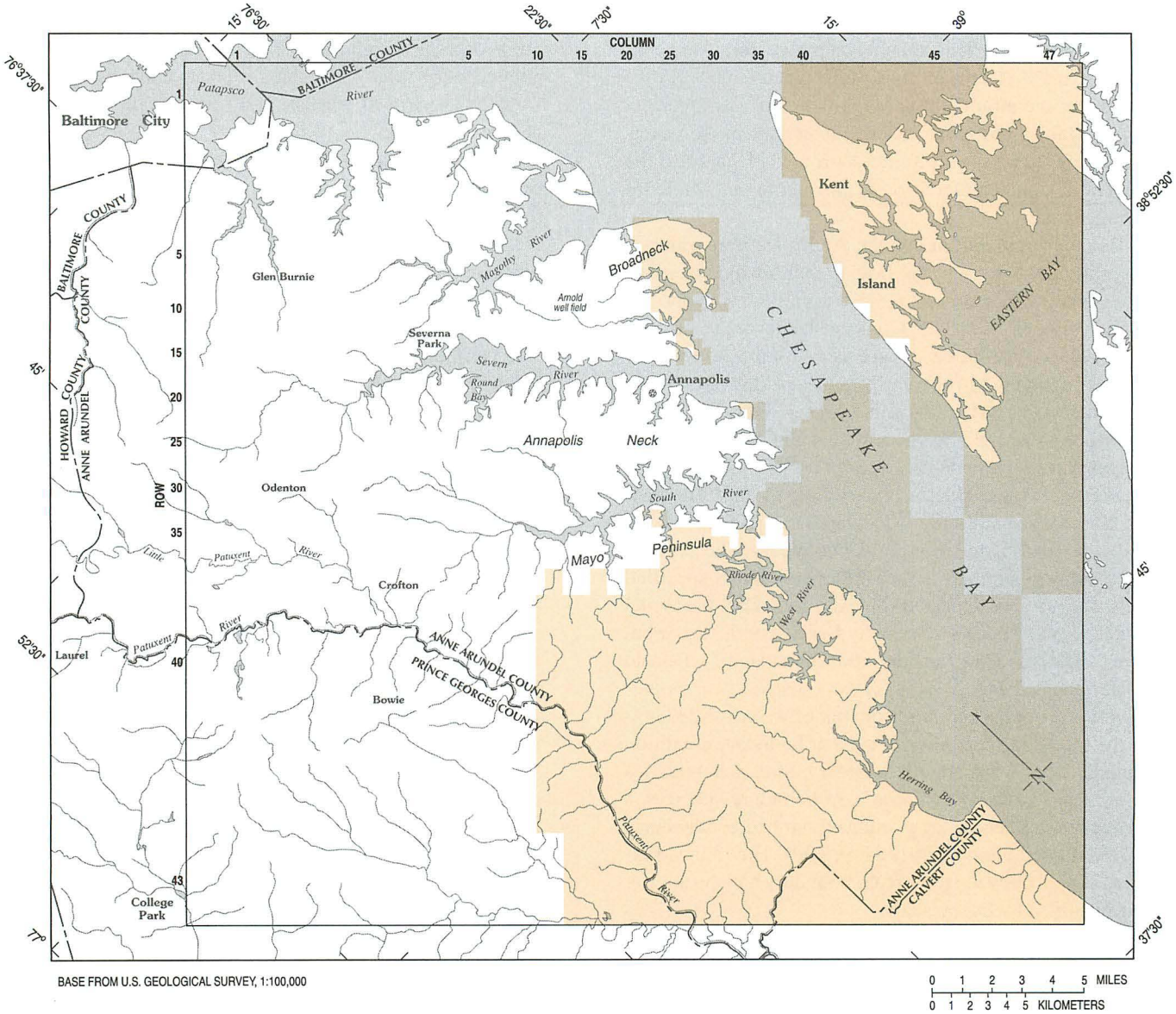
Layer 5 is the bottommost layer of the ground-water-flow model and, thus, is specified as a no-flow boundary. This no-flow boundary represents the silt and clay confining unit between the Upper Patapsco aquifer (layer 5) and the deeper Lower Patapsco aquifer. The other boundary conditions for layer 5 are similar to layers 2-4 and are indicated in figures 29 and 30.

Initial conditions

Initial conditions for the model were prepumping heads obtained from maps of hydraulic heads for each model layer and prepared for prepumping conditions from data stored in the U.S. Geological Survey's water data bases (WATSTORE).

Model calibration

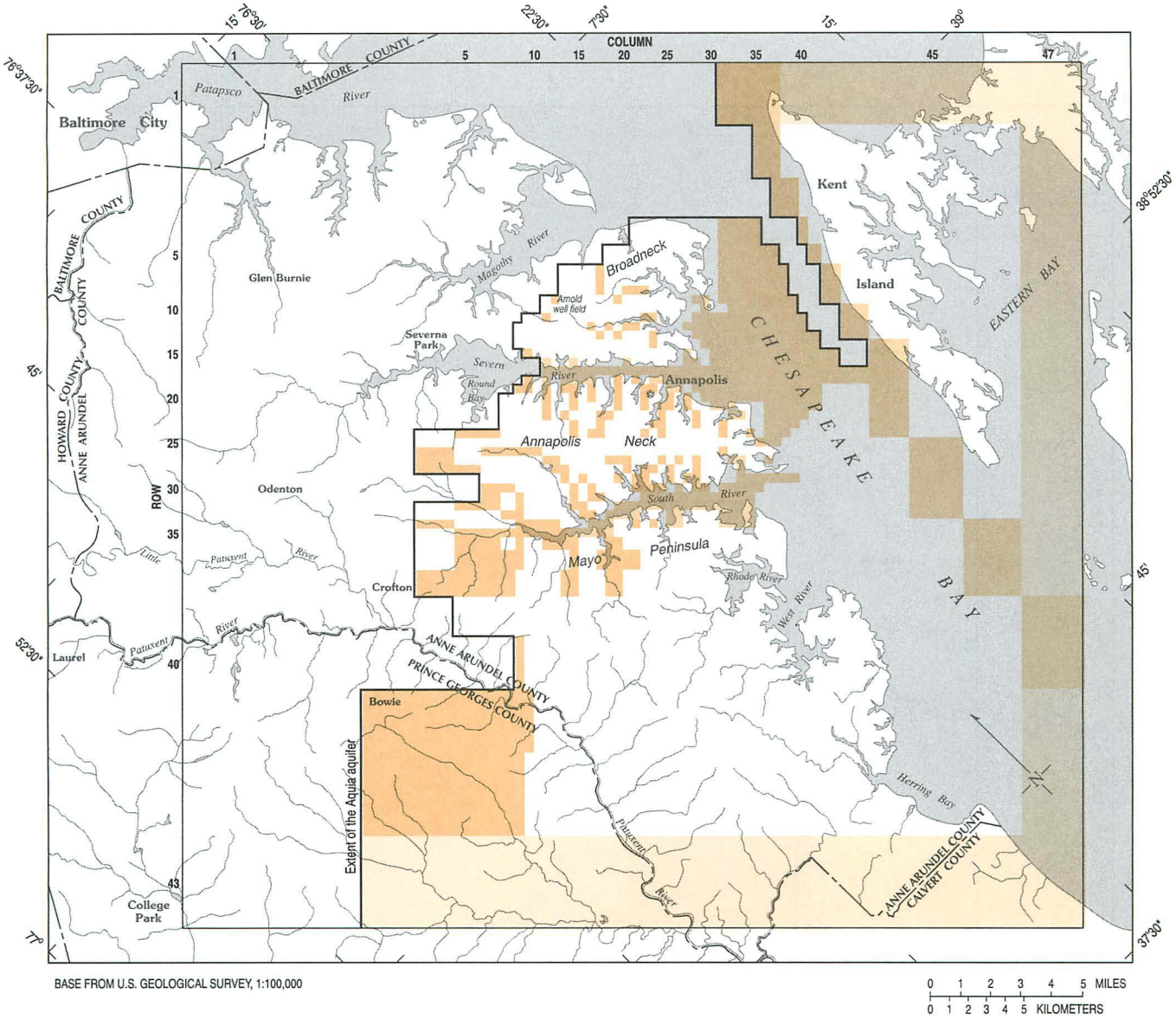
Initially, a model is constructed using best estimates for the necessary hydraulic properties and boundary conditions. The next step in the modeling process is model calibration. Calibration is the process in which model input is adjusted



EXPLANATION

CELLS WITH CONSTANT-HEAD BOUNDARY CONDITION

Figure 21. Boundary conditions used in ground-water-flow model for layer 1 (water-table aquifer).



EXPLANATION

CELLS WITH GENERAL-HEAD BOUNDARY CONDITION

CELLS WITH CONSTANT-HEAD BOUNDARY CONDITION

CELLS WITH STREAM BOUNDARY CONDITION

Figure 22. Constant-head, general-head, and stream boundary conditions used in ground-water-flow model for layer 2 (Aquia aquifer).

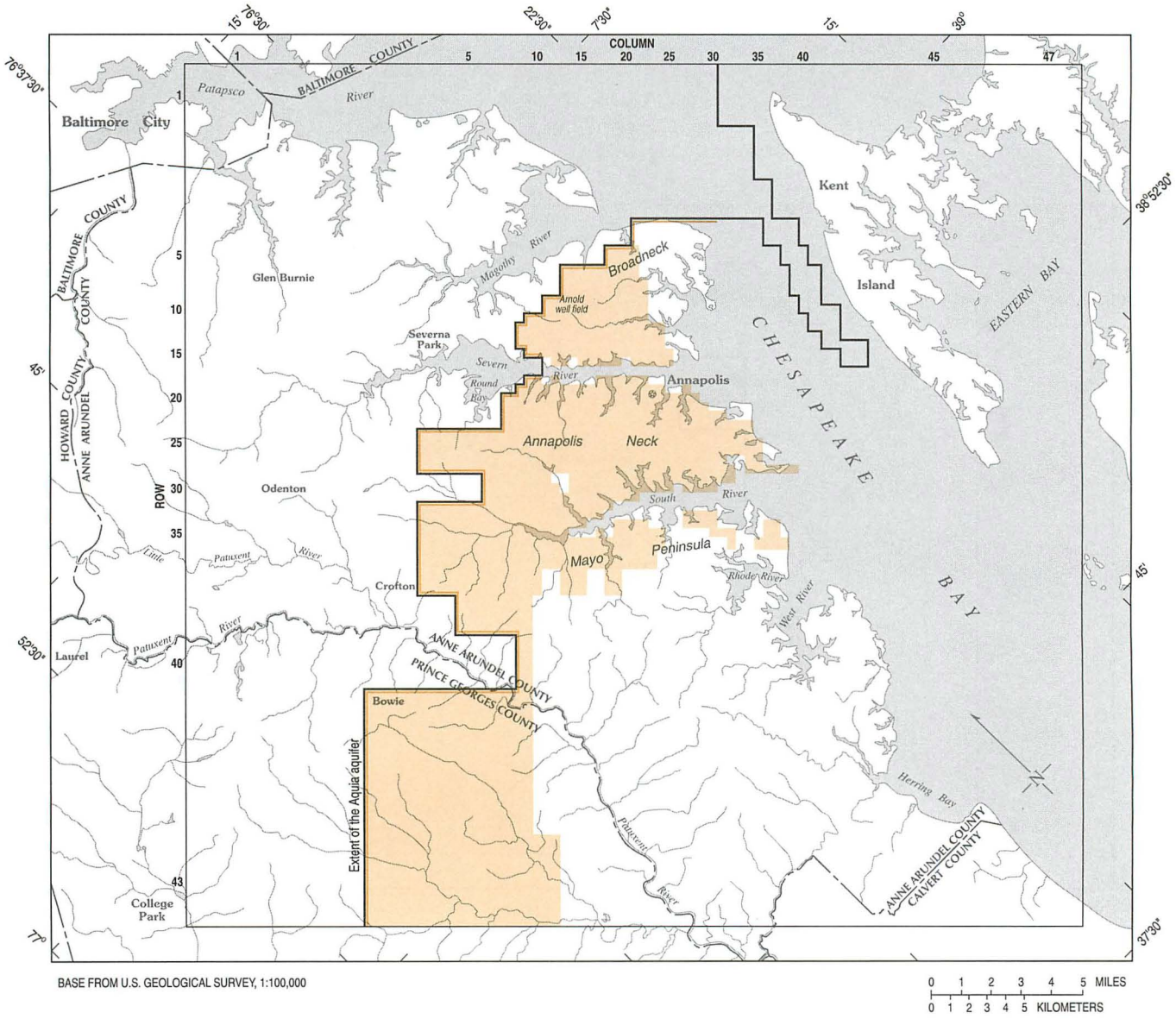


Figure 23. Applied recharge and no-flow boundary conditions used in ground-water-flow model for layer 2 (Aquia aquifer).

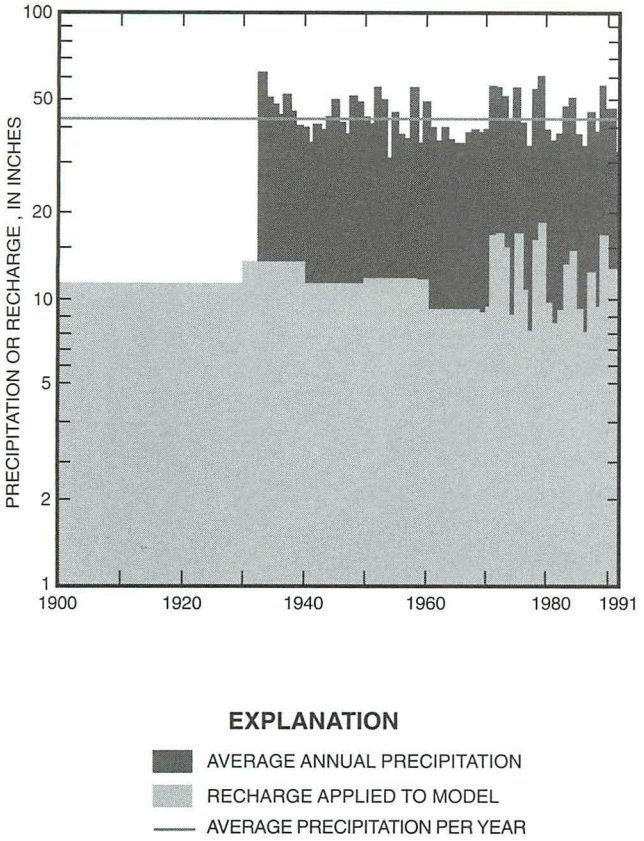


Figure 24. Graph showing recharge, as input to ground-water-flow model, compared to average annual precipitation (based on data from 22 streamflow-gaging stations and 14 precipitation stations).

until model output is consistent with measured head conditions. A model is not usable until it is able to reproduce within reasonable limits measured head conditions. When a model is satisfactorily calibrated it may be used to test various predictive hypotheses. In this study, calibration was a two-step process. First the model was crudely calibrated under steady-state unstressed conditions. The results of this step then were used as initial conditions for calibration of the model for the transient period 1900-90.

Steady-state calibration.— The ground-water-flow model was first calibrated under steady-state conditions. This steady-state model was an approximation of conditions that existed prior to any pumpage; therefore, no pumpage is input to the model, and recharge is held constant. A steady-state solution is independent of time, and therefore, water in storage remains constant. Thus, storage parameters are not calibrated. The procedure involved hydraulic-head calculations based on the original input data sets. The calculated heads were compared to earliest measured heads reported in the literature.

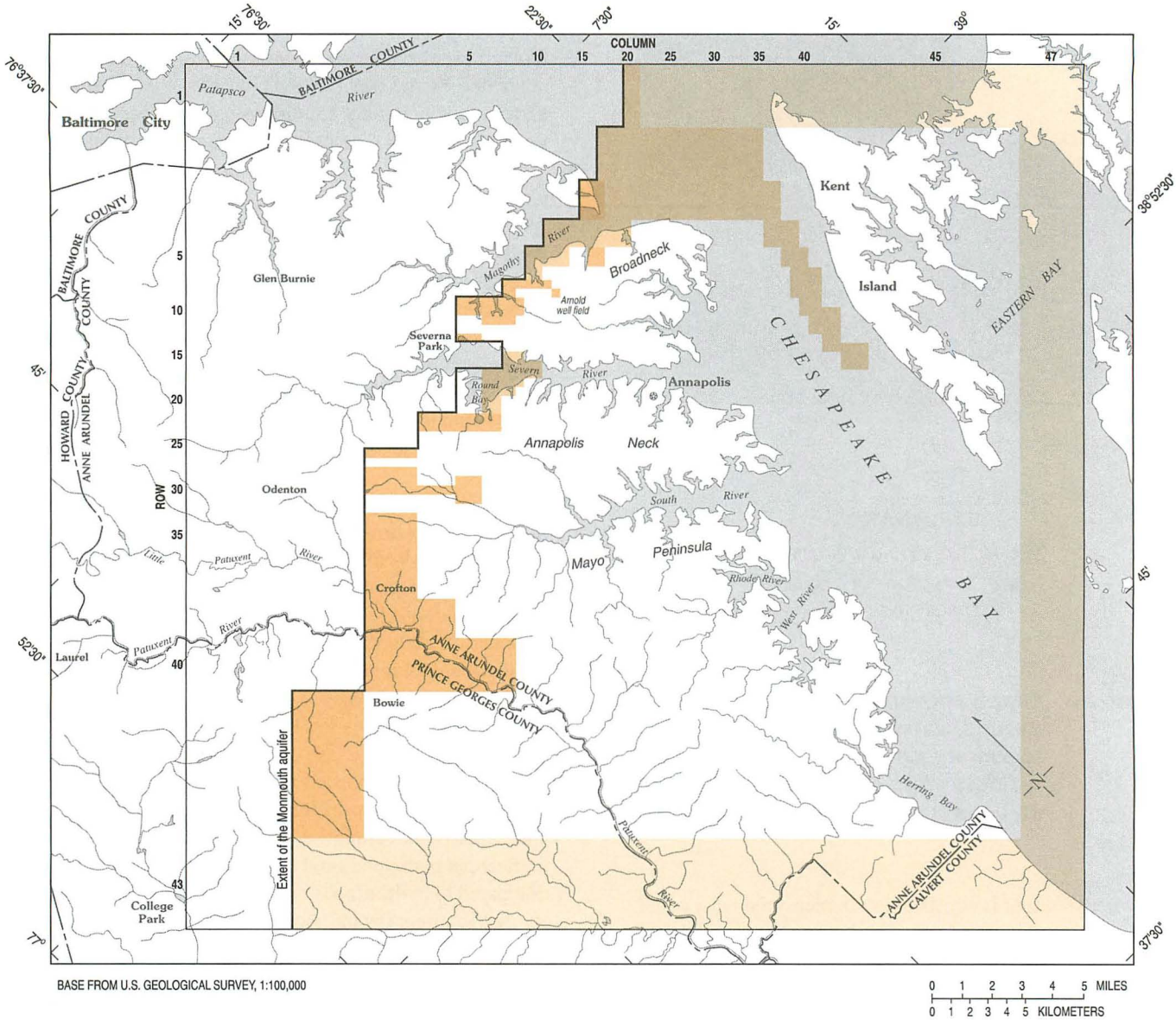
The boundary conditions, as previously discussed, included recharge to those cells that represented aquifer outcrops, constant-head conditions, general-head conditions, and no-flow boundaries. For the steady-state model, an average recharge of 11 in/yr was applied to each model cell that represented the outcrop areas. The total outcrop area as simulated by the model was 332 mi^2. Both constant-head and no-flow boundary conditions were the same as used in the transient calibration and as discussed in the section on "Boundary conditions." The general-head boundary cells along the west side and across the northern and southern model limits represent the best estimate of the prepumping heads that existed some distance outside the model.

The purpose of calibrating the flow model under prestress steady-state conditions was to obtain reasonable head arrays for the initial head conditions to be used as input to the transient-flow model. To do this it was necessary to make some modifications to the input values. For this calibration the only input values modified were aquifer transmissivities and streambed leakance.

Transient calibration.— The second step in the calibration process was to simulate the transient period 1900 through 1990. The stress on the ground-water-flow system due principally to pumpage withdrawals resulted in changing or transient conditions. Table 4 indicates the discretization of the time period 1900 through 1990 into 27 stress periods and the total budget for each stress period for storage, constant heads, pumpage, recharge, streams, and general heads.

Pumpage stresses in 1900 were negligible, and therefore, initial conditions used as input to the transient calibration simulations consisted of the hydraulic heads derived from the steady-state, unstressed calibrated model. For each simulation of the calibration process, adjustments were made to the input parameters and the model simulated heads were compared to hydrographs of measured heads. Transmissivity distributions for the Aquia (Chapelle and Drummond, 1983), Magothy (Mack and Mandle, 1977), and Upper Patapsco (Mack and Achmad, 1986) aquifers were calibrated for earlier model studies and were incorporated into this model. These earlier studies established a transmissivity framework that was used as initial input to the model. Generally, modification of these transmissivities during calibration was slight. An exception was that for the Magothy aquifer; some of the high transmissivities previously used were reduced by as much as 50 percent. This was necessary in order to calibrate the newer observation-well measurements made during the last 15 years. The transmissivity distribution for layer 4 (Magothy aquifer) of the transient model is shown in figure 31. The transmissivity distribution for layer 2 (Aquia aquifer) of the transient model ranged from near zero at its western limit to about 1,100 ft^2/d near Annapolis to a high of 3,100 ft^2/d in the southern part of the model area. The transmissivity distribution of layer 5 (Upper

(Text continued on p. 52.)



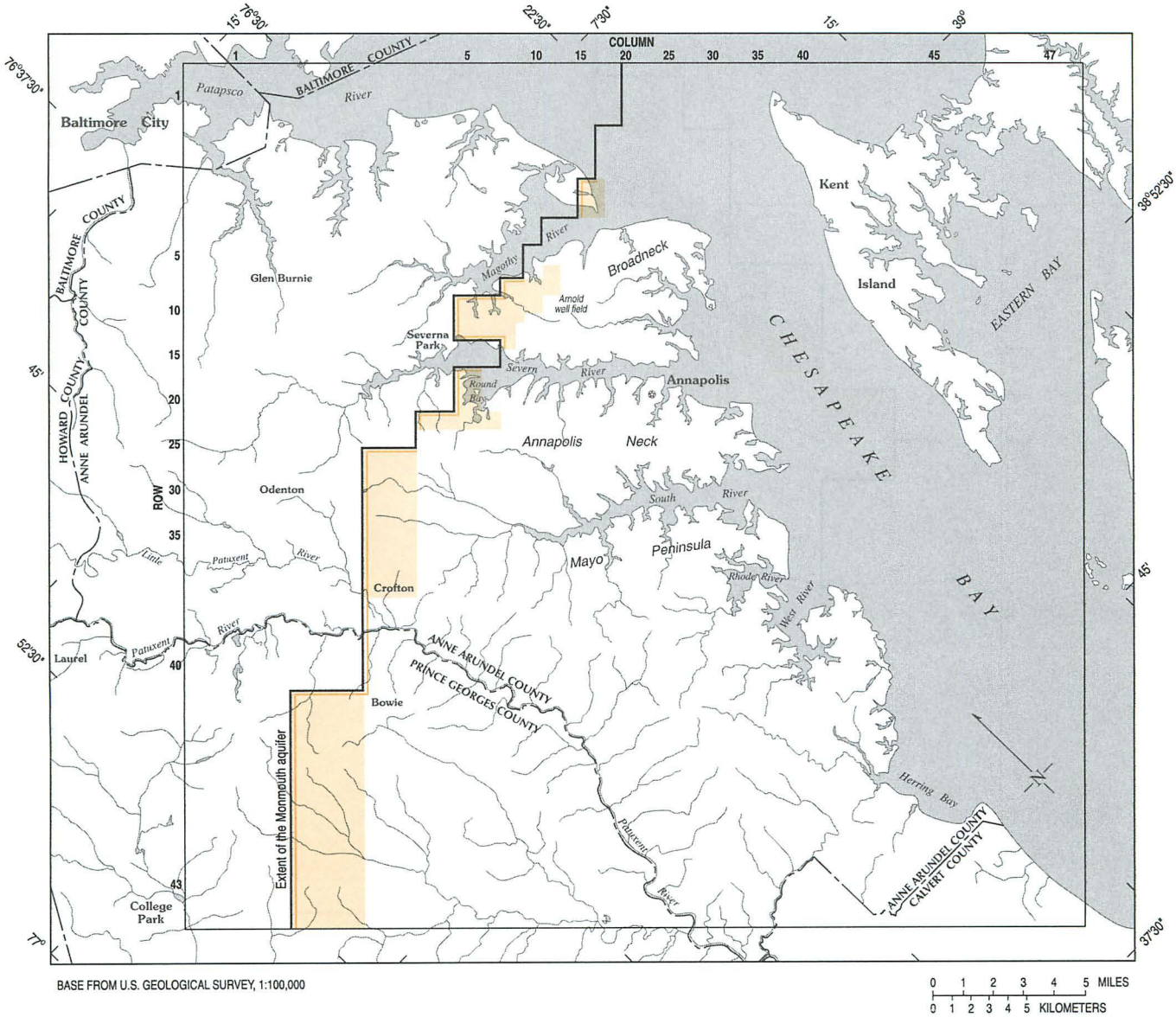
EXPLANATION

CELLS WITH GENERAL-HEAD BOUNDARY CONDITION

CELLS WITH CONSTANT-HEAD BOUNDARY CONDITION

CELLS WITH STREAM BOUNDARY CONDITION

Figure 25. Constant-head, general-head, and stream boundary conditions used in ground-water-flow model for layer 3 (Monmouth aquifer).

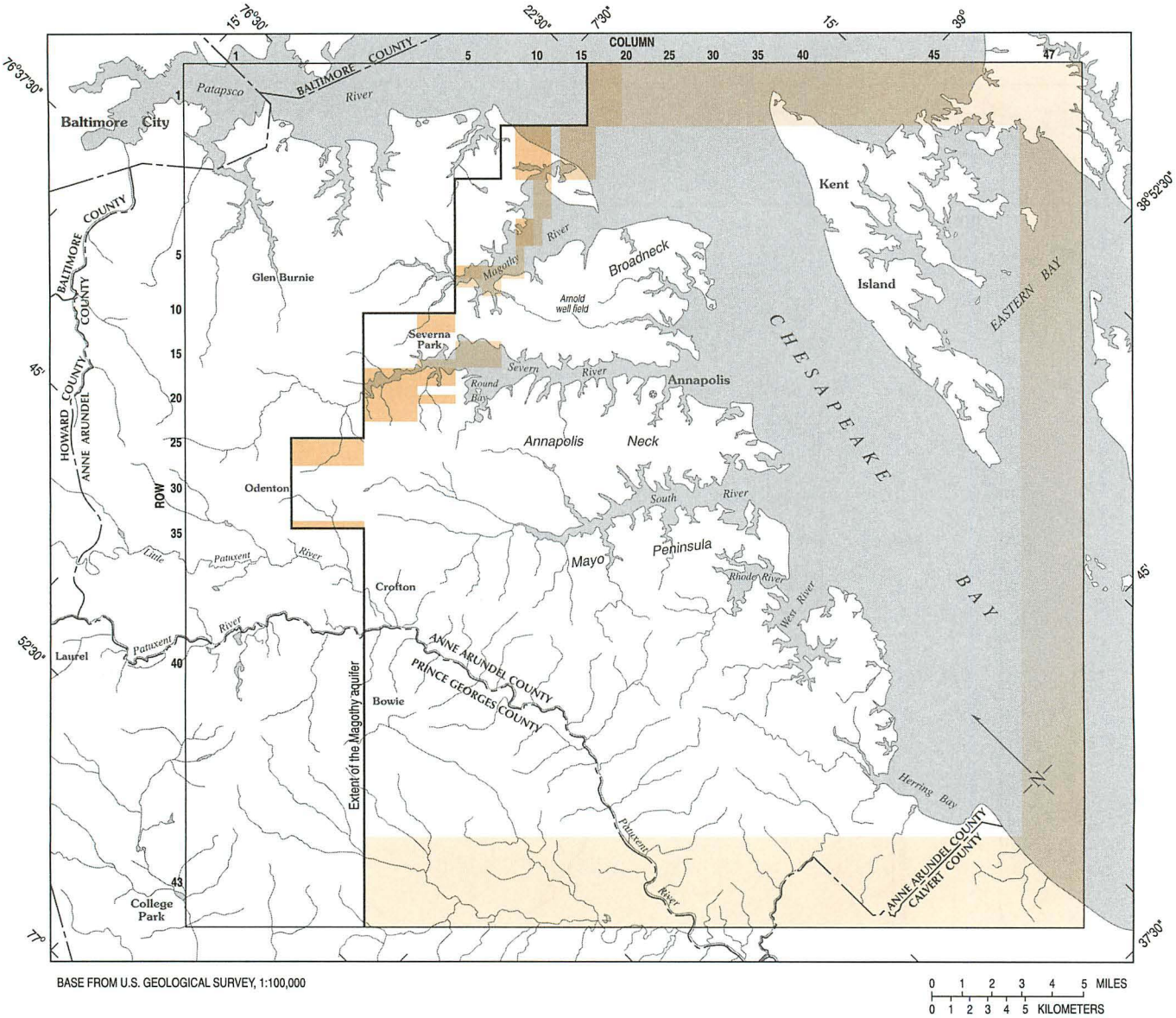


EXPLANATION

CELLS WITH APPLIED RECHARGE BOUNDARY CONDITION

NO-FLOW BOUNDARY

Figure 26. Applied recharge and no-flow boundary conditions used in ground-water-flow model for layer 3 (Monmouth aquifer).



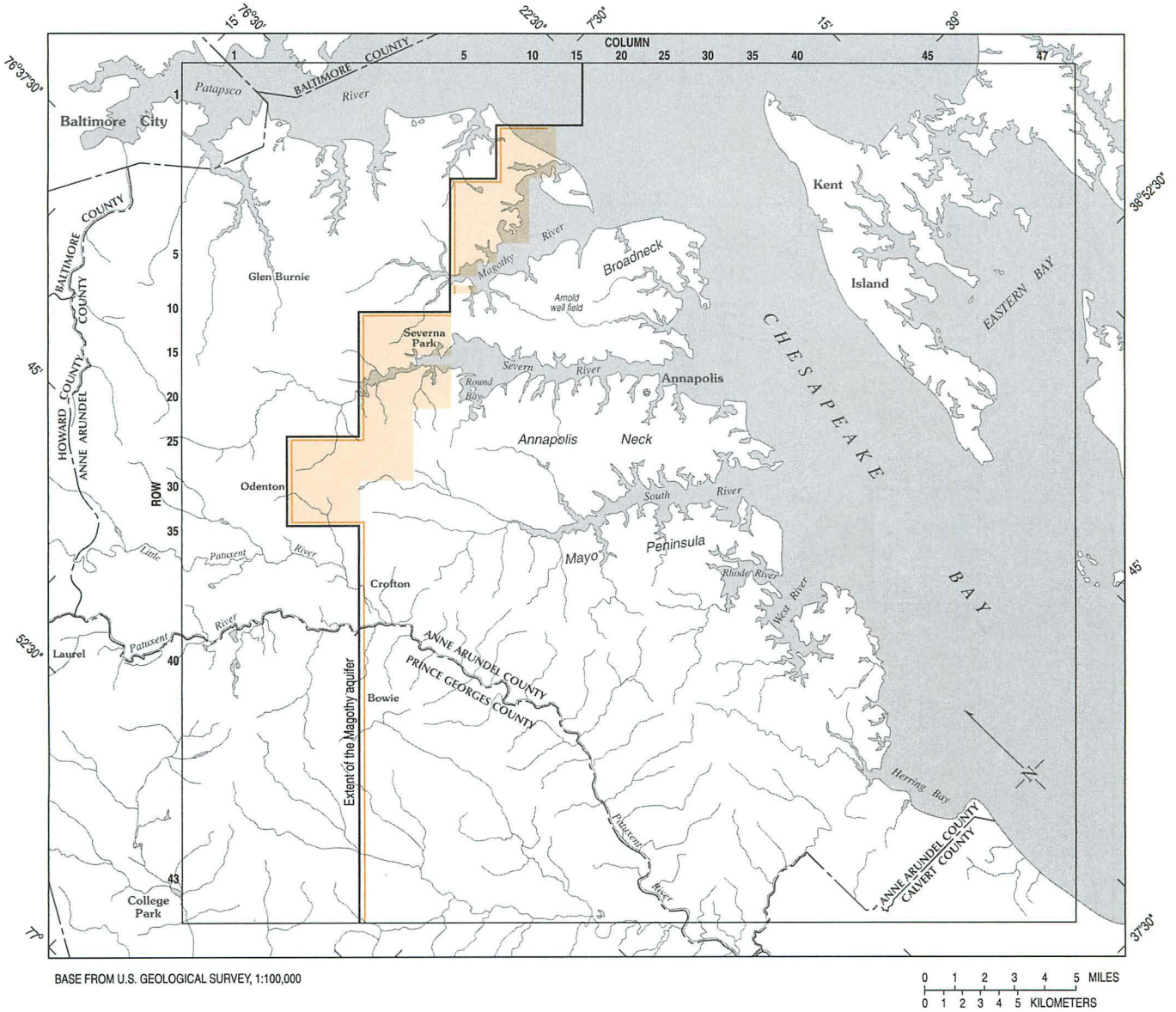
EXPLANATION

CELLS WITH GENERAL-HEAD BOUNDARY CONDITION

CELLS WITH CONSTANT-HEAD BOUNDARY CONDITION

CELLS WITH STREAM BOUNDARY CONDITION

Figure 27. Constant-head, general-head, and stream boundary conditions used in ground-water-flow model for layer 4 (Magothy aquifer).

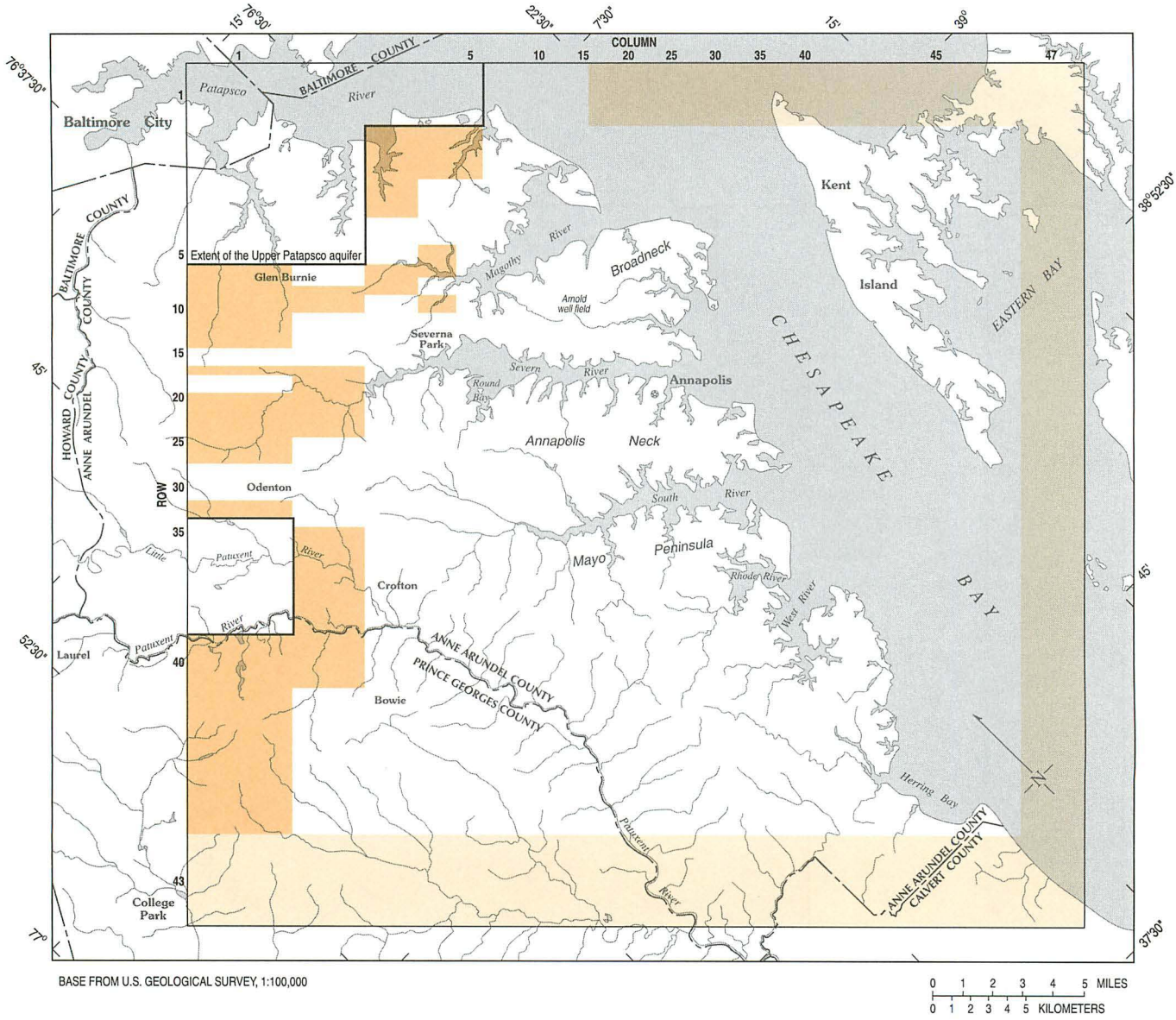


EXPLANATION

CELLS WITH APPLIED RECHARGE BOUNDARY CONDITION

NO-FLOW BOUNDARY

Figure 28. Applied recharge and no-flow boundary conditions used in ground-water-flow model for layer 4 (Magothy aquifer).

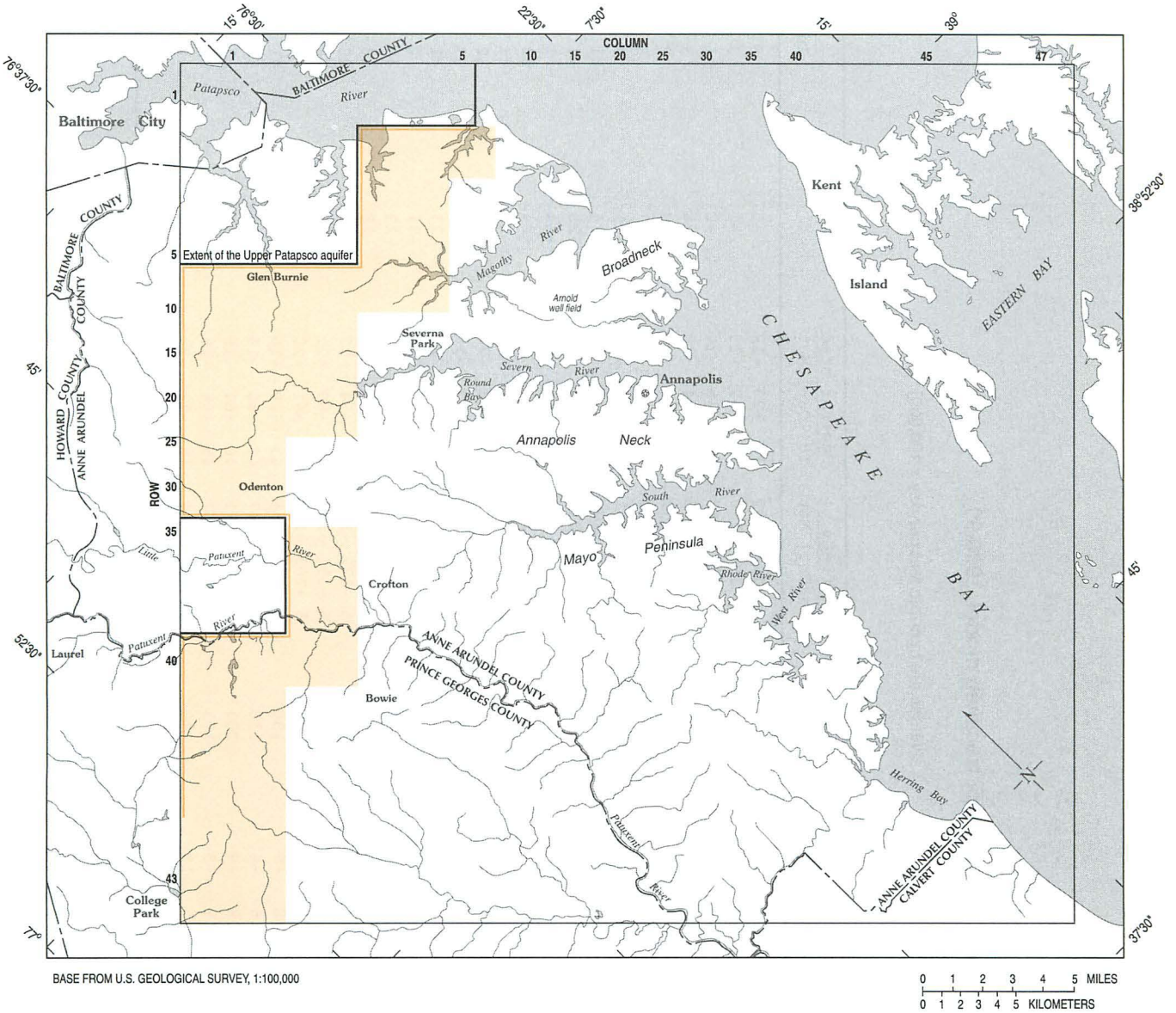


EXPLANATION

CELLS WITH GENERAL-HEAD BOUNDARY CONDITION

CELLS WITH STREAM BOUNDARY CONDITION

Figure 29. General-head and stream boundary conditions used in ground-water-flow model for layer 5 (Upper Patapsco aquifer).



EXPLANATION

CELLS WITH APPLIED RECHARGE BOUNDARY CONDITION

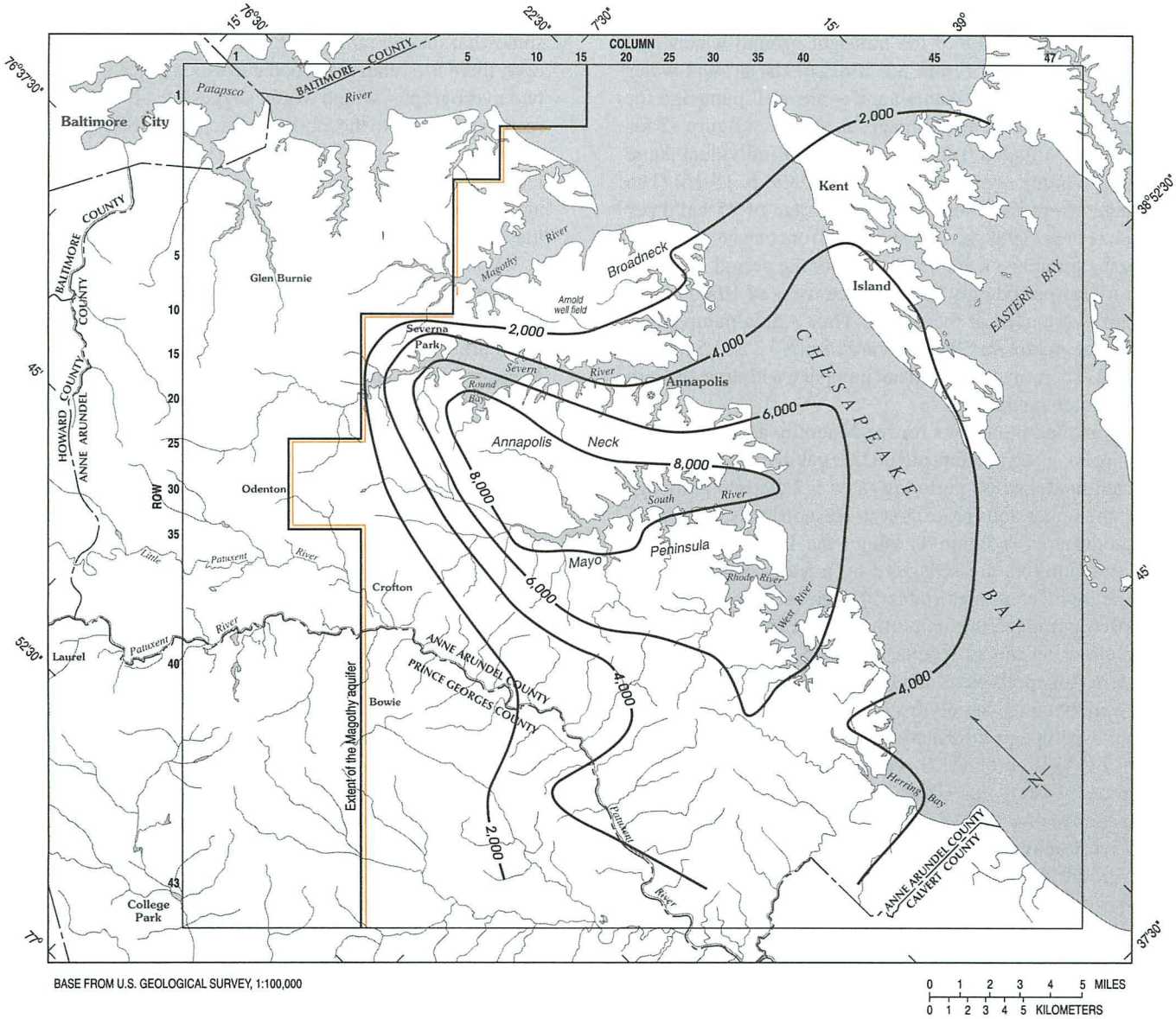
NO-FLOW BOUNDARY

Figure 30. Applied recharge and no-flow boundary conditions used in ground-water-flow model for layer 5 (Upper Patapsco aquifer).

Table 4. Stress periods and water budget for transient model, 1900-90

[Values are in cubic feet per day x 100,000]

Stress period	Time simulated	Constant head			Recharge	Stream			General head			Pumpage	Storage		
		In	Out	Net		In	Out	Net	In	Out	Net		In	Out	Net
1	1900-19	7	-23	-16	237	4	-196	-192	10	-28	-18	-1	8	-17	-9
2	1920-29	7	-23	-16	237	4	-194	-190	10	-30	-20	-1	3	-12	-9
3	1930-39	6	-25	-19	279	4	-222	-218	12	-36	-24	-2	<1	-16	-16
4	1940-49	7	-23	-16	238	4	-197	-193	14	-34	-20	-6	3	-6	-3
5	1950-59	7	-23	-16	242	4	-196	-192	16	-36	-20	-10	2	-5	-3
6	1960-69	7	-20	-13	190	5	-157	-152	17	-34	-17	-17	9	-1	8
7	1970	8	-20	-12	194	5	-156	-151	17	-34	-17	-21	9	-2	7
8	1971	7	-23	-16	345	5	-205	-200	19	-40	-21	-24	<1	-83	-83
9	1972	7	-24	-17	352	4	-223	-219	20	-44	-24	-25	<1	-68	-68
10	1973	7	-24	-17	310	4	-219	-215	22	-45	-23	-24	1	-32	-31
11	1974	7	-22	-15	228	5	-194	-189	24	-3	21	-24	23	-44	-21
12	1975	7	-24	-17	352	4	-230	-226	25	-50	-25	-23	<1	-61	-61
13	1976	7	-22	-15	221	5	-194	-189	26	-48	-22	-26	32	-2	30
14	1977	8	-20	-12	160	5	-165	-160	28	-47	-19	-25	57	>-1	56
15	1978	7	-23	-16	335	4	-214	-210	29	-53	-24	-23	<1	-64	-64
16	1979	7	-25	-18	383	4	-240	-236	31	-58	-27	-31	2	-74	-72
17	1980	8	-20	-12	200	5	-194	-189	34	-53	-19	-23	49	-5	44
18	1981	8	-19	-11	172	5	-175	-170	35	-54	-19	-18	48	-2	46
19	1982	8	-18	-10	192	5	-172	-167	37	-54	-17	-20	25	-2	23
20	1983	8	-19	-11	272	5	-191	-186	38	-59	-21	-32	4	-27	-23
21	1984	9	-20	-11	299	5	-203	-198	41	-61	-20	-38	4	-35	-31
22	1985	9	-18	-9	190	6	-172	-166	43	-59	-16	-40	41	>-1	40
23	1986	10	-16	-6	158	6	-153	-147	44	-60	-16	-38	50	>-1	49
24	1987	9	-18	-9	253	5	-176	-171	46	-64	-18	-39	3	-20	-17
25	1988	9	-17	-8	193	5	-162	-157	46	-65	-19	-33	23	-1	22
26	1989	9	-20	-11	345	5	-209	-204	48	-72	-24	-30	<1	-75	-75
27	1990	9	-20	-11	264	5	-197	-192	49	-72	-23	-28	2	-12	-10



EXPLANATION

—4,000— LINE OF EQUAL TRANSMISSIVITY -- Interval 2,000 feet squared per day.

NO-FLOW BOUNDARY

Figure 31. Distribution of transmissivity values used in transient ground-water-flow model for layer 4 (Magothy aquifer).

Patapsco aquifer) south of Annapolis is poorly known and for the transient model was set at about 4,400 ft^2/d. Elsewhere, the transmissivity of layer 5 gradually diminished to near zero in model cells that represent the western limit of the aquifer.

Pumpage withdrawals from the Aquia aquifer that were used in the calibration of the transient ground-water-flow model are shown in figure 32. Most of the ground-water withdrawals from the Aquia aquifer are well pumpage for domestic supplies. The pumpage, as shown in figure 32 for 1990, was estimated from census data for individual Anne Arundel County census tracts (Speer, 1989, p. 15-16). The estimates were based on an average usage of 75 gal/d per person (Fetter, 1988, p. 1). Estimates from census tracts for domestic pumpage were made only for the period 1980-90. Prior to this period only appropriated users of 10,000 gal/d or more were used in the model. Thus Aquia pumpage as used in the model for 1980 increased from 0.3 to 3.5 Mgal/d (table 6). There are no significant pumpage withdrawals from the Monmouth aquifer.

Simulated pumpages for the Magothy aquifer and underlying Patapsco aquifers of 100,000 gal/d or more are listed for each model stress period in table 5. Patapsco pumpage is for the upper aquifer, except in the northwestern part of the model area (column 1) where the Upper and Lower Patapsco aquifers are separated by a leaky confining bed and are undifferentiated (table 5). The inclusion of Lower Patapsco pumpage in this portion of the model has negligible effect on model results within the area of principal concern (Annapolis Neck and Broadneck peninsulas). These data were obtained largely from Wheeler and Wilde (1989). Updated pumpage information for 1981-90 was obtained from J.C. Wheeler (U.S. Geological Survey, written commun., 1991). For stress periods 17-19 (1980-1982) pumpage data for the Anne Arundel County public-supply wells were unavailable.

A total of 176 observation wells with water levels measured from about 1950 through 1990 and located within the modeled area were used to calibrate the transient model. These observation wells included 52 wells screened in the Aquia aquifer, 2 in the Monmouth aquifer, 75 in the Magothy aquifer, and 47 in the Upper Patapsco aquifer. The location of the Aquia, Magothy, and Upper Patapsco observation wells is shown in figures 33 through 35. These maps indicate that the areal distribution of wells screened in the Aquia and Magothy aquifers is very extensive. In the case of the Upper Patapsco aquifer, there is only one well in the downdip part of the modeled area. However, in the area of principal concern, there are many observation wells screened in the Upper Patapsco aquifer with good long-term records. The Monmouth aquifer generally is not considered a viable aquifer, and it is only slightly used. Consequently, only two observation wells had sufficient water-level measurements for use in this study, and thus, model calibration for the Monmouth aquifer was tenuous at best.

Measured and simulated hydraulic heads for the Aquia aquifer are compared in figure 36. Well AA De 99 is located in the middle of Annapolis Neck. The measured water levels fluctuate between about 19 and 26 ft above sea level. This fluctuation is partly an effect of variable recharge to the aquifer. The model-calculated heads fluctuate over a somewhat smaller range of 18 to 22 ft above sea level. However, there is a relatively good correspondence between the two hydrographs, which would suggest that the variation in recharge as input to the model is matched by the actual variation in recharge to the Aquia aquifer. The reduced amplitude of the model-calculated water levels is due to the averaging procedure used to calculate recharge as explained in the section on "Boundary conditions."

Wells AA De 117 and AA Df 86, figure 36, are both located near the shore of Chesapeake Bay, and measured water levels only fluctuate a small amount. Both of these wells are well represented by the model-calculated heads. Measured water levels in well AA Ef 17 fluctuate about 5 ft. The model-calculated heads for this well are higher than the measured heads, which suggests that there may be some local pumpage withdrawals unaccounted for in the model. The last well shown in figure 36, well AA Fe 48, is located in southern Anne Arundel County and has experienced considerable water-level declines as a result of extensive pumpage south of the model area. General-head boundary conditions for layer 2, figure 22, were specified for each stress period, and in the vicinity of well AA Fe 48 were specified to account for the developing cone of depression to the south of the model area. Simulated heads for well AA Fe 48 shown in figure 36 indicate the effect of the general-head boundary condition.

The measured and simulated medians of hydraulic heads in observation wells screened in the Aquia, Magothy, and Upper Patapsco aquifers are shown in figure 37. For the Aquia aquifer, this analysis was based on data from 35 wells. The range in measured heads for 1990 was from 29 ft below sea level to 37 ft above sea level. The difference between the medians of the measured and simulated heads was 2.2 ft (fig. 37), which is about 3.3 percent of the total measured range of 66 ft.

The medians of measured and simulated hydraulic heads for 66 Magothy aquifer wells are also shown in figure 37. The range in measured heads for 1990 was from 14 ft below sea level to 87 ft above sea level. The difference between the measured and simulated medians was about 4.5 ft, which is about 4.5 percent of the total measured range of 101 ft.

Hydrographs of five wells used in calibrating model layer 4, corresponding to the Magothy aquifer, are shown in figure 38. All five of the wells are located in the area of greatest model detail. Well AA Ce 105 is located near Round Bay (fig. 34) and within the area of Magothy aquifer out

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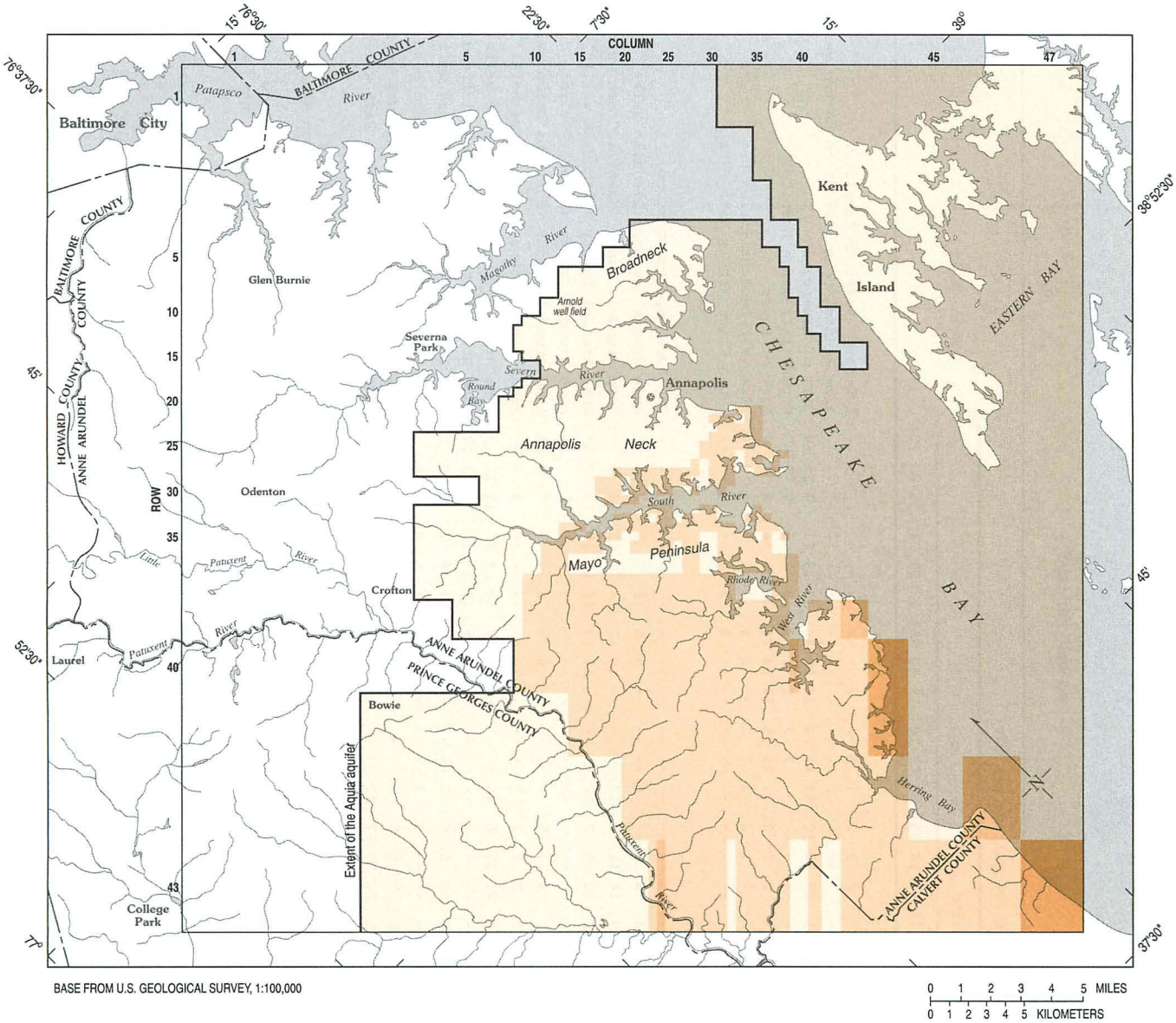


EXPLANATION

PUMPING RATE, IN THOUSANDS OF GALLONS PER DAY

0	51-100
1-50	101-150

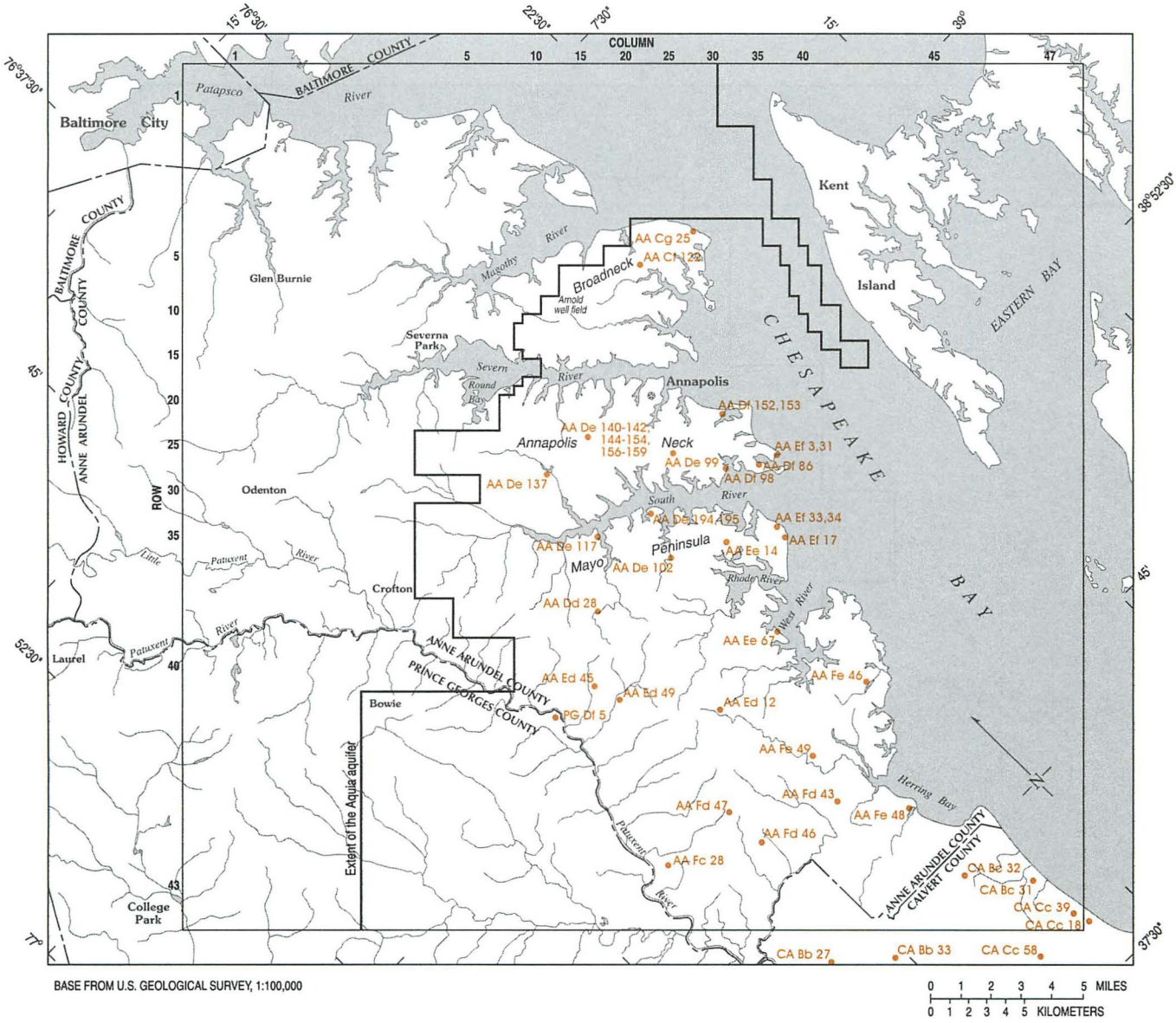
Figure 32. Distribution of pumpage from the Aquia aquifer (layer 2) used as input to the transient ground water-flow model for stress period 27, 1990.

Table 5. Well pumpage from the Magothy and Upper Patapsco aquifers of 100,000 gallons per day or more used as input to the transient ground-water-flow model

[--, no well pumpage]

Model cell		Well pumpage, in 100,000 gallons per day																											
Row	Column	Stress period																											Well owner
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	
Magothy aquifer																													
1	2	--	--	--	2	2	2	2	2	2	2	2	2	2	1	2	1	5	--	2	--	--	--	--	--	--	--	--	U.S.Navy (Research facility)
15	15	--	--	--	--	--	--	2	3	4	4	2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	Anne Arundel County(Pines on Severn well)
28	13	--	--	--	20	27	26	28	30	34	28	28	31	27	30	32	32	41	24	25	28	36	37	19	13	17	24	14	City of Annapolis
29	5	--	--	4	4	4	4	5	5	5	2	2	--	--	--	--	--	2	2	2	2	2	2	2	2	2	1	2	Crownsville State Hospital
40	3	--	--	--	--	--	2	3	5	4	2	2	3	2	2	2	1	25	25	24	24	24	23	25	24	6	4	4	City of Bowie
42	17	--	--	--	--	--	--	--	--	1	1	1	2	2	1	2	2	2	2	--	2	3	4	3	3	4	4	4	First Maryland Utilities
43	36	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	2	1	--	--	--	--	Lyons Creek Mobile Home Park
Upper Patapsco aquifer																													
6	1	--	--	--	--	--	2	2	2	3	2	2	--	2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	Two Guys Department Store
6	1	--	--	--	--	--	--	4	6	6	4	4	3	4	5	--	6	--	--	--	8	8	8	7	7	7	7	6	Anne Arundel County (Glendale well)[1]
7	1	--	--	--	2	5	12	14	15	15	14	10	9	14	11	8	17	--	--	--	18	17	14	14	13	14	5	--	Anne Arundel County (Sawmill Creek well)[1]
7	2	--	--	--	--	8	14	15	14	13	13	13	12	12	9	7	12	--	--	--	19	13	12	17	19	12	8	13	Anne Arundel County (Harundale well)[1]
7	21	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1	1	2		1	Anne Arundel County (Amberly wells)
10	1	--	--	--	--	--	--	4	5	5	5	5	5	4	4	5	4	--	--	--	6	8	5	6	7	7	7	8	Anne Arundel County (Phillips Drive well)[1]
10	1	--	--	--	--	--	--	--	--	-3	3	3	3	3	3	3	3	--	--	--	--	--	--	--	--	3	--	--	Anne Arundel County (Thelma Ave Well)[1]
11	1	--	--	--	--	5	12	15	16	15	15	14	11	21	25	6	44	--	--	--	12	37	36	28	21	19	11	7	Anne Arundel County (Dorsey Road wells)[1]
11	15	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	17	15	19	21	21	21	19	17	Anne Arundel County (Arnold well field)
12	1	--	--	--	--	--	--	1	5	4	5	4	4	5	5	6	7	--	--	--	8	6	6	6	7	6	7	7	Anne Arundel County (Elvaton Road well)[1]
13	1	--	--	--	--	--	--	--	3	4	5	2	--	--	--	3	3	--	--	--	8	8	7	6	8	8	8	7	Anne Arundel County (Quarterfield Road well)[1]
13	1	--	--	--	--	--	--	--	--	--	--	2	4	7	6	6	6	--	--	--	8	8	9	7	9	7	8	9	Anne Arundel County (Crain Highway well)[1]
13	5	--	--	--	--	1	6	8	12	13	16	20	21	24	20	27	32	--	--	--	--	--	--	--	--	--	--	--	Anne Arundel County (Severna Park well)
14	26	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	--	--	--	--	--	--	--	--	U.S. Navy (golf course well)
15	26	--	--	--	3	4	4	3	3	3	4	3	--	--	--	--	--	--	--	3	--	--	4	5	4	--	--	--	U.S. Navy (Research facility)
16	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2	7	7	6	5	6	Anne Arundel County (Stevenson Road well)
20	23	9	10	10	10	10	10	13	13	14	13	14	14	13	14	15	14	16	--	19	12	21	23	23	22	15	12	12	U.S.Navy (Naval Academy wells)
23	1	--	--	--	--	--	--	--	--	--	--	1	--	--	--	1	1	1	--	--	1	--	--	--	--	--	--	--	Anne Arundel County (Meade Village well)
23	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	8	10	9	8	9	8	Anne Arundel County (Telegraph Road well)
25	1	--	--	--	--	--	--	--	--	1	2	2	--	--	--	--	--	--	4	4	2	5	5	4	5	5	5	4	Severn Water Company
29	1	--	--	--	7	11	18	24	22	22	22	24	26	28	26	24	27	24	20	16	16	16	18	19	22	20	20	18	Nevamar Corporation
29	14	--	--	--	--	--	1	1	1	2	1	2	2	2	2	2	3	4	4	4	4	6	8	9	8	5	6	6	Anne Arundel County (Broad Creek wells)
29	15	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	6	5	5	5	Anne Arundel County (Broad Creek wells)
31	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	11	7	3	--	--	--	--	--	--	--	Anne Arundel County (Kings Heights well)
40	1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1	1	2	2	2	2	2	2	4	4	4	3	3	Patuxent Wildlife Research Center
41	1	--	--	--	--	--	7	10	14	9	11	12	11	13	12	12	8	2	--	--	--	--	--	--	--	--	--	--	City of Bowie

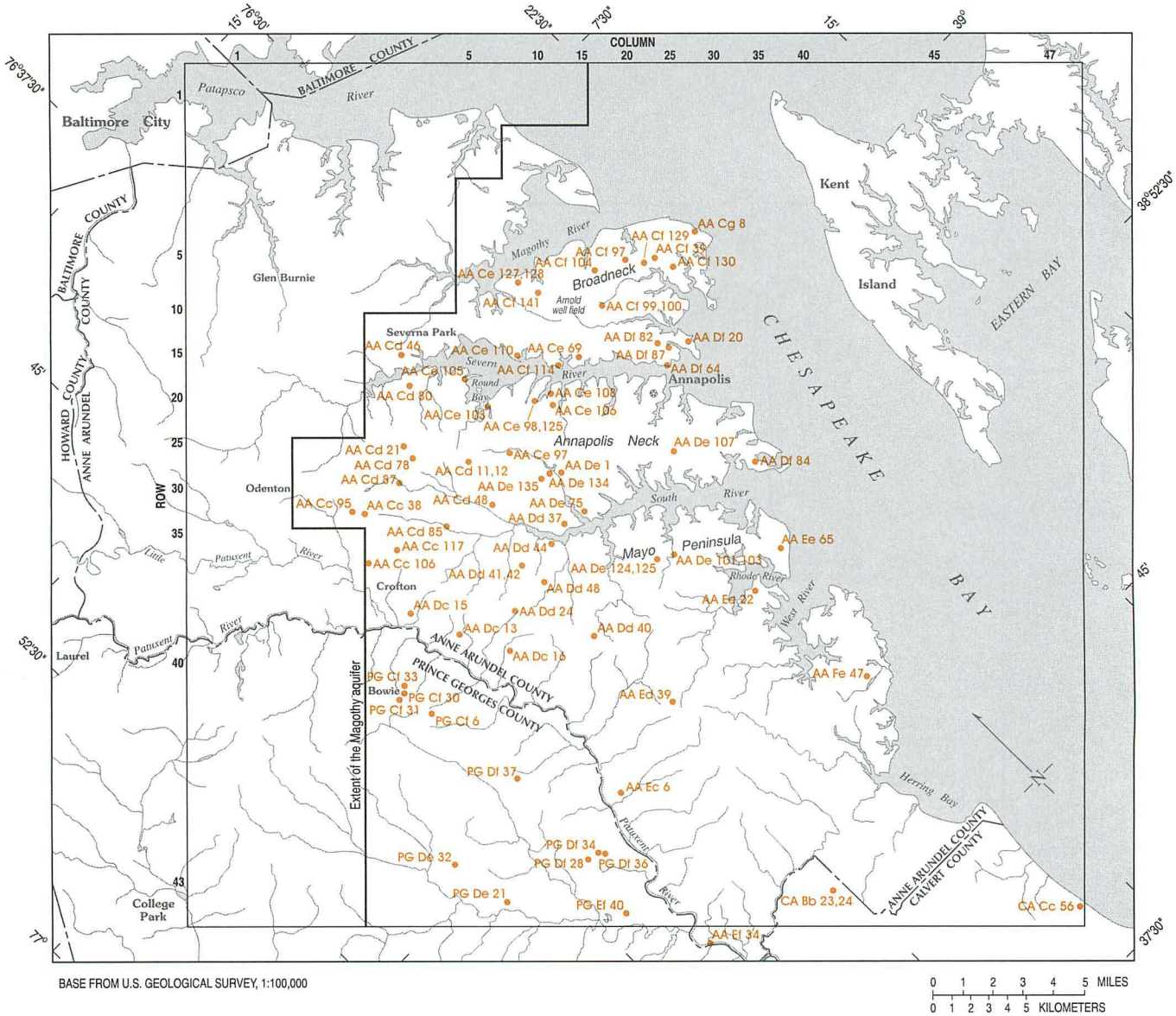
[1] Pumpage mostly from Lower Patapsco aquifer (Achmad, 1991, p.51).



EXPLANATION

AA Cf 122 ● OBSERVATION WELL AND NUMBER

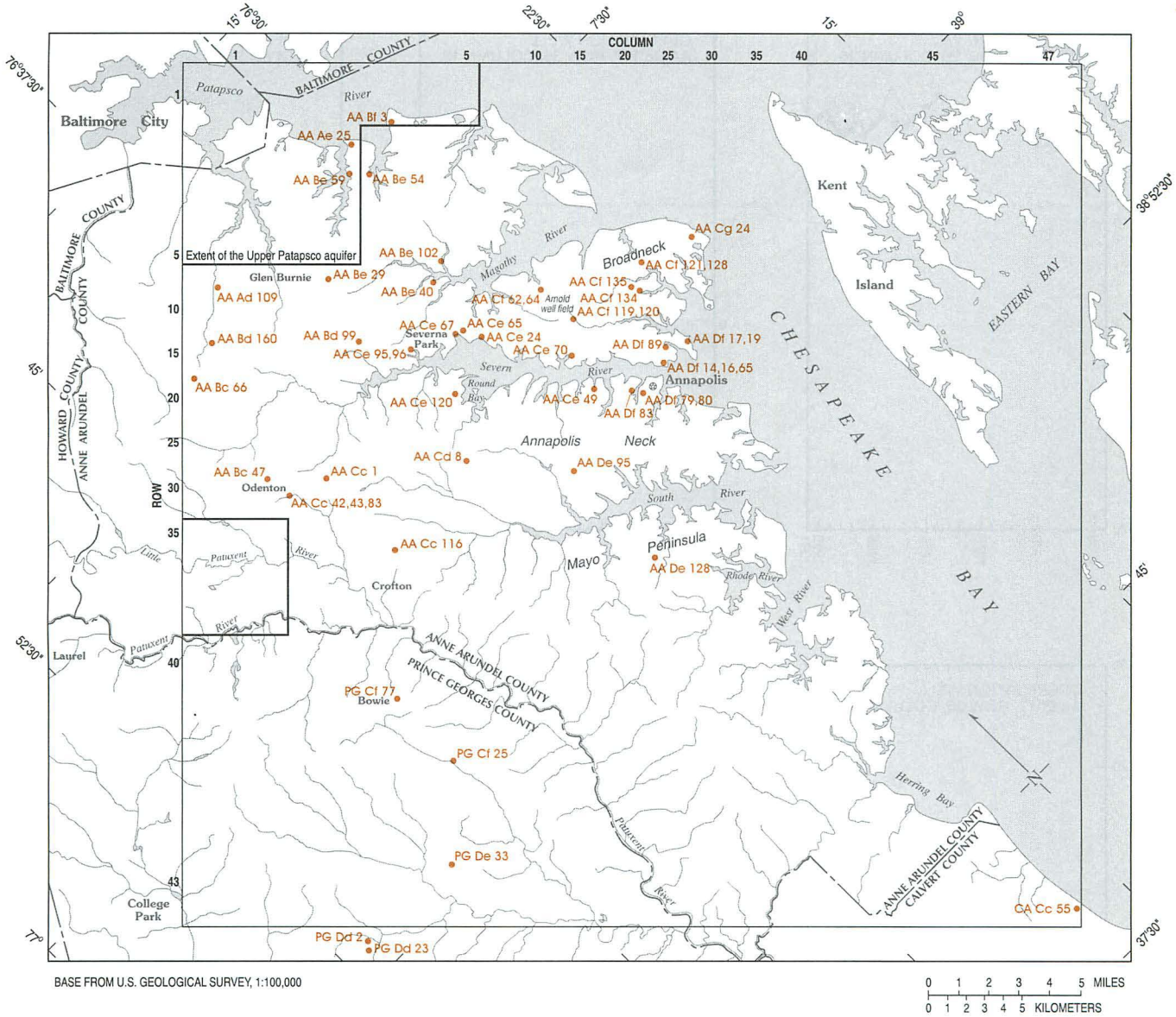
Figure 33. Location of observation wells screened in the Aquia aquifer (layer 2) for which water-level measurements were available for transient model calibration.



EXPLANATION

AA Cg 8 ● OBSERVATION WELL AND NUMBER

Figure 34. Location of observation wells screened in the Magothy aquifer (layer 4) for which water-level measurements were available for transient model calibration.



EXPLANATION

AA Cg 24 ● OBSERVATION WELL AND NUMBER

Figure 35. Location of observation wells screened in the Upper Patapsco aquifer (layer 5) for which water-level measurements were available for transient model calibration.

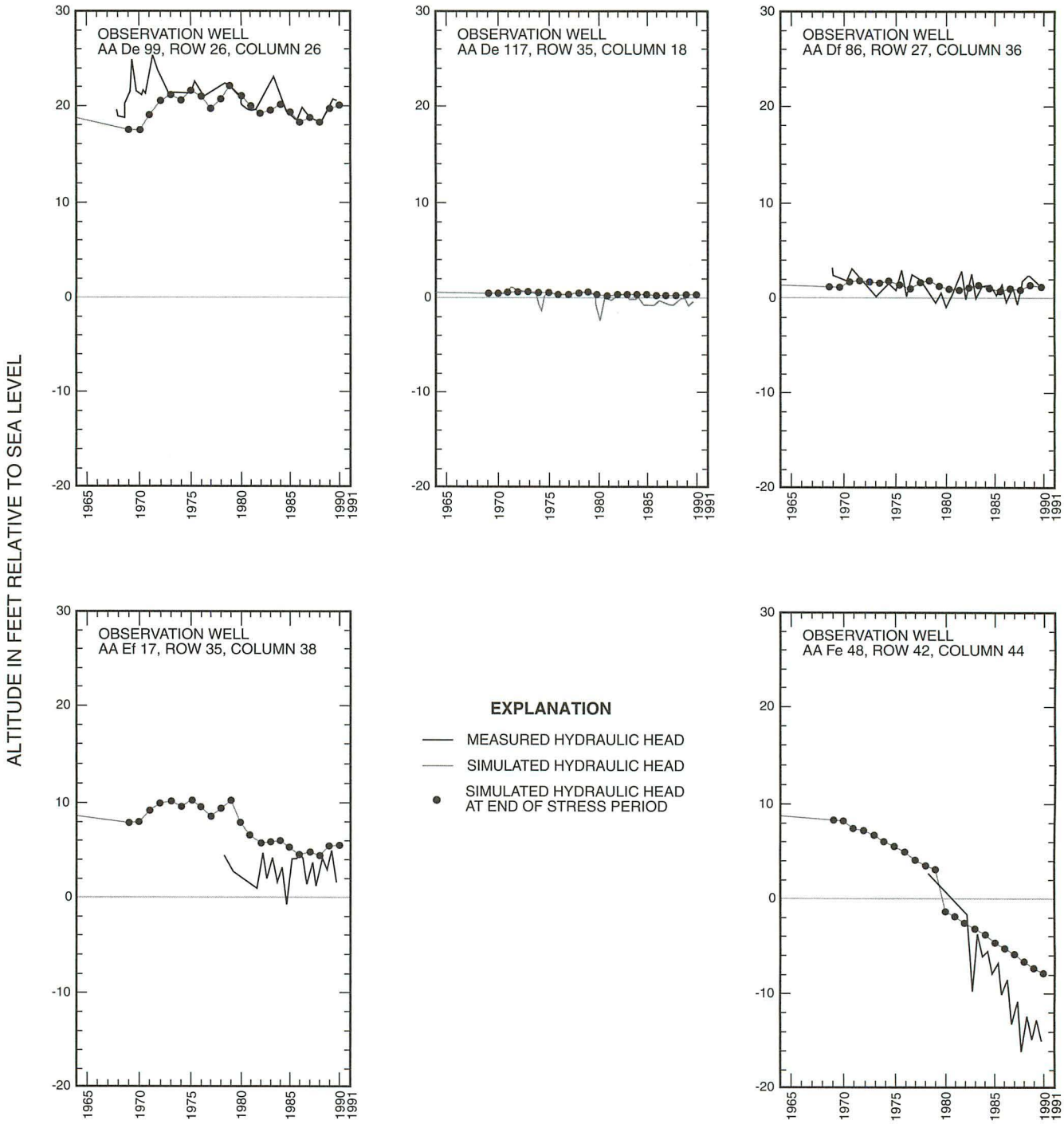


Figure 36. Hydrographs of measured and simulated hydraulic heads in wells screened in the Aquia aquifer, 1965-90.

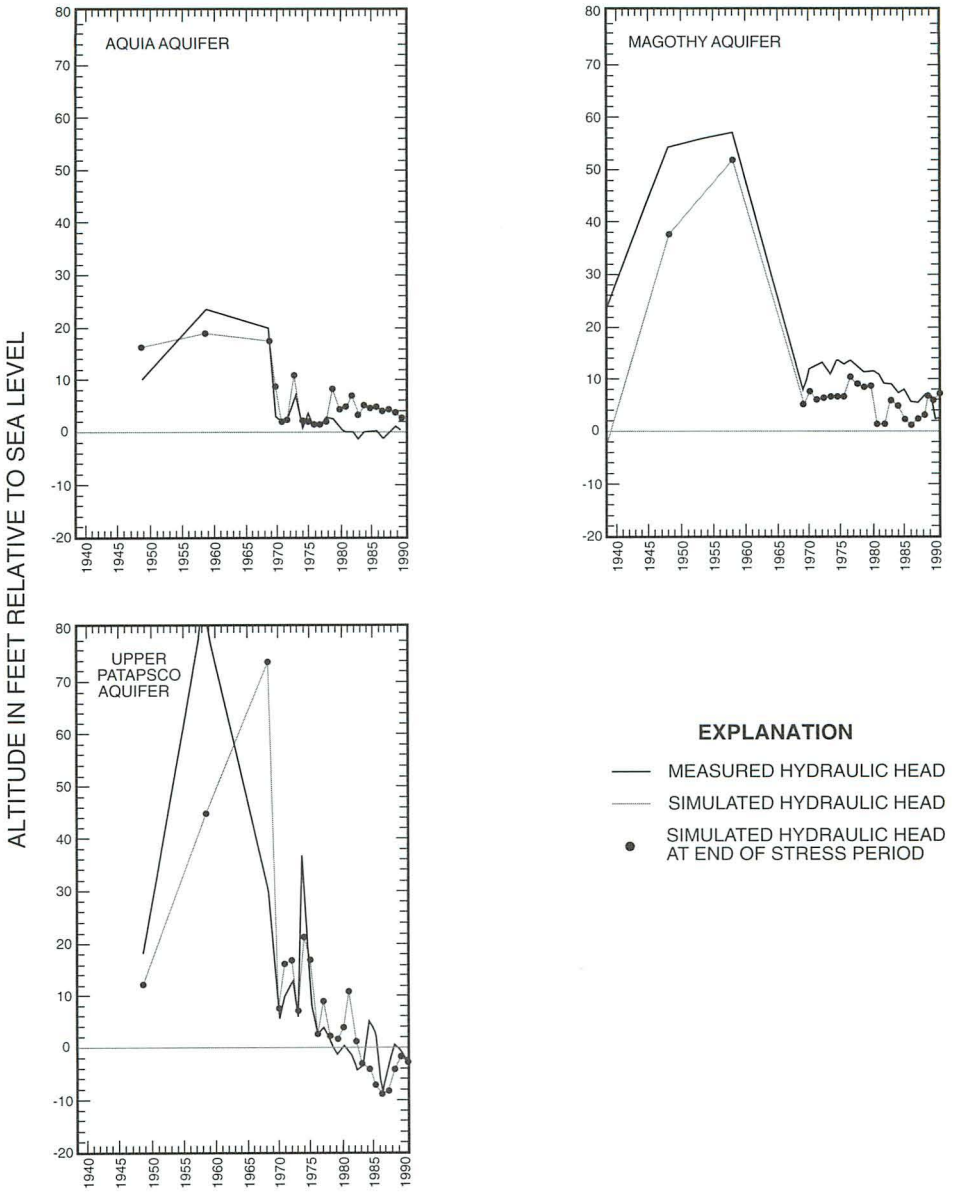


Figure 37. Hydrographs of medians of measured and simulated hydraulic heads in wells screened in the Aquia, Magothy, and Upper Patapsco aquifers, 1940-90.

crop. Both the measured and simulated hydraulic heads reflect water-table conditions wherein continuous recharge balances the pumpage withdrawals from the confined part of the aquifer and thus limits the extent of the cone of depression that has formed farther east. Both the measured and simulated heads for the other four wells clearly indicate the cone of depression that developed as a result of large pumpage withdrawals from the Magothy and Upper Patapsco aquifers.

The difference between the measured and simulated medians for hydraulic heads in the Upper Patapsco aquifer was less than 1 ft (fig. 37). This analysis is based on records from 47 Upper Patapsco wells. The measured heads for 1990 in the wells ranged from 36 ft below sea level to 121 ft above sea level. The difference between the measured and simulated medians was 0.3 ft, which is 0.2 percent of the measured range.

Hydrographs of measured and simulated hydraulic heads for six of the Upper Patapsco wells used to calibrate the model are shown in figure 39. Well PG De 33, as with the Aquia well AA Fe 48 (fig. 36), indicates the effects of the specified heads that were used to simulate the general-head boundary conditions. Well AA Be 102 is located on the edge of the outcrop area (fig. 35) and, therefore, is under water-

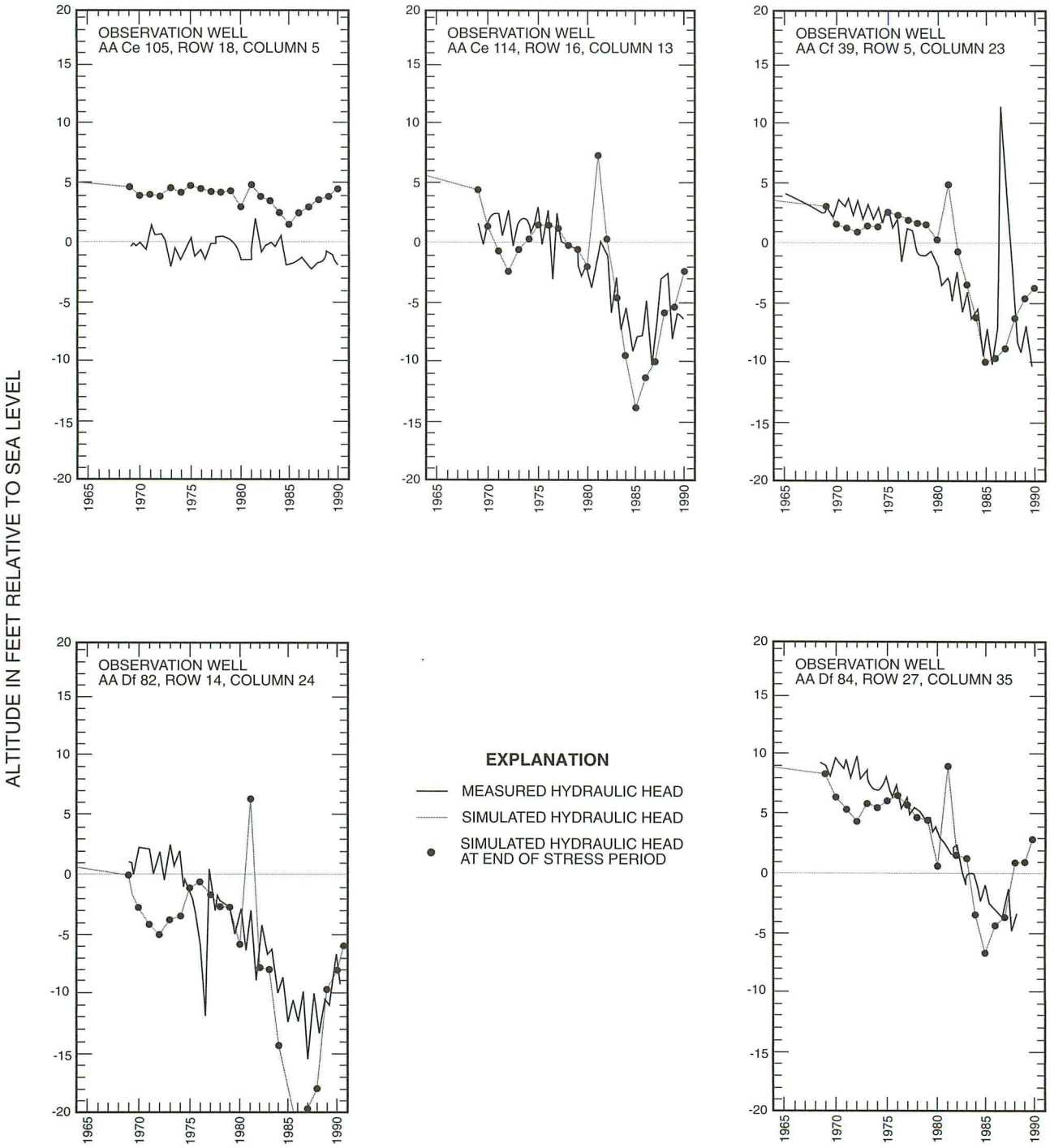


Figure 38. Hydrographs of measured and simulated hydraulic heads in wells screened in the Magothy aquifer, 1965-90.

table conditions. The other wells clearly indicate, both with respect to the measured and the simulated heads, the effects of pumpage withdrawals. In the transient model simulation, well pumpage in all layers reached a maximum of 4 million ft^3/d in 1985 (table 4).

The close approximation between the measured and simulated heads of the hydrographs shown in figures 36-39 and the small differences between the medians of the measured and simulated heads indicate that the model calibration was satisfactory for the Aquia, Magothy, and Upper Patapsco aquifers.

Probable effects of projected pumpage

The calibrated transient model was used to project changes in water levels and flow directions that might result as a consequence of changes in pumpage rates. Ten different alternatives were used to simulate changes in pumpage ranging from as much as a 10-percent decrease to as much as a 30-percent increase. These alternatives are listed in table 6. Initial hydraulic heads for each aquifer were the 1990 model-calibrated heads. Each pumpage alternative simulated a steady-state solution to indicate the maximum changes that would occur for the indicated pumpage changes. Increased pumpage for each aquifer for any given alternative was a percentage increase of the maximum pumpage rate for that aquifer during 1980-90 (table 7). For the Aquia aquifer the maximum pumpage rate was 4.1 Mgal/d in 1990. For the Magothy aquifer, the maximum pumpage rate was 8.0 Mgal/d in 1980, and for the Upper Patapsco aquifer it was 20.6 Mgal/d in 1987. Similarly, decreased pumpage was a percentage of the minimum pumpage rate for 1980-90. The minimum pumpage rate for the Aquia aquifer was 3.5 Mgal/d in 1980, for the Magothy aquifer it was 2.7 Mgal/d in 1990, and for the Upper Patapsco aquifer it was 4.4 Mgal/d in 1981. Table 5 indicates the location and amounts of pumpage from the Magothy and Upper Patapsco aquifers for users of more than 100,000 gal/d.

Aquia aquifer.—In alternative 1, as indicated in table 6, the pumpage from all aquifers was held constant at the 1990 rates. Drawdown in the Aquia aquifer for alternative 1 was less than 0.1 ft throughout the modeled area. This indicates that average water levels in the Aquia for 1990 had reached equilibrium with the average annual 1990 pumpage rates.

For alternative 2, pumpage in all three of the aquifers was increased by 30 percent. For the Aquia aquifer, the 4.1 Mgal/d withdrawal for 1990 was increased to 5.3 Mgal/d. This pumpage rate was evenly spread over 363 model cells, for an average withdrawal of about 0.015 Mgal/d per cell. The maximum pumpage rate in any one cell was 0.18 Mgal/d. The effect on water levels in the Aquia aquifer was minimal. The maximum drawdown from the 1990 water levels was 3.5 ft. This drawdown was located in southern Anne Arundel County within the confined part of the Aquia aquifer. For the unconfined part of the Aquia aquifer, the maximum drawdown, about 0.7 ft, was located along the southern shore of Annapolis Neck.

The results of pumpage alternative 3 were analyzed to demonstrate the rates and directions of ground-water flow in the Aquia aquifer from an area of recharge either to areas of natural ground-water discharge or to areas of minor domestic pumpage withdrawals. The computer program MODPATH (Pollock, 1989) was used to calculate particle flow. MODPATH is a post-processing program designed for use with the output from the ground-water-flow model (McDonald and Harbaugh, 1984) used in this study. MODPATH is a tracking program that computes three-dimensional pathlines and times of travel for individual particles. For alternative 3, the paths of 24 water particles were traced from a point of recharge to the point of discharge from the ground-water-flow system (fig. 40). A two-dimensional representation of the flow paths of the 24 water particles analyzed is shown in figure 40. Traveltime for these particles from recharge to discharge to and from the ground-water-flow system was as little as 40 years to as much as 810 years. Water particles discharging to natural surface-

Table 6. Pumpage alternatives and simulated change from 1990 model-calibrated hydraulic heads

Alternative	Percentage change in pumpage, 1990-2020											
	Aquia aquifer				Magothy aquifer				Upper Patapsco aquifer			
	-10	0	10	30	-10	0	10	30	-10	0	10	30
1		X				X				X		
2				X				X				X
3			X			X				X		
4	X					X				X		
5			X							X		
6			X		X					X		
7			X			X					X	
8			X			X			X			
9			X				X				X	
10		X				X						X

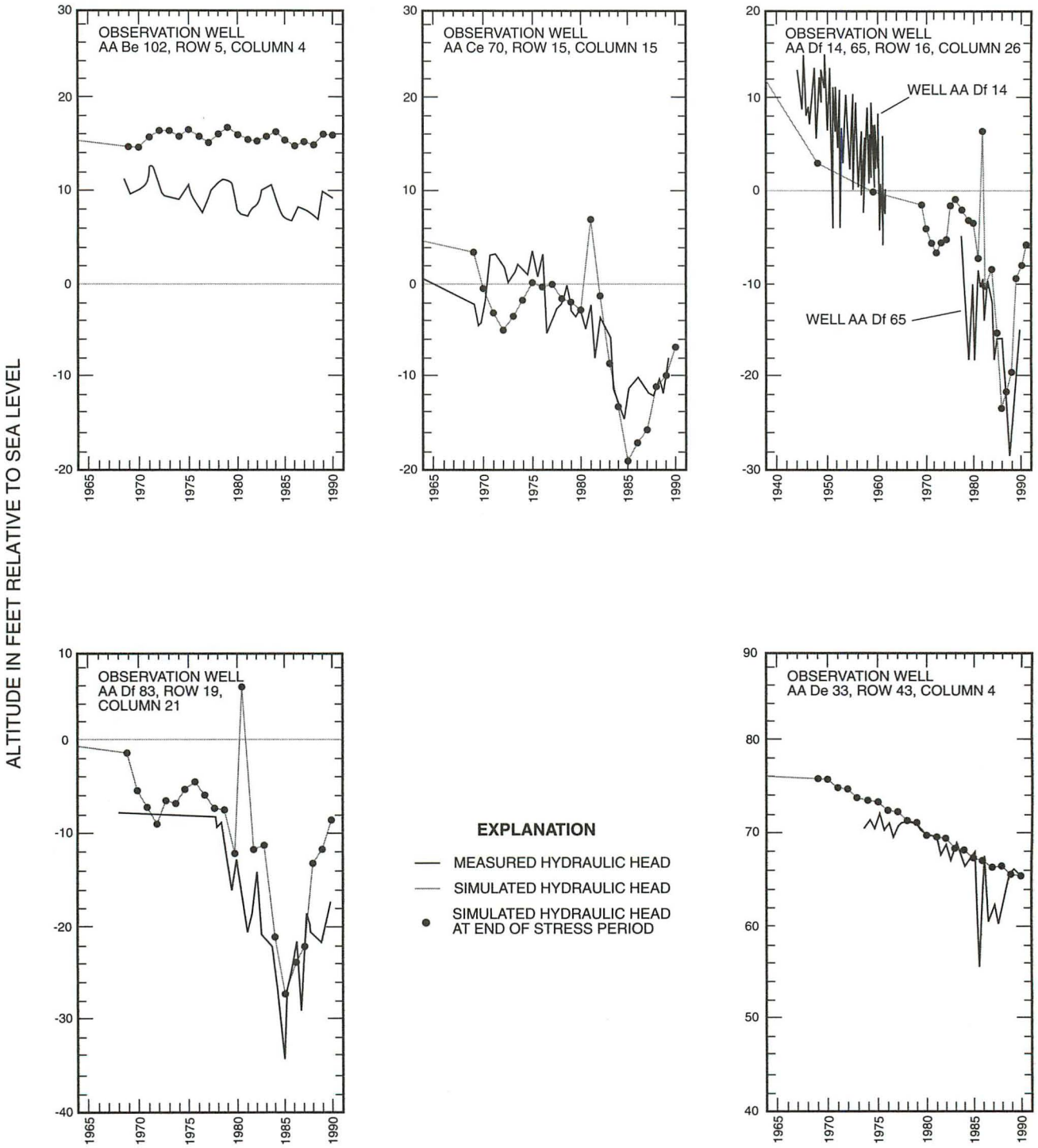


Figure 39. Hydrographs of measured and simulated hydraulic heads in wells screened in the Upper Patapsco aquifer, 1940-90.

Table 7. Pumpage rate for each aquifer as used in model

Stress period		Pumpage rate, in million gallons per day		
No.	Years	Aquia aquifer	Magothy aquifer	Upper Patapsco aquifer
1	1900-19	0	0	0.9
2	1920-29	<.1	0	1.0
3	1930-39	<.1	.3	1.1
4	1940-49	<.1	2.6	2.3
5	1950-59	.1	3.3	4.6
6	1960-69	.1	3.6	8.9
7	1970	.1	4.2	11.8
8	1971	.2	4.9	13.5
9	1972	.2	5.3	13.5
10	1973	.2	4.2	13.8
11	1974	.2	4.0	13.8
12	1975	.2	3.9	13.1
13	1976	.2	3.7	15.5
14	1977	.3	3.7	14.8
15	1978	.3	4.0	13.0
16	1979	.3	4.0	19.0
17	1980	3.5	8.0	6.5
18	1981	3.5	5.8	4.4
19	1982	3.5	5.6	5.9
20	1983	3.6	6.1	14.8
21	1984	3.6	7.1	17.6
22	1985	3.7	7.2	18.9
23	1986	3.7	5.4	19.9
24	1987	3.9	4.7	20.6
25	1988	4.0	3.3	17.7
26	1989	4.1	3.7	14.9
27	1990	4.1	2.7	14.2

water drainage had traveltimes of 150 to 250 years. These particles, as indicated in figure 40, are those that traveled either to the northeast or to the southwest from the recharge area. The only nearby pumpage modeled in alternative 3 was directly south of the recharge area. Pumpage in this area is for domestic supplies and typifies communities of about 25 to 50 homes per square mile to as much as about 150 homes per square mile. Most of the water particles in the southern part of the recharge area had simulated traveltimes of 40 to 120 years and discharged from the ground-water-flow system as domestic pumpage. However, two water particles that passed through this area of domestic pumpage were slowed sufficiently to take 760 and 810 years before reaching and discharging to the estuary. The same analysis was performed for alternative 4 in which pumpage was reduced. Those particles that discharged to domestic pumpage had slightly different flow paths and slightly longer traveltimes; otherwise, the results were identical.

In alternative 4, the pumpage from the Aquia aquifer was decreased from 3.5 to 3.2 Mgal/d. The maximum change from the 1990 water levels was an increase of about 2 ft. In alternatives 5-9, the pumpage from the Aquia aquifer was increased by 10 percent of the 1990 pumpage in conjunction with different changes in pumpage from either the Magothy or Upper Patapsco aquifers. The resultant water-level changes did not exceed 1.5 ft. In alternative 10, the pumpage from the Upper Patapsco aquifer was increased by 30 percent, while the pumpage from all other aquifers was unchanged from the 1990 pumpage. The maximum drawdown in the Aquia aquifer was 0.3 ft.

Magothy aquifer.—Alternative 1 simulated a steady-state solution for the 1990 stresses. Water-level changes, as compared to the calibrated model for 1990, were 0.1 ft or less, indicating that 1990 water levels have reached or approximate a steady-state adjustment with respect to aquifer stresses.

Pumpage alternative 2 simulated the maximum change of any of the 10 alternatives. In this alternative, pumpage was increased in all three pumped aquifers by 30 percent

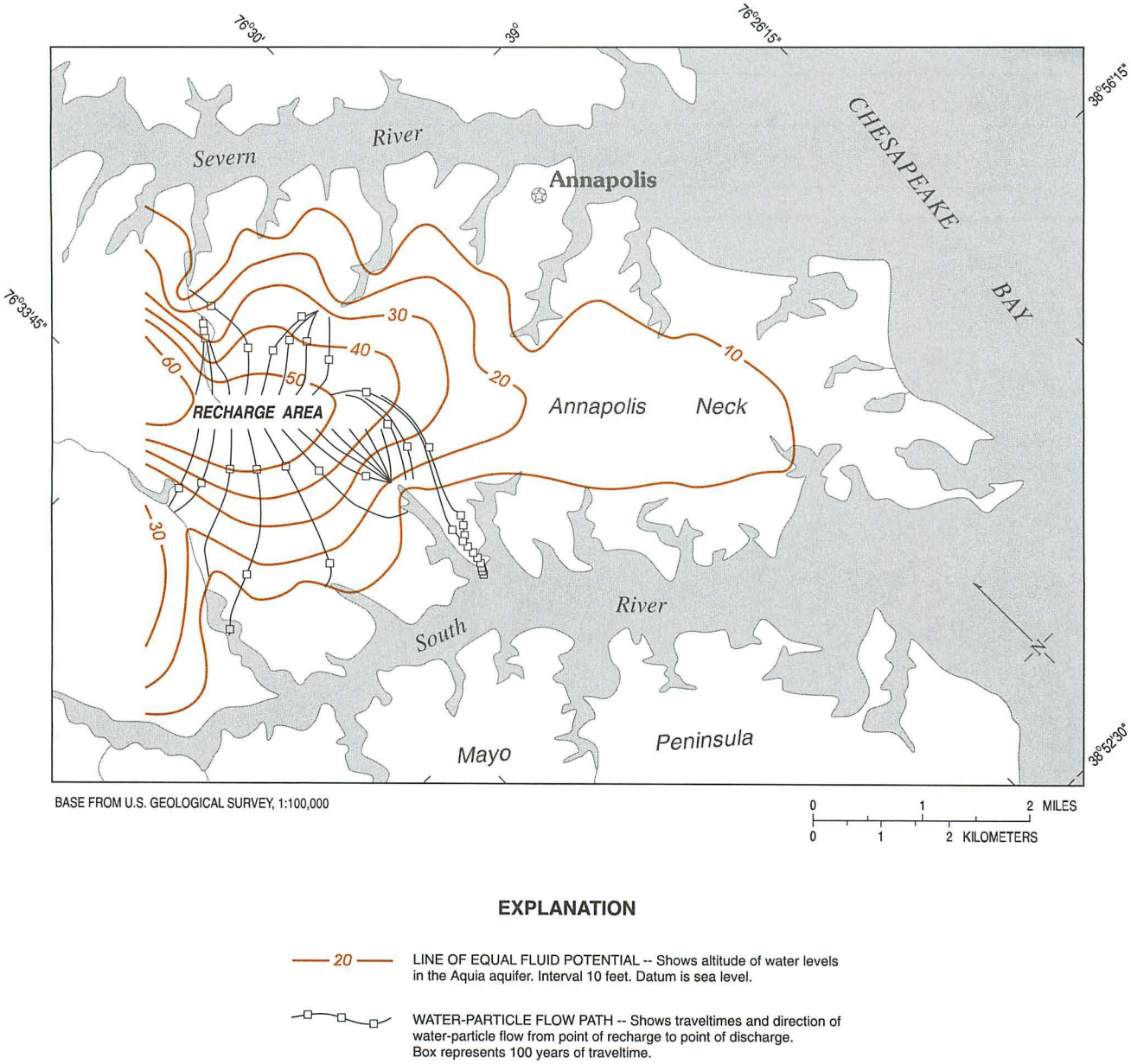
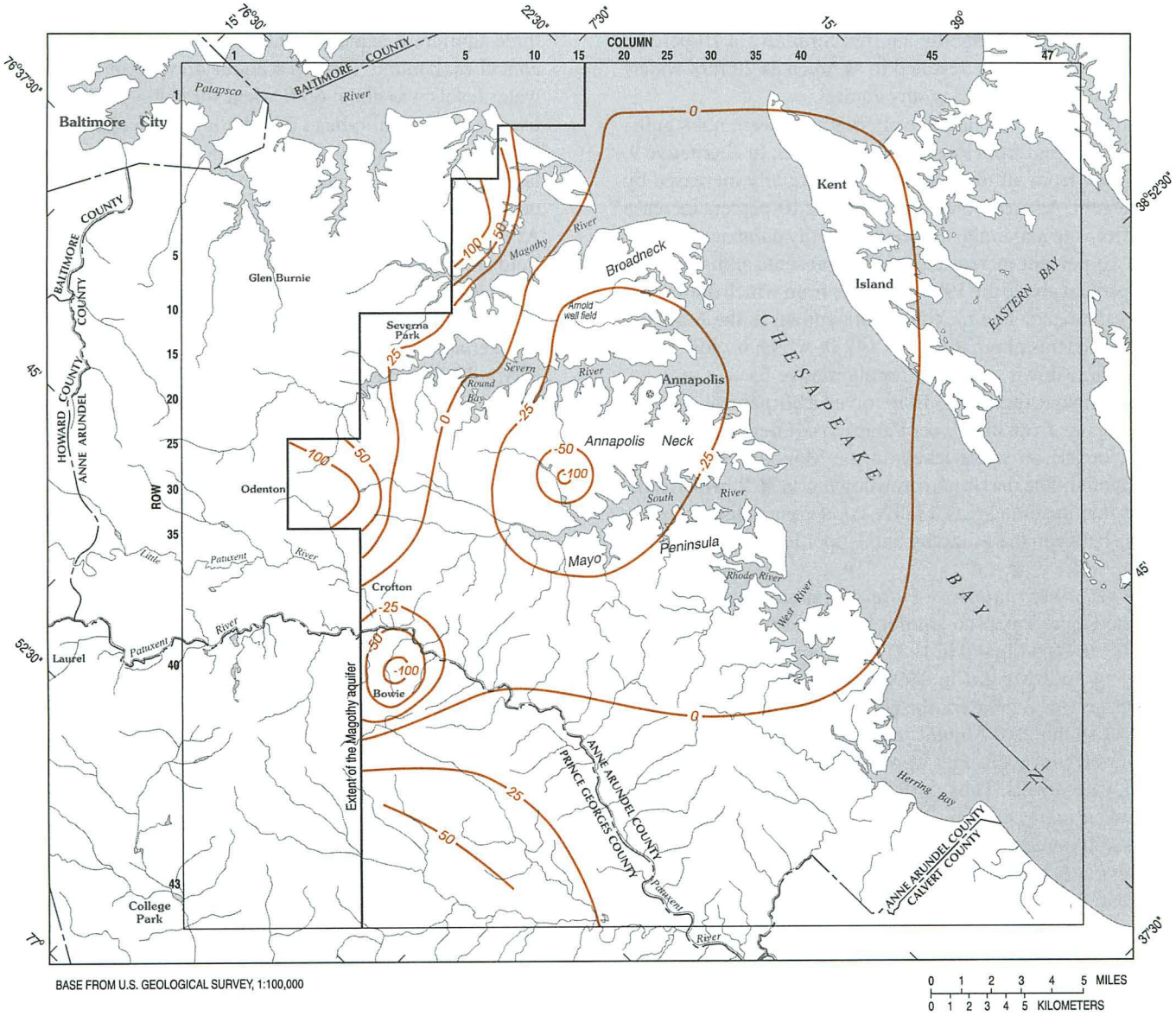


Figure 40. Lines of equal fluid potential and flow paths for water particles in the Aquia aquifer as simulated for pumpage alternative 3, Annapolis Neck.

above the maximum pumpage rate. For the Magothy aquifer, the maximum pumpage rate was 8.0 Mgal/d in 1980. In alternative 2, this was increased to 10.4 Mgal/d. This pumpage was distributed among only 25 model cells. As a consequence, the maximum drawdown from the 1990 model heads was as much as 173 ft. A drawdown of about 90 ft in the vicinity of the City of Annapolis well (cell row 28, column 13) resulted in a water level of about 107 ft below sea level. The lines of equal fluid potential for the Magothy aquifer as simulated for alternative 2 are shown in figure 41.

For alternatives 3 and 4, pumpage was unchanged for all aquifers except the Aquia (table 6). The effects of these alternatives on water levels in the Magothy aquifer were negligible.

Pumpage for alternatives 5 and 6 was increased or decreased by 10 percent (table 6). For alternative 5, a 10-percent increase in the 1980 pumpage resulted in a maximum water-level decline of 139 ft below the 1990 water levels. The minimum pumpage rate from the Magothy aquifer for 1980-90 was 2.7 Mgal/d in 1990. A decrease of 10



EXPLANATION

—— 25 —— LINE OF EQUAL FLUID POTENTIAL -- Shows altitude of water levels in the Magothy aquifer. Interval is variable. Datum is sea level.

Figure 41. Lines of equal fluid potential for the Magothy aquifer as simulated for pumpage alternative 2.

percent resulted in only small water-level increases. The maximum water-level increase was about 3 ft.

For alternatives 7 and 8, pumpage from the Upper Patapsco aquifer was varied by 10 percent. In alternative 7, a 10-percent increase resulted not only in continued drawdowns in the Upper Patapsco aquifer but as much as 19 ft of drawdown in the Magothy aquifer. Similarly, a 10-percent decrease in pumpage resulted in as much as 28 ft of water-level recovery in the Magothy aquifer.

The results of pumpage alternative 9 were not significantly different from those of alternative 5. In alternative 9, pumpage from all three aquifers was equally increased by 10 percent. As previously indicated, the 10-percent increase was from the maximum modeled Magothy pumpage of 1980. This 10-percent increase actually represents an increase of 220 percent above the 1990 pumpage from which drawdown was calculated. The maximum drawdown in the Magothy aquifer for this alternative was 142 ft, which is close to the 139 ft drawdown simulated for alternative 5.

Pumpage alternative 10 involved a 30-percent increase in pumpage from the Upper Patapsco aquifer. The effect of this increase on water levels in the Magothy aquifer was substantial. The maximum drawdown was 26 ft, which indicates that in some areas a fairly good connection probably exists between the Magothy and Upper Patapsco aquifers.

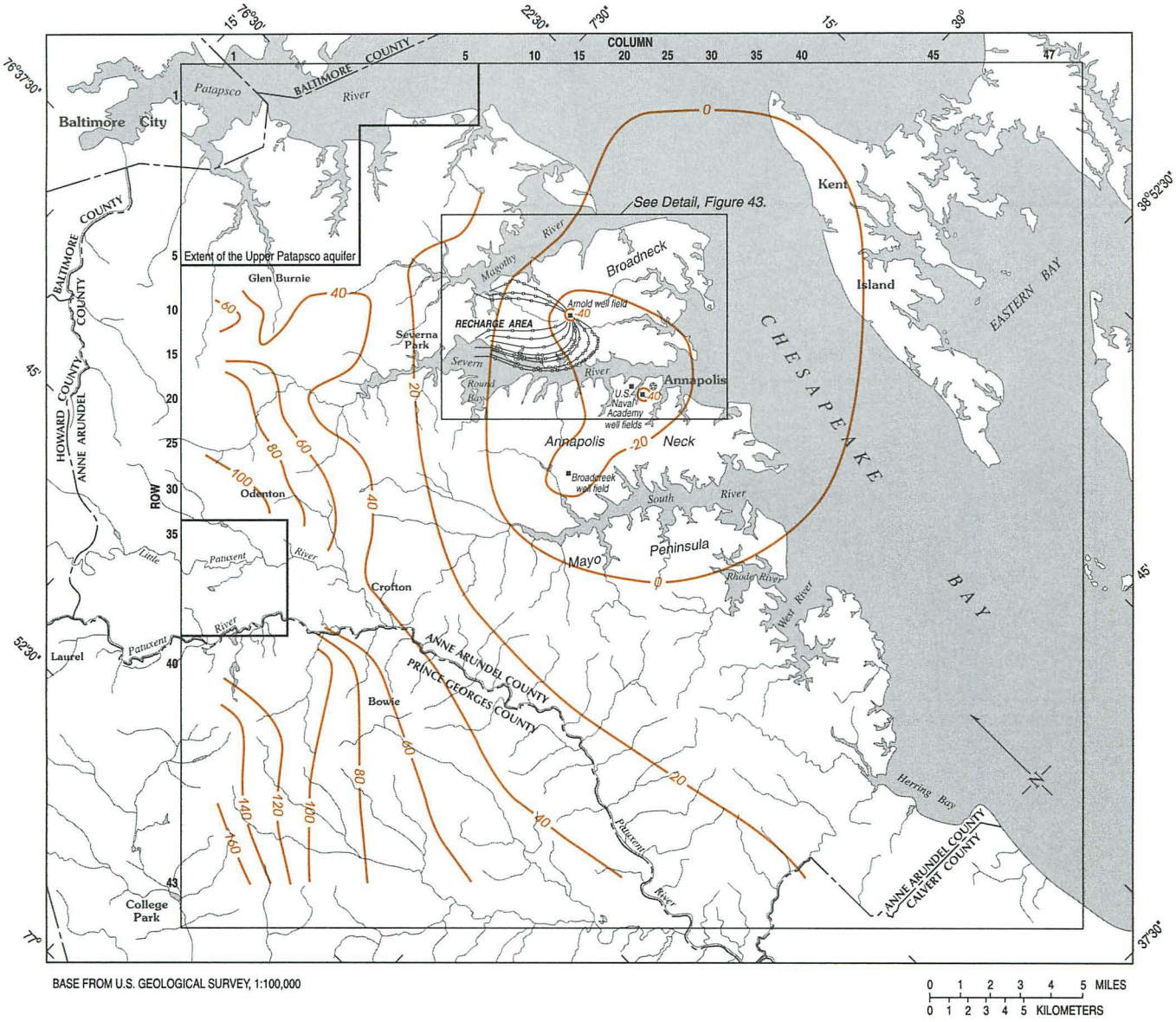
Upper Patapsco aquifer.—Pumpage rates used in the model for the Upper Patapsco aquifer increased from 4.4 Mgal/d in 1981 to 20.6 Mgal/d in 1987 and then decreased substantially to 14.2 Mgal/d in 1990. In the alternatives where pumpage was increased, the percentage increase was with respect to the 20.6 Mgal/d pumpage rate for 1987. Maximum water-level changes were compared to the 1990 simulated water levels. Thus, a 10-percent increase in pumpage meant an increase from 20.6 to 22.7 Mgal/d. This represents a 60-percent increase above the 1990 pumpage. Again, as previously stated, the model-computed drawdown for each alternative was the total drawdown from 1990 water levels and not 1987 water levels.

In alternative 1, the 1990 pumpage stresses were continued until a steady-state head distribution was attained. As previously indicated, the pumpage stresses from 1987 to 1990 had decreased by about 30 percent. As a consequence, there were a number of locations where upward readjustments in response to the declining stresses were continuing. However, the maximum readjustment was no more than 0.1 ft, so that the resultant head distribution was essentially unchanged from the 1990 transient-model heads. This indicates that the flow system, as modeled, adjusts rather quickly in response to the stress changes that were taking place during the latter part of the transient simulation.

For alternatives 2 and 10, the pumpage rate from the Upper Patapsco aquifer was increased to 26.8 Mgal/d. This represented a 30-percent increase above the maximum annual pumpage rate of 20.6 Mgal/d for 1987. However, with respect to the 1990 average pumpage rate of 14.2 Mgal/d, it represents an increase of 89 percent. In alternative 10, pumpage from the Magothy and Aquia aquifers remained unchanged from the 1990 pumpage totals of the transient simulation. In contrast, for alternative 2, pumpage from all three aquifers was increased by 30 percent above previous annual maximums. The maximum drawdown from 1990 water levels was about 65 ft when simulating both alternatives. The hydraulic-head distribution using alternative 10 for the Upper Patapsco aquifer as calculated by model simulation is shown in figure 42. Pumpage rates from the three pumping centers at the Anne Arundel County well fields at Arnold and Broad Creek and the U.S. Naval Academy well field are represented in both alternatives 2 and 10 by withdrawals of 2.7, 1.8, and 2.8 Mgal/d, respectively. The simulated results are coalescing cones of depression as indicated for alternative 10 in figure 42. The simulated hydraulic heads at Arnold, Broad Creek, and the Naval Academy well fields are 61, 59, and 72 ft, respectively. For alternative 2, the heads at these three sites were drawn down another 8, 21 and 15 ft, respectively. These additional drawdowns for alternative 2 compared to alternative 10 indicate that the Upper Patapsco confining unit separating the Magothy and Upper Patapsco aquifers is very leaky.

The rest of the alternatives in which pumpage was increased for either the Magothy or the Upper Patapsco aquifers also indicates the interconnection between the two aquifers. In alternative 5, increased pumpage of 10 percent for the Magothy aquifer resulted in further drawdown of Upper Patapsco hydraulic heads, and in particular drawdowns of 6.5, 16.2, and 11.9 ft at the Arnold, Broad Creek, and Naval Academy well fields, respectively. In alternative 7, pumpage from the Upper Patapsco aquifer only was increased by 10 percent. In alternative 9, pumpage from the Aquia, Magothy, and Upper Patapsco aquifers was increased 10 percent. Comparison of drawdowns at the Arnold, Broad Creek and Naval Academy well fields indicates that drawdowns resulting from alternative 7 of 15.8, 15.0, and 27.2 ft were drawn down further to 22.3, 31.2, and 39.0 ft, respectively, when pumpage from all three aquifers was increased 10 percent.

For alternative 10 in which pumpage from the Upper Patapsco aquifer was increased by 30 percent, an analysis of traveltimes and flow directions are depicted in figure 43. The Magothy aquifer subcrops under the bottom sediments of the Magothy and Severn Rivers. Figure 43 traces water particles from the subcrop area of the Magothy aquifer to the Upper Patapsco wells at the Arnold well field. The estimated time for these water particles to travel from the rivers to the wells ranged from 293 to 1,657 years. These times represent advective flow and, as such, indicate approximate lengths of time required for brackish water from the river estuaries to travel through the ground-water-flow system to the well heads in the Upper Patapsco aquifer at Arnold.



EXPLANATION

—— 20 —— LINE OF EQUAL FLUID POTENTIAL -- Shows altitude of water levels in the Upper Patapsco aquifer. Interval 20 feet. Datum is sea level.

WATER-PARTICLE FLOW PATH -- Shows traveltimes and direction of water-particle flow from point of recharge to point of discharge. Box represents 100 years of traveltime.

Figure 42. Lines of equal fluid potential and flow paths for water particles in the Upper Patapsco aquifer as simulated for pumpage alternative 10. (See Detail, Figure 43.)

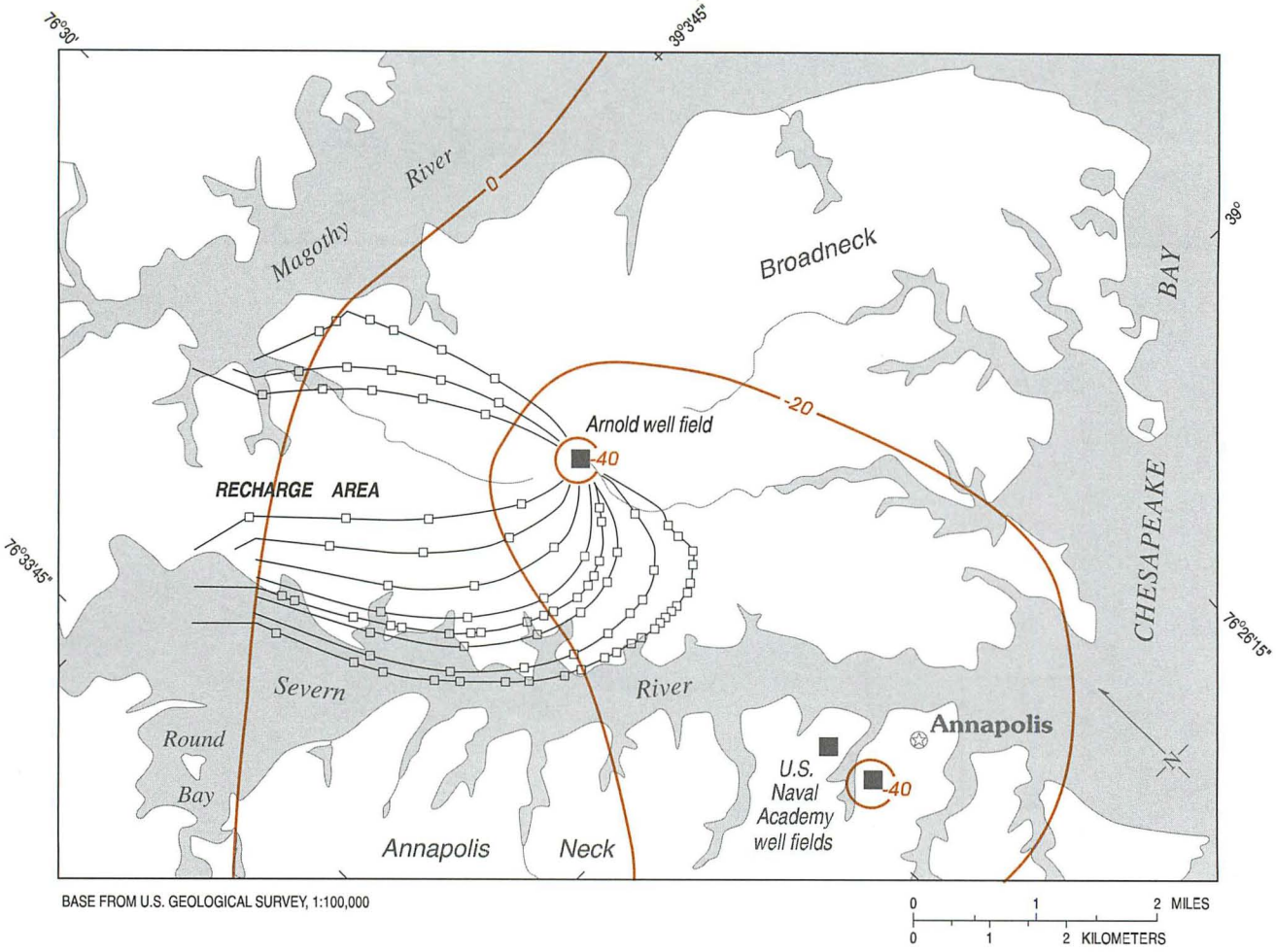


Figure 43. Lines of equal fluid potential and flow paths for water particles in the Upper Patapsco aquifer from recharge area to Arnold well field, as simulated in pumpage alternative 10. (See Figure 42 for location of Detail.)

Sensitivity analysis

A series of computer simulations were made with the calibrated transient model to illustrate the sensitivity of the model to changes in nine different input parameters. These parameters were general-head boundary altitudes and hydraulic conductances, stream elevations and hydraulic conductances, leakance of confining units, aquifer transmissivities and storativities, pumpage withdrawals, and recharge.

To test the sensitivity of the model, each of the nine parameters were separately varied with respect to each other and globally varied for all model cells, and then the transient model for 1900-90 was computed. The model results for 1990 were compared to measured hydraulic heads from 161 observation wells. A root mean square error (RMSE) was calculated for the simulated heads with respect to the measured heads. This RMSE then was compared to the RMSE for the calibrated model.

The model is especially sensitive to decreased transmissivities. Multiplying the transmissivities by $10^{-0.7}$ and 10^{-1} changed the RMSE by 170 and 6,000 percent, respectively. However, multiplying by $10^{0.7}$ and 10^{1} only changed the RMSE by 25 and 37 percent, respectively.

Sensitivities to the other model parameters were con-

siderably less than was the decrease in transmissivity. For the general-head boundaries, a 10-ft addition in altitude and a 10^{+2} multiplication in hydraulic conductance changed the RMSE by a maximum of 17 and 3 percent, respectively. For the simulated streams, a change of 10 ft in altitude and by a factor of 10^{+1} in hydraulic conductance changed the RMSE by a maximum of 10 and 28 percent, respectively. However, a change in hydraulic conductance by a factor of 10^{-2} resulted in a large change in RMSE of 200 percent. Changes in aquifer storativity and confining-unit leakance by factors of 10^{+2} resulted in maximum RMSE changes of 23 and 79 percent, respectively. For both storativity and leakance the model was more sensitive to increases in these parameters than to decreased values. Changes in pumpage withdrawals by factors of $10^{\pm 0.3}$ changed the RMSE by a maximum of 22 percent. However, a change by a factor of 10^{+1} changed the RMSE by 790 percent.

In summary, the analysis indicated that the model was especially sensitive to decreasing transmissivities and, to a lesser extent, increasing pumpage withdrawals. Transmissivities used in the model were largely values obtained from previous modeling studies and, therefore, were assumed to be representative of actual transmissivities. Pumpage withdrawals for earlier time periods are speculative. However, the pumpage data base for the decade 1981-90 was based on relatively accurate records.

BRACKISH-WATER INTRUSION

BRACKISH-WATER INTRUSION IN THE AQUIA AND MONMOUTH AQUIFERS

Brackish water from the Chesapeake Bay and its tributaries is intruding into the Aquia and Monmouth aquifers underlying Annapolis Neck and the Mayo Peninsula. This conclusion is based on chloride concentrations detected in wells located near the shoreline on both peninsulas that exceed the U.S. Environmental Protection Agency (1986) recommended Secondary Maximum Contaminant Level (SMCL) of 250 mg/L . The Aquia aquifer, and to a lesser extent the Monmouth aquifer, are important sources of water supply for individual residential use. The purpose of this section of the report is to describe the extent and distribution of brackish-water intrusion in the Aquia and Monmouth aquifers.

A series of test wells were drilled and sampled during the study to help define the distribution of brackish-water intrusion. The test sites were located near the shoreline (fig. 16). At each site, one to three wells were completed at discrete depths to determine the vertical distribution of chloride. Chloride moves through the aquifers at nearly the same rate as the ground-water flow and is usually the first indicator of intrusion. Water samples were collected from the wells, and analyses of major inorganic ions were made. In addition to the test wells, water samples from selected residential wells were analyzed for chloride, bromide, and nitrogen (as nitrate + nitrite). Analytical results of the sampling are given in appendixes C and D.

Elevated chloride concentrations from sources other than Chesapeake Bay occur throughout the study area. Other sources of chloride may include sewage effluent from private septic systems and public sewer lines, residential water-softener effluent, and road de-icing salt. To accurately determine the extent of brackish-water intrusion, it was necessary to differentiate between chloride from Chesapeake Bay and chloride from other sources. A discussion of the methods used to differentiate chloride sources follows this section. Chloride concentrations used in this section are attributed solely to brackish-water intrusion.

The brackish-water/freshwater interface in the Aquia and Monmouth aquifers was penetrated by test wells at five sites: Londontown Public House Park, Quiet Waters Park, Bay Ridge, Arundel-on-the-Bay, and Mayo Beach Park (fig. 16). The interface was not encountered at three other test locations—Annapolis Roads, Hillsmere, and South River Farms Park. The vertical distribution of chloride and the geophysical logs at those sites are shown in figure 44. Also shown are profiles at four sites tested to determine the presence of brackish-water intrusion in the Magothy and Upper Patapsco aquifers.

Gamma ray and electrical-resistivity logs were run in the deepest hole at each test well site. Gamma ray logs record the natural gamma radiation of the sediments. Clay emits more gamma radiation (primarily through the decay of uranium-238) than sand (Keys, 1990). Therefore, deflections to the right on the gamma log indicate a clay, and deflections to the left indicate a sand. Drill cuttings from the test wells were examined to determine lithology and to help interpret the geophysical logs. Resistivity logs measure the ability of Earth materials to resist an electrical current. The amount of resistance is affected by the type of material and the specific conductance of the water in the pore spaces. Sand and gravel sediments saturated with freshwater have relatively high resistivity readings, whereas clay and silt show lower readings. The presence of high-specific-conductance water, such as brackish-water or seawater, in the sediment lowers the resistivity. Therefore, low resistivity within a sand layer can be an indication of brackish-water intrusion.

The Londontown Public House Park test well site, located on the Mayo Peninsula, consists of three wells, two of which penetrate the interface. One well, AA De 194, com-

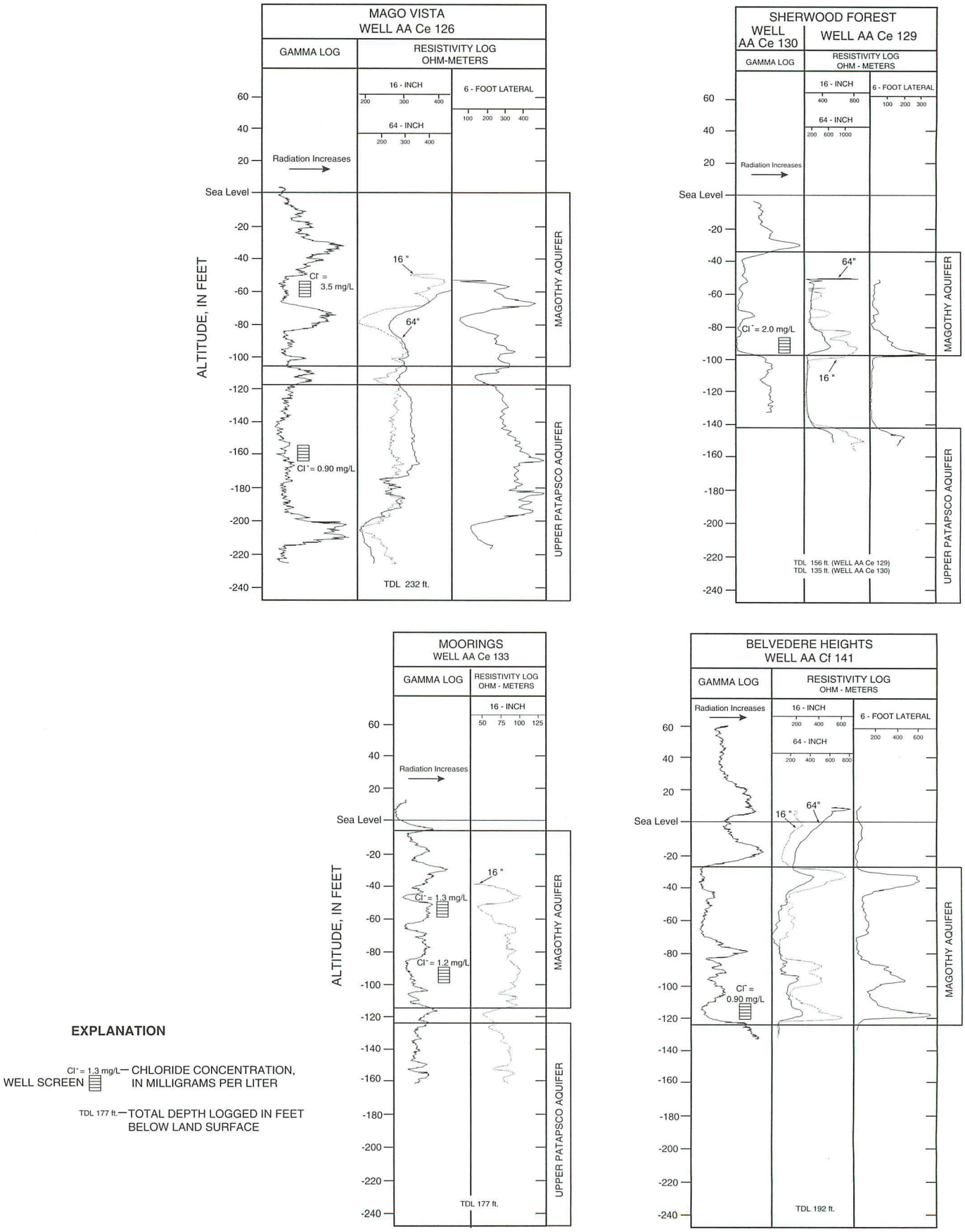


Figure 44. Geophysical log profiles at test well sites used in this study.

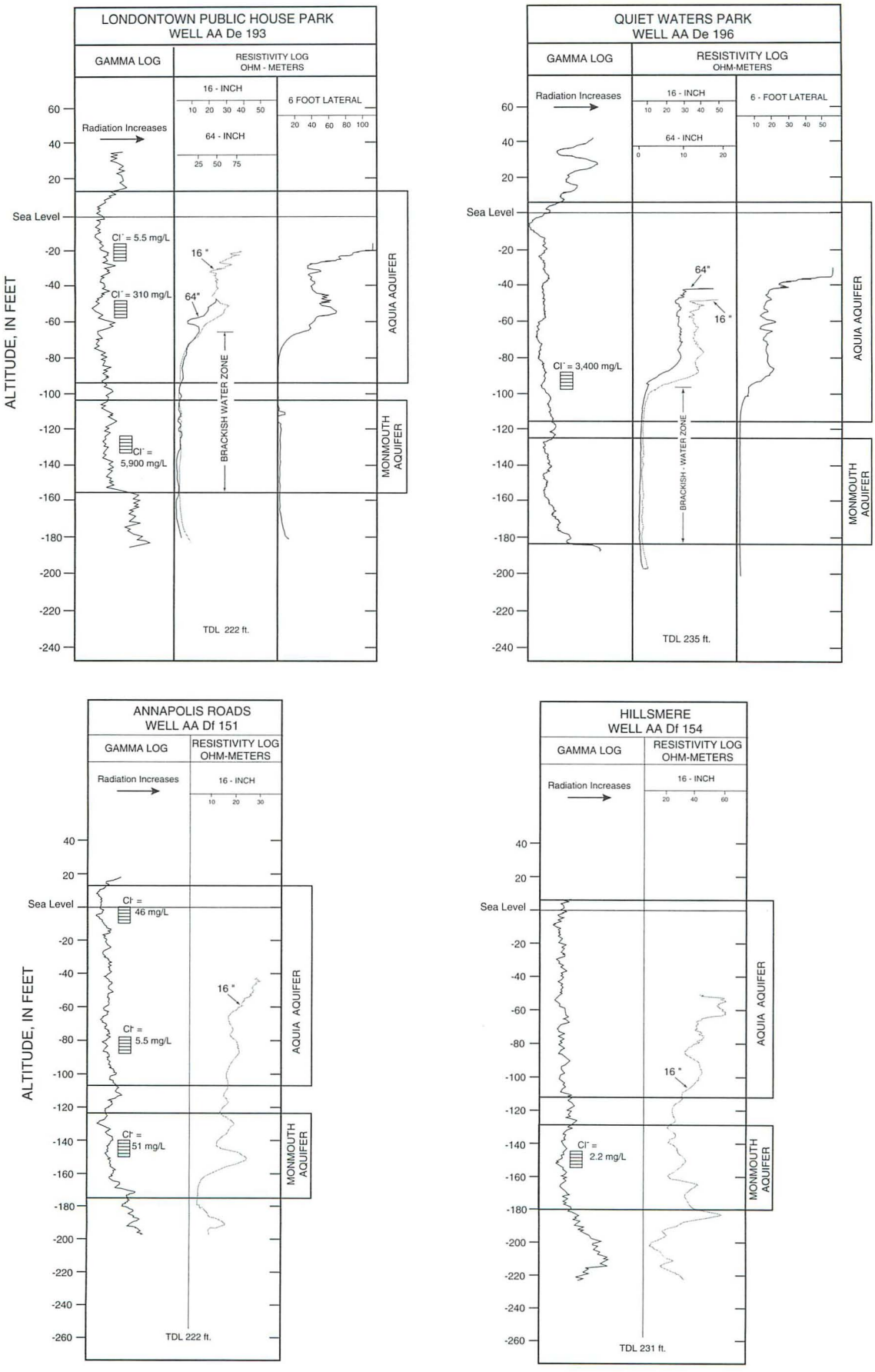


Figure 44.—Continued.

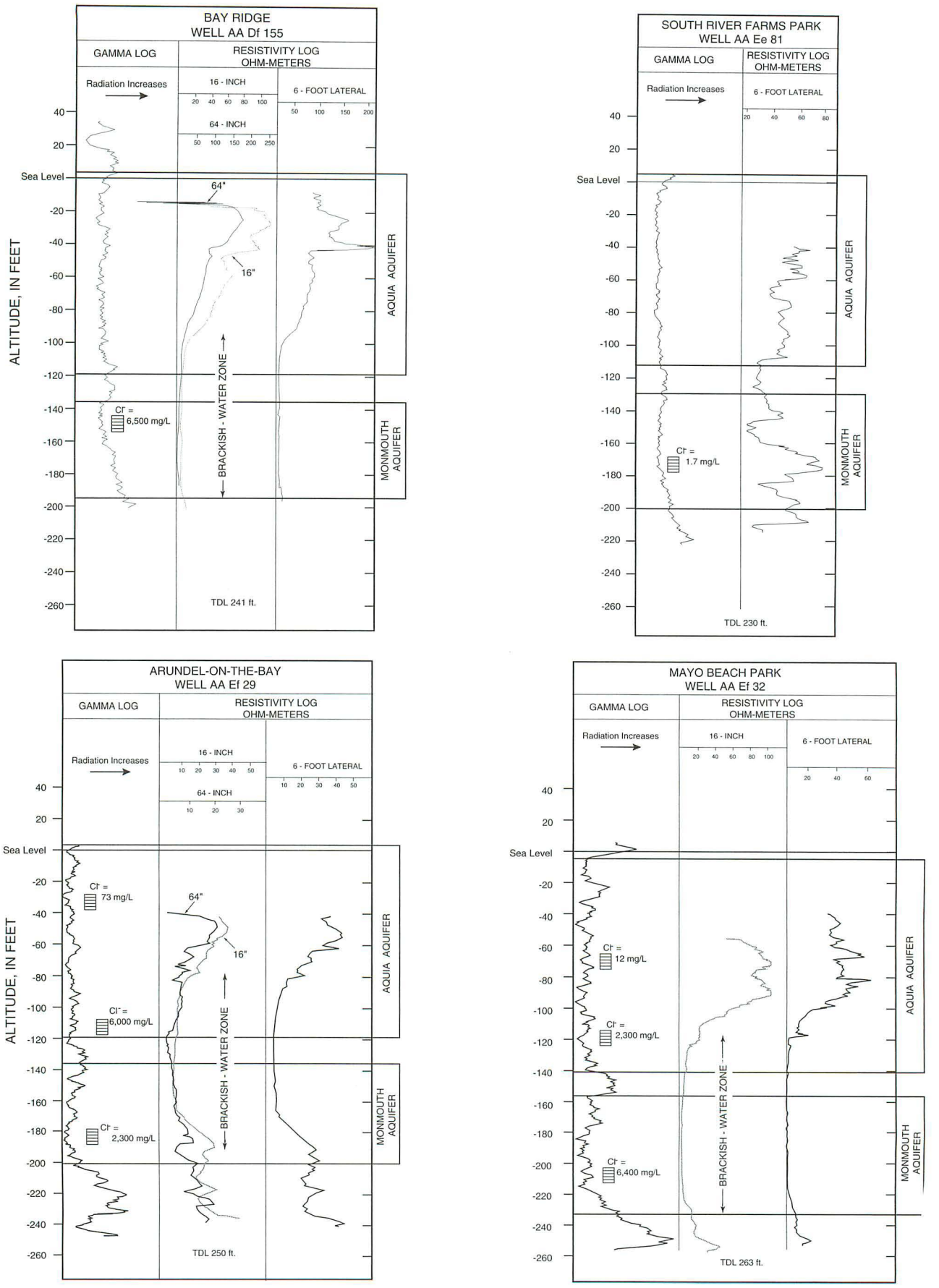


Figure 44.—Continued.

pleted within the interface (45 to 55 ft below sea level) contained water that had a chloride concentration of 310 mg/L. A sample collected below the interface had a chloride concentration of 5,900 mg/L, and the resistivity log indicated the presence of brackish water below the interface.

At the Quiet Waters Park test well site, a series of wells were drilled in a line perpendicular to the shoreline. A profile of well AA De 196, located closest to the shore (about 100 ft), is shown in figure 44. The top of the interface at well AA De 196 is about 85 ft below sea level. The transition zone is marked by an abrupt decrease in resistivity between 85 and 97 ft below sea level. The chloride concentration in water sampled in the screened interval between 89 and 99 ft below sea level was 3,400 mg/L. A cross section through this site (pl. 5) indicates a sharp brackish-water/freshwater interface sloping steeply between the shore and well AA De 196. The interface flattens out considerably past this point. The geophysical logs and water-quality data from the well located farthest from shore (well AA De 201), at 300 ft, indicate that the brackish-water/freshwater interface occurs at the base of the Aquia aquifer. The slope of the interface between well AA De 196 and well AA De 201 is about 0.1. If this gradient continues past well AA De 201, then the maximum lateral extent of brackish-water intrusion is estimated at about 450 ft from shore. Beyond this point both the Aquia and Monmouth aquifers would contain freshwater. The brackish-water/freshwater interface at this site has extended farther inland than at the other sites tested. This could be caused by the reduction of recharge to the aquifer from precipitation by an impervious clay layer in the Talbot Formation, which overlies the Aquia aquifer at this location.

At the Bay Ridge test well site the top of the brackish-water/freshwater interface is located at about 85 ft below sea level, and the resistivity logs indicate brackish water to the bottom of the test hole. One well was completed at this site with a screen set at 145 to 155 ft below sea level. The highest chloride concentration analyzed during this study (6,500 mg/L) was in water from this well.

At the Arundel-on-the-Bay test well site, the lowest resistivity levels and highest chloride concentrations (6,000 mg/L) were in the lower section of the Aquia aquifer and upper section of the Monmouth aquifer. Water in the lower section of the Monmouth aquifer contained about half the amount of chloride (2,300 mg/L) than did water from the Aquia aquifer. The decrease in chloride concentration with depth probably is caused by an intervening layer of low permeability sediments, possibly cemented sandstone, that is impeding the landward flow of the brackish water. This conclusion is based primarily on the presence of some hard, chalky calcareous material in the drill cuttings around the depth of the resistivity increase in the Monmouth aquifer. The Brightseat Formation, which consists of silty sand and clay and usually behaves as a leaky confining unit, is located in the middle of the low resistivity band and is not related to the variation in chloride distribution (fig. 44).

The final test site that showed the brackish-water/freshwater interface is the Mayo Beach Park test well site located on the southern end of the Mayo Peninsula. The interface at this location is at a depth of about 100 ft below sea level. The source of the brackish water at this site is thought to be from a tidal pond located about 100 ft from the test wells. The distance from the test site to the Chesapeake Bay is much greater (about 700 ft).

The brackish-water/freshwater interface was not found at the Annapolis Roads test well site; however, a water sample from the deepest well (AA Df 151) screened in the Monmouth aquifer contained 51 mg/L chloride. The exact cause of the elevated chloride is uncertain, however, the bromide:chloride ratio, the sample depth as related to the theoretical depth of the Ghyben-Herzberg interface (Fetter, 1988), and the absence of nitrate suggest that the source of the chloride is brackish water from the Chesapeake Bay. This site is located 600 ft from shore.

The areal distribution of chloride concentrations in water from the Aquia and Monmouth aquifers sampled between 1988 and 1990 is shown in figure 16 and plate 1. Elevated chloride concentrations originating from sources other than Chesapeake Bay water are also plotted. On Annapolis Neck, the highest chloride concentrations sampled occur on the southern end near Hillsmere, Arundel-on-the-Bay and Bay Ridge. On the Mayo Peninsula, high chloride concentrations occur all along the shoreline of the South River. The widest range in chloride concentrations occurs within a narrow band bordering the shoreline. Concentrations ranging from 2 to 6,500 mg/L were sampled within this band.

Chloride concentrations in water from the Aquia and Monmouth aquifers on Annapolis Neck and the Mayo Peninsula are generally within the background range (less than 10 mg/L). A median concentration of 6 mg/L was calculated from 62 water samples collected from 1988-90 (table 2). However, concentrations increase substantially near the shore. A graph of chloride concentrations related to depth and distance to shore beneath Annapolis Neck and the Mayo Peninsula is shown in figure 45. This plot displays chloride concentrations in water from the Aquia and Monmouth aquifers analyzed between 1988 and 1990 and indicates conditions at those sampling sites only. It provides a general view of chloride distribution and, therefore, should not be used to predict chloride concentrations at a specific site. The aquifer boundaries are not shown because of differences of depth caused by the dip of the sediments. Chloride concentrations shown in figure 45 are divided into three groups—less than 10 mg/L, freshwater with background concentrations of chloride; 10 to 250 mg/L, freshwater showing signs of brackish-water mixing; and, greater than 250 mg/L, brackish water. The graph illustrates how chloride concentrations increase with depth and nearness to the shore. Three zones are indicated on the section: (1) a zone likely affected by brackish-water intrusion, (2) a zone of local variability, and (3) a zone not likely affected by brackish-water intrusion. The highest

concentrations of chloride occurred in water from the Monmouth aquifer and from the lower section of the Aquia aquifer. Virtually the entire upper section of the Aquia aquifer is free of brackish-water intrusion, except in areas about 100 ft from the shore of Chesapeake Bay.

At two test well sites, the southern end of Arundel-on-the-Bay and the area along Sands Avenue in Bay Ridge, the brackish-water/freshwater interface is shallower and extends farther inland (fig. 45). At the southern end of Arundel-on-the-Bay, a chloride concentration of 480 mg/L was analyzed in water from a residential well (AA Ef 36) located 300 ft from shore. The well was screened in the lower part of the Aquia aquifer between 81 and 88 ft below sea level. Along Sands Avenue in Bay Ridge, a chloride concentration of 1,700 mg/L was analyzed in water sampled from a residential well (AA Df 32) located 250 ft from shore and screened in the upper part of the Aquia aquifer between 28 and 35 feet below sea level. The extent of brackish-water intrusion in these areas could be due in part to a long history of domestic pumpage, which would allow time for the transport of chloride from Chesapeake Bay. The Arundel-on-the-Bay and Bay Ridge communities are among the oldest in the area.

Well-completion-report data obtained from the Maryland Water Resources Administration and the Anne Arundel County Department of Health indicate that approximately 95 percent of all the domestic wells drilled on Annapolis Neck and the Mayo Peninsula during 1970-90 are less than 90 ft deep. Therefore, even in topographically low areas, the brackish-water/freshwater interface would not be reached by the majority of the existing wells provided that those wells are not located within about 250 ft of Chesapeake Bay. Well drillers who encounter brackish water typically will raise

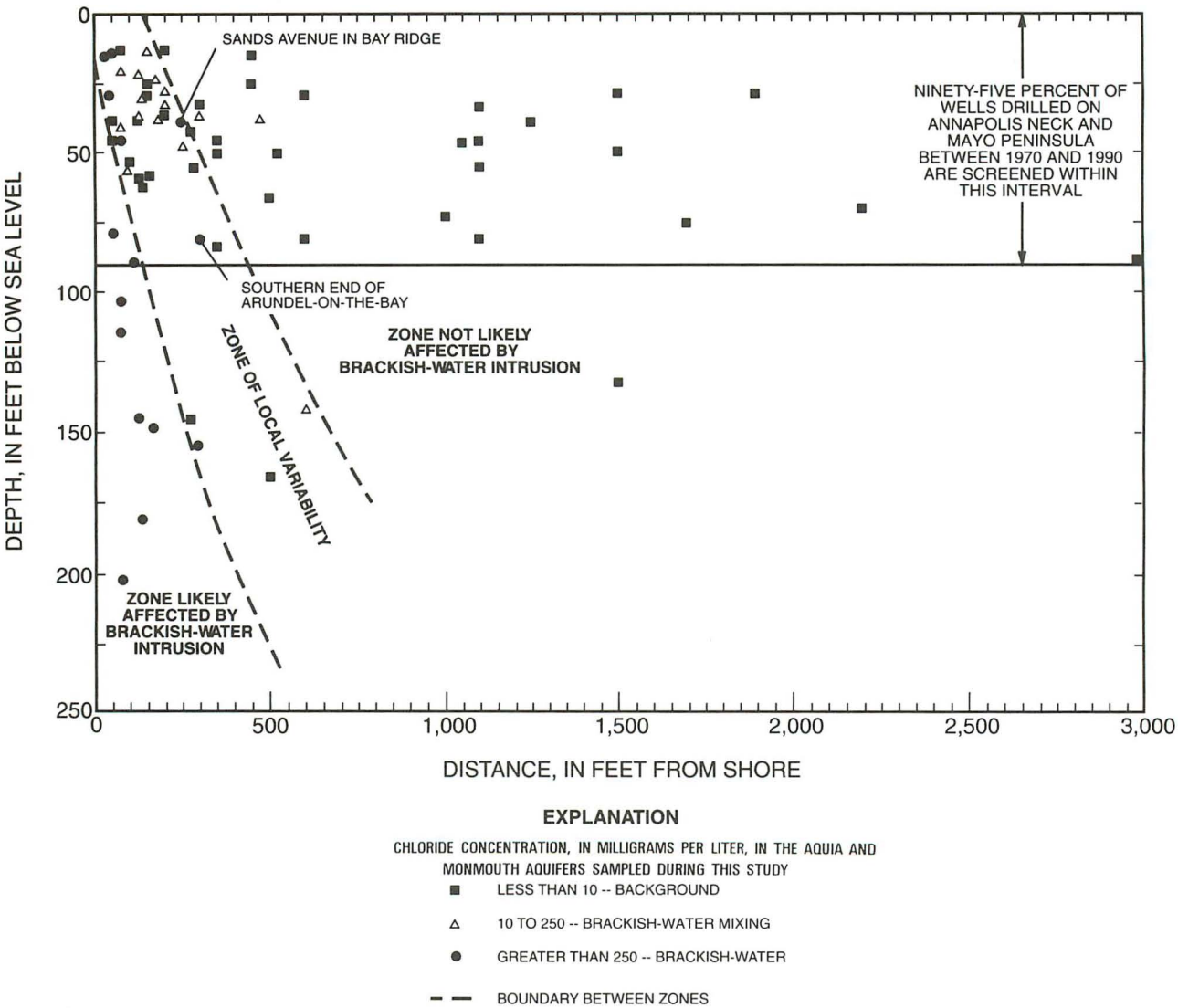


Figure 45. Graph showing chloride concentrations beneath Annapolis Neck and Mayo Peninsula, 1988-90.

the entire well casing-screen assemblage to a depth above the interface or abandon the well and redrill to the deeper Magothy aquifer.

In summary, the present distribution of brackish-water intrusion in the Aquia and Monmouth aquifers on Annapolis Neck and the Mayo Peninsula is limited mostly to nearshore locations. In the Aquia aquifer, brackish-water intrusion generally does not occur more than 200 ft inland. However, at three test well sites—Quiet Waters Park, the southern end of Arundel-on-the-Bay, and along Sands Avenue at Bay Ridge—the extent of brackish-water intrusion was greater at about 450, 300, and 250 ft from shore, respectively. Brackish-water intrusion typically extends as much as about 500 ft inland in the Monmouth aquifer. Chloride concentrations in water from the aquifer zone affected by brackish-water intrusion ranged from about 20 to 6,500 mg/L. In general, the denser brackish water toes inland in a wedge-shaped manner. The Monmouth aquifer generally contains higher concentrations of chloride than the overlying Aquia aquifer. The interface between brackish water and freshwater is relatively sharp and is steeply inclined near the shore. The average distance across the zone of mixing between brackish water and freshwater is about 30 ft. In general, the distribution and extent of the intrusion are locally variable and dependent on the permeability of the aquifers and overlying layers, local hydraulic-head conditions, and pumpage history.

Differentiation of Chloride Sources

Dissolved chloride (Cl^-) accounts for approximately 54 percent of the dissolved solids in brackish water from the Chesapeake Bay and is the primary indicator of brackish-water intrusion in ground water. However, in relatively shallow aquifers, such as the Aquia and Monmouth aquifers in east-central Anne Arundel County, elevated chloride concentrations also can indicate the effects of sources other than brackish water. Other chloride sources commonly found in the mostly urban setting of the study area include sewage effluent from private septic systems and public sewer lines, residential water-softener effluent, and road de-icing salt. To differentiate between chloride from anthropogenic sources and chloride from brackish water from Chesapeake Bay, the following factors were examined: (1) bromide:chloride (Br^-:Cl^-) ratios related to the Br^-:Cl^- ratio in water from Chesapeake Bay, (2) nitrogen (N) concentrations (as nitrite + nitrate) as a possible indicator of sewage effluent, and (3) position of well screens in the sampled wells related to the theoretical brackish-water/freshwater interface estimated using the Ghyben-Herzberg principle (Fetter, 1988). Table 8 lists chloride concentrations, Br^-:Cl^- ratios, and nitrogen concentrations in water from the Aquia and Monmouth aquifers. Other factors, including ionic ratios and water chemical types, can be used to determine whether aquifer water is affected by brackish-water intrusion; however, these methods are complicated by chemical reactions such as cation exchange.

Most of the study area is served by public sewers, and the remaining areas rely on individual septic systems. Leakage of sewage at sewer-pipe connections and beneath drain fields and septic tanks can infiltrate downward into the aquifer. Chloride concentrations in sewage effluent can range from 1.0 to 830 mg/L and are dependent on the human diet (Bashar and others, 1990). These concentrations could be higher in public sewers that accept certain types of commercial waste and in public sewers and septic tanks that receive brine effluent from ion-exchange water softeners. Chloride concentrations in ground water attributed to sewage effluent have been shown to range from 0.5 to 560 mg/L (Bashar and others, 1990). Nitrogen, primarily in the form of nitrate, usually accompanies chloride in ground water affected by sewage effluent.

Effluent from residential water softeners can contribute chloride to the ground water. Typical water softeners used in domestic water-treatment systems within the study area utilize ion-exchange reactions to replace calcium (Ca^{++}) and magnesium (Mg^+) with sodium (Na^+). The ion-exchange resin is regenerated with sodium ions about every 4 to 6 days by passing a briny salt (NaCl) solution through the resin bed (Lehr and others, 1988). The brine is then drained from the system through a discharge line. Quite often within the study area discharge lines are routed to outdoor drains. In these cases, the brine effluent can infiltrate down into the aquifer. Water-softener effluent also can contribute calcium to ground water.

Road de-icing salt, typically sodium chloride (NaCl) or calcium chloride ($CaCl_2$), also can cause elevated chloride concentrations in ground water. Chloride leaching off roadways salted in the winter can migrate downward into the aquifer and affect the quality of the water supply.

Chloride concentrations in ground water affected by road salt and water-softener effluent can be significantly higher than those concentrations attributed to sewage effluent. Regardless of the source, the concentration of chloride in ground water is dependent on the distance to the source and the amount of solute dispersion. Concentrations generally decrease away from the source. Bromide is generally not a common constituent in these chloride sources.

Water in Chesapeake Bay is a mixture of seawater from the Atlantic Ocean and freshwater from rivers and streams. The most abundant chemical constituent in seawater is dissolved chloride. Bromide (Br^-), chemically similar to chloride, is also present in seawater. Chloride and bromide are chemically conservative in aqueous solutions; that is to say, they do not become involved in the chemical reactions typical of natural aqueous environments. As a result, the ratio of bromide to chloride is essentially constant at any given location. As seawater mixes with freshwater in Chesapeake Bay, the concentrations of chloride and bromide decrease,

Table 8. Chloride concentrations, bromide:chloride ratios, and nitrogen concentrations in water from the Aquia and Monmouth aquifers, 1988-90

[mg/L, milligrams per liter; --, not determined; <, less than]

Sample number (fig. 46)	Well number	Chloride, (mg/L)	Bromide: chloride ratio	Nitrogen as (NO_2+ NO_3), (mg/L)	Sample number (fig. 46)	Well number	Chloride, (mg/L)	Bromide: chloride ratio	Nitrogen as (NO_2+ NO_3), (mg/L)
1	AA Cg 25	6	0.022	0.1	33	AA Df 121	140	0.0011	0.2
2	AA De 64	100	.00062	3.9	34	AA Df 123	88	.0051	.9
3	AA De 165	41	.0020	1.5	35	AA Df 124	120	.0032	1.2
4	AA De 167	19	.0037	--	36	AA Df 126	4	.0056	<.1
5	AA De 168	120	.0030	--	37	AA Df 136	11	.0068	<.1
6	AA De 173	17	.0029	--	38	AA Df 139	14	.0051	1.3
7	AA De 174	10	.0080	--	39	AA Df 146	4	.0060	<.1
8	AA De 175	46	.0015	--	40	AA Df 147	19	.0028	15.0
9	AA De 176	4	.0080	--	41	AA Df 148	1,100	.0030	1.0
10	AA De 179	8	.0068	--	42	AA Df 150	300	.0003	--
11	AA De 187	400	.0035	2.8	43	AA Df 151	51	.0037	<.1
12	AA De 188	9	.011	--	44	AA Df 152	6	.0011	.3
13	AA De 189	5	.0040	<.1	45	AA Df 153	46	.0018	7.8
14	AA De 190	37	.0022	<.1	46	AA Df 154	3	.014	<.1
15	AA De 191	24	.0011	.9	47	AA Df 155	6,500	.0040	<.1
16	AA De 193	5,900	.0034	<.1	48	AA Ee 71	11	.0027	--
17	AA De 194	310	.0042	<.1	49	AA Ee 77	15	.0053	--
18	AA De 196	3,400	.0035	<.1	50	AA Ee 78	11	.0023	--
19	AA De 197	3	.0071	<.1	51	AA Ef 17	48	.0014	--
20	AA De 198	4,600	.0037	.1	52	AA Ef 20	110	.0013	1.5
21	AA De 200	6,400	.0034	<.1	53	AA Ef 22	1,000	.0043	<.1
22	AA De 201	3,700	.0038	<.1	54	AA Ef 23	73	.0026	--
23	AA Df 32	1,700	.0028	.3	55	AA Ef 24	63	.0029	--
24	AA Df 86	190	.0043	1.4	56	AA Ef 27	190	.0030	--
25	AA Df 98	22	.0030	5.8	57	AA Ef 28	860	.0033	.4
26	AA Df 103	56	.0011	1.5	58	AA Ef 30	73	.0023	<.1
27	AA Df 105	22	.0027	3.5	59	AA Ef 31	6,000	.0032	<.1
28	AA Df 108	160	.0016	3.4	60	AA Ef 33	2,300	.0037	<.1
29	AA Df 112	28	.0036	2.6	61	AA Ef 34	12	.0058	<.1
30	AA Df 114	29	.0033	<.1	62	AA Ef 35	2,300	.0037	<.1
31	AA Df 118	26	.0058	--	63	AA Ef 36	480	.0038	--
32	AA Df 119	24	.0075	.2	64	AA Ef 37	190	.0038	--

dependent on the distance from the mouth of the bay and on the depth in the water column, but the $Br^-:Cl^-$ ratio remains constant. The theoretical ratio of Br^- to Cl^- for seawater is 3.5×10^{-3} based on average Cl^- and Br^- concentrations in seawater of 19,000 to 65 mg/L, respectively (Hem, 1985). Seawater is the primary source of Cl^- and Br^- in water from Chesapeake Bay. Stream water contributes negligible quantities of Cl^- and Br^-. A survey of water-quality analyses made by the U.S. Geological Survey between 1990-91 from 39 fresh surface-water sites within Maryland's part of the Chesapeake Bay watershed showed Cl^- concentrations less than 24 mg/L and Br^- concentrations less than 0.08 mg/L. The $Br^-:Cl^-$ ratio in water from Chesapeake Bay, as determined at three locations within the study area (data points A, B, and C; fig. 48), ranged from 3.8×10^{-3} to 4.6×10^{-3}. A partial chemical analysis for these sites is given in table 9. The differences in the ratios probably are caused by analytical error in the chemical analysis. Chloride and bromide are very mobile in ground water and, therefore, migrate through the bottom mud of Chesapeake Bay and aquifer material unaltered. Consequently, ground water intruded by brackish water should have a $Br^-:Cl^-$ ratio similar to that of water from the bay.

Across the Chesapeake Bay at Kent Island, the Aquia aquifer is affected by brackish-water intrusion (Drummond, 1988). The aquifer is overlain by clay layers that effectively seal it from surficial contamination. Therefore, the Chesapeake Bay at this location is the sole source of chloride and bromide to the aquifer above background levels. Water samples from the Aquia aquifer collected from 1988 to 1991 show the variations in $Br^-:Cl^-$ ratios that could be expected in brackish-water intrusion unaffected by surficial contamination (fig. 46).

Depth to the brackish-water/freshwater interface at each well sampled was calculated from the altitude of the water table using the Ghyben-Herzberg principle (Fetter, 1988, p. 151). This principle states that the depth to the interface is approximately 80 times the height of the water level above sea level, assuming that the density of the brackish water within the study area is about one-half that of seawater. This relation also assumes a sharp brackish-water/freshwater interface and hydrostatic conditions. The interface between brackish water and freshwater as determined at five test well sites is relatively sharp (approximately 30 ft across); therefore, the second assumption is reasonable. Effects of upconing, dispersion, or variations in aquifer permeability are not accounted for. The position of well screens in sampled wells was compared to the theoretical depth to the interface. One-hundred feet is used arbitrarily to represent a substantial difference between well-screen position and the interface.

Chloride, bromide, and nitrogen concentrations were analyzed in water samples from the Aquia and Monmouth aquifers. The ratio of bromide to chloride, related to chloride concentrations, is plotted (fig. 46) for comparison with two trend lines—a horizontal line reflecting the theoretical $Br^-:Cl^-$ ratio in water from Chesapeake Bay and a diagonal line indicating ground water with an ambient bromide concentration affected by a nonbromide-chloride source, such as road salt, sewage effluent, and water-softener effluent. Also plotted in figure 46 are $Br^-:Cl^-$ ratios determined in water samples from Chesapeake Bay collected at three locations and $Br^-:Cl^-$ ratios in water samples from the Aquia aquifer on Kent Island. Water samples with nitrogen concentrations (as nitrite + nitrate) greater than 3.0 mg/L are identified in figure 46 as well as water samples from wells screened more than 100 ft above the calculated brackish-water/freshwater interface.

Water samples that are most likely affected solely by brackish-water intrusion have the following characteristics: (1) $Br^-:Cl^-$ ratios similar to the ratio in Chesapeake Bay water, (2) well-screen positions within or near the calculated interface, and (3) nitrogen concentrations (as nitrate + nitrite) less than a level that might suggest sewage contamination (about 3.0 mg/L). It should be noted that samples affected by both brackish-water intrusion and other chloride sources would not likely have these characteristics. Therefore, only samples affected solely by brackish-water intrusion can be identified using these characteristics. Data plotted in figure 46 are distributed into two distinct groups: (1)

Table 9. Results of analysis of selected chemical constituents in water samples collected from the mouth of the South and Severn Rivers and Harness Creek, October 30, 1991

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

Sample location (fig. 48)	Sample number	Sample date	Specific conductance (µS/cm)	pH (standard units)	Chloride (mg/L)	Bromide (mg/L)
Mouth of Severn River	A	10/30/91	24,800	7.7	6,400	24
Mouth of South River	B	10/30/91	23,600	7.9	6,200	24
Harness Creek	C	10/30/91	23,600	7.7	6,300	29

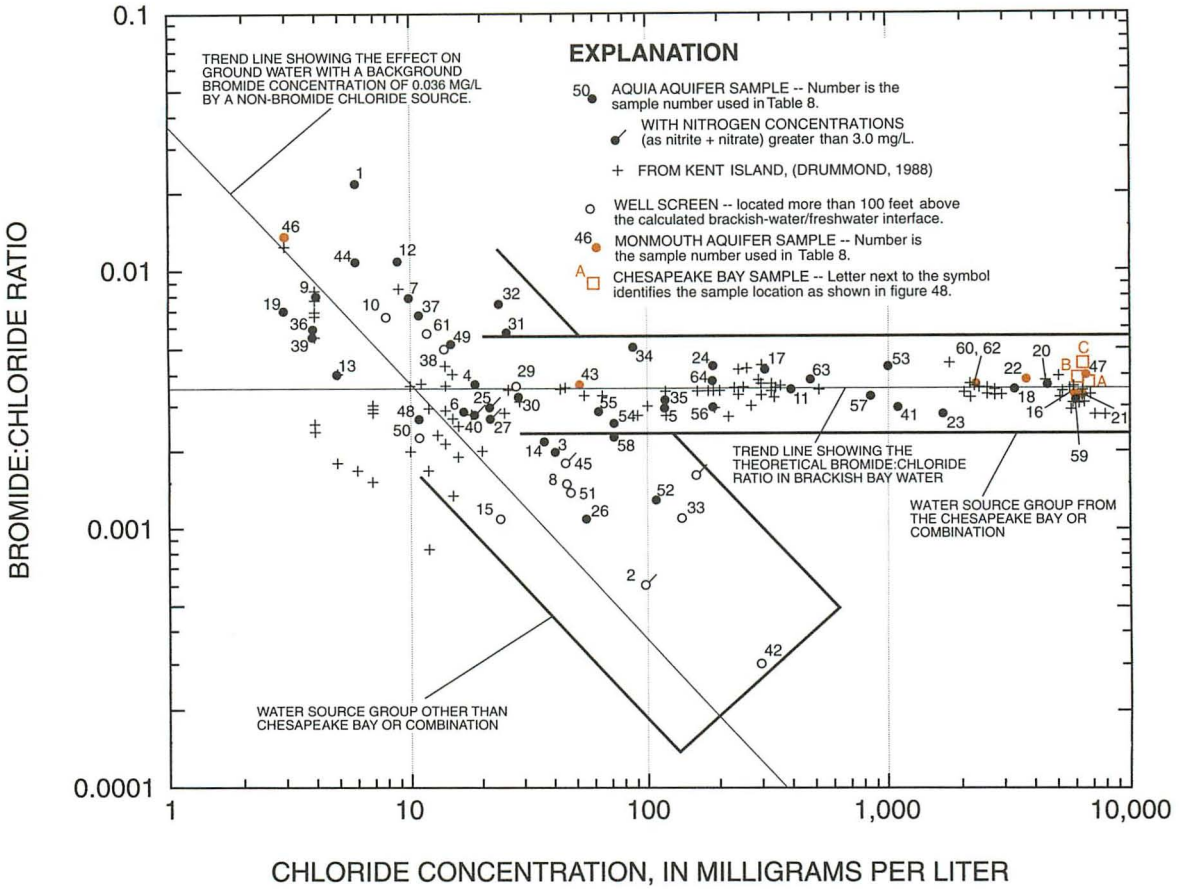


Figure 46. Bromide:chloride ratios related to chloride concentrations in the Aquia and Monmouth aquifers, 1988-90, and in the Aquia aquifer at Kent Island, 1988-91.

brackish-water source group ($Br^-:Cl^-$ ratios similar to the $Br^-:Cl^-$ ratio in Chesapeake Bay water) and (2) non-brackish-water source group or combination of Chesapeake Bay water and another chloride source—that is, $Br^-:Cl^-$ ratios that diverge from the $Br^-:Cl^-$ ratio in water from Chesapeake Bay.

Water samples with chloride concentrations of 1 to 10 mg/L show widely scattered $Br^-:Cl^-$ ratios. A median concentration for bromide calculated from 10 Aquia aquifer samples and 1 Monmouth aquifer sample with chloride concentrations less than 10 mg/L is 0.036 mg/L. The primary natural source of chloride and bromide in the Aquia and Monmouth aquifers within the study area is marine aerosols and precipitation. The average $Br^-:Cl^-$ ratio in rainfall has been reported to be generally reflective of seawater (Gerritse and George, 1988). Therefore, the ratio of bromide to chloride in the ground water with ambient water quality should be similar to that of water from Chesapeake Bay. However, the $Br^-:Cl^-$ ratios for low chloride water plot considerably above the brackish-water ratio (fig. 46). This increase in $Br^-:Cl^-$ ratio could be attributed to bromide enrichment of recharge water in the soil zone caused by soil decomposition (Gerritse and George, 1988). The Aquia samples from Kent Island with chloride concentrations less than 10 mg/L have generally lower ratios, which suggests that the confined nature of the aquifer might limit or exclude the above process.

Bromide:chloride ratios within the 10-to-100 mg/L chloride range are widely scattered, which is caused by interference from non-brackish-water chloride sources. Samples with chloride originating from brackish-water intrusion within this interval are grouped around the brackish-water $Br^-:Cl^-$ ratio line. The majority of these samples do not have elevated nitrogen concentrations and are from wells with screen positions within the calculated brackish-water/freshwater interface. Samples that plot substantially above and below the brackish-water $Br^-:Cl^-$ ratio line tend to be from wells with screen positions substantially above the interface. Also, one sample within this group had a nitrogen concentration (as nitrite + nitrate) greater than 3.0 mg/L. Analytical error in the chemical analysis makes it difficult to differentiate between chloride sources in samples with chloride concentrations less than about 25 mg/L.

Bromide:chloride ratios in samples with chloride con-

centrations greater than 100 mg/L plot mostly within the brackish-water source group ($Br^-:Cl^-$ ratio near that of Chesapeake Bay water). The amount of scatter in these data is consistent with that at Kent Island and with the three bay-water samples. These samples are from wells screened below the calculated interface and do not contain elevated nitrogen concentrations.

Five samples within the 100-to-1,000 mg/L chloride interval plot substantially below the brackish-water $Br^-:Cl^-$ ratio trend line and indicate samples affected by a non-brackish-water chloride source. Four of these samples are from wells located between 700 and 3,500 ft from the shoreline with well screens above the calculated brackish-water/freshwater interface. Two samples had nitrogen concentrations greater than 3.0 mg/L, which suggests possible contamination from sewage effluent.

If samples plotted in figure 46 within the brackish-water source group are disregarded, a downward trend, $Br^-:Cl^-$ ratio decreasing with increasing chloride content, is observed in the data. This trend generally coincides with the line representing Aquia and Monmouth aquifer water affected by a non-bromide chloride source. This trend line can be shifted to a parallel position depending on the value used for background bromide.

The areal distribution of chloride from non-brackish-water sources is shown in figure 16. The anomalous chloride concentrations are a widespread phenomenon not restricted to any particular location within the study area.

Ground-Water Quality Affected by Brackish-Water Intrusion

Water from the Aquia and Monmouth aquifers affected by brackish-water intrusion is characterized by a substantial increase in concentrations of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and sulfate (SO_4). Dissolved iron and manganese, and hardness, as high as 240,000 µg/L, 2,500 µg/L, and 8,500 mg/L, respectively, also were observed in water affected by brackish-water intrusion. The ratios of Ca, Mg, Na, and K to chloride and the elevated iron and manganese concentrations suggest that geochemical processes other than simple dilution of brackish water with aquifer water affect the water chemistry within the zone of brackish-water intrusion. The purpose of this section is to describe the water quality of the Aquia and Monmouth aquifers intruded by brackish water and to suggest some possible explanations for the variations in the major inorganic constituents. A quantitative analysis of the geochemical processes affecting the activity of these constituents is beyond the scope of this report.

An idealized hydrogeologic section of the Aquia and Monmouth aquifers (fig. 47) illustrates generalized chemical environments and reactions across an idealized brackish-water/freshwater interface. In this illustration the Aquia and Monmouth aquifers are viewed as one unit for simplification. Two chemically distinct water-quality zones — brackish water and freshwater — occur beneath the coastal margin. The position and movement of these zones are affected by the hydrologic flow system. In general, the direction of ground-water flow is from topographically high areas to the shore. Ground water discharges to the rivers and Chesapeake Bay near the shore. A major flow boundary occurs at the interface between the brackish water and freshwater. The chemical environment of the freshwater part of the aquifer is characterized as oxidizing. The water type is calcium and magnesium bicarbonate with variable amounts of dissolved iron. Dissolved solids are generally less than 250 mg/L. Freshwater enters the aquifer as acidic precipitation. Further acidification is caused by the reaction between carbon dioxide produced in the soil zone and the water (table 10). As the water percolates downward, calcium and magnesium carbonate shell material and iron-bearing minerals in the aquifer are dissolved releasing calcium, magnesium, and ferrous iron ions (table 10). These reactions are reversible and are dependent on redox (reduction-oxidation) potentials, pH, and ion concentrations. Ferrous iron is unstable in oxidizing environments and rapidly returns to a solid phase (that is, iron hydroxide). Dissolved calcium and magnesium on the other hand are more stable and can be transported along ground-water flow paths until saturation limits are reached before being redeposited. Solubility of these ions are dependent on bicarbonate concentrations and pH. Locally developed layers of secondary precipitated calcium-, magnesium-, and iron-bearing minerals occur throughout the Aquia and Monmouth aquifers.

A major change in geochemistry occurs at the boundary between brackish water and freshwater. On the bay side of the brackish-water/freshwater interface, the chemical environment is generally reducing with low concentrations of dissolved oxygen. The water in this part of the aquifer is a calcium chloride type, with wide ranging concentrations of dissolved iron and manganese and high dissolved-solids concentrations (as much as 14,500 mg/L). The change in the geochemical environment is attributed to the chemically active zone within the relatively thin layer of organic-rich sediment that underlies the bay. Brackish water entering the aquifer is chemically altered within this layer of sediment. The most important changes result from the oxidation of organic material that consumes dissolved oxygen and other oxidants, such as sulfate, and produces reducing conditions.

Changes in water chemistry from Chesapeake Bay water to aquifer water affected by brackish-water intrusion can be illustrated by examining pore fluid from selected bottom cores from the bay (table 11). Major ion concentrations in bay water in the vicinity of the study area is estimated to be about one-half the concentrations found in ocean water. The bottom-core data from Chesapeake Bay represent conditions at a particular sample location and depth only. The concen-

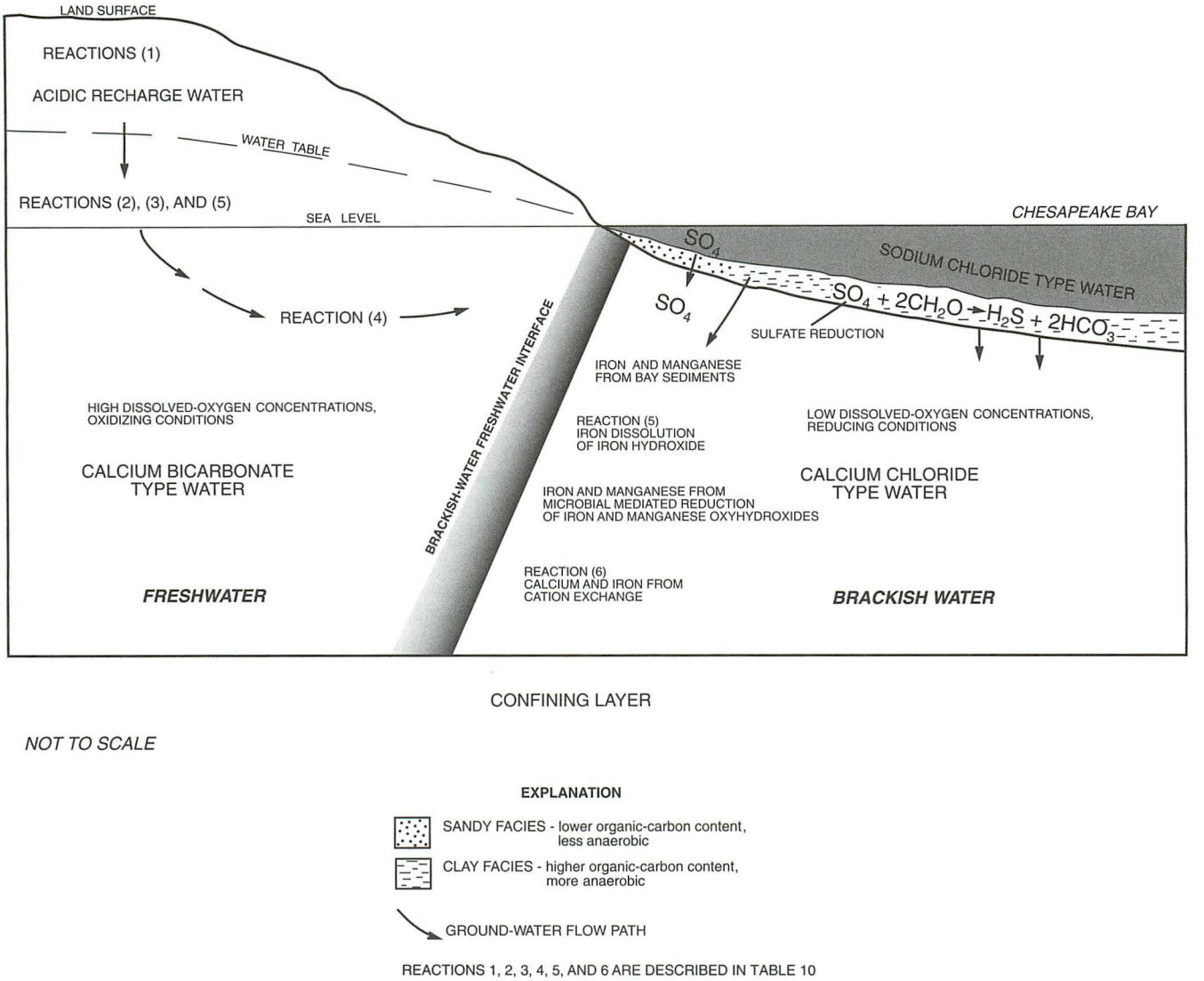


Figure 47. Schematic cross section showing generalized chemical environments and reactions across an idealized brackish-water/freshwater interface in the Aquia and Monmouth aquifers.

tration of any chemical species at any depth interval represents a dynamic balance of transport and equilibrium and non-equilibrium reactions (James Hill, Maryland Geological Survey, written commun., 1991). These mechanisms and reactions continue throughout the sediment column with the most active zone within the first 3 ft of sediment below the sediment-water interface (James Hill, Maryland Geological Survey, written commun., 1991). Therefore, data from the bottom of the cores (minimum depth of 26 in.) were used to approximate the type of water entering the aquifer. The location of sampling sites for the sediment cores is shown in figure 48.

Water from the Aquia and Monmouth aquifers affected by brackish water is predominantly a calcium chloride type (fig. 17). Brackish water, as evidenced by pore water in bay-sediment cores, is predominantly a sodium chloride type. As brackish water mixes with fresh aquifer water (calcium and magnesium bicarbonate type), calcium ions on cation exchange sites are replaced with sodium ions from the brackish water, resulting in a calcium chloride-type water. As a consequence, hardness concentrations are greatly elevated (as much as 8,500 mg/L). A trilinear diagram illustrates these three water types (fig. 17). The fresh ground-water and brackish-water data are for the most part tightly grouped, whereas the brackish ground-water data show some shift toward sodium chloride-type water. The distribution of the data points probably is dependent on the degree of cation exchange taking place in the aquifer. One sample affected by brackish-water intrusion (well AA Df 151, plot number 15, fig. 17) plots as a calcium bicarbonate-type water; however, the

Table 10. Major chemical reactions affecting water chemistry in the Aquia and Monmouth aquifers and across the brackish-water/freshwater interface

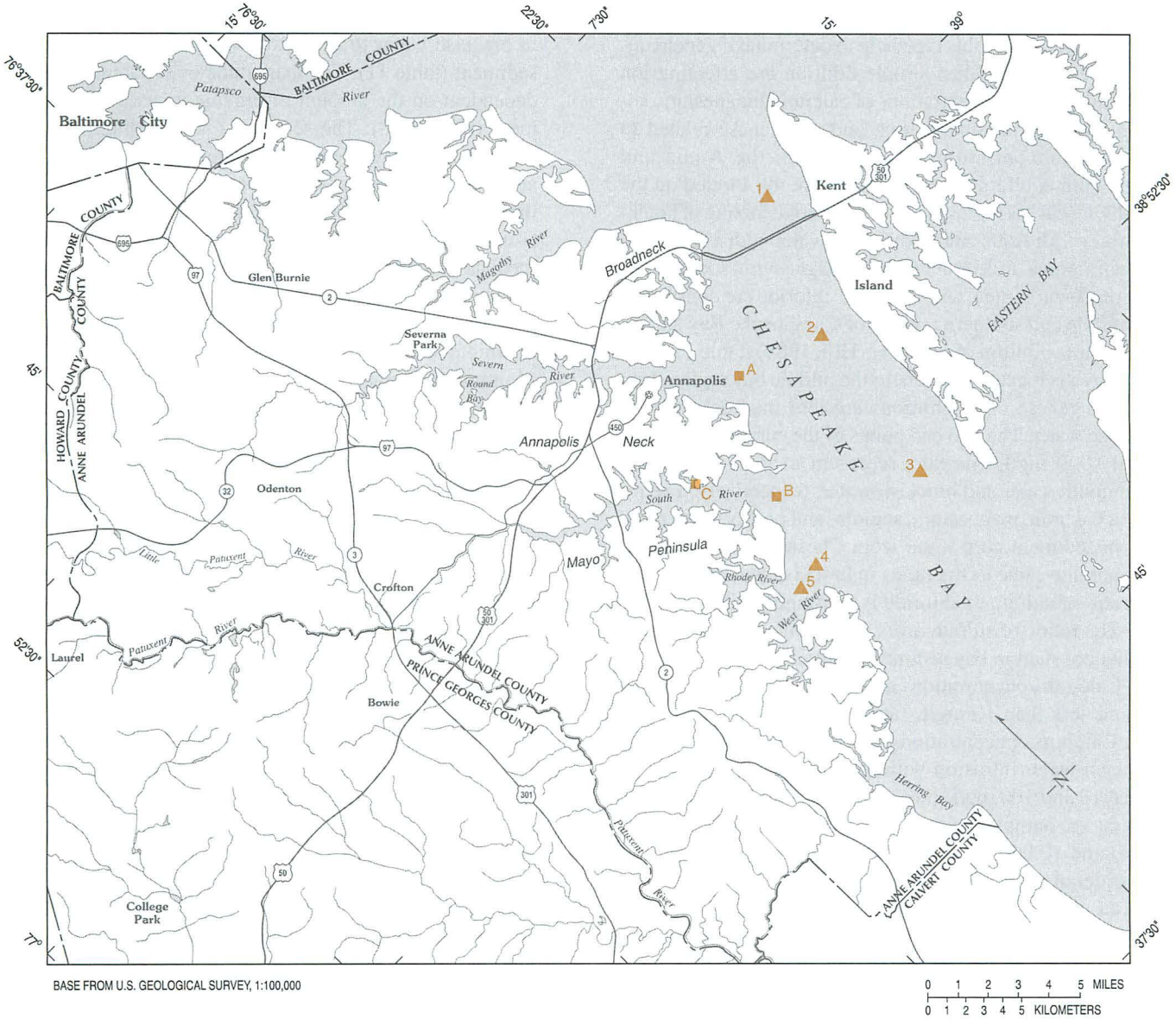
Reaction Number (Figure 47)	Chemical Reaction
(1) Carbonic acid production: (Freeze and Cherry, 1979, p. 95; Chapelle, 1985, p. 59)	$O_{2\,(g)} + \underset{\textit{(organic material)}}{CH_2O_{(s)}} \rightarrow \begin{array}{l} \textit{(soil zone } CO_2\textit{)} \\ CO_{2\,(g)} + H_2O \rightleftharpoons H_2CO_3 \\ \textit{(pH < 5.5)} \\ CO_{2\,(g)} + H_2O \rightleftharpoons H_2CO_3 \\ \textit{(atmospheric } CO_2\textit{)} \quad \textit{(carbonic acid)} \end{array}$
(2) Dissolution of carbonate material: (Chapelle and Drummond, 1983, p. 79)	$CaCO_{3\,(s)} + H_2O \rightarrow Ca^{2+}_{(aq)} + HCO^-_{3\,(aq)} + OH^-_{(aq)}$
(3) Weathering of glauconite: (Chapelle and Knobel, 1983, p. 350)	$\begin{array}{l} \textit{(glauconite)} \\ (K)_2(Fe_{1-x}, Mg_x)_2\,Al_6\,(Si_4O_{10})_3\,(OH)_{12\,(s)} + \frac{3}{2}O_{2\,(g)} \\ + 6H^+_{(aq)} \rightarrow 2K^+_{(aq)} + 2x \cdot Mg^{2+}_{(aq)} + 6SiO_{2\,(aq)} \\ + 2(1\text{-}x) \cdot Fe(OH)_{3\,(s)} + \frac{3}{2}\,Al_4(Si_4O_{10})\,(OH)_{8\,(s)} \end{array}$
(4) Precipitation of carbonate material:	$Ca^{2+}_{(aq)} + HCO^-_{3\,(aq)} + OH^-_{(aq)} \rightarrow CaCO_{3\,(s)} + H_2O$
(5) Dissolution of iron hydroxide: (Chapelle, 1985, p. 61)	$Fe(OH)_3 + H^+ \rightarrow Fe^{2+} + \frac{1}{4}O_2 + \frac{5}{2}H_2O$
(6) Cation exchange: (Chapelle and Knobel, 1983, p. 344)	$X^{2+} + 2Y \cdot Ex_{(ad)} \rightleftharpoons 2Y^+ + X \cdot Ex_{(ad)}$ where $X = Ca^{2+}, Fe^{2+}$, and $Y = Na^+, Mg^+, Fe^+$

Table 11. Major inorganic constituents found in pore fluid from selected bottom-sediment cores in the Chesapeake Bay near the study area (Tyree and others, 1981)

[Numbers listed in left column are concentrations in milligrams per liter; numbers listed in right column are ratios between the constituent and chloride x 10^{-1}; analyses are from the bottom part of the sediment-core; minimum depth is 26 inches below bottom surface]

Core number (fig. 48)	Calcium		Magnesium		Sodium		Potassium		Bicarbonate		Sulfate		Chloride		Iron [2]	Manganese [2]
1	174	0.20	582	0.65	5,040	5.7	176	0.2	1,470	1.7	2.1	0.002	8,890	1	4.3	7.3
2	190	.18	607	.61	5,600	5.6	189	.2	1,397	1.4	21	0.2	9,890	1	.2	2.5
3	30	.03	764	.73	5,960	5.7	210	.2	2,300	2.3	1.6	0.002	10.50	1	4.0	15.4
4	128	.22	375	.66	3,294	5.8	132	.23	976	1.7	2.1	0.004	6,712	1	.1	.7
5	150	.24	420	.67	3,339	5.4	129	.21	195	.31	14	0.2	6,231	1	.1	1.3
Bay water [1]	205	.22	675	.71	5,250	5.5	195	.20	71	.7	1,350	1,350	9,500	1	<.1	<.1

[1] Estimated as one-half the concentration of ocean water. Ocean water analysis is from Hem (1985).
[2] Values listed are concentrations in milligrams per liter for comparison purposes.



EXPLANATION

1▲ BOTTOM-SEDIMENT CORE COLLECTED FROM CHESAPEAKE BAY -- Number corresponds to that used in Table 11.

A■ WATER SAMPLE COLLECTED FROM CHESAPEAKE BAY -- Letter corresponds to that used in Table 9 and Figure 46.

Figure 48. Collection sites for selected bottom-sediment cores and water samples from Chesapeake Bay.

amount of exchangeable ions from brackish water in this sample is low.

Another useful means to compare concentrations of major ions in aquifer water affected by brackish-water intrusion is to plot ion concentrations against chloride concentrations. Plots of this type help to determine if geochemical processes other than simple dilution are affecting ion concentrations. Concentrations of calcium, magnesium, sodium, potassium, sulfate, iron, and manganese related to chloride concentrations in water from the Aquia and Monmouth aquifers are shown in figure 49. Plotted on the graphs are curves representing conservative mixing of brackish water with Aquia and Monmouth water with average ion concentrations. Ratios of calcium, magnesium, sodium, potassium, bicarbonate, and sulfate to chloride are constant in the middle and southern regions of Chesapeake Bay and reflect simple dilution of seawater (Hill, 1988) (table 11). The study area is located adjacent to the middle bay region. Iron and manganese concentrations are less than detection in brackish water. The two end points of the curves, at 10 mg/L and 10,000 mg/L chloride, represent average Aquia and Monmouth water and brackish water, respectively. The ratios of calcium, magnesium, sodium, and potassium to chloride in sediment-core water from Chesapeake Bay are essentially the same as the ratios in brackish water; however, the ratio of sulfate to chloride is substantially lower (table 11). The ratios of sulfate, iron, and manganese to chloride are not constant in bay sediment (table 11).

Calcium concentrations in water with chloride concentrations less than 10 mg/L range from 2 to100 mg/L (fig. 49). Calcium concentrations in two samples affected by brackish-water intrusion with chloride concentrations between 10 and 100 mg/L plot along the brackish-water dilution curve. Samples with chloride concentrations between 1,000 and 10,000 mg/L contain calcium at concentrations one order of magnitude higher than the brackish-water dilution curve. The concentration of calcium in brackish water is approximately 200 mg/L (table 11), whereas Aquia and Monmouth aquifer water affected by brackish-water intrusion contain concentrations as high as 2,600 mg/L (appendix C). The increase in calcium is accompanied by decreases in magnesium, sodium, and potassium with respect to the brackish-water dilution curve (fig. 49). It is thought that magnesium, sodium, and potassium in the intruding brackish water is exchanged for calcium on glauconite. The Aquia and Monmouth aquifers contain abundant quantities of the mineral glauconite, which is an effective cation-exchange medium.

Sulfate concentrations in water affected by brackish-water intrusion generally reflect simple dilution of brackish water with aquifer water (fig. 49). Most of the samples with chloride concentrations greater than 40 mg/L plot along the brackish-water dilution curve. However, three samples in this group plot below the dilution curve. This could be caused by the chemical reduction of sulfate by decaying organic material in the Chesapeake Bay sediment. As brackish water moves through the bay sediments, sulfate is reduced by decaying organic material and produces bicarbonate and hydrogen sulfide (Hill, 1988). This reduction is evident in the decrease in sulfate concentrations from about 1,350 mg/L in brackish water to less than 14 mg/L in water from bay sediment (table 11). The magnitude of sulfate reduction is dependent on the amount of organic material in the sediment (Hill, 1988). The sediments surrounding Annapolis Neck and the Mayo Peninsula are generally sandy, are more aerated and contain lesser amounts of organic material than the finer grained sediments found in deeper parts of the bay (Kerhin and others, 1988). Also, microorganisms, which mediate sulfate reduction, are strict anaerobes and are inhibited by strong oxidants present in aerated water. Therefore, sulfate that has passed through a more oxygenated bay-sediment environment could move to the Aquia and Monmouth aquifers with relatively little reduction. This could explain why the majority of Aquia and Monmouth aquifers samples plot along the brackish-water dilution curve.

Dissolved iron and manganese analyzed in water from 21 Aquia wells and 12 Monmouth wells ranged from 5 to 240,000 µg/L and 8 to 2,500 µg/L, respectively (appendix C). The highest concentrations of iron and manganese occurred in water with high concentrations of chloride (fig. 49). Background iron concentrations ranged from 5 to 15,000 µg/L in water with chloride concentrations less than 10 mg/L. Manganese concentrations in water with chloride concentrations less than 10 mg/L ranged between 8 to 360 µg/L. Iron concentrations in water affected by brackish-water intrusion ranged from 30 to 240,000 mg/L. Manganese concentrations in water affected by brackish-water intrusion ranged from 50 to 2,500 µg/L.

The stability of iron and manganese in various oxidation and physical states is dependent on the Eh (oxidation-reduction potential) and pH of the water and can be determined by equilibrium thermodynamic analysis (Hem, 1985). In general, iron present in an oxidizing environment is primarily in the ferric (Fe^{+3}) oxidation state as solid amorphous ferric hydroxide, $Fe(OH)_3$ or as a ferric oxyhydroxide such as limonite, $FeO(OH) \times nH_2O$, or goethite, FeOOH. In this type of environment, less iron can be held in solution. In a reducing environment the ferrous ion (Fe^{+2}) is the dominant dissolved-iron species. Under reducing conditions, larger amounts of iron can be held in solution. Ferrous iron can be produced in both oxidizing and reducing conditions through the oxidation of pyrite (FeS_2) or the reduction of $Fe(OH)_3$ and FeO(OH) (Hem, 1985). The chemical stability of manganese is more complex than that of iron. In general, manganese naturally occurs as manganese dioxide, MnO_2, on grain coatings in aerated sand and gravel streambed sediment (Hem, 1985) and in Chesapeake Bay sediment (Hill, 1988). Reduction of MnO_2 by organic material in anaerobic environments liberates the Mn^{+2} ions. In both cases, dissolved-iron and manganese concentrations not only depend

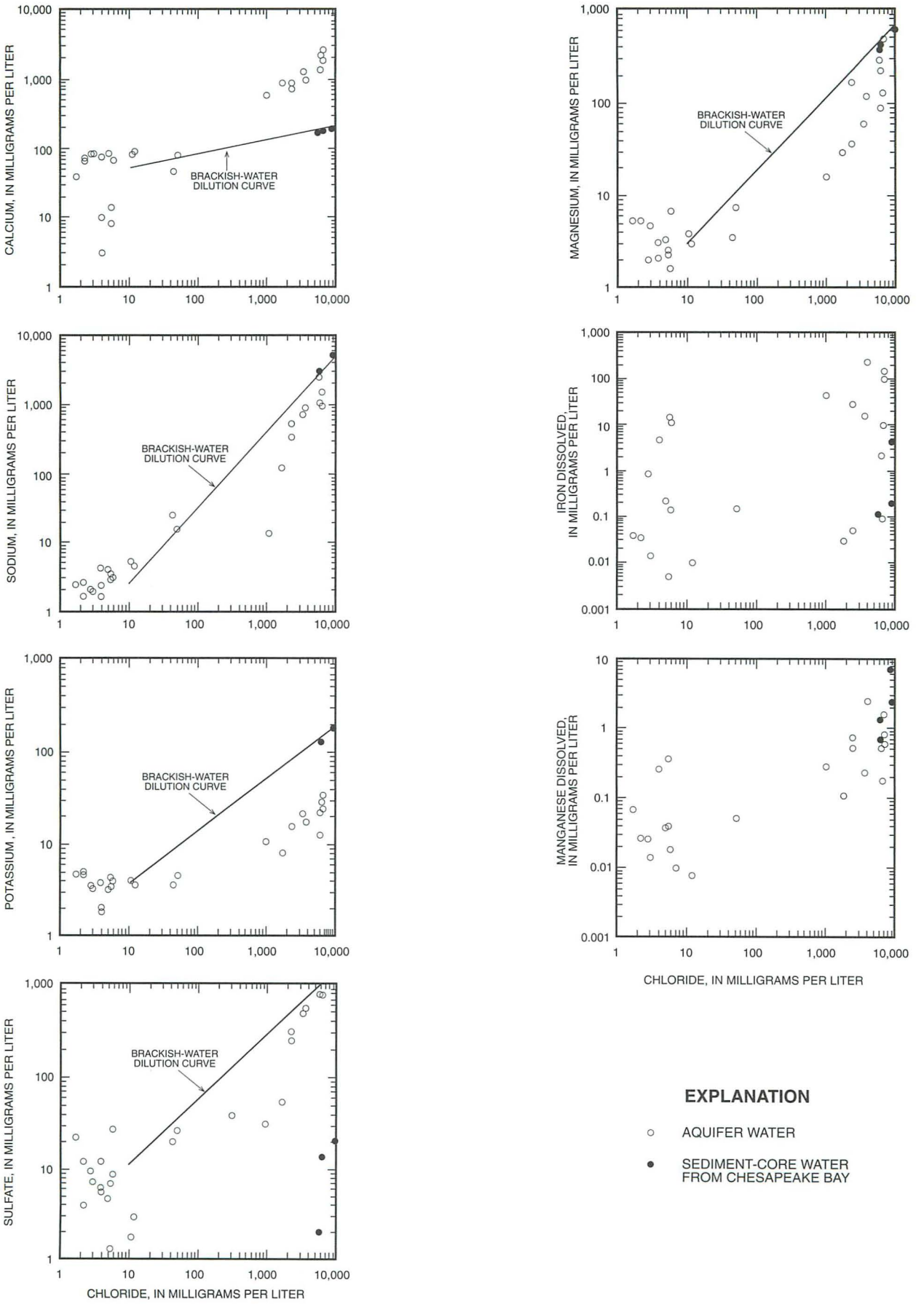


Figure 49. Concentrations of selected chemical constituents related to chloride concentrations in the Aquia and Monmouth aquifers.

on the Eh and pH of the water but also on the formation of inorganic and organic complexes that can either remove or retain $Fe^{\pm 2}$ and $Mn^{\pm 2}$ ions in solution. Constituents that help to define reducing and oxidizing conditions, such as dissolved-oxygen concentration and Eh, were not measured in the water samples from the Aquia and Monmouth aquifers. However, it is reasonable to assume that for iron and manganese to exist in solution at the concentrations observed, the chemical environment is most likely reducing, has a low dissolved-oxygen concentration, and is acidic. The average pH of the Aquia and Monmouth water with iron concentrations greater than 10,000 µg/L was 6.5. The retention of high iron concentrations in solution also may be helped by the formation of ion complexes as is evident in some brines (Hem, 1985).

The major cause of the high iron and manganese concentrations is thought to be the microbially-mediated reduction of iron oxyhydroxide and manganese oxide. Chapelle (1992) has shown that microbial-mediated Fe^{+3} reduction plays a key role in the creation of high-iron zones in aquifers containing iron oxyhydroxides. The Aquia and Monmouth aquifers are rich in Fe^{+3}-bearing minerals that are primarily derived from the oxidation of glauconite (iron-aluminum silicate).

A secondary cause of the elevated iron and manganese concentrations is the transport of Fe^{+2} and Mn^{+2} from bay sediments. Dissolved iron and manganese concentrations as high as 26,000 and 32,000 µg/L, respectively, have been detected in bay-sediment cores (Tyree and others, 1981). The sole source of iron and manganese in bay sediment is from grain coatings and other authigenic solid phases (Hill, 1988). Iron concentrations in brackish water are below detection (table 11). Iron and manganese, under reducing conditions, can be transported with the inland migrating brackish-water/freshwater front (fig. 47). This same phenomena was observed in ground water affected by brackish-water intrusion at Joppatowne, Harford County, Maryland (Nutter, 1977) where elevated manganese concentrations were observed, and in the Canton area of Baltimore City, Maryland (Chapelle, 1985), where elevated concentrations of iron and manganese were observed.

A third, minor source of iron in the brackish-water zone is cation exchange. Glauconite in the Aquia and Monmouth aquifers has demonstrated the ability for cation exchange. The exchange sites on glauconite in the outcrop area are predominantly occupied by calcium ions. However, it is possible that some iron might also be attached to exchange sites. If this is the case, then magnesium, sodium, and potassium in the intruding brackish water could be exchanged for iron.

POTENTIAL FOR BRACKISH-WATER INTRUSION IN THE MAGOTHY AND UPPER PATAPSCO AQUIFERS

The Magothy and Upper Patapsco aquifers are also important sources for water supply. There is no evidence to date that these aquifers, within the study area, are intruded by brackish water; however, there is a potential for intrusion into the Magothy aquifer as a result of lowering of pressure heads caused by pumpage from both the Magothy and Upper Patapsco aquifers. On Annapolis Neck and the Mayo Peninsula, the Magothy aquifer is overlain by the Matawan confining unit, a low permeability clay, which effectively seals the aquifer from downward leaking brackish water. On Broadneck, however, the Magothy aquifer subcrops beneath the Severn and Magothy Rivers providing an entry point for brackish-water intrusion. Although as shown in figure 43, the estimated time for brackish-water to travel from the rivers to the Arnold well field ranges from 293 to 1,657 years.

SIMULATION OF BRACKISH-WATER INTRUSION IN THE AQUIA AQUIFER IN THE ANNAPOLIS AREA USING A SOLUTE-TRANSPORT MODEL[2]

INTRODUCTION

The use of coastal aquifers for drinking water is limited by their vulnerability to brackish-water intrusion because relatively small concentrations of dissolved minerals can affect the taste of freshwater. The U.S. Environmental Protection Agency does not require an enforceable limit on dissolved solids in drinking water but recommends a Secondary Maximum Contaminant Level of 500 mg/L for dissolved solids (U.S. Environmental Protection Agency, 1986).

Most domestic water wells in the Annapolis, Md., area pump freshwater from the unconfined Aquia aquifer. Some wells near the shore of the Chesapeake Bay in the Annapolis area, however, pump brackish water (dissolved solids from 1,000 to 10,000 mg/L), which generally renders the water unusable for drinking. Well drillers also occasionally find saltwater (greater than 10,000 mg/L dissolved solids) near the shore when drilling new wells.

When brackish water or saltwater is found in the Aquia aquifer, the strata containing such water must be sealed from the rest of the well. The deeper part of the well bore might be sealed by grout, a well screen might be set above

[2]This section was written by Barry S. Smith, U.S. Geological Survey.

the brackish water where the Aquia aquifer still contains freshwater, or the well might be abandoned.

A single domestic well generally has a negligible effect on the flow of ground water and solutes in the aquifer except in the immediate vicinity of the well. If the pumped well is near the interface between brackish water and freshwater, it could, however, draw water with high concentrations of dissolved solids. In time, the well water could become more and more salty, and the user may eventually reject the well water because of taste. Declines in water levels in the Aquia aquifer in the Annapolis area from large numbers of closely spaced domestic wells and a few commercial wells or from municipal and commercial pumping in aquifers below the Aquia also could possibly cause the intrusion of brackish water, followed by saltwater near the shore.

Scope of Local Study

The potential for brackish-water intrusion into the unconfined Aquia aquifer at Quiet Waters Park, a typical shallow aquifer near Annapolis, Md., is the subject of this section of the report (fig. 50). The local study at Quiet Waters Park is a focused investigation and is only a small part of the entire study area. The local study area is contained within one or two nodal blocks of the regional ground-water-flow model described in previous sections of this report.

The Maryland Geological Survey and the U.S. Geological Survey began an investigation of brackish-water intrusion in Anne Arundel County in 1988. As part of that study, five wells were installed along a linear section at Quiet Waters Park near Annapolis to determine the location and nature of a typical transition from freshwater to brackish water in the unconfined Aquia aquifer and the geohydrologic units immediately below. The potential for intrusion of brackish water in the Aquia aquifer was investigated using a calibrated, two-dimensional, solute-transport model. Intrusion caused by pumping a typical domestic well was simulated, as well as that caused by a more general lowering of water levels.

Geologic, hydrologic, and water-quality information used in this section was collected and analyzed by William Fleck of the U.S. Geological Survey (Towson, Maryland) and by David Andreasen of the Maryland Geological Survey (Annapolis, Maryland).

Description of Local Study Site

Quiet Waters Park is immediately south of Annapolis in Anne Arundel County and is bordered by the South River and Harness Creek. The park is about 5 km (3 mi) up the South River from the main channel of Chesapeake Bay.

Quiet Waters Park is a landscaped, open green, with some wooded areas near the edges of the park. The park contains a small landscaped wetland, numerous picnic pavilions, a visitors center, a playground, a skating pond, bicycle paths, and walking trails.

The study section stretches 104 m (341 ft) from the shore of Harness Creek to the turning circle and parking lot for the South River overlook at Quiet Waters Park (fig. 51). The altitude of the site is about 13 m (43 ft) above sea level, and steep banks generally rise from the South River and Harness Creek up to the level of the park. A pelecypod shell bed, the remains of a previous oyster shell dump about 0.3 m (1 ft) thick, is evident at the study site near the top of the bank above Harness Creek. The water table is just above sea level at the park in the Aquia Formation, which is exposed along the banks of the South River and Harness Creek.

Local-Study Approach

Three boreholes were drilled at Quiet Waters Park approximately aligned to form a section perpendicular to Harness Creek. Resistivity and gamma ray logs of the open holes were recorded (pl. 5). Two additional shallow holes were drilled, and five wells numbered AA De 189, 196, 197, 200, and 201 were installed along the section. The geohydrologic units at Quiet Waters were determined, and water samples were collected from the wells and analyzed for general chemical constituents (appendix C). Water-level recorders were installed on the wells for a brief period in August 1990. Transmissivities of the formations were estimated by aquifer tests.

The U.S. Geological Survey saturated-unsaturated transport (SUTRA) computer code was used to construct a vertical, two-dimensional, solute-transport model for the Quiet Waters study area. The sectional model was calibrated to the dynamic equilibrium measured in 1990 by dissolved-solid concentrations in water from the five wells. Sensitivity of the calibrated solute-transport model was also tested.

The calibrated, solute-transport model was used to simulate intrusion of brackish water and saltwater caused by changes in water levels. Movement of brackish water toward a typical, hypothetical, domestic well pumping from the unconfined Aquia aquifer was simulated. Another simulation considered the potential movement of brackish water and saltwater caused by a general lowering of water levels in the aquifer. Such a decline possibly could be caused by pumping of nearby domestic wells or possibly by greater pumpages farther away.

Previous Solute-Transport Studies

Brackish-water intrusion from the Patapsco River estuary into the Patuxent aquifer beneath the harbor at Baltimore, Md., was simulated in an areal, two-dimensional model by Chapelle (1985, 1986). Previous withdrawals of ground water in the Baltimore area had induced brackish water from the Patapsco River through Pleistocene channels or breaches in the river bottom. The rate of brackish-water leakage into

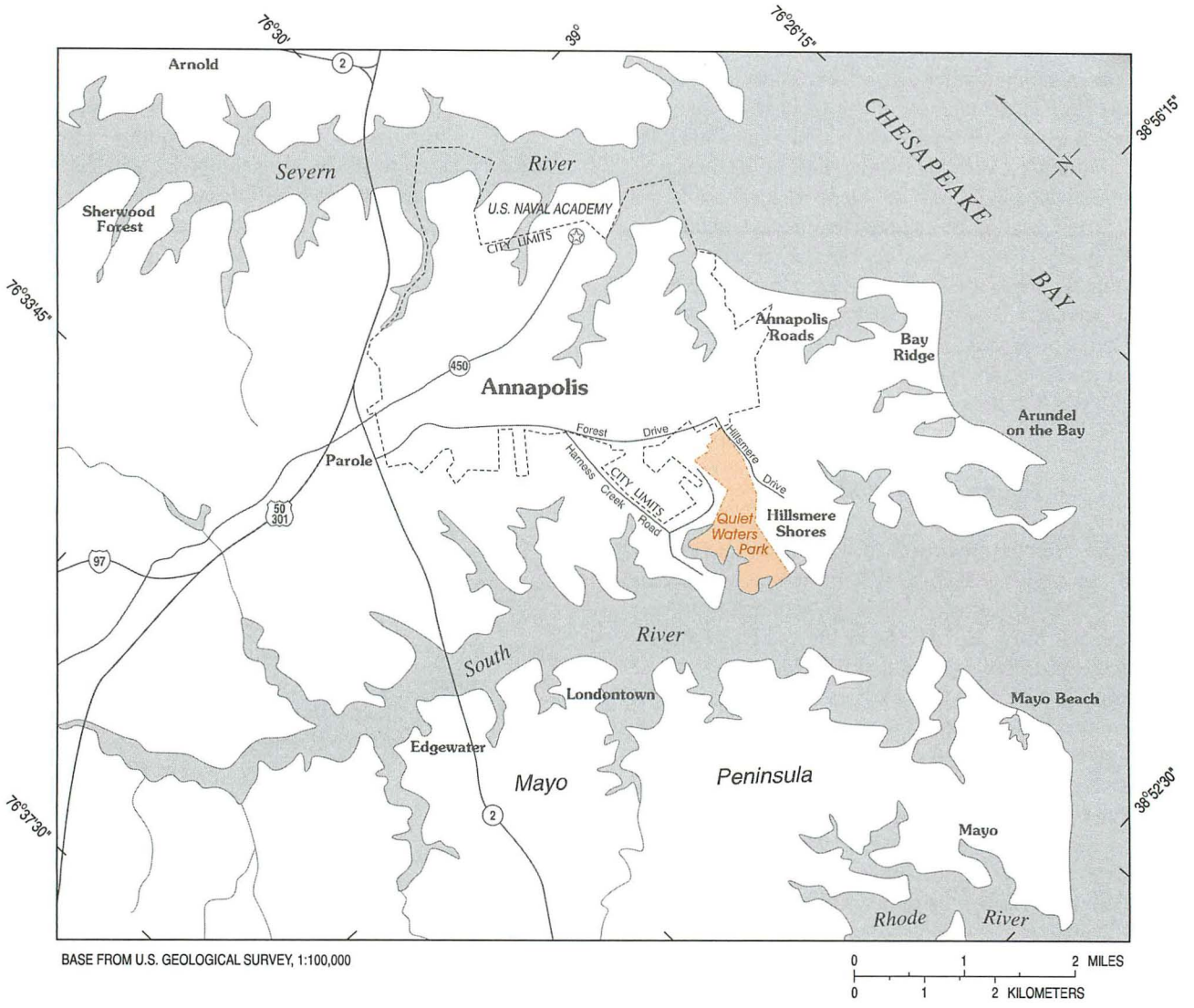


Figure 50. Location of Quiet Waters Park in Anne Arundel County, Maryland.

the aquifer was affected by the difference in water levels between the river and the aquifer and by the thickness and hydraulic conductivity (permeability) of the intervening sediments. Flow of brackish water within the aquifer was affected by the direction of ground-water flow and the dispersive properties of the aquifer matrix.

Brackish-water flow in an 8-km (5-mi) vertical section of the confined Aquia aquifer on the Kent Island, Md., was simulated by Drummond (1988). Movement of brackish water beneath Kent Island and Chesapeake Bay was simulated in response to ground-water withdrawals on and near Kent Island. Sensitivity analyses by Drummond indicated that the movement of brackish water in the confined Aquia aquifer was affected by variations in water density, water pressure, the presence of calcite-cemented (less-permeable) layers in the Aquia aquifer, paleochannel (more permeable) sediments, and the permeability of the overlying confining unit.

Definition of Water Types

Water types can be classified by concentration of dissolved solids. In coastal areas, classification with respect to the dissolved-solids concentration of seawater, generally assumed to be near 35,000 mg/L, is advantageous because relatively small concentrations of dissolved minerals can affect the taste of freshwater. The following classification derived after Davis and Dewiest (1966, p. 118) and Robinove and others (1958, p. 3) is used in this section:

Classification	Concentration of dissolved solids (in milligrams per liter)	Percent seawater
Freshwater	Less than 1,000	Less than 2.9
Brackish water	1,000 to 10,000	2.9 to 29
Saltwater	10,000 to 35,000	29 to 100
Brine	Greater than 35,000	Greater than 100

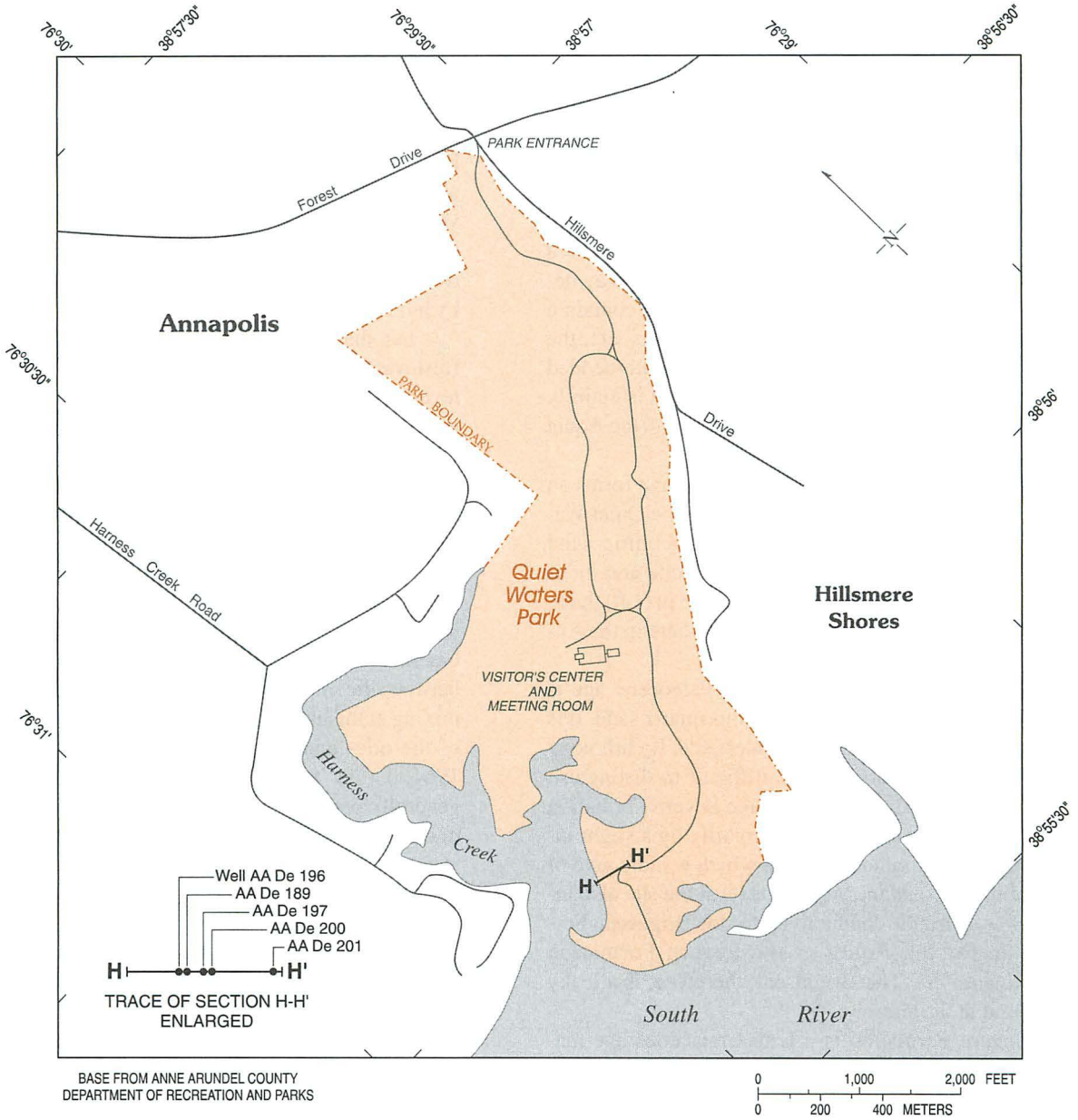


Figure 51. Location of observation wells and trace of section in Quiet Waters Park near Annapolis, Maryland.

Residents in some areas of the United States have used water containing more than 1,000 mg/L dissolved solids all their lives without any apparent detrimental effects (Hem, 1985, p. 212). The U.S. Environmental Protection Agency (1986) does not require an enforceable limit on the concentrations of dissolved solids in drinking water but recommends a Secondary Maximum Contaminant Level of 500 mg/L dissolved solids.

Geohydrologic Framework

The geohydrologic framework at Quiet Waters Park was determined by D. C. Andreasen of the Maryland Geological Survey (pl. 5). The framework is similar to that described by Mack and Andreasen (1991) for the Broadneck area of Anne Arundel County north of Annapolis.

Three boreholes were drilled each to a depth of about 73 m (240 ft) below the land surface perpendicular to the shore of Harness Creek at Quiet Waters Park. Resistivity and gamma ray logs of the open holes were recorded, the geologic units were described, the geohydrologic framework was interpreted from the logs, and the location of the interface between brackish water and freshwater was determined from the resistivity records. Two additional holes were drilled, and five wells were installed at the site.

From land surface downward, the geologic formations are the Talbot, Aquia, Brightseat, Severn, and Matawan Formations (pl. 5). The Talbot Formation discontinuously overlies the Aquia Formation throughout the Annapolis area (Clark, 1916). The Talbot is a Pleistocene silt and clay deposit of estuarine origin that, in places, can also contain a sand facies of fluvial origin. At the Quiet Waters site, the Talbot Formation is predominantly a silty clay interbedded with fine sand. It is about 6 m (20 ft) thick and is entirely above the water table at Quiet Waters. Recharge to the Aquia aquifer is inhibited by the Talbot clay above.

The Aquia Formation of Late Paleocene age forms an unconfined aquifer in the Annapolis area. At the Quiet Waters site, it consists of quartzose and glauconitic sand interbedded with thin silt stringers. Thin calcite and indurated iron-oxide layers, generally less than 0.3 m (1 ft) thick, are present in the Aquia at the site and elsewhere in the Annapolis area.

The Brightseat Formation of Early Paleocene age is comprised of silty, glauconitic, micaceous quartz sand. It is about 3 m (10 ft) thick at the Quiet Waters site. By lithology alone, the Brightseat Formation is difficult to distinguish from the Aquia Formation above and the Severn Formation below, but differentiation is made primarily by a slight increase in recorded gamma radiation, which is indicative of an increase in clay content. Aquifer tests at the site also indicate a lower hydraulic conductivity for the Brightseat Formation than for the Aquia or the Severn Formation (Monmouth aquifer). The Brightseat, therefore, is a leaky confining unit at the site.

The Severn Formation is a Late Cretaceous age marine, inner-shelf deposit. It consists of fine to silty, partially glauconitic, quartzose sand interbedded with gray clay lenses. Indurated zones are present within the Severn elsewhere. The Severn forms a poor aquifer throughout the area. The term "Severn Formation" was suggested by Minard, Sohl, and Owens (1977) for beds previously designated the "Monmouth Formation" on the western shore of Chesapeake Bay and correlative units on the eastern shore. Water-bearing sands of the Severn Formation are called the Monmouth aquifer in this report. The Monmouth aquifer, however, contains saltwater at the Quiet Waters site.

The Matawan Formation is marine clay of Late Cretaceous age. It forms a relatively impermeable confining unit at the site.

Ground-Water Flow

Precipitation is generally plentiful in the humid climate of Maryland. Some of the precipitation runs off the land into streams, some is taken up by soil and plants, some evaporates, and some infiltrates through the unsaturated zone between the land surface and the water table to recharge shallow aquifers. Recharge of the water table occurs principally after a rain when plants are dormant and soil moisture is high. Recharge to shallow aquifers varies with the seasons and with wet and dry cycles that may last for months or years, but generally, a relatively constant recharge rate persists and aquifer water levels are maintained within a relatively narrow range for decades or centuries if not affected by human activities.

In a shallow coastal aquifer recharged by precipitation, freshwater heads are naturally higher than the adjacent sea level, and the freshwater continually flows from the land toward the coast where the freshwater is discharged (fig. 52). Freshwater is lighter than saltwater and flows across the top of the aquifer toward the shore, whereas the heavier saltwater moves beneath, in the opposite direction, from the bottom of the sea, bay, or estuary to fill the lower section of the aquifer.

Some of the freshwater mixes with the saltwater at the interface creating a diffuse or transition zone comprised of brackish water. A diffuse zone rather than a sharp interface between the saltwater and freshwater, results from continual mixing at the interface caused by the reciprocation motions of the tides and seasonal variations in recharge (Cooper, 1964, p. C1). Tidal and seasonal variations in water levels generally persist within relatively narrow ranges for years or decades, forcing shallow aquifer systems toward a virtual steady state or a dynamic equilibrium.

Resistivity logs were used to locate the depth of the transition zone from freshwater to brackish water in three boreholes at Quiet Waters Park (pl. 5). The interface sloped upward toward the shore as would be expected where freshwater is flowing toward and discharging offshore.

Water Levels

Two wells (AA De 189 and AA De 197) were screened in the freshwater part of the Aquia aquifer above the transition zone, and one well (AA De 196) was screened within the transition zone in the Aquia aquifer so that water levels could be measured and samples collected. Two more wells (AA De 200 and AA De 201) were screened beneath the leaky confining deposits of the Brightseat Formation in the saltwater of the Severn Formation (Monmouth aquifer).

Water-level recorders were installed on the wells for a brief period in August 1990. The water levels generally fluctuated in concert, maintaining constant differences through

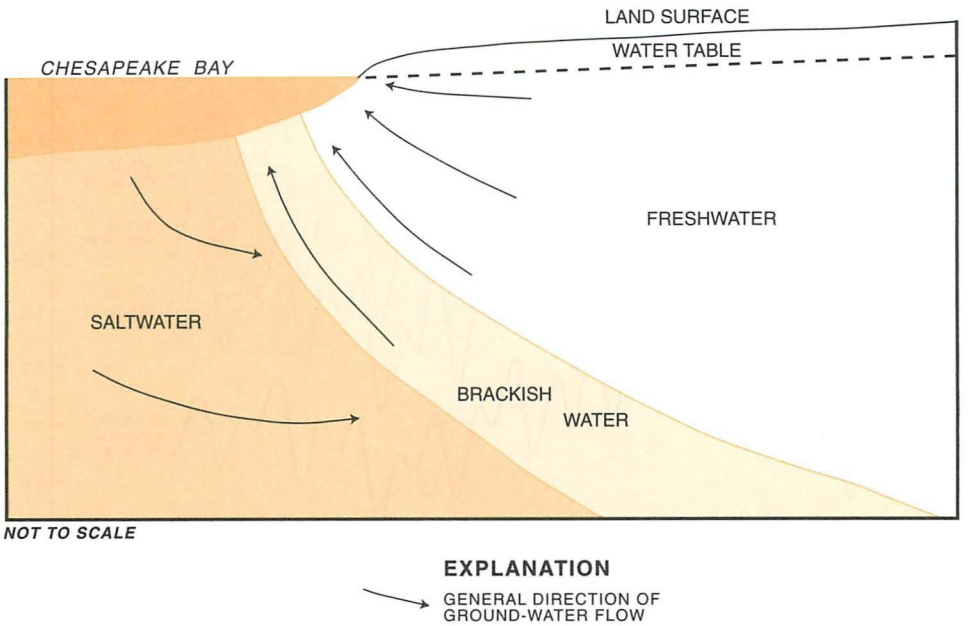


Figure 52. Schematic diagram showing freshwater mixing with saltwater in an unconfined coastal aquifer.

daily tidal fluctuations of about 0.1 m, about 0.3 ft (fig. 53). The water levels were always above sea level and above the mean tide level of 0.2 m (0.6 ft) above sea level at Edgewater, Md. (National Oceanic and Atmospheric Administration, 1989, p. 218). The difference between the mean high tide and the mean low tide at Edgewater, Md., about 5 km (3 mi) up the South River from Quiet Waters Park, is 0.3 m (1 ft).

Water levels in the two wells screened in the freshwater part of the Aquia aquifer at the Quiet Waters site showed a slight hydraulic gradient sloping toward Harness Creek, which would indicate freshwater flow toward the tidal creek. All of the water levels at the Quiet Waters site were generally about 13 m (43 ft) below the land surface, but only about 0.5 m (1.6 ft) above sea level.

The water levels were not corrected for density differences. Such corrections would be small for well AA De 196, about +0.01 m (+0.03 ft) because the well does not penetrate very far into the denser water. A larger correction of about +0.16 m (+0.52 ft) would be required for well AA De 200, but inferences concerning the direction of hydraulic gradients or flow between the Aquia and Severn Formations from the equivalent freshwater heads may be misleading because flow directions in the two units are generally in opposite directions. Just four of the five continuous records are shown because mechanical problems resulted in missing records for one of the wells screened in the Severn Formation (Monmouth aquifer).

Transition from Freshwater to Saltwater

Water samples were collected from the Quiet Waters wells in April 1990 and analyzed for general chemical constituents (appendix C). Concentrations of dissolved solids from the samples were used to indicate concentration gradients from freshwater to brackish water and saltwater. Concentrations of dissolved solids from the well samples at the Quiet Waters site ranged from 270 mg/L (about 1 percent of the concentration of dissolved solids generally assumed for seawater) to 12,200 mg/L, or about 35 percent seawater. The transition from freshwater to brackish water was located within the bottom of the Aquia aquifer and sloped upward toward the shore (pl. 5). Saltwater was present in the wells open to the Severn Formation (Monmouth aquifer).

The concentrations of dissolved solids increased downward at the site and in the direction of Harness Creek as would be expected if the source of dissolved solids was the tidal water of the creek, which is connected to the South River about 5 km (3 mi) from the main stem of Chesapeake Bay. Previous studies have shown that brackish water from the tributaries of Chesapeake Bay (Chapelle, 1985, 1986) and from the main stem of the Chesapeake Bay (Drummond, 1988) has intruded into adjacent aquifers when induced by pumping of ground water.

The Maryland Geological Survey has investigated the general chemistry of interstitial water from cores of the first

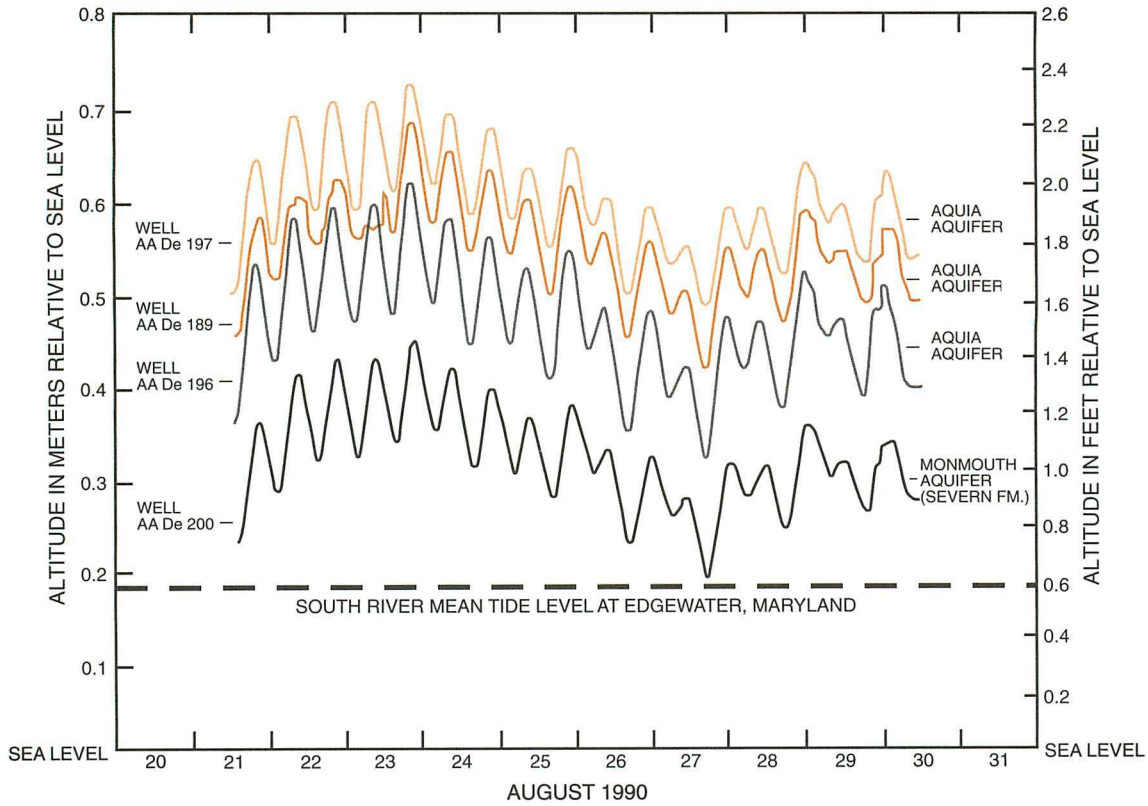


Figure 53. Graph showing water-level fluctuations in wells at Quiet Waters Park from August 21-30, 1990.

meter of sediments beneath the main stem of Chesapeake Bay near the mouth of the South River (Bricker and others, 1977). Drummond (1988) showed that, although the chloride of the interstitial water of the cores varied near the top in response to fluctuation in the concentration of the bay waters, the concentrations of chloride near the bottom of the cores approached a more consistent concentration of about 10,500 mg/L (Drummond, 1988, p. 28 and fig. 17). Assuming a concentration of chloride in seawater of 19,000 mg/L, a concentration of 10,500 mg/L chloride is about 55-percent seawater and represents the source of brackish water beneath the main stem of Chesapeake Bay.

Hydraulic and Transport Properties

Transmissivity of the Aquia aquifer, the Brightseat confining unit, and the Monmouth aquifer at the Quiet Waters site was estimated by drawdown and recovery tests from pumping each well at the site and measuring water-level changes at the other wells. Time-drawdown curves for the observation wells were plotted and compared to leaky aquifer curves after the methods of Hantush and Jacob (1955) as described in previous sections of this report. Corrections were made for partial penetration of the aquifers.

Horizontal hydraulic conductivities for the hydrologic units were calculated from the transmissivities using the formation thicknesses at Quiet Waters and then were converted to permeabilities, which are required for the solute-transport method. The permeabilites were calculated assuming a uniform density of 1,000 kg/m^3, a uniform viscosity of 0.001 kg/m-s, and an acceleration of gravity of 9.80 m/s^2:

Hydrologic unit	Horizontal hydraulic conductivity (meters per day)	Horizontal permeability (square meters)
Aquia aquifer	1.0	1.2×10^{-12}
Brightseat confining unit	0.1	1.2×10^{-13}
Monmouth aquifer	1.0	1.2×10^{-12}

Density variations between freshwater and seawater have a negligible effect on the permeability. Temperatures of shallow aquifers generally are maintained near an annual average, and therefore, viscosity also has a negligible effect on permeability.

The vertical hydraulic conductivity and permeability for each hydrologic unit were assumed to be one order of magnitude less than the horizontal hydraulic conductivity and permeability; therefore, the vertical to horizontal anisotropy ratio is 0.1. Most aquifers of water-deposited sediments are stratified and, therefore, are anisotropic (Jacob, 1963, p.

274). The degree of anisotropy is, however, not known. Doubling and halving vertical to horizontal anisotropy in the calculations of transmissivity had little effect on the results of the aquifer tests. Anisotropy of one order of magnitude was assumed to be a reasonable approximation.

Specific yield for the top 1.0 m (3.3 ft) of the unconfined Aquia aquifer was estimated to be 0.20 for simulation of transient responses to pumping. Modifications to the U.S. Geological Survey SUTRA computer code allowed a separate storativity for the top row of model nodes (Souza and Voss, 1987, p. 22). Reducing the specific yield by 50 percent had virtually no effect on tested results, and simulations were generally carried through to a dynamic equilibrium with respect to solute concentrations as well as pressures.

The storage coefficient of the confined Aquia aquifer in the Kent Island area was estimated at 0.0002 on the basis of values determined from previous reports that ranged from 0.0001 to 0.0004 (Drummond, 1988, p. 15). The storage coefficient was incorporated into the matrix compressibility of the SUTRA code, 7.7×10^{-7} kPa, by Drummond (1988, p. 70). An identical value of 7.7×10^{-7} kPa was assigned for the depths below the top 1.0 m (3.3 ft) at Quiet Waters Park. The analyses at Kent Island and at the Quiet Waters site were not, however, sensitive to matrix compressibility.

Recharge to the water table at Quiet Waters was unknown. Solute-transport simulations of the location of the transition zone between freshwater and saltwater were, however, sensitive to the recharge rate. An initial estimate of 3.2×10^{-5} kg/s per node, equivalent to 0.25 m/yr (9.8 in/yr), in the solute-transport model resulted in virtually no flow of brackish water into the simulated section even after 600 years. Subsequent calibration and sensitivity analyses of the transport model indicated that a recharge rate of 1.8×10^{-5} kg/s per node, equivalent to 0.14 m/yr (5.5 in/yr), was a more reasonable approximation.

Effective porosity of the Aquia aquifer on Kent Island was simulated at 0.30 (Drummond, 1988, p. 16). The effective porosity at Kent Island was based primarily on neutron logs, which indicated a range in effective porosity from 0.25 to 0.30. Effective porosity of the units at the Quiet Waters site was also assumed to be 0.30 or 30 percent on the basis of these previous studies. The density of a solid grain of a porous medium was specified as 2,700 kg/m^3 after Hillel (1982, p. 9). The solute-transport model was not, however, sensitive to changes in the density of the matrix.

Macrodispersivity is the large-scale property of hydrodynamic dispersion. Dispersivity of the Aquia aquifer at the Quiet Waters site was unknown. Longitudinal dispersivity of the units at the Quiet Waters site was initially estimated to be 1.0 m (3.3 ft) on the basis of values of macrodispersion calculated from flow-meter and tracer tests in a sand and gravel aquifer at Cape Cod, Massachusetts (Hess and others, 1991, p. 6 and 7). Transverse dispersivity initially was assumed to be one order of magnitude less or 0.1 m (0.33 ft) because the magnitude of dispersion perpendicular to the principal velocity is generally much smaller than that in the direction of velocity (Henry, 1964, p. C73). Simulation and sensitivity analyses of the solute-transport model resulted in calibrated values of 10.0 m (32.8 ft) for longitudinal dispersivity and 0.1 m (0.33 ft) for transverse, a ratio of 100:1. A transverse dispersivity of zero produced a slightly poorer approximation of the measured dissolved-solids fraction than did the 0.1 m (0.33 ft) used in the calibrated model.

SIMULATION OF BRACKISH-WATER INTRUSION

The potential for brackish-water intrusion into the Aquia aquifer was investigated by solute-transport simulation. A solute-transport model representing the vertical section at Quiet Waters Park, a typical shallow aquifer near Annapolis, was calibrated to the hydraulic heads (pressures) and dissolved-solids concentrations (mass fractions as a percentage of seawater) measured in April 1990. A dynamic equilibrium was assumed. A dynamic equilibrium with respect to hydraulic heads and concentrations would be expected in a shallow unconfined coastal aquifer not significantly affected by human activities.

Solute-Transport Simulation

SUTRA, a two-dimensional, density-dependent, solute-transport model was used to simulate freshwater, brackish-water, and saltwater movement for the vertical section at Quiet Waters Park. The solute-transport method used for the Quiet Waters site is similar to that described for the seawater-intrusion problem in the SUTRA documentation (Voss, 1984, p. 196-202.) The method compares mass fractions of a solute, such as the dissolved-solids concentrations, to those of seawater. Full saturation, uniform temperature, and two-dimensional flow were assumed for this investigation. Fluid properties used in the simulations are given in table 12.

A vertical, two-dimensional grid comprised of 783 nodes (intersecting points) and 728 rectangular elements was devised to represent the Quiet Waters site (fig. 54). Each element was 4 m (13 ft) long, 2 m (6.6 ft) high, and 1 m (3.3 ft) wide. Nodes and elements of the grid were assigned initial values for aquifer and transport properties as previously described. The five observation wells used to calibrate the model to fluid pressures and dissolved-solids concentrations were represented by the nodes nearest the center of the screened intervals when the grid was overlain on a drawing of the vertical section.

Boundaries for the Quiet Waters model were similar to those described for the saltwater intrusion problem of Henry (1964, p. C74-C82) as described by Voss (1984, p. 196-202); however, the Aquia aquifer is unconfined at the site, and an updated version of the SUTRA code was used to simulate unconfined storage properties in the topmost nodes of the grid (Souza and Voss, 1987, p. 22).

Table 12. Fluid properties used in simulation of freshwater, brackish-water, and saltwater movement

Fluid Property	Value
Fluid compressibility	4.47×10^{-10} meter-seconds squared/kilogram
Fluid base concentration	0 milligrams per liter
Dissolved-solids base concentration as a mass fraction	0 kilograms per kilograms seawater
Dissolved-solids concentration of seawater as mass fraction	0.0357 kilograms per kilograms seawater
Density of freshwater	1,000 kilograms per cubic meter
Density of seawater	1,025 kilograms per cubic meter
Fluid viscosity	0.001 kilogram per meter-second
Fluid diffusivity	1.00×10^{-9} square meters per second
Density change with solute concentration	700 square kilograms (seawater) per kilogram dissolved solids-cubic meter

Freshwater recharge was specified at the water table. Freshwater inflows were also specified along the landward vertical boundary representing flow in the Aquia aquifer from beyond the simulated section (fig. 54). A static boundary of brackish water with a pressure of sea level and a maximum inflow concentration of 35 percent seawater was specified for the opposite side of the grid to represent brackish-water intrusion from the tidal creek. The concentration of brackish water from the direction of Harness Creek was assumed to be 35-percent seawater because that was the highest concentration of dissolved solids measured in ground water at the site.

The bottom of the grid was specified as a no-flow boundary, assuming that a negligible amount of water or solutes would move across the Matawan confining unit beneath the salty Monmouth aquifer. Similarly, the landward vertical boundaries of the Brightseat confining unit and the Monmouth aquifer were assumed to have a negligible effect on the movement of solutes and no-flow boundaries were specified there.

Equal time steps of 1 year were used for the simulations. Flow and transport solutions were calculated for each time step. Convergence criteria for the numerical solution with regard to flow was specified as a change of 100 Pa (kilograms per meter-seconds squared) or less and with respect to transport as a change in mass fraction of 0.01-percent seawater or less. The specified-condition boundary factor (GNU) was set at 0.01. See Voss (1984, p. 252) for a more detailed discussion of the GNU.

Model Calibration

The solute-transport model was calibrated from an initial state of freshwater throughout the section to the steady-state pressures and concentrations measured in August 1990. Initial pressures for the first time step of each solute-transport simulation (cold start) were calculated by SUTRA from a steady-state simulation based on the aquifer properties and boundaries specified previously (see Voss, 1984, p. 275). Then, beginning with the calculated starting pressures, transient flow and transport were simulated until a new dynamic equilibrium with respect to solutes was established. Dissolved-solids concentrations as a mass fraction (percentage of seawater) were simulated and compared to measured concentrations of dissolved solids as a percentage of seawater. Simulated pressures also were compared to measured water levels, as pressures. Pressures, however, were much less sensitive to changes in hydraulic and transport properties than the concentrations.

Calibration of the model required testing two unknowns for which little or no information was available—freshwater inflows and dispersivity. Freshwater inflows included flow from the landward direction in the Aquia aquifer and recharge to the surface of the unconfined Aquia aquifer. The rate of freshwater flow from the landward direction was assumed to be approximately equal to recharge to the water table and such a ratio was maintained throughout calibration. Longitudinal dispersivity was initially assumed to be 1.0 m (3.3 ft)—10 times greater than transverse—but was adjusted during calibration to 10.0 m (32.8 ft)—100 times transverse.

The model was calibrated by testing reasonable values for the two unknowns while holding all other properties constant. Solute movement was simulated from the initial state of freshwater throughout the section until a new equilibrium was established. Simulated dissolved solids, as a percentage of seawater, were then compared to those measured in April 1990 at the five observation wells. Differences between the measured and simulated seawater fractions were summed and plotted. A region of lowest differences with respect to both unknowns was thus defined (fig. 55). A re-

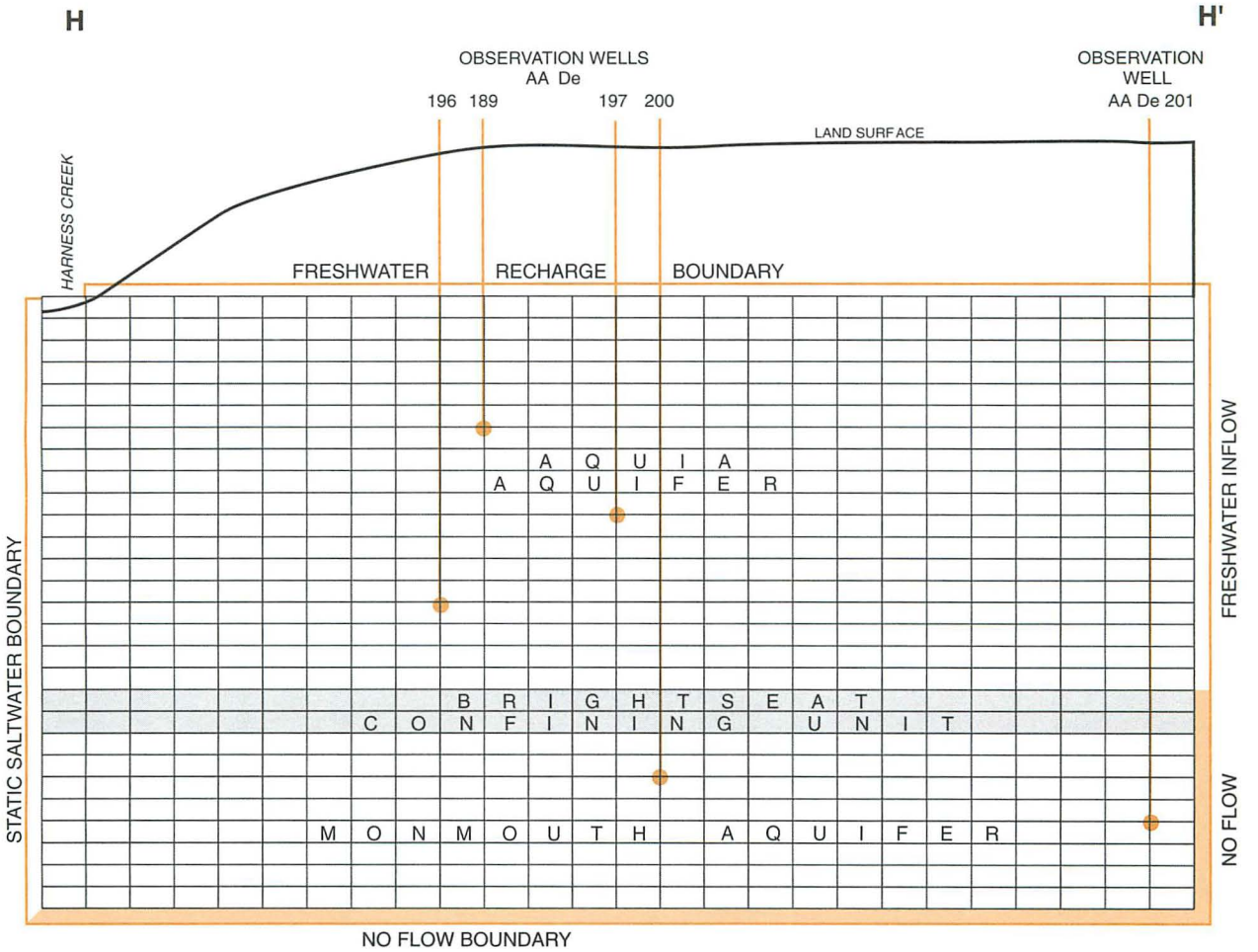


Figure 54. Schematic diagram showing model grid, location of observation wells, and boundaries of the Quiet Waters solute-transport model.

charge rate of 1.825 x 10^{-5} kg/s per node, equivalent to 0.15 m/yr (5.9 in/yr), and a longitudinal dispersivity of 10 m (33 ft) and a transverse of 0.1 m (0.3 ft) gave the lowest absolute differences and was considered a reasonable calibration.

At calibration, the sum of absolute differences was a mass fraction of about 4 percent for the five observation wells (table 13). The median measured hydraulic heads from hydrographs of the five wells were compared to the simulated heads. The sum of absolute differences between measured and simulated hydraulic heads, at calibration, was 1.75 m (5.74 ft).

The calibrated model reached a dynamic equilibrium with respect to solutes after approximately 600 years of simulation time (fig. 56). Brackish water and saltwater had moved significantly into the study area in much less time, and after 300 years the solutes were at approximately 90 percent of the steady-state concentrations; however, the approach to a more complete dynamic equilibrium took another 300 years.

The calibrated model simulated the dynamic equilibrium of the shallow Aquia aquifer in a manner similar to that described by Cooper (1964, p. C8). Simulated dissolved-solids concentrations and vectors indicate freshwater flowing from the land and mixing with saltwater migrating from the opposite direction to form a transition zone of brackish water (fig. 57). Freshwater flows in the Aquia aquifer above the heavier saltwater and discharges just offshore. Saltwater migrates slowly inland, then mixes with the freshwater to form brackish water, which is swept beneath the freshwater back toward the bottom of the tidal creek.

Freshwater moved in the Aquia aquifer at a rate of about 2 m/yr (7 ft/yr), whereas saltwater moved in the Monmouth aquifer at only 0.1 m/yr (0.3 ft/yr) and leakage through the Brightseat confining unit was about 0.03 m/yr (0.1 ft/yr) in the simulation. Vertical leakage is indicated in figure 57 at a depth of 36 to 40 m (118 to 131 ft) below sea level where the Brightseat confining unit impedes flow between the Aquia aquifer and the Monmouth aquifer beneath.

A mass balance of inflows and outflows indicates the relative proportion of freshwater to brackish water and saltwater in the calibrated dynamic equilibrium of the simulated section:

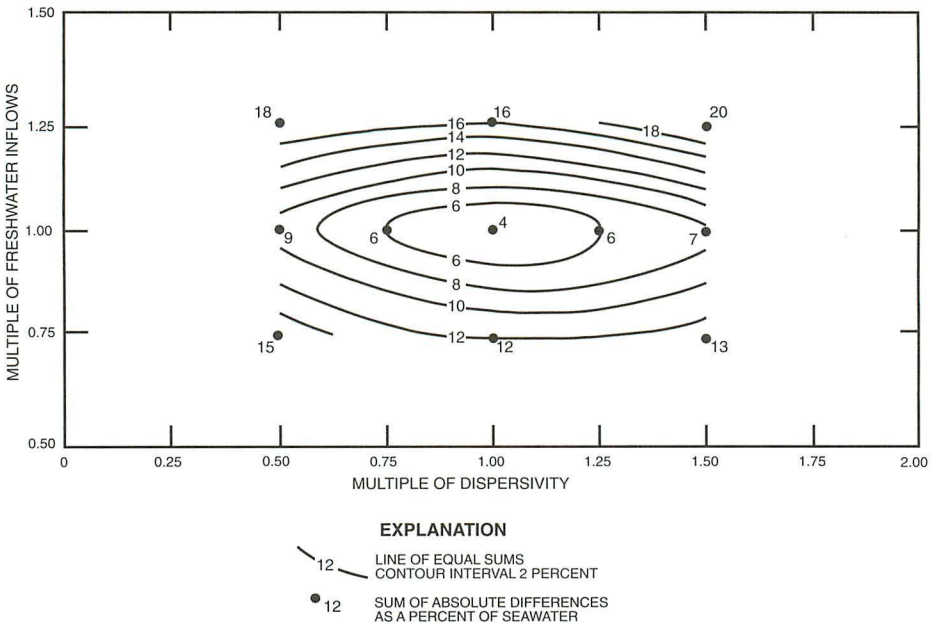


Figure 55. Graph showing model sensitivity with respect to changes in dispersivity and freshwater inflows.

Table 13. Measured and simulated hydraulic heads and dissolved-solids concentrations in the Aquia aquifer at Quiet Waters Park, April 1990

Observation well no.	Model node	Hydraulic heads (in meters)			Dissolved-solids concentration (as a percentage of seawater)		
		Measured	Simulated	ABS[1]	Measured	Simulated	ABS[1]
AA De 189	605	0.55	0.20	0.35	0.8	0	0.8
AA De 196	388	.46	.09	.37	21.9	22.6	.7
AA De 197	500	.61	.23	.38	.8	.2	.6
AA De 200	150	.30	.01	.29	34.2	32.7	1.5
AA De 201	134	.43	.07	.36	28.0	28.6	.6
Sum of ABS's				1.75			4.2

[1]ABS is the absolute difference between measured and simulated values.

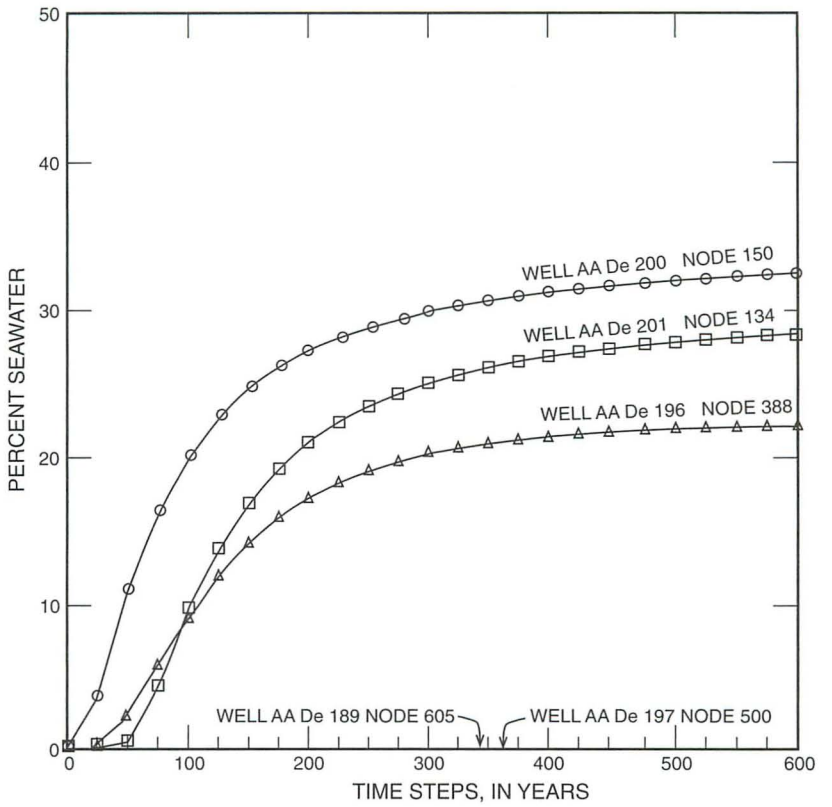


Figure 56. Graph showing simulated dissolved solids as a percentage of seawater for observation-well points (nodes) approaching the calibrated dynamic equilibrium.

	Inflows		Outflows	
	(kilograms per second)	(percent)	(kilograms per second)	(percent)
Freshwater	0.00079	95	0.00069	83
Brackish water	0	0	0.00013	16
Saltwater	0.00004	5	0.00001	1
Totals	0.00083	100	0.00083	100

Freshwater accounted for 95 percent of the inflows, whereas saltwater accounted for 5 percent of the inflows. Freshwater is also a larger proportion of the outflows (83 percent), whereas brackish water comprised virtually all of the remaining outflows (16 percent) and saltwater comprised about 1 percent. In effect, 12 percent of the inflowing freshwater mixed with 4 percent of the inflowing saltwater to form the 16 percent of brackish-water outflow.

Model Sensitivity

Sensitivity of the calibrated, dynamic-equilibrium model was tested by changing one of the hydraulic or transport properties while all others remained unchanged. The model was rerun with the changed property from the initial condition of freshwater throughout the section until a new dynamic equilibrium was approximated. Absolute differences between measured and simulated dissolved-solids concentrations as a percentage of seawater for the five observation-well points (nodes) were summed for the new equilibrium and plotted with the multiple of the change (fig. 58). Then a new change was introduced, and the same procedure followed. Equilibrium time varied somewhat depending on the changes but generally required from 400 to 800 years before a new steady state was approximated.

Sensitivity of the model was somewhat symmetrical for equal increases and decreases in a property, with the exception of changes in permeability. The model was more sensitive to decreases in horizontal and vertical permeability than to equivalent increases, probably because permeability is log-normally distributed in porous media.

The model was particularly sensitive to changes in the permeability of the geohydrologic units and in the concentrations of the brackish-water source. An increase in the inflow concentration of brackish water at the source boundary by a multiple of 1.25 (25 percent) caused a change in the

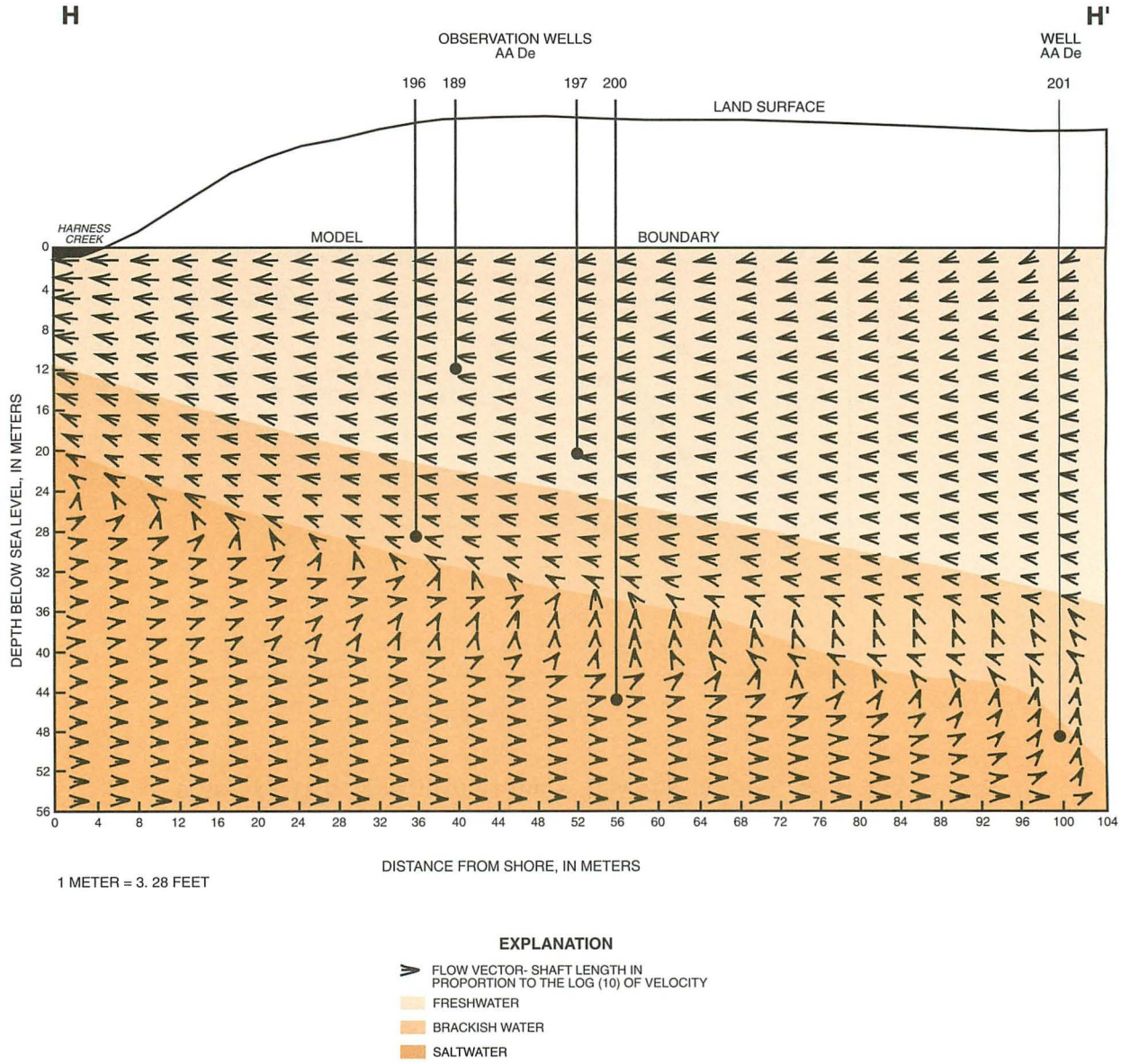


Figure 57. Section showing simulated dynamic equilibrium after 600 years, flow vectors, and location of observation wells used in the Quiet Waters solute-transport model.

sum of absolute differences at the five observation wells from 4- to 34-percent seawater. A similar result occurred with an equal incremental decrease (multiple of 0.75) in inflow concentrations of brackish water. Thus, information about the brackish-water source concentration, permeability of the geohydrologic units; and to a lesser extent, freshwater inflow rates and recharge rates are important for calibration at the five observation wells, assuming comparability of those properties.

Comparison of hydraulic and transport properties bearing different measuring units is problematical. The sensitivity graph does indicate, however, that the model was not very sensitive to changes in porosity and dispersivity (fig. 58). When a transverse dispersivity of zero was simulated with all other properties unchanged, the sum of absolute differences was just 8 percent (4 percent above the calibrated sum) for the five observation wells points.

POTENTIAL FOR BRACKISH-WATER INTRUSION

The potential for brackish-water intrusion into the Aquia aquifer in the Annapolis area was investigated using the calibrated dynamic-equilibrium model for Quiet Waters Park. Movement of brackish water and saltwater in the vicinity of a hypothetical, pumping domestic well was simulated, as well as the potential for brackish-water intrusion caused by a more general lowering of water levels in the aquifer. The

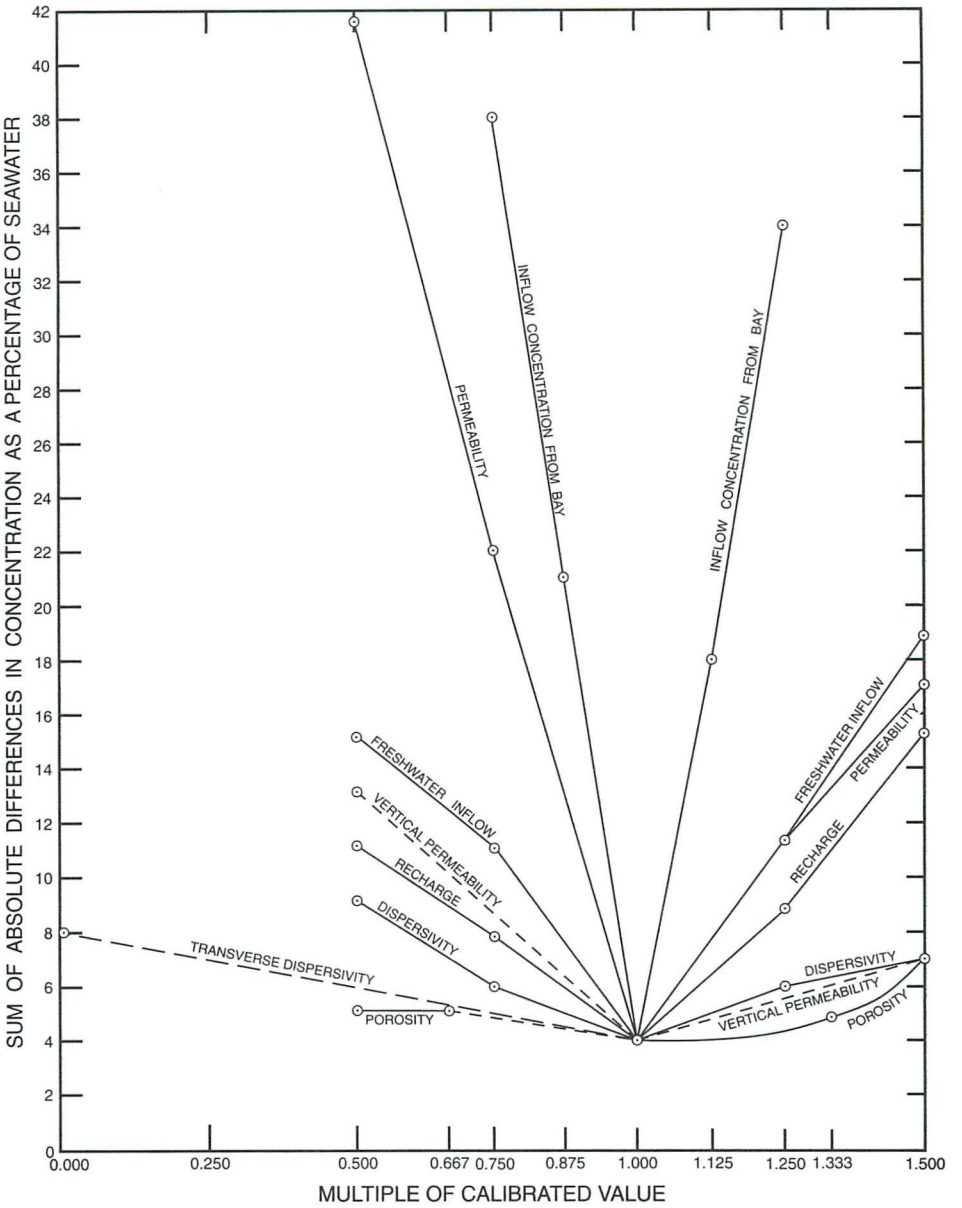


Figure 58. Graph showing sensitivity of calibrated solute-transport model to changes in hydraulic and transport properties.

combined effects of both a pumping domestic well and lowering of water levels were also investigated.

Brackish-Water Intrusion Caused by a Pumped Domestic Well

Water-level declines from a single pumping domestic well are small and extend only a few meters from the well. Thus, a single domestic well generally has a negligible effect on the movement of water and solutes in the aquifer except in the immediate vicinity of the well. If the pumping well is near the interface between brackish water and freshwater, however, it could draw water of increasingly concentrated dissolved solids into its area of influence. In time, the well water could become increasingly saline, and the residents may eventually reject the well water because of taste.

A domestic well in the unconfined Aquia aquifer typically pumps about 0.3 m^3/d (80 gal/d) of water per person (Wheeler, 1991, p. 3). In a standard household of three individuals, about 0.9 m^3/d (240 gal/d) of water would be pumped. Pumping 0.9 m^3/d for 1 year would result in a drawdown of 0.10 m (0.33 ft) within 0.3 m (1.0 ft) of the well using aquifer properties of the Aquia aquifer at Quiet Waters Park, and the Theis equation. The same drawdown in the two-dimensional, solute-transport model was found by

trial and error to be caused by withdrawing 3 x 10^{-4} kg/s of water. The trial-and-error approach was necessary because two-dimensional withdrawal rates in the solute-transport model cannot be converted directly to the three-dimensional withdrawal rates of the real aquifer system.

A domestic well was simulated pumping 3 x 10^{-4} kg/s from a well screen centered about 10 m (33 ft) above the calibrated brackish-water/freshwater interface. Such a well would cause brackish water to move upward in the section and toward the well, but the well would still pump freshwater (1.1-percent seawater) after 50 years, as indicated by the solute-transport simulation (fig. 59). The brackish-water front would move quickly at the onset of pumping and then slow as a new equilibrium is approached. A new equilibrium with respect to the brackish-water front would be reached in about 100 years. After 100 years, the well would still pump freshwater (1.8-percent seawater), but the water would be somewhat more saline than before.

Brackish water would move upward at the onset of pumping, and toward the pumping well, but saltwater would not move very far from the position indicated at calibration during the first 50 years following the onset of pumping (fig. 60). Subsequent simulation indicated that the saltwater front would continue moving upward in the section and toward the well even after the brackish-water front had slowed considerably. The saltwater front would reach a new equilibrium position in about 200 years, parallel to the brackish-water front at about the same distance beneath as it was before the pumping began.

Simulated upwelling of the brackish-water front did not occur directly beneath the well but began from the seaward side and moved somewhat horizontally from the seaward direction toward the well. A seaward displacement of the upwelling was caused primarily because horizontal velocities were greater than vertical velocities, particularly in the freshwater portion of the section (fig. 60). Greater horizontal to vertical velocities were caused by a ratio of horizontal to vertical permeabilities of 10:1 (anisotropy) assigned to the units because of the stratified nature of the sediments. The anisotropy also caused the freshwater discharge area to extend offshore beyond the section rather than stopping at the shoreline.

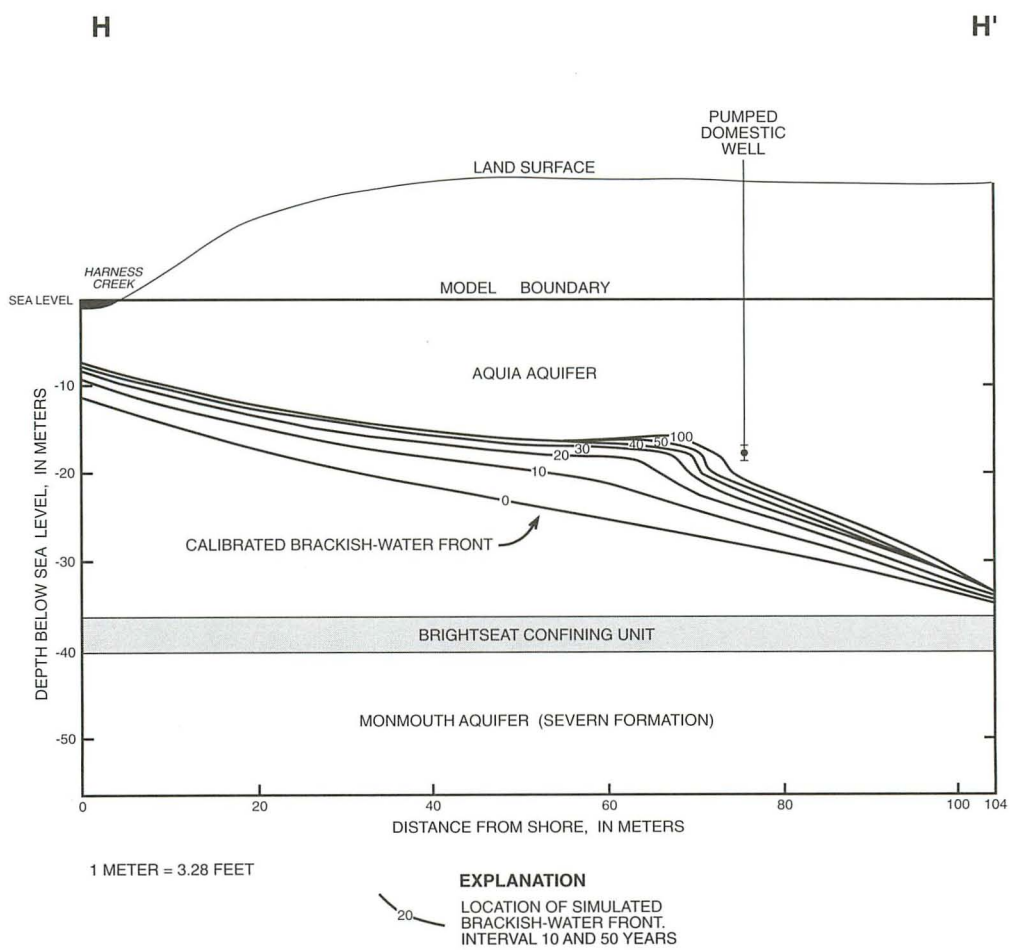


Figure 59. Section showing simulated movement of the brackish-water front caused by a typical domestic well pumping from 10 meters above the calibrated brackish-water front.

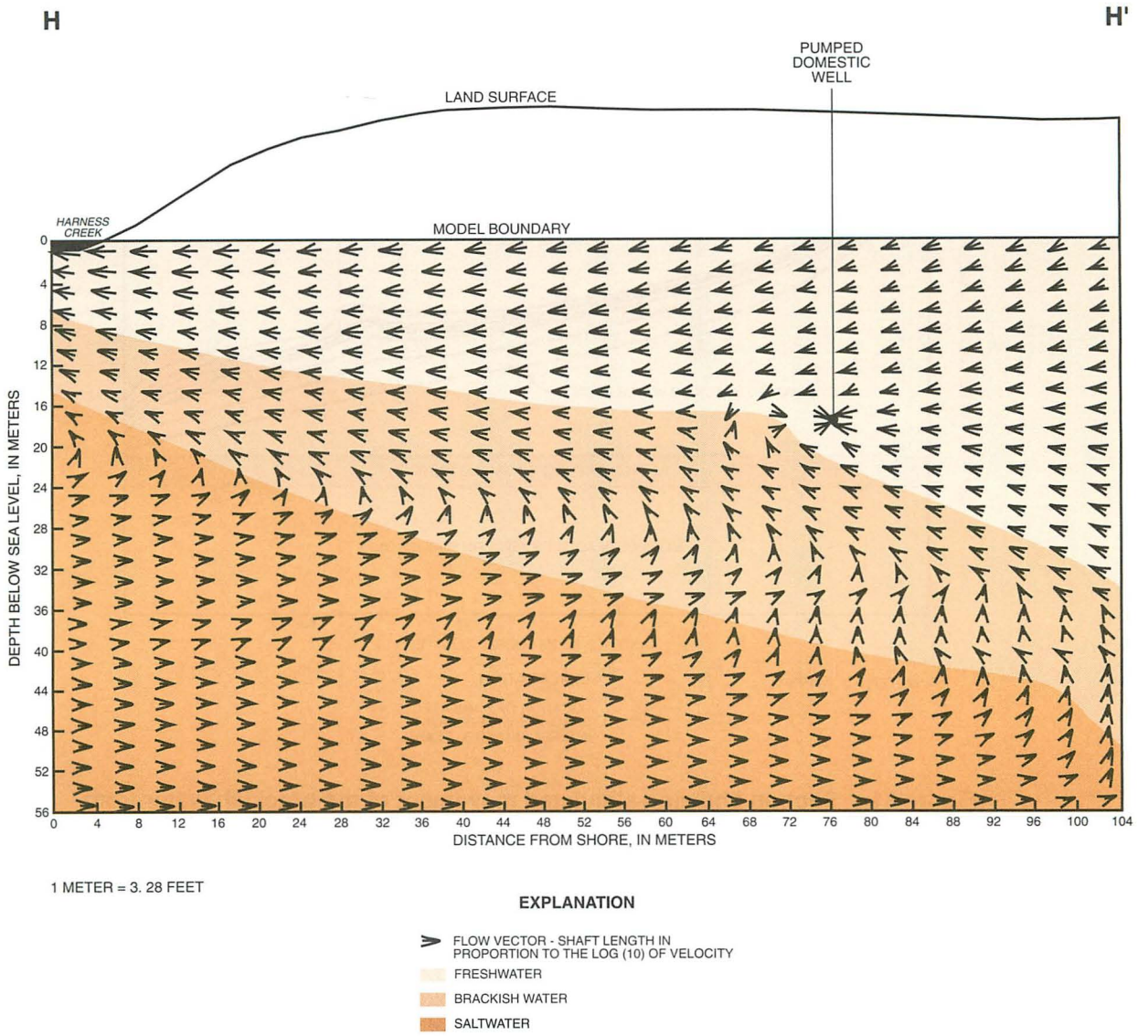


Figure 60. Section showing simulated flow vectors and extent of brackish-water and saltwater intrusion after 50 years of pumping from 10 meters above the calibrated brackish-water front.

Simulating the same pumping rate used in the previous simulation but with the vertical permeability equal to the horizontal (isotropy) resulted in a more symmetrical upwelling of the brackish-water front almost directly beneath the pumping well, but it was still displaced slightly seaward in the early times by about 4 m or 13 ft (fig. 61). Also, the freshwater discharge area offshore was slightly displaced seaward by about 4 m (13 ft) at the water table. Some seaward displacement of the brackish-water front at the shore and slightly seaward of a pumping well would be expected in an isotropic system because the freshwater flow velocities are driven seaward by hydraulic gradients, whereas the flow of brackish water and saltwater is the result of slow, generally vertical, density gradients.

Using isotropic permeabilities, the domestic well would still pump freshwater (2.2-percent seawater) after 50 years, but it would pump saltwater (3.0-percent seawater) before 100 years had passed. Somewhat different conclusions about the later water quality in the well could, therefore, be drawn depending on whether anisotropic or isotropic permeability were simulated. Some anisotropy is probable, but the degree of anisotropy is not known. A ratio of horizontal to vertical anisotropy of one order of magnitude is not unreasonable and was used to calibrate the model and in all subsequent simulations.

The effect of the proximity of the well screen or pumping depth to the interface of brackish water and freshwater was investigated. A well was simulated pumping at the same

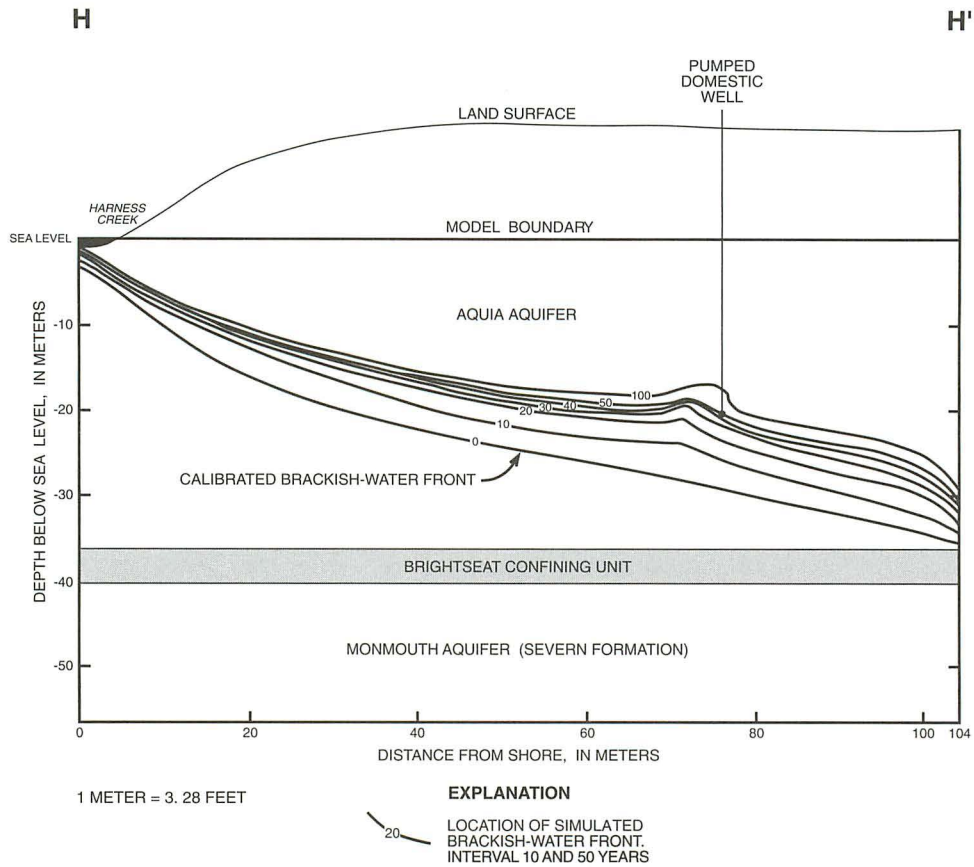


Figure 61. Section showing simulated movement of the brackish-water front caused by a typical domestic well pumping from 10 meters above the calibrated brackish-water front using isotropic permeability in the solute-transport model.

rate as before, 3.0 x 10^{-4} kg/s, but from a well screen centered 6 m (20 ft) above the interface, which is 4 m (13 ft) deeper than that of the previous simulation. Such a well would pump freshwater for more than 10 years but would begin pumping brackish water in less than 20 years as indicated by the solute-transport simulation (fig. 62). The deeper screened interval being closer to the original interface of brackish water and freshwater would cause upwelling of the brackish-water front much sooner even though the well was pumped at the same rate as in the previous simulation. A relatively small difference in the well-screen setting with respect to the original interface of brackish water and freshwater thus can make a significant difference in the freshwater life of the well.

As in the previous simulations, the brackish-water front would not begin rising directly beneath the well but would begin moving upward and horizontally toward the well from the seaward side because of velocity differences caused by hydraulic gradients and anisotropic permeabilities (fig. 63). The brackish-water front would continue moving past the well, if the well continued to pump, with much the same shape until a new equilibrium position was reached. Saltwater would continue rising even after the brackish-water front had reached equilibrium until it also reached a new equilibrium parallel to the brackish-water front.

Brackish-Water Intrusion Caused by General Water-Level Declines

General declines in water levels in the Aquia aquifer in the Annapolis area could result from pumping of large numbers of relatively, closely spaced domestic wells, from pumping of a few nearby commercial wells, or possibly from wells pumping larger amounts of water from aquifers below the Aquia aquifer. Such declines possibly could cause the intrusion of brackish water and saltwater into the aquifer on a broad front near the shore of Chesapeake Bay. An increase in pumping of 30 percent for existing wells was simulated using the areal ground-water-flow model described in previous sections of this report (pumping alternatives). The areal simulation indicated a decline in water levels of only 0.03 m (0.1 ft) in Quiet Waters Park.

In the solute-transport model, a decline in water levels

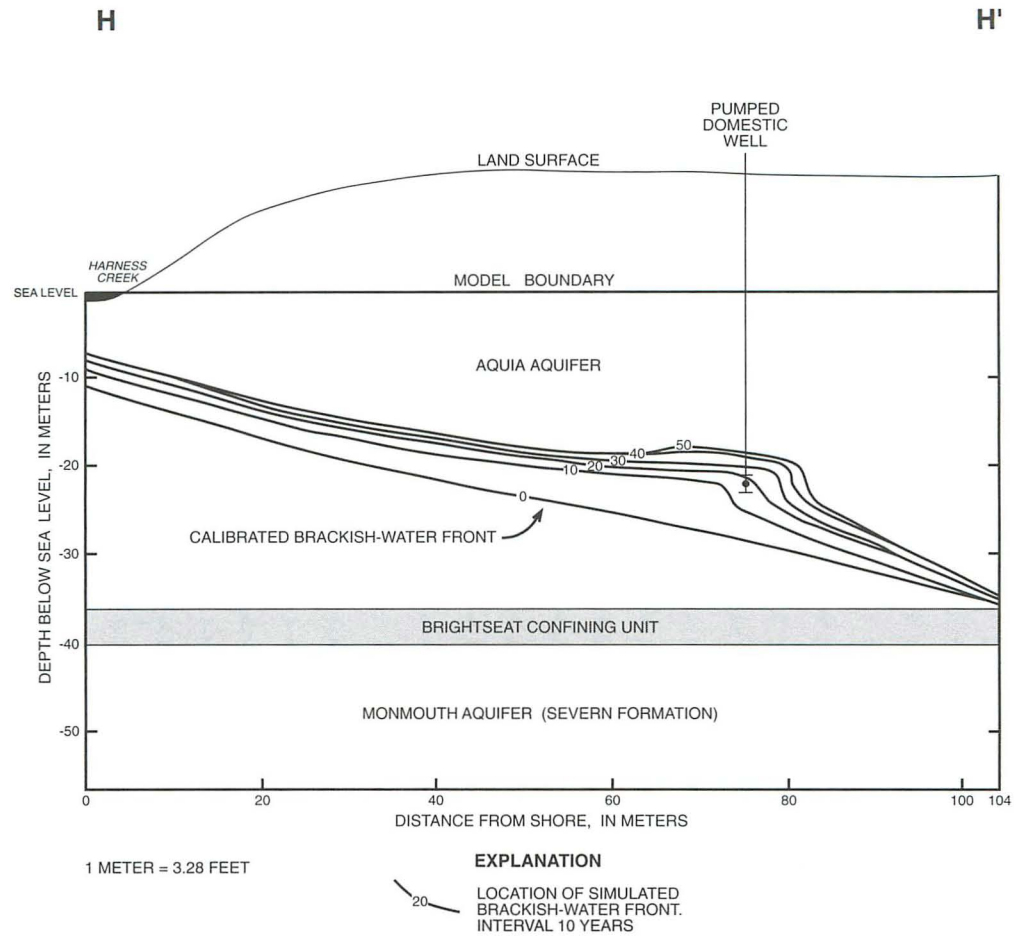


Figure 62. Section showing simulated movement of the brackish-water front caused by a typical domestic well pumping from 6 meters above the calibrated brackish-water front.

of 0.1 m (0.3 ft) at the landward boundary was simulated by eliminating all of the freshwater inflow from the landward direction, which in the calibrated transport model was 3.2 x 10^{-4} kg/s and which is close to the amount simulated previously to represent a typical domestic well. If freshwater from the landward direction were thus captured by pumping, the brackish-water front would rise along the length of the section, with the greatest vertical movement at the landward boundary and diminishing vertical movements toward the shore (fig. 64). The brackish-water front would move upward more rapidly at first and would continue moving upward at a slowing rate as equilibrium was approached. After 100 years, the brackish-water front would approach a new equilibrium position.

If observation wells were placed at the previous pumping sites 10 m (33 ft) and 6 m (20 ft) above the brackish-water/freshwater interface and 28 m (92 ft) from the boundary, those points would be in brackish water in slightly less than 50 years and 20 years, respectively, even though no pumping was simulated there. Thus, water-level declines can cause brackish-water intrusion at least 28 m (92 ft) shoreward of a domestic well and farther shoreward of a well pumping larger amounts of water.

More pumping landward of the section could reverse the flow of freshwater there. Such a reversal, simulated as -3.2 x 10^{-4} kg/s at the landward vertical boundary of the solute-transport model, resulted in a general decline in water levels of 0.2 m (0.7 ft) at the landward boundary, twice that of the previous simulation. If the flow of water were reversed at the landward boundary, the brackish-water front would rise in a manner similar to that of the previous simulation, but farther and faster (fig. 65). Observation wells at the same locations as the previous simulation would indicate the arrival of brackish water in just 20 years and 10 years, respectively, even though no pumping was simulated there. The extent and speed of brackish-water intrusion would depend on the amount of freshwater diverted landward of the site, the proximity of the pumping wells, and thus the severity of the water-level declines in and near the site.

In the transport simulation, the brackish-water front rose

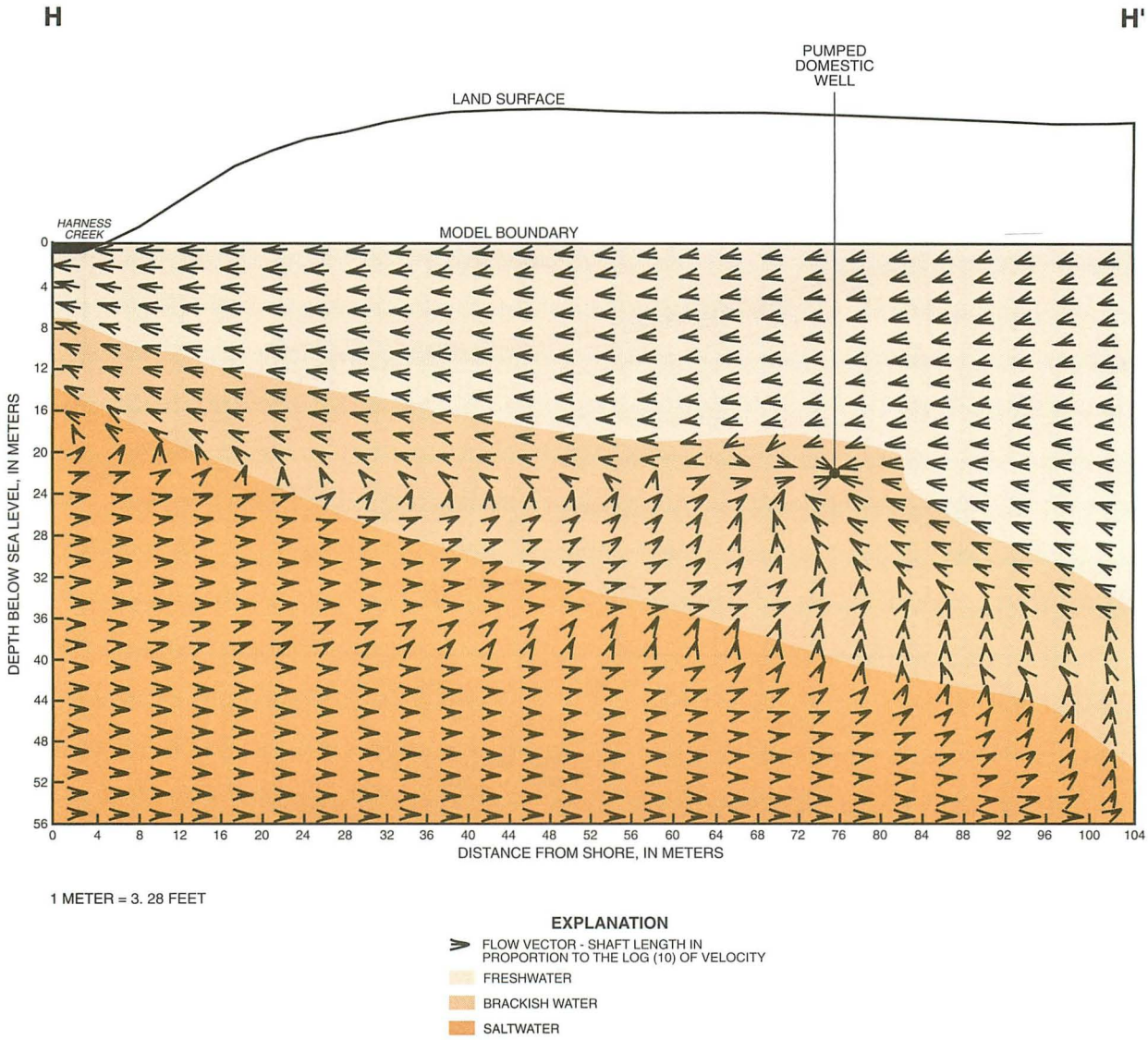


Figure 63. Section showing simulated flow vectors and extent of brackish-water and saltwater intrusion after 50 years of pumping from 6 meters above the calibrated brackish-water front.

smoothly along the length of the section for the first 50 years but then rose slightly more steeply at one point after 100 years. A small mound of brackish water rose slowly and approached a new equilibrium position after 200 years (fig. 65). Such a mound of brackish water would result from upwelling near a ground-water divide formed between freshwater flowing toward wells landward of the section and freshwater flowing toward the shore (fig. 66). The location of the brackish-water mound was slightly shoreward of the ground-water divide as indicated by diverging vectors at the water-table surface.

Effects of a Pumped Domestic Well and General Water-Level Declines

The effects on the flow of brackish water caused by withdrawals by a pumped domestic well as well as a general lowering of water levels were investigated. A domestic well was simulated by pumping as before—3.0 x 10^{-4} kg/s from 10 m (33 ft) above the original brackish-water/freshwater interface; however, no freshwater inflow was simulated at the landward boundary of the Aquia aquifer, which was previously 3.2 x 10^{-4} kg/s. Such conditions would cause a draw-

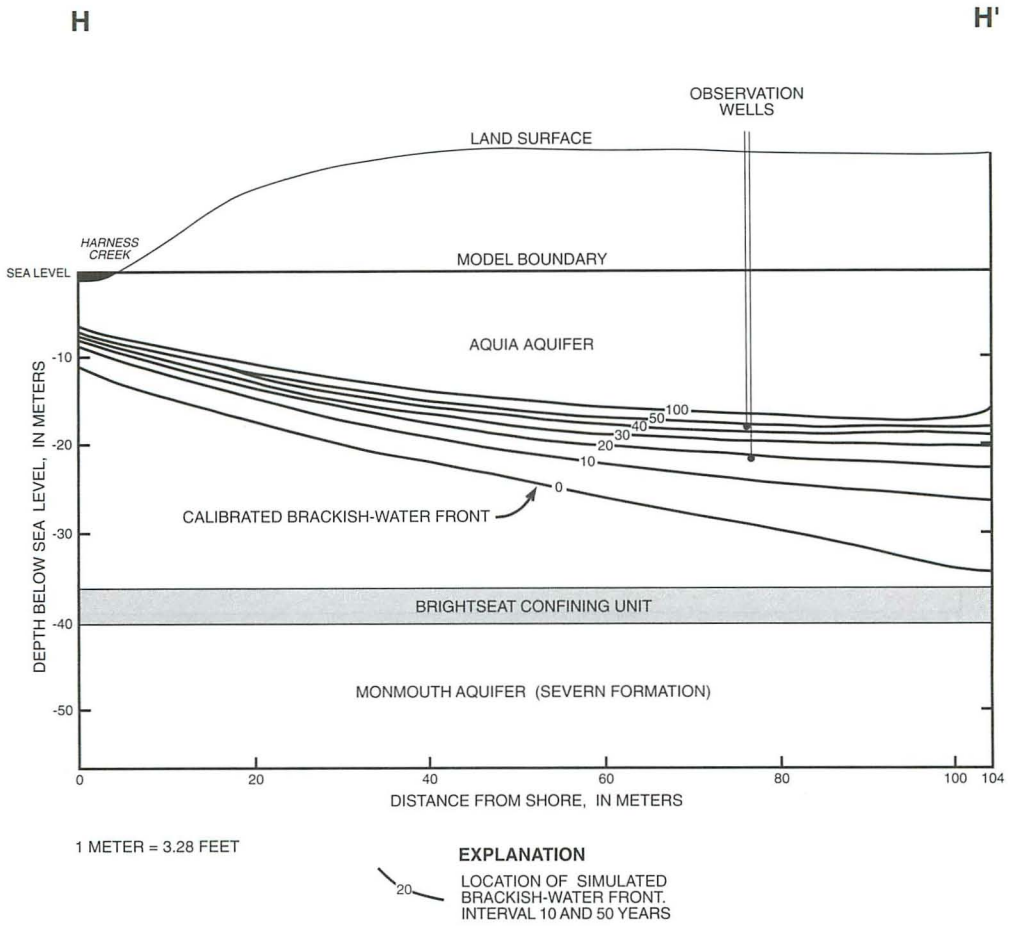


Figure 64. Section showing simulated movement of the brackish-water front caused by elimination of freshwater flow from the landward direction.

down of about 0.2 m (0.7 ft) at the landward boundary, similar to the drawdown of the last previous simulation.

Movement of the brackish-water front would also be similar to the last previous simulation, and the domestic well would pump brackish water (2.8-percent seawater) in slightly less than 10 years (fig. 67). The brackish-water front would, however, begin upwelling slightly in the vicinity of the pumping domestic well and would continue bulging upward past the well screen if pumping were continued until a new equilibrium were established.

After 50 years, the well would still pump brackish water (about 12-percent seawater) according to the simulation, and the brackish-water front would not yet have reached a new equilibrium (fig. 68). The saltwater front would lag many years behind as in the previous simulations. Freshwater would still recharge the water table and flow toward the well and the shore in the upper part of the Aquia aquifer. The freshwater would still mix with the saltwater rising from below to form the brackish-water transition zone. The extent and speed of brackish-water intrusion would depend, as before, on the proximity of the well screen to the original interface, on the amounts of freshwater diverted landward of the site, on the proximity of the pumped wells, and on the severity of the water-level declines that result in and near the site.

SUMMARY AND CONCLUSIONS

Geologic units that underlie Broadneck, Annapolis Neck, and the Mayo Peninsula in east-central Anne Arundel County, Maryland, include the Patapsco, Magothy, Matawan, Severn, Brightseat, Aquia, and Talbot Formations. The Patapsco Formation is composed of sediments deposited in an anastomosing fluvial environment resulting in typical

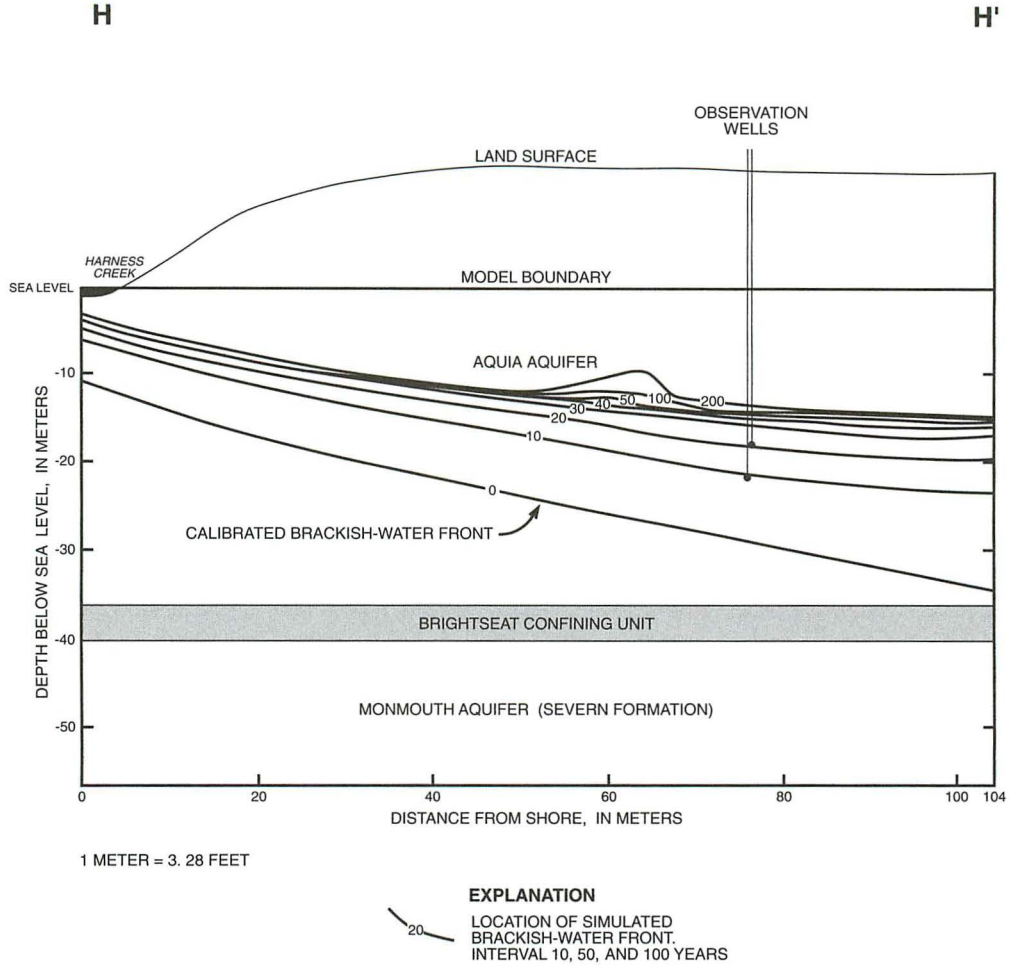


Figure 65. Section showing simulated movement of the brackish-water front caused by reversal of flow from the landward direction.

upward-fining sequences. Overlying the Patapsco Formation and separated by a major unconformity is the Magothy Formation. The contact between the Magothy and the Patapsco Formations may occur within sand beds which often in the past resulted in identifying the upper part of the Patapsco Formation sand as part of the lower part of the Magothy Formation. Above the Magothy Formation is the Matawan Formation composed predominantly of glauconitic clay. Overlying the Matawan Formation is fine glauconitic sand of the Severn Formation. The Severn Formation is overlain by clayey silt and fine sands assigned to the Brightseat Formation. The Aquia Formation, consisting chiefly of medium sand, overlies the Brightseat Formation. The Aquia Formation crops out in much of the area and is composed of glauconitic sand. The Talbot Formation is predominantly a silty, brown to gray clay, which forms a thin veneer that discontinuously overlies the Aquia Formation.

The three principal aquifers described in this report are the Aquia, Magothy, and Upper Patapsco aquifers. The Aquia aquifer within the study area is generally unconfined. However, south of the Mayo Peninsula the Aquia aquifer is confined. The thickness of this aquifer averages about 130 ft. Horizontal hydraulic conductivity calculated from aquifer tests at the Quiet Waters Park test site on Annapolis Neck averaged about 4 ft/d. Specific storage as determined from these aquifer tests was in the range of 4×10^{-6} to 7×10^{-6} ft^{-1}. Hydraulic conductivity and specific storage calculated from an aquifer test at Southern Estates on the southern end of Annapolis Neck were about 30 ft/d and 5×10^{-6} ft^{-1}, respectively. The Magothy aquifer, which dips 35 ft/mi to the southeast, is about 120 ft thick and consists mostly of medium sand within the study area. Horizontal hydraulic conductivities calculated from specific capacities averaged about 40 ft/d. The Patapsco Formation is composed of two prominent sand units separated by a thick clay unit. The upper sand unit is the Upper Patapsco aquifer, which ranges in thickness from 200 to 300 ft.

Ambient water quality within the study area in the Aquia and Monmouth aquifers is generally suitable for most uses. The pH tends to range from 4.4 to 8.0. Low pH is primarily

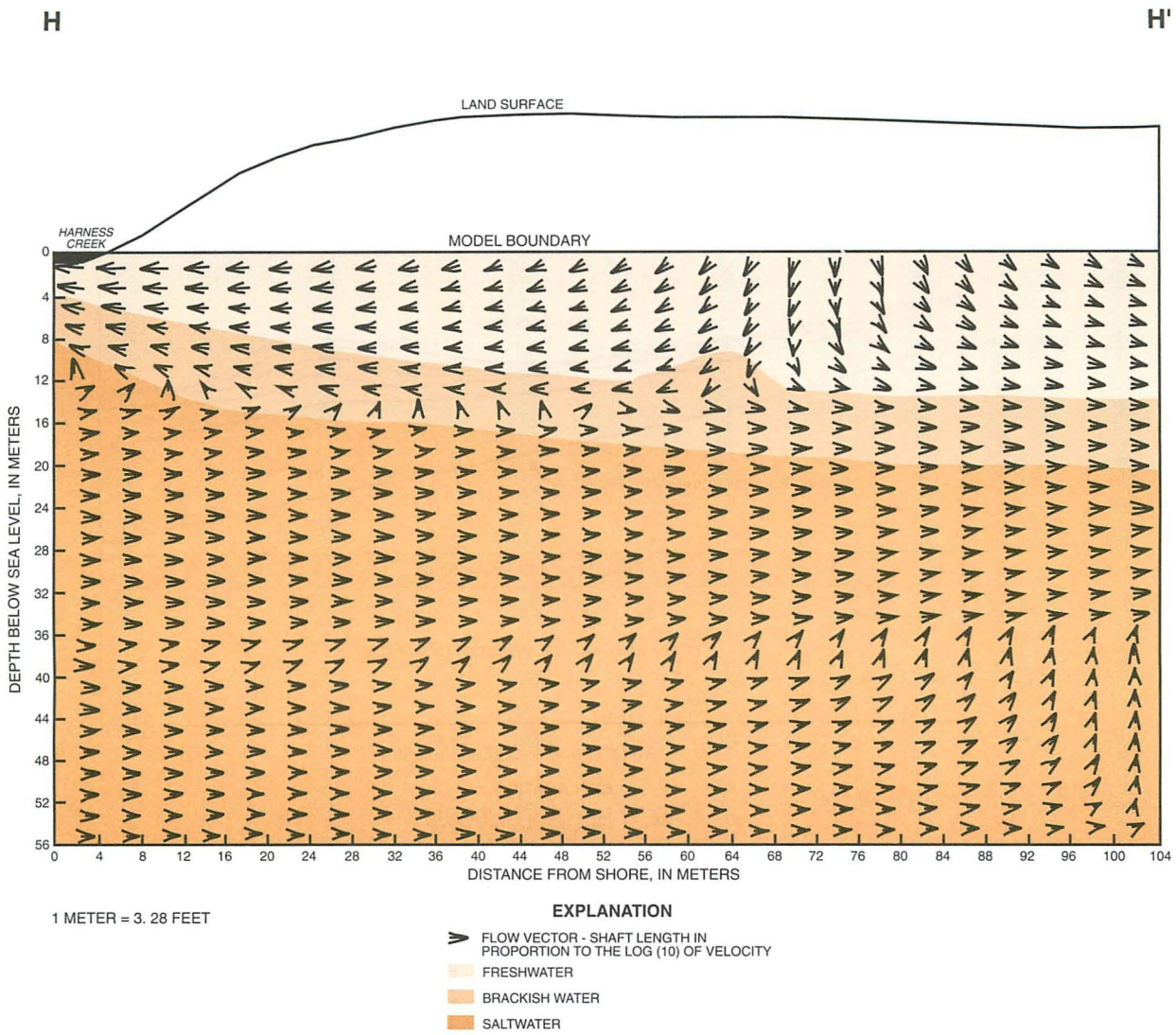


Figure 66. Section showing simulated flow vectors and extent of brackish-water and saltwater intrusion after 200 years of flow reversal from the landward direction.

due to acidic precipitation recharging the aquifers. The presence of weathered carbonate shell material in the Aquia and Monmouth aquifers results in an increased pH. The shell material also results in an increase in dissolved calcium and magnesium, which produce very hard water. Approximately 30 to 40 percent of the sand in the Aquia Formation is glauconite and goethite. In the outcrop area where aquifer water is typically acidic and oxygenated, the glauconite is weathered, producing goethite and iron hydroxide. Generally ambient chloride concentrations in the aquifers are about 2 to 3 mg/L. Slightly higher concentrations are a result of wind-driven marine aerosols. Chloride concentrations in 62 water samples from the Aquia and Monmouth aquifers ranged from 2 to 300 mg/L with an average value of 6 mg/L. Nitrogen concentrations in water from the Aquia and Monmouth aquifers are generally less than the U.S. Environmental Protection Agency's Maximum Contaminant Level of 10 mg/L for drinking water. The water in the Aquia and Monmouth aquifers not affected by brackish-water intrusion is characterized as a calcium and magnesium bicarbonate-type.

Magothy aquifer water, which is very acidic, is an iron sulfate-type. Concentrations of iron range from 3,600 to 5,400 µg/L. Dissolved-solids concentrations are low, ranging from 21 to 81 mg/L. Previous investigations have shown that the ambient water quality of the Upper Patapsco aquifer is very similar to the water quality of the Magothy aquifer.

A quasi-three-dimensional flow model simulated ground-water flow underlying an area of 870 mi^2 and encompassing a five-layered system consisting of the water-table, Aquia, Monmouth, Magothy, and Upper Patapsco aquifers. Calibration was accomplished for transient conditions of changing hydraulic heads for the time period 1900 through 1990 by comparing measured water levels for 176

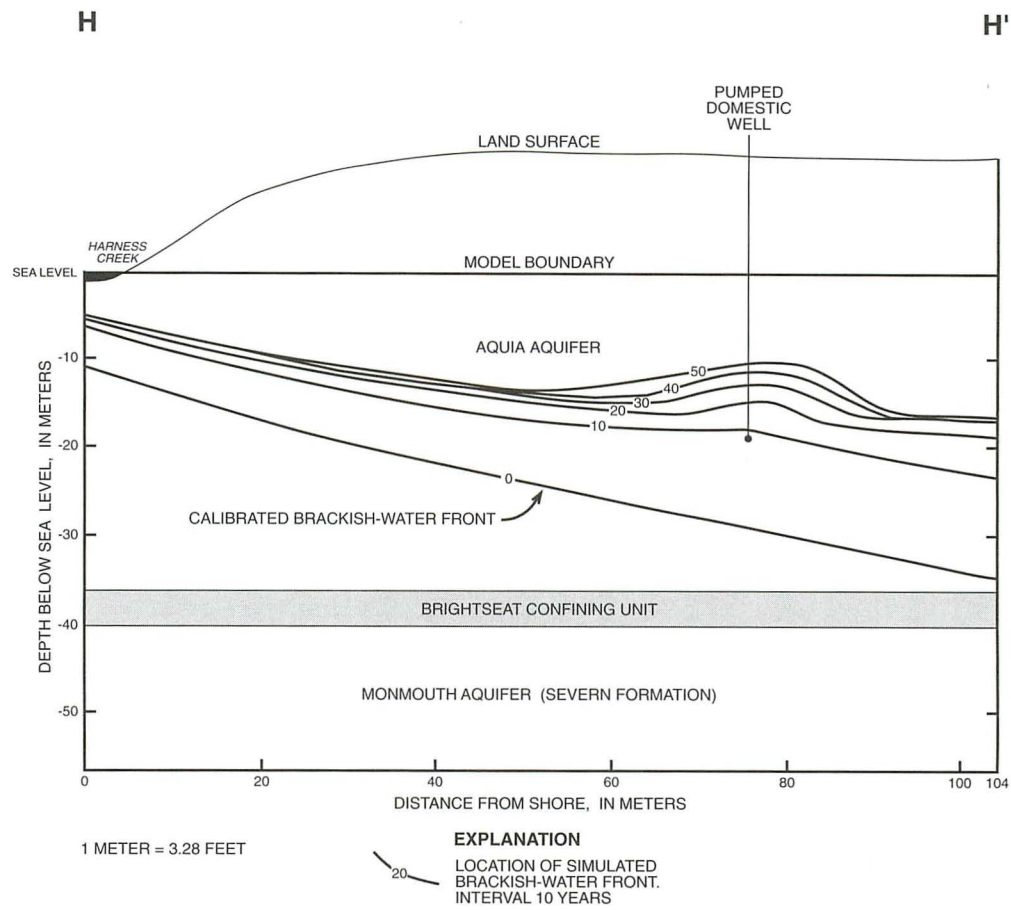


Figure 67. Section showing simulated movement of the brackish-water front caused by a domestic well pumping from 10 meters above the calibrated brackish-water front and no freshwater flow from the landward direction.

observation wells to model-simulated hydraulic heads. The differences between the medians of measured and model-simulated calibrated heads for the Aquia, Magothy, and Upper Patapsco aquifers were 2.2, 4.5, and 0.3 ft, respectively.

An analysis of the rates and direction of ground-water flow for the Aquia aquifer from areas of recharge on Annapolis Neck to points of discharge indicate that ground water moves away from areas of higher elevations towards pumping wells, streams, and Chesapeake Bay estuaries. Traveltimes from recharge to discharge varied from 40 to 810 years. A similar analysis for the Upper Patapsco aquifer indicated traveltimes of 293 to 1,657 years. In this analysis, pumpage from the Upper Patapsco aquifer was increased by 30 percent above the maximum for the transient simulation 1900-90. Calculations of traveltimes and flow directions for ground water recharged into the Magothy aquifer in the vicinity of Round Bay and discharging from wells screened in the Upper Patapsco aquifer at Arnold showed that it would take as many as 1,657 years for advective flow of brackish estuarine water to reach the Arnold well field.

A wedge of brackish water in the Aquia and Monmouth aquifers from Chesapeake Bay and its tributaries underlies a nearshore strip of land on Annapolis Neck and the Mayo Peninsula. Test wells screened in the Aquia and Monmouth aquifers at five of eight test sites along this strip penetrated into brackish water. Chloride concentrations at four of these locations exceeded 5,900 mg/L. The thickness of the brackish-water wedge, as defined by geophysical resistivity logs, was as much as 120 ft. The interface between brackish water and freshwater is relatively sharp and is steeply inclined near the shore. The brackish water extends as much as about 500 ft inland in the Monmouth aquifer and generally does not exceed more than 200 ft inland in the Aquia aquifer. In general, the distribution and extent of the intrusion is locally variable and dependent on the permeability of the aquifers and confining units, local hydraulic-head distribution, and pumpage history.

Elevated concentrations of dissolved chloride may indicate brackish-water intrusion or may be due to anthropogenic sources. Three criteria were used to differentiate between these two possible sources: (1) bromide:chloride ra-

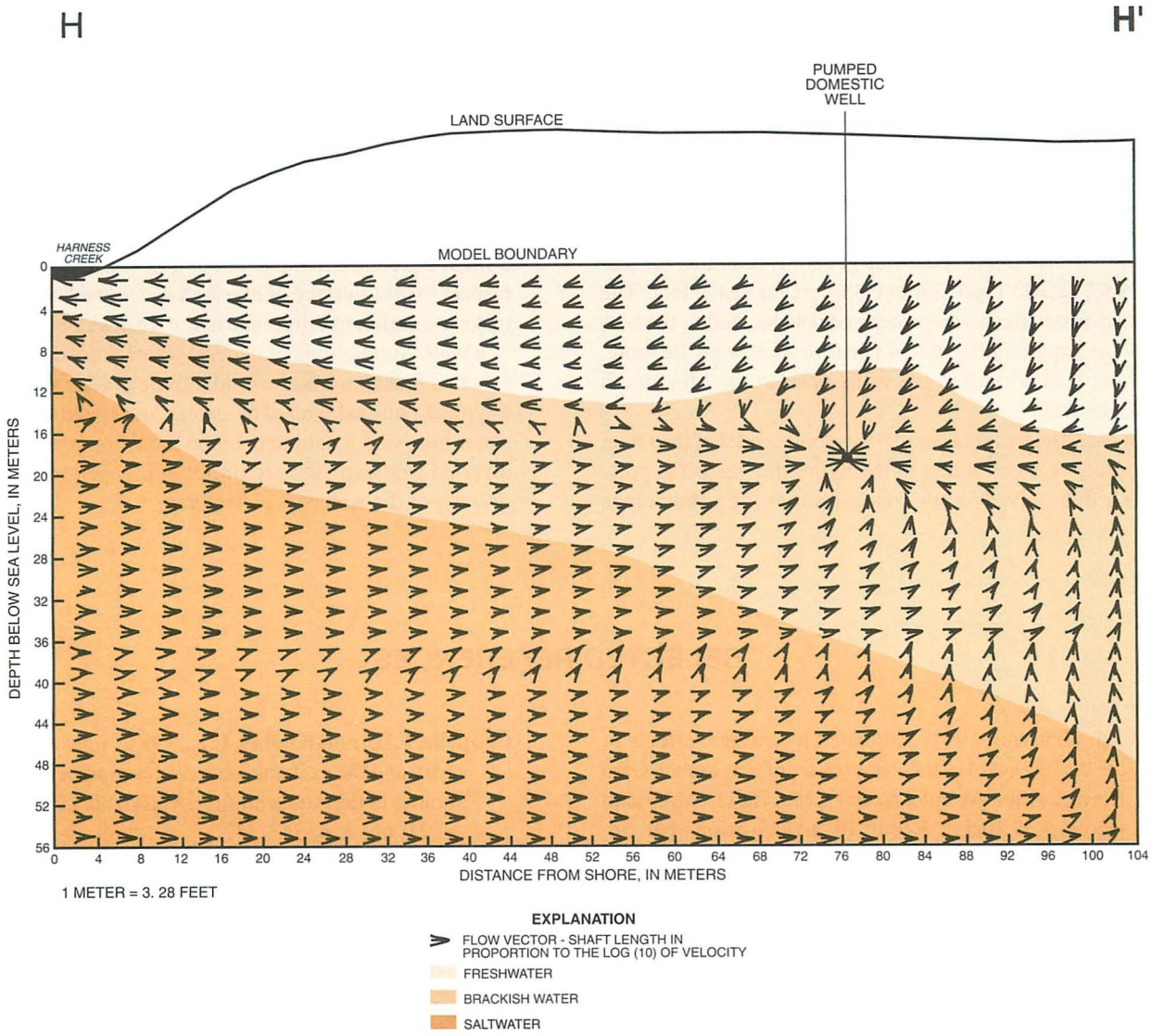


Figure 68. Section showing simulated flow vectors and extent of brackish-water and saltwater intrusion after 50 years of pumping from 10 meters above the calibrated brackish-water front and no freshwater flow from the landward direction.

tio, (2) nitrogen concentration, and (3) location of the Ghyben-Herzberg interface. The bromide:chloride ratio for brackish water is 3.5×10^{-3}. Any divergence from this ratio indicates an anthropogenic source. Nitrogen concentrations greater than about 3 mg/L may indicate an anthropogenic source such as sewage effluent. Wells screened above the theoretical brackish-water/freshwater interface as determined by the Ghyben-Herzberg 80:1 ratio would indicate a source other than brackish-water intrusion.

Water chemistry in the Aquia and Monmouth aquifers within the zone affected by brackish-water intrusion is affected by (1) a chemically reducing, anoxic environment beneath the bottom of Chesapeake Bay; (2) brackish-water dilution; and (3) cation exchange. The effect of the first factor is the reduction and mobilization of ions such as iron and manganese, which are typically relatively insoluble in the water-table environment. Iron and manganese concentrations as high as 240 and 2.5 mg/L, respectively, were measured. The second factor, brackish-water dilution, results in a substantial increase in concentrations of calcium, magnesium, sodium, potassium, and sulfate. Plots of ion ratios indicate that calcium and sodium concentrations occur at levels higher and lower, respectively, than what is predicted by simple dilution of brackish water with aquifer water. This is a result of cation exchange between calcium and sodium on the mineral glauconite. Examination of ion ratios also indicates a reduction in sulfate concentrations likely caused by chemical reduction within the organic, anoxic Chesapeake Bay sediments.

Water levels in two wells installed in the freshwater part of the Aquia aquifer at Quiet Waters Park near Annapolis, Maryland, show a hydraulic gradient from the land toward the shoreline. The hydraulic gradient toward Harness Creek, a tidal tributary of the South River and Chesapeake Bay, indicates freshwater is flowing from the land toward the tidal creek. Concentrations of dissolved solids in ground-water samples from the five observation wells installed at the Quiet Waters site ranged from 270 mg/L (about 1 percent of the concentration of dissolved solids generally assumed for seawater) to 12,200 mg/L (about 35-percent seawater). The brackish-water/freshwater interface was located in the bottom of the Aquia aquifer and sloped upward toward the shore. Saltwater was present in the wells open to the Monmouth aquifer beneath.

A two-dimensional, solute-transport model of the Quiet Waters site was calibrated to the hydraulic heads (as pressures) and dissolved-solids concentrations (as a percentage of seawater) measured in 1990. Calibration was accomplished by adjusting rates of freshwater inflow in conjunction with dispersivity. A dynamic equilibrium with respect to the dissolved-solids concentrations in 1990 was approached after 600 years of simulation time. The potential for brackish-water intrusion into the Aquia aquifer in the Annapolis area was investigated using the calibrated, dynamic equilibrium model of the Quiet Waters site.

Results of the brackish-water simulations indicate that a small difference in the depth of a well-screen setting with respect to the interface of brackish water and freshwater can make a significant difference in the freshwater-yielding life of a well. Simulations of general water-level declines indicate that brackish water would intrude at sites shoreward of a typical pumped well. The extent and speed of brackish-water intrusion would depend on the amount of freshwater diverted landward, the proximity of pumped wells, and the severity of the water-level declines.

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APPENDIXES

Appendix A. Records of wells drilled during this study, 1988-90

[Md. State WRA, Maryland State Water Resources Administration; ft, feet; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot; --, not determined]

Well number (plate 1)	State permit number	Location	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)	Diameter of well (inches)	
							Casing	Screen
AA Ce 126[1/]	--	Mago Vista	Branham Contractors, Inc.	04-17-89	6	--	--	--
AA Ce 127	AA-88-1899	do.	Branham Contractors, Inc.	04-18-89	6	75	4	4
AA Ce 128	AA-88-1901	do.	Branham Contractors, Inc.	05-15-89	6	175	4	4
AA Ce 129[1/]	--	Sherwood Forest	Md. State WRA	12-05-89	5	--	--	--
AA Ce 130	AA-88-3765	do.	Md. State WRA	01-17-90	5	103	4	4
AA Ce 133	AA-88-4893	Moorings-on-the-Bay	Md. State WRA	07-26-90	15	117	4	4
AA Ce 134	AA-88-4892	do.	Md. State WRA	08-08-90	15	77	4	4
AA Cf 141	AA-88-1663	Belvedere Heights	Branham Contractors, Inc.	04-21-89	62	185	4	4
AA De 189	AA-88-4027	Quiet Waters Park	Md. State WRA	02-21-90	42	95	4	4
AA De 193	AA-88-1497	Londontown Public House Park	Branham Contractors, Inc.	12-22-88	37	155	4	4
AA De 194	AA-88-1496	do.	Branham Contractors, Inc.	12-23-88	37	97	4	4
AA De 195	AA-88-1495	do.	Branham Contractors, Inc.	12-27-88	37	65	4	4
AA De 196	AA-88-4026	Quiet Waters Park	Md. State WRA	02-01-90	41	145	4	4
AA De 197	AA-88-4028	do.	Md. State WRA	02-14-90	42	115	4	4
AA De 200	AA-88-4029	do.	Md. State WRA	02-27-90	42	205	4	4
AA De 201	AA-88-4127	do.	Md. State WRA	03-08-90	41	230	4	4
AA Df 151	AA-88-1491	Annapolis Roads	Branham Contractors, Inc.	12-14-88	22	178	4	4
AA Df 152	AA-88-1490	do.	Branham Contractors, Inc.	12-20-88	22	118	4	4
AA Df 153	AA-88-1489	do.	Branham Contractors, Inc.	12-20-88	22	38	4	4
AA Df 154	AA-88-1891	Hillsmere	Branham Contractors, Inc.	01-25-89	5	165	4	4
AA Df 155	AA-88-2046	Bay Ridge	Branham Contractors, Inc.	02-27-89	39	199	4	4
AA Ee 81[2/]	--	South River Farms Park	Branham Contractors, Inc.	01-10-89	11	191	4	4
AA Ee 83	AA-88-1416	do.	Branham Contractors, Inc.	05-10-89	11	191	4	4
AA Ef 29[2/]	--	Arundel-on-the-Bay	Branham Contractors, Inc.	12-07-88	5	182	4	4
AA Ef 30	AA-88-1498	do.	Branham Contractors, Inc.	12-08-88	5	50	4	4
AA Ef 31	AA-88-1499	do.	Branham Contractors, Inc.	01-04-89	5	135	4	4
AA Ef 32	AA-88-1494	Mayo Beach Park	Branham Contractors, Inc.	01-19-89	8	225	4	4
AA Ef 33	AA-88-1493	do.	Branham Contractors, Inc.	01-20-89	8	137	4	4
AA Ef 34	AA-88-1492	do.	Branham Contractors, Inc.	01-20-89	8	85	4	4
AA Ef 35	AA-88-1500	Arundel-on-the-Bay	Branham Contractors, Inc.	01-05-89	5	200	4	4

[1/] Borehole.

[2/] Well abandoned.

Depth to top of screen (ft below land surface)	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]	Well number (plate 1)
--	--	--	--	--	--	--	--	--	AA Ce 126
60	10	Magothy	7	21	06-07-89	38	4	3	AA Ce 127
160	10	Magothy	9	22	06-08-89	64	4	5	AA Ce 128
--	--	--	--	--	--	--	--	--	AA Ce 129
88	10	Magothy	6	14	05-04-90	35	4	4	AA Ce 130
102	10	Magothy	10	93	08-28-90	9	4	0.1	AA Ce 133
62	10	Magothy	10	22	08-27-90	10	4	.8	AA Ce 134
170	10	Magothy	68	127	06-02-89	28	4	.47	AA Cf 141
80	10	Aquia	40	62	04-20-90	11	4	.50	AA De 189
140	10	Monmouth	36	138	05-24-89	22	4	.22	AA De 193
82	10	Aquia	35	73	05-23-89	21	4	.55	AA De 194
50	10	Aquia	36	47	04-05-89	13	4	1.2	AA De 195
130	10	Aquia	40	85	04-19-90	9	4	.2	AA De 196
100	10	Aquia	40	75	04-26-90	10	4	.3	AA De 197
190	10	Monmouth	41	97	05-11-90	3	0.4	.05	AA De 200
195	10	Monmouth	36	94	06-01-90	6	.4	.1	AA De 201
163	10	Monmouth	21	79	02-08-89	13	4	.22	AA Df 151
103	10	Aquia	22	64	02-09-89	20	4	.5	AA Df 152
23	10	Aquia	21	28	02-10-89	23	4	3.3	AA Df 153
150	10	Monmouth	3	141	05-18-89	13	4	.1	AA Df 154
184	10	Monmouth	39	150	05-22-89	14	4	.13	AA Df 155
176	10	Monmouth	7	120	03-15-89	25	4	.2	AA Ee 81
176	10	Monmouth	8	84	05-19-89	30	3	.4	AA Ee 83
167	10	Monmouth	--	--	--	--	--	--	AA Ef 29
35	10	Aquia	4	30	02-02-89	14	4	.5	AA Ef 30
120	10	Aquia	4	42	02-07-89	22	4	.6	AA Ef 31
210	10	Monmouth	7	162	05-31-89	15	4	.1	AA Ef 32
122	10	Aquia	7	82	05-30-89	60	4	.8	AA Ef 33
70	10	Aquia	7	62	05-26-89	60	4	1	AA Ef 34
185	10	Monmouth	2	108	02-06-89	12	4	.1	AA Ef 35

Appendix B. Records of selected wells used in this report

[ft, feet; gal/min, gallons per minute; (gal/min)/ft, gallons per minute per foot; AA Co, Anne Arundel County; --, not determined]

Well number (plate 1)	State permit number	Owner	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)
AA Cf 138	AA-74-1692	Arundel Structures, Inc.	Wolford's Well and Pump Service, Inc.	02-14-80	25	72
AA Cf 139	AA-81-5842	Miciche, Gary	Slater's Well Drilling, Inc.	01-11-86	12	130
AA Cf 140	AA-81-2006	Derby, Steven	Wolford's Well and Pump Service, Inc.	07-27-83	19	117
AA De 64	AA-02-1718	Rose, Morris	Leatherbury	- -56	30	55
AA De 90	AA-01-0206	Edgewater Elementary School	Layne-Atlantic Co.	- -52	23	90
AA De 117	AA-71-0449	Piera, Michael	East Coast Well and Pump, Inc.	- -71	40	84
AA De 163	AA-73-3272	Hannigan, William	Purner Well Drilling, Inc.	07-19-74	30	48
AA De 164	AA-81-6984	Harrison, David	Collier Well Drilling Co.	09-08-86	26	82
AA De 165	AA-81-0135	Govatos, George	Slater's Well Drilling, Inc.	02-05-87	31	50
AA De 166	AA-74-0196	Nichols, Zane	Branham Contractors, Inc.	01-08-79	19	55
AA De 167	AA-74-0482	Liberty Marina	H. H. Bunker and Sons, Inc.	04-13-79	4	42
AA De 168	AA-74-2710	Eisinger, Richard	H. H. Bunker and Sons, Inc.	03-12-81	9	43
AA De 169	AA-81-9951	Boswell, Thomas	East Coast Well and Pump, Inc.	01-15-88	27	77
AA De 170	AA-81-9950	Boswell, Thomas	East Coast Well and Pump, Inc.	01-30-88	25	90
AA De 171	AA-81-9952	Boswell, Thomas	East Coast Well and Pump, Inc.	01-30-88	26	75
AA De 172	AA-81-2849	Haschert, Doris	H. H. Bunker and Sons, Inc.	02-22-84	27	78
AA De 173	AA-73-6663	Londontown Public House Park	H. J. Greer Drilling Co., Inc.	03-02-77	34	70
AA De 174	AA-81-0972	South River Landing	H. J. Greer Drilling Co., Inc.	10-16-82	15	50
AA De 175	AA-70-0474	Panks, James	Purner Well Drilling, Inc.	01-02-70	55	83
AA De 176	AA-74-0898	Haskett, Patrick	H. J. Greer Drilling Co., Inc.	07-18-79	73	110
AA De 178	AA-73-6683	Pritt, Frederick	Branham Contractors, Inc.	11-04-76	51	105
AA De 179	AA-74-2057	Dabbs	H. J. Greer Drilling Co., Inc.	06-17-80	45	65
AA De 180	AA-81-9229	Golkin, Paul	Slater's Well Drilling, Inc.	08-28-87	27	80
AA De 181	AA-86-0268	Bryant, William	Slater's Well Drilling, Inc.	03-11-88	43	100
AA De 182	AA-81-1925	Bywaters, Jeanru	H. J. Greer Drilling Co., Inc.	08-17-83	2	60
AA De 183	AA-74-3436	Woodland Beach Fire Department	Purner Well Drilling, Inc.	07-20-81	22	100
AA De 184	AA-81-8049	AA Co., Heights Dr. Sewage Pumping Station	Schummer Well Drilling, Inc.	05-10-87	26	123
AA De 185	AA-81-6435	Tingman, William	Wolford's Well and Pump Service, Inc.	06-30-86	51	87
AA De 186	AA-73-8941	AA Co., South River Farms Park	H. H. Bunker and Sons, Inc.	09-05-78	13	45
AA De 187	AA-73-5289	Hogan, Robert	Purner Well Drilling, Inc.	11-21-75	20	40
AA De 188	AA-74-2604	Gray, Dale	H. J. Greer Drilling Co., Inc.	04-02-81	6	50
AA De 190	AA-73-6741	Brady, Ralph	H. H. Bunker and Sons, Inc.	02-03-77	10	58
AA De 191	AA-73-0334	Jehovah's Witnesses	Purner Well Drilling, Inc.	09-28-72	50	57
AA De 198[1]	--	Mitchel, Nicholas	Branham Contractors, Inc.	04-29-89	29	115
AA Df 32	AA-00-0358	Gates, Herbert	H. H. Bunker and Sons, Inc.	- -46	20	65
AA Df 86	AA-70-0141	U.S. Coast Guard, Thomas Pt. Station	H. H. Bunker and Sons, Inc.	- -69	7	49
AA Df 96	AA-71-0898	Bay Ridge Beach, Inc.	Layne-Atlantic Co.	06-01-71	21	113
AA Df 98	AA-74-3787	Vanderhoof, James	H. H. Bunker and Sons, Inc.	11-04-81	11	40
AA Df 103	AA-73-3315	Coman, Daniel	Slater's Well Drilling, Inc.	09-01-74	27	46
AA Df 104	AA-73-2641	Coman, Daniel	Slater's Well Drilling, Inc.	02-26-74	28	90
AA Df 105	AA-73-2079	Hollander, Charles	Frank's Well Drilling, Inc.	10-15-73	10	58
AA Df 107	AA-81-8714	Cronin, David	H. H. Bunker and Sons, Inc.	07-11-87	39	95
AA Df 108	AA-73-0789	Curtin, Gerard	H. H. Bunker and Sons, Inc.	01-15-73	46	48
AA Df 109	AA-73-7399	Nunley, Amanda	H. H. Bunker and Sons, Inc.	07-01-77	6	62
AA Df 110	AA-81-0428	Wheeler, Charles	Purner Well Drilling, Inc.	05-08-82	28	69
AA Df 111	AA-72-0581	Russell, John	H. H. Bunker and Sons, Inc.	11-17-71	30	94
AA Df 112	AA-73-8738	Brungot, George	Slater's Well Drilling, Inc.	06-30-78	35	57
AA Df 113	AA-73-4335	McMurdock	Purner Well Drilling, Inc.	04-21-75	7	45
AA Df 114	AA-81-1709	Moses, John	H. H. Bunker and Sons, Inc.	07-02-83	18	62
AA Df 115	AA-74-1734	Moses, John	H. J. Greer Drilling Co., Inc.	02-23-80	18	50
AA Df 117	AA-81-0421	Hillsmere Pool Association	H. H. Bunker and Sons, Inc.	05-21-82	22	111
AA Df 118	AA-72-0587	Smithson, Frederick	H. J. Greer Drilling Co., Inc.	11-26-71	10	40
AA Df 119	AA-74-3547	Bauer, Erwin	Purner Well Drilling, Inc.	08-12-81	18	71
AA Df 121	AA-74-2825	Weber, Edwin	H. H. Bunker and Sons, Inc.	04-28-81	48	60
AA Df 122	AA-81-3998	Murphy, Jean	H. H. Bunker and Sons, Inc.	12-29-84	11	33

[1] Well abandoned.
[2] Use of water: C = commercial; D = domestic; I = institutional; O = other.
[3] Borehole - drilled to 220 feet.
[4] Reported by owner.

Diameter of well (inches)		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]	Use[2/] of water	Well number (plate 1)
Casing	Screen				Static	Pumping						
4	3	65	7	Magothy	26	45	02-14-80	15	1.5	0.79	D	AA Cf 138
4	2	123	7	Magothy	10	16	01-11-86	50	4	.8	D	AA Cf 139
4	2	110	7	Magothy	17	20	07-27-83	30	24	10	D	AA Cf 140
4	--	40	15	Aquia	7	16	04-03-56	10	4	1	D	AA De 64
6	3	75	15	Aquia	14	29	05-28-52	60	3	4	I	AA De 90
4	3	74	10	Aquia	40	60	- -71	18	4	.9	D	AA De 117
4	2	44	4	Aquia	28	44	07-19-74	15	1	.94	D	AA De 163
4	2	72	10	Aquia	29	36	09-08-86	60	6	9	D	AA De 164
4	2	43	7	Aquia	30	35	02-05-87	10	4	2	D	AA De 165
4	4	48	7	Aquia	14	55	01-08-79	15	2	.37	D	AA De 166
4	2	35	7	Aquia	5	12	04-13-79	15	1	2	C	AA De 167
4	2	36	7	Aquia	8	25	03-12-81	12	3	.7	D	AA De 168
4.5	3	62	15	Aquia	27	48	01-15-88	36	4	1.7	D	AA De 169
4.5	3	65	15	Aquia	27	46	01-30-88	36	4	1.9	D	AA De 170
4.5	3	60	15	Aquia	27	49	01-30-88	36	4	1.6	D	AA De 171
4	2	71	7	Aquia	21	42	02-22-84	10	1	.5	D	AA De 172
4	2	65	5	Aquia	35	40	03-02-77	15	1	3	C	AA De 173
4	2	45	5	Aquia	11	27	10-16-82	30	2	2	D	AA De 174
4	--	65	8	Aquia	55	80	01-02-70	8	1	.3	D	AA De 175
4	2	103	7	Monmouth	46	58	07-18-79	15	1	1.2	D	AA De 176
4	2	98	7	Monmouth	40	55	11-04-76	12	2	.8	D	AA De 178
4	2	60	5	Aquia	25	35	06-17-80	15	1	2	D	AA De 179
4	4	70	10	Aquia	20	30	08-28-87	30	4	3	D	AA De 180
4	--	90	10	Aquia	20	26	03-11-88	30	4	5	D	AA De 181
4	2	55	5	Aquia	7	22	08-17-83	15	1	1	D	AA De 182
4	2	93	7	Aquia	25	93	07-20-81	50	6	.7	O	AA De 183
4	4	103	20	Aquia	8	100	05-10-87	100	8	1	O	AA De 184
4	2	80	7	Aquia	36	60	06-30-88	30	2	1	D	AA De 185
4	2	38	7	Aquia	10	12	09-05-78	15	1	8	C	AA De 186
4	4	35	5	Aquia	20	30	11-21-75	10	2	1	D	AA De 187
4	2	45	5	Aquia	7	15	04-02-81	15	2	2	D	AA De 188
4	2	53	5	Aquia	8	30	02-03-77	15	1	.7	D	AA De 190
4	2	53	4	Aquia	28	53	09-28-72	12	2	.48	C	AA De 191
4	--	108	7	Aquia	--	--	--	--	--	--	C	AA De 198
2	--	48	17	Aquia	6	--	04-04-46	4	--	--	D	AA Df 32
4	--	44	5	Aquia	4	20	08-18-69	20	1	1	I	AA Df 86
6	6	108	5	Aquia	21	65	06-01-71	50	4	1	C	AA Df 96
4	2	33	7	Aquia	10	13	11-04-81	15	1	5	D	AA Df 98
4	2	39	7	Aquia	23	40	09-01-74	4	3	.2	D	AA Df 103
4	2	83	7	Aquia	30	50	02-26-74	15	10	.8	D	AA Df 104
4	3	48	10	Aquia	8	58	10-15-73	15	1	.3	D	AA Df 105
4	2	88	7	Aquia	27	60	07-11-87	15	2	.4	D	AA Df 107
4	2	43	5	Aquia	22	34	01-15-73	7	1	.6	D	AA Df 108
4	2	57	5	Aquia	5	12	07-01-77	15	1	2	D	AA Df 109
4	2	62	7	Aquia	17	62	05-08-82	20	2	.4	D	AA Df 110
4	2	89	5	Aquia	31	65	11-17-71	15	1	.4	D	AA Df 111
4	2	50	7	Aquia	12	17	06-30-78	20	4	4	D	AA Df 112
4	4	40	5	Aquia	7	17	04-21-75	10	2	1	D	AA Df 113
4	2	55	7	Aquia	18	25	07-02-83	15	1	2	D	AA Df 114
4	2	45	5	Aquia	12	18	02-23-80	13	2	2	D	AA Df 115
4	2	104	7	Aquia	16	30	05-21-82	40	2	3	C	AA Df 117
4	2	35	5	Aquia	6	10	11-26-71	20	1	5	D	AA Df 118
4	2	65	6	Aquia	25	65	08-12-81	15	2	.38	D	AA Df 119
4	2	53	7	Aquia	30	33	04-28-81	12	1	4	D	AA Df 121
4	2	26	7	Aquia	3	11	12-29-84	20	1	2	D	AA Df 122

Appendix B. Records of selected wells used in this report—Continued

Well number (plate 1)	State permit number	Owner	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)
AA Df 123	AA-81-6890	Rose, Michael	H. H. Bunker and Sons, Inc.	09-20-86	10	50
AA Df 124	AA-81-7771	Williams, Stacy	H. H. Bunker and Sons, Inc.	02-21-87	8	27
AA Df 125	AA-73-5763	AA Co., Bay Ridge Sewage Pumping Station	Frank's Well Drilling, Inc.	07-15-76	17	68
AA Df 126	AA-74-1911	AA Co., Thomas Point Sewage Pumping Station	Wolford's Well and Pump Service, Inc.	08-29-80	9	90
AA Df 127	AA-86-0278	Faulk, Jasper	East Coast Well and Pump, Inc.	04-04-88	10	334
AA Df 128	AA-81-9920	Strum, James	East Coast Well and Pump, Inc.	05-05-88	10	444
AA Df 129	AA-88-0035	Southern Estates	Branham Contractors, Inc.	05-08-88	31	165
AA Df 130	AA-88-0037	Southern Estates	Branham Contractors, Inc.	05-06-88	30	91
AA Df 131	AA-88-0036	Southern Estates	Branham Contractors, Inc.	05-11-88	44	191
AA Df 132	AA-88-0038	Southern Estates	Branham Contractors, Inc.	05-10-88	44	110
AA Df 133[3/]	--	Southern Estates	Branham Contractors, Inc.	05-04-88	30	--
AA Df 134	AA-73-4973	Gerrior's Nursery and Garden Center	Purner Well Drilling, Inc.	08-29-75	25	100
AA Df 135	AA-73-1601	Baker	H. J. Greer Drilling Co., Inc.	09-16-73	32	50
AA Df 136	AA-81-4320	Wilson, Sammie	H. H. Bunker and Sons, Inc.	02-23-85	5	58
AA Df 137	AA-73-9562	Gateau, Sandy	Branham Contractors, Inc.	09-18-78	9	83
AA Df 138	AA-71-0639	Hellar, Austin	Purner Well Drilling, Inc.	03-21-71	19	56
AA Df 139	AA-81-3545	Gateau, David	Dennis's Well Drilling	08-08-84	38	105
AA Df 140	AA-81-5061	Wendell, Lilly	Slater's Well Drilling, Inc.	11-07-85	37	52
AA Df 141	AA-73-4136	Wiley, David	H. J. Greer Drilling Co., Inc.	02-26-75	6	28
AA Df 143	AA-73-2915	Peterson, Frank	Slater's Well Drilling, Inc.	05-24-74	37	85
AA Df 144	--	Hilterbrick, Robert	Wolford's Well and Pump, Inc.	07-01-81	47	85
AA Df 145	AA-70-0276	Gasch, Helen	Purner Well Drilling, Inc.	10-27-69	26	54
AA Df 146	AA-86-0329	Hughes	Slater's Well Drilling, Inc.	03-16-88	19	95
AA Df 147	AA-81-1834	Brooks, Dan	Slater's Well Drilling, Inc.	06-22-83	20	50
AA Df 148	--	Longo, Charles	--	--	5	26
AA Df 149	AA-88-1484	Longo, Charles	Branham Contractors, Inc.	11-05-88	5	310
AA Df 150	AA-73-4985	Lester, James	Branham Contractors, Inc.	09-15-75	30	87
AA Ee 49	AA-03-1288	Mayo Elementary School	Layne-Atlantic Co.	- -58	45	106
AA Ee 70	AA-73-0208	Smithsonian Institution	Purner Well Drilling, Inc.	09-06-72	11	70
AA Ee 71	AA-81-9887	Moulden, Thomas	H. H. Bunker and Sons, Inc.	01-16-88	15	59
AA Ee 73	AA-81-3780	Thorne, Cathy	H. J. Greer Drilling Co., Inc.	--	5	95
AA Ee 74	AA-81-8050	AA Co., Glebe Hts. Sewage Pumping Station	Schummer Well Drilling Co.	05-20-87	114	223
AA Ee 75	AA-81-5707	AA Co., Glebe Hts. Sewage Pumping Station	L. Franklin Easterday, Inc.	12-24-85	107	125
AA Ee 76	AA-73-2504	Selby Bay Yacht Club	Purner Well Drilling, Inc.	02-14-74	6	60
AA Ee 77	AA-73-2949	Perrie	Purner Well Drilling, Inc.	05-13-74	28	80
AA Ee 78	AA-88-1069	AA Co., Mayo Water Reclamation Plant	East Cost Well and Pump, Inc.	10-10-88	18	98
AA Ee 79	AA-88-1070	AA Co., Mayo Water Reclamation Plant	East Coast Well and Pump, Inc.	10-10-88	15	50
AA Ee 80	AA-88-1207	AA Co., Holly Hill Sewage Pumping Station	Branham Contractors, Inc.	11-17-88	5	46
AA Ef 17	AA-71-0808	Fuller	Purner Well Drilling, Inc.	05-03-71	20	41
AA Ef 20	AA-68-1017	Black, William	Crowner Well Drilling	05-14-68	12	32
AA Ef 21	AA-74-1831	AA Co., Mayo Beach Park	H. H. Bunker and Sons, Inc.	05-24-80	11	75
AA Ef 22	AA-73-9723	Watergate Community Beach	H. H. Bunker and Sons, Inc.	10-20-78	5	42
AA Ef 23	AA-81-8921	Garner, Eileen	H. H. Bunker and Sons, Inc.	08-15-87	17	62
AA Ef 24	AA-74-2996	Burda, Adeline	Branham Contractors, Inc.	04-06-81	24	66
AA Ef 26	AA-81-7681	AA Co., Triton Beach Park	Branham Contractors, Inc.	12-29-86	15	50
AA Ef 27	AA-81-7977	Norfolk, Bill	Purner Well Drilling, Inc.	02-06-87	15	41
AA Ef 28	--	Norfolk, Bill	--	--	15	75
AA Ef 36	AA-88-4124	Hilliard, Alma	Branham Contractors, Inc.	03-06-90	7	95
AA Ef 37	AA-81-4044	Taylor, Jackson	H. H. Bunker and Sons, Inc.	02-16-85	4	26

Diameter of well (inches)		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]	Use[2/] of water	Well number (plate 1)
Casing	Screen				Static	Pumping						
4	2	43	7	Aquia	10	20	09-20-86	30	1	3	D	AA Df 123
4	4	22	5	Aquia	6	15	02-21-87	20	2	2	D	AA Df 124
4	2	63	5	Aquia	12	17	07-15-76	20	2	4	O	AA Df 125
4	3	83	7	Aquia	7	25	08-29-80	20	1.5	1	O	AA Df 126
4.5	2	324	10	Magothy	14	60	04-04-88	60	4	1	D	AA Df 127
4.5	2	434	10	Magothy	12	60	05-05-88	50	8	1	D	AA Df 128
4	2	158	7	Monmouth	25	45	05-08-88	25	3	1.2	D	AA Df 129
4	2	84	7	Aquia	25	45	05-06-88	20	3	1	D	AA Df 130
4	2	184	7	Monmouth	37	60	05-11-88	25	3	1	D	AA Df 131
4	2	103	7	Aquia	37	60	05-10-88	20	3	0.9	D	AA Df 132
--	--	--	--	--	--	--	--	--	--	--	--	AA Df 133
4	2	94	6	Aquia	33	94	08-29-75	20	2	.3	C	AA Df 134
4	2	45	5	Aquia	28	36	09-16-73	12	1	2	D	AA Df 135
4	2	51	7	Aquia	4	25	02-23-85	10	1	.5	D	AA Df 136
4	2	76	7	Aquia	8	40	09-18-78	30	2	1	D	AA Df 137
4	2	52	4	Aquia	16	52	03-21-71	10	1	.3	D	AA Df 138
4	2	85	20	Aquia	30	105	08-08-84	18	3	.2	D	AA Df 139
4	2	45	7	Aquia	22	30	11-07-85	20	4	2	D	AA Df 140
4	2	23	5	Aquia	5	8	02-26-75	12	1	4	D	AA Df 141
4	2	80	5	Aquia	36	--	05-24-74	15	2	--	D	AA Df 143
4	2	78	7	Aquia	40	55	07-01-81	15	1	1	D	AA Df 144
4	--	49	5	Aquia	29	35	10-27-69	10	4	2	D	AA Df 145
4	2	85	10	Aquia	30	40	03-16-88	20	4	2	D	AA Df 146
4	2	43	7	Aquia	15	20	06-22-83	40	4	8	D	AA Df 147
--	--	22	--	Aquia	--	--	--	--	--	--	D	AA Df 148
4	2	303	7	Magothy	50	70	11-05-88	45	3	2	D	AA Df 149
4	2	80	7	Aquia	29	50	09-15-75	10	2	.5	D	AA Df 150
6	--	101	5	Aquia	37	90	07- -58	60	8	1	I	AA Ee 49
4	4	65	5	Aquia	12	22	09-06-72	10	2	1	I	AA Ee 70
4	2	52	7	Aquia	12	46	01-16-88	8	1	.2	D	AA Ee 71
4	2	90	5	Aquia	6	15	--	25	1	3	D	AA Ee 73
4	4	203	20	Aquia	108	136	05-20-87	35	8	1.2	O	AA Ee 74
6	6	110	15	Aquia	15	125	12-24-85	6	6	.05	O	AA Ee 75
4	4	55	5	Aquia	5	15	02-14-74	10	2	1	C	AA Ee 76
4	4	75	5	Aquia	28	38	05-13-74	10	2	1	D	AA Ee 77
4.5	3	88	10	Aquia	13	60	10-10-88	60	6	1	O	AA Ee 78
4	3	43	7	Aquia	7	32	10-10-88	30	2	1	O	AA Ee 79
4	2	36	10	Aquia	8	20	11-17-88	40	3	3	O	AA Ee 80
4	2	37	4	Aquia	10	37	05-03-71	15	1	.6	D	AA Ef 17
4	4	27	5	Aquia	13	22	05-14-68	10	2	1	D	AA Ef 20
6	2	61	14	Aquia	9	30	05-24-80	60	3	3	C	AA Ef 21
4	2	35	7	Aquia	5	20	10-20-78	18	2	1	C	AA Ef 22
4	2	55	7	Aquia	15	20	08-15-87	60	1	10	D	AA Ef 23
4	2	59	7	Aquia	25	35	04-06-81	20	2	2	D	AA Ef 24
4	4	40	10	Aquia	8	20	12-29-86	10	3	.8	C	AA Ef 26
4	2	35	6	Aquia	15	--	02-06-87	30	2	--	D	AA Ef 27
--	--	68[4/]	7[4/]	Aquia	--	--	--	--	--	--	D	AA Ef 28
4	2	88	7	Aquia	4	83	03-06-90	25	3	.3	D	AA Ef 36
4	2	19	7	Aquia	3	10	02-16-85	8	1	1	D	AA Ef 37

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

[ft, feet; mg/L, milligrams per liter; --, no analysis made; µg/L, micrograms per liter; µS/cm, microsiemens per centimeter; deg. C, degrees Celsius]

Well number (plate 1)	Aquifer	Date sampled	Altitude, (ft above sea level)	Depth of well (ft)	Depth to top of screen (ft below land surface)	Alkalinity, laboratory (mg/L as $CaCO_3$)	Bicarbonate (mg/L as HCO_3)	Bromide, dissolved (mg/L)	Calcium, dissolved (mg/L)	Chloride, dissolved (mg/L)
AA Ce 127	Magothy	06-07-89	6	75	60	<1	--	--	3.6	3.5
AA Ce 128	Magothy	06-08-89	6	175	160	<1	--	--	2.6	.9
AA Ce 130	Magothy	05-04-90	5	103	88	<1	--	0.02	2.3	2.0
AA Ce 133	Magothy	08-28-90	15	117	102	<1	--	--	2.7	1.2
AA Ce 134	Magothy	08-27-90	15	77	62	<1	--	--	3.7	1.3
AA Cf 79	Monmouth	06-02-60	95	128	123	--	9	--	2.8	4.0
AA Cf 141	Magothy	06-02-89	62	185	170	<1	--	--	6.0	.9
AA Cg 25	Aquia	01-24-89	17	107	100	32	92	.12	8.2	5.5
AA De 35	Aquia	06-25-46	10	81	--	--	220	--	67	2.2
AA De 105	Aquia	11-22-68	50	83	--	--	130	--	47	44
AA De 159	Aquia	12-07-87	70	109	64	19	--	--	9.8	4.0
AA De 189	Aquia	04-20-90	42	95	80	230	--	.02	86	5.0
AA De 193	Monmouth	05-24-89	37	155	140	51	--	20	1,400	5,900
AA De 194	Aquia	05-23-89	37	97	82	160	--	1.3	--	310
AA De 195	Aquia	04-05-89	37	65	50	48	--	<.01	14	5.5
AA De 196	Aquia	04-19-90	41	145	130	100	--	12	1,300	3,400
AA De 197	Aquia	04-26-90	42	115	100	200	--	.02	85	2.8
AA De 200	Monmouth	04-27-90	42	205	190	<1	--	22	1,900	6,400
AA De 201	Monmouth	06-01-90	41	230	195	<1	--	14	1,000	3,700
AA Df 32	Aquia	10-06-88	9	48	--	140	--	4.7	910	1,700
AA Df 103	Aquia	05-24-90	27	46	39	19	21	.06	15	56
AA Df 131	Monmouth	05-19-88	44	183	176	230	--	--	84	3.0
AA Df 132	Aquia	05-17-88	44	100	93	170	--	--	68	5.9
AA Df 151	Monmouth	02-08-89	22	178	163	170	--	.19	82	51
AA Df 152	Aquia	02-09-89	22	118	103	220	--	.06	83	5.5
AA Df 153	Aquia	02-10-89	22	38	23	7	--	.08	16	46
AA Df 154	Monmouth	05-18-89	5	165	150	200	--	.03	71	2.2
AA Df 155	Monmouth	05-02-90	39	199	184	5	--	26	2,600	6,500
AA Ee 10	Aquia	06-29-46	5	72	--	--	250	--	76	3.9
AA Ee 68	Aquia	05-14-81	55	170	150	160	--	--	62	6.2
AA Ee 81	Monmouth	03-15-89	11	191	176	110	--	<.01	39	1.7
AA Ef 2	Aquia	06-18-46	5	65	--	--	260	--	83	11
AA Ef 18	Aquia	06-09-81	10	100	90	49	--	--	600	980
AA Ef 30	Aquia	02-02-89	5	50	35	100	--	.17	--	73
AA Ef 31	Aquia	02-07-89	5	135	120	83	--	19	2,200	6,000
AA Ef 32	Monmouth	05-31-89	8	225	210	1	--	8.5	1,900	6,400
AA Ef 33	Aquia	05-30-89	8	137	122	86	--	8.5	900	2,300
AA Ef 34	Aquia	05-26-89	8	85	70	230	--	.07	91	12
AA Ef 35	Monmouth	02-06-89	5	200	185	2	--	7.5	730	2,300

1/ Use of water: C = commercial; D = domestic; T = test; I = institution.

2/ Dissolved solids reported as the sum of constituents.

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

Well number (plate 1)	Color (platinum-cobalt units)	Fluoride, dissolved (mg/L)	Hardness, total (mg/L as $CaCO_3$)	Iron, dissolved (µg/L)	Iron, total (µg/L)	Magnesium, dissolved (mg/L)	Manganese, dissolved (µg/L)	Manganese, total (µg/L)	Nitrogen, $NO_2 + NO_3$ total (mg/L)	pH, field (standard units)	pH, lab (standard units)
AA Ce 127	10	0.1	16	14,000	14,000	1.7	130	120	<.10	5.2	3.6
AA Ce 128	25	.1	11	8,400	8,700	1.2	93	90	<.10	4.1	3.6
AA Ce 130	<1	.1	9	3,400	3,500	.9	64	60	<.10	3.8	4.7
AA Ce 133	5	<.1	12	8,900	9,100	1.3	120	120	<.10	3.8	3.9
AA Ce 134	<1	.1	15	15,000	15,000	1.3	110	110	<.10	4.7	3.4
AA Cf 79	5	<.1	10	--	270	.7	--	<5	--	6.6	--
AA Cf 141	150	.2	25	30,000	30,000	2.5	210	200	<.10	6.2	5.4
AA Cg 25	--	.6	30	15,000	--	2.3	360	370	<.10	6.4	6.4
AA De 35	3	.1	190	--	1,400	5.4	--	--	--	7.8	--
AA De 105	--	.2	130	--	2,800	3.5	--	30	--	8.1	--
AA De 159	--	.6	33	4,600	--	2.1	260	--	--	6.4	6.1
AA De 189	6	.3	230	220	340	3.3	37	50	<.10	7.1	7.5
AA De 193	130	<.1	3,900	2,200	42,000	90	530	590	<.10	6.7	6.4
AA De 194	25	.2	--	--	4,900	--	--	130	<.10	6.8	7.0
AA De 195	1	.1	46	5	50	2.6	39	40	.30	5.8	6.3
AA De 196	110	1.0	3,500	16,000	16,000	61	230	280	<.10	6.6	6.7
AA De 197	16	.3	220	900	1,000	2.0	26	30	<.10	7.1	7.5
AA De 200	14	.2	5,300	10,000	110,000	130	820	990	<.10	6.2	6.2
AA De 201	2	<.1	3,000	240,000	220,000	120	2,500	2,200	<.10	--	4.8
AA Df 32	--	.1	2,400	30	190	30	110	120	.30	6.8	7.2
AA Df 103	--	<.1	62	19	650	6.0	12	10	1.5	5.4	5.7
AA Df 131	--	.3	230	14	1,000	4.7	14	20	<.10	7.1	7.5
AA Df 132	--	.2	176	140	930	1.6	18	10	<.10	7.4	7.7
AA Df 151	10	.2	240	150	3,800	7.4	52	70	<.10	7.2	7.1
AA Df 152	1	.2	220	160	1,200	2.2	16	20	.30	7.8	7.5
AA Df 153	<1	<.1	61	27	150	5.2	12	20	7.8	5.3	5.4
AA Df 154	25	.2	200	34	1,900	5.3	27	30	<.10	--	7.5
AA Df 155	<1	<.1	8,500	100,000	140,000	490	600	570	<.10	6.3	6.0
AA Ee 10	6	<.1	200	--	2,400	3.1	--	--	--	7.2	--
AA Ee 68	3	.2	180	1,300	1,100	6.9	10	10	<.10	7.5	8.0
AA Ee 81	30	.2	120	38	6,000	5.3	67	70	<.10	6.9	7.3
AA Ef 2	3	<.1	220	--	4,000	3.9	--	--	--	7.4	--
AA Ef 18	1	<.1	1,600	44,000	52,000	16	280	390	.24	7.3	7.6
AA Ef 30	--	--	--	--	--	--	--	--	<.10	6.8	7.0
AA Ef 31	3	<.1	6,400	90	21,000	230	180	180	<.10	7.0	6.7
AA Ef 32	<1	<.1	5,700	150,000	170,000	240	1,600	1,500	<.10	6.2	5.0
AA Ef 33	250	.1	2,400	50	10,000	37	530	500	<.10	6.9	6.7
AA Ef 34	10	.1	240	10	110	3.0	8	30	<.10	7.0	7.7
AA Ef 35	2	<.1	2,500	29,000	82,000	170	760	700	<.10	6.5	5.2

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

Well number (plate 1)	Potassium, dissolved (mg/L)	Phosphorus total (mg/L)	Silica, dissolved (mg/L as SiO_2)	Specific conductance, laboratory (µS/cm)	Specific conductance, field (µS/cm)	Sodium, dissolved (mg/L)	Dissolved solids, residue at 180 deg. C, dissolved (mg/L)	Sulfate, dissolved (mg/L)	Temperature (deg. C)	Use of water[1/]
AA Ce 127	1.6	0.03	9.3	169	113	1.7	81	33	13.0	T
AA Ce 128	1.3	.03	9.5	169	114	1.5	56	33	13.5	T
AA Ce 130	1.4	.08	13	62	65	1.5	21	17	14.0	T
AA Ce 133	1.4	<.01	10	122	106	1.7	59	35	14.5	T
AA Ce 134	1.5	<.01	10	196	83	2.1	73	37	15.6	T
AA Cf 79	1.9	--	15	--	38	2.3	39	5.6	13.5	C
AA Cf 141	2.0	<.01	11	107	195	1.3	70	35	13.5	T
AA Cg 25	3.5	1.0	27	125	105	3.4	118[2/]	6.9	13.3	T
AA De 35	5.0	--	33	--	365	2.6	238	12	13.5	D
AA De 105	3.7	--	22	--	399	26	234	20	14.0	T
AA De 159	2.1	--	17	89	110	1.6	79[2/]	12	15.0	T
AA De 189	3.3	.09	31	455	415	4.0	276	4.7	--	T
AA De 193	13	.09	21	17,300	15,000	2,600	11,900	790	15.0	T
AA De 194	--	.05	--	1,580	1,680	--	990	38	14.8	T
AA De 195	4.4	.01	24	117	121	2.9	82	1.3	14.5	T
AA De 196	22	<.01	32	10,500	--	760	7,830	490	15.0	T
AA De 197	3.6	.01	30	441	417	2.0	270	9.6	15.2	T
AA De 200	25	.04	31	18,100	16,400	1,600	12,200	770	18.0	T
AA De 201	18	.06	11	10,600	--	940	10,000	560	--	T
AA Df 32	8.2	<.01	30	5,100	3,600	130	2,990	54	15.0	D
AA Df 103	3.6	.05	17	253	258	21	--	9.3	13.5	T
AA Df 131	3.4	.02	35	447	430	1.9	259	7.2	14.4	D
AA Df 132	4.1	.02	29	361	391	3.1	214	8.7	13.5	D
AA Df 151	4.7	.60	36	507	475	16	336	26	15.0	T
AA Df 152	4.0	.60	37	414	400	3.2	263	4.3	15.0	T
AA Df 153	6.9	<.10	27	244	186	16	156	.40	15.0	T
AA Df 154	4.7	.12	27	385	400	1.6	229	4.0	16.0	T
AA Df 155	35	.03	25	19,700	18,300	1,000	14,500	790	16.0	T
AA Ee 10	3.9	--	45	--	408	4.2	271	6.1	--	D
AA Ee 68	3.6	.07	35	378	375	4.1	265	24	15.0	I
AA Ee 81	4.8	.24	20	254	200	2.4	158	22	15.5	T
AA Ef 2	4.1	--	32	--	430	5.2	276	1.8	14.0	D
AA Ef 18	11	.20	30	2,940	3,210	14	2,640	31	16.0	D
AA Ef 30	--	--	--	442	460	--	--	--	--	T
AA Ef 31	23	.02	25	17,200	--	1,100	10,600	780	16.0	T
AA Ef 32	30	<.01	30	17,900	16,000	1,600	12,000	760	16.5	T
AA Ef 33	16	.01	27	7,420	6,830	550	4,500	310	16.0	T
AA Ef 34	3.8	.07	35	464	480	4.6	308	3	15.9	T
AA Ef 35	16	.20	23	6,880	5,100	350	4,050	250	16.0	T

Appendix D. Chloride, bromide, and nitrogen concentrations and other selected chemical constituents in water representative of the Aquia aquifer in east-central Anne Arundel County, Maryland

[ft, feet; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter; --, no analysis made; chloride, bromide, nitrogen, specific conductance, and alkalinity are laboratory determinations, and pH is a field determination unless where noted otherwise]

Well number (plate 1)	Date sampled	Altitude (ft above sea level)	Depth to top of screen (ft below land surface)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Nitrogen, NO_2+NO_3 total (mg/L)	Specific conductance, field (µS/cm)	pH field (standard units)	Alkalinity, laboratory (mg/L as $CaCO_3$)
AA De 64	03-02-60	30	40	2.0	--	--	206	7.6	--
	10-31-88	--	--	100	0.06	3.4	580	7.3	120
	05-09-89	--	--	74	.06	3.9	510	7.1	110
AA De 90	03-02-60	23	75	1.5	--	--	352	7.9	--
	11-16-88	--	--	5.2	--	--	324	7.4	170
	05-11-89	--	--	5.6	--	--	380	6.9	170
AA De 163	10-25-88	30	44	11	--	--	72	4.9	1
	5-02-89			10	<.01	--	70	5.8	2
AA De 164	11-02-88	26	72	4.3	--	--	76	6.3	20
AA De 165	10-25-88	31	43	41	.08	1.5	136	4.6	3
	05-04-89	--	--	30	<.01	1.2	148	5.2	2
AA De 166	11-16-88	19	48	5.6	--	--	152	6.5	53
	05-12-89	--	--	2.5	--	--	156	5.9	54
AA De 167	10-27-88	4	35	54	.20	--	220	5.9	19
	05-11-89	--	--	19	.07	--	140	6.0	20
AA De 168	05-05-89	9	36	120	.36	--	635	7.0	110
AA De 169	02-02-88	27	62	300[1]	--	--	--	--	--
AA De 170	02-02-88	25	65	800[1]	--	--	--	--	--
AA De 171	02-02-88	26	60	60[1]	--	--	--	--	--
AA De 173	11-16-88	34	65	19	.07	--	152	6.1	36
	05-09-89			17	.05	--	162	6.6	37
AA De 174	10-31-88	15	45	18	.11	--	160	5.2	19
	05-12-89			10	.08	--	128	6.2	17
AA De 175	11-02-88	55	65	46	.07	--	545	7.3	200
AA De 176[2]	11-16-88	73	103	4.5	.04	--	82	6.2	5
	05-12-89			4.5	.02	--	69	5.5	40
AA De 179	10-27-88	45	60	8.5	.06	--	81	5.1	4
	05-02-89			5.6	<.01	--	71	4.5	4
AA De 180	10-27-88	27	70	2.5	--	--	74	6.3	22
	05-05-89			4.4	--	--	81	6.7	22
AA De 181	10-27-88	43	90	7.9	--	--	107	6.3	31
	05-12-89			7.7	--	--	132	6.9	31
AA De 182	10-31-88	2	55	6.9	--	--	435	7.0	220
	05-09-89			7.3	--	--	470	7.3	230
AA De 184	11-02-88	28	103	6.3	--	--	340	7.7	180
	05-15-89			4.3	--	--	355	--	180
AA De 185	10-28-88	51	80	4.4	--	--	310	7.3	160
	05-05-89			4.4	--	--	310	7.6	160
AA De 187	11-16-88	20	35	570	1.9	2.9	1,760	6.0	50
	05-09-89			400	1.4	2.8	1,350	6.6	55
AA De 188	11-16-88	6	45	8.9	.10	--	240	6.4	38
AA De 190	10-31-88	10	53	37	.08	<0.10	420	7.6	180
AA De 191	11-17-88	50	53	24	.03	.90	163	6.1	30
	05-05-89			34	<.01	--	250	5.8	25
AA De 198	05-10-89	29	108	4,600	70	.10	11,400	6.6	43
AA Df 32	10-06-88	20	48	1,700	4.7	.30	3,600	6.8	140
AA Df 86	10-19-88	6	44	190	.82	1.4	1,000	6.6	160
	04-27-89			210	.54	--	1,000	6.7	160
AA Df 98	10-20-88	11	33	22	.07	5.8	370	7.0	130
	05-16-89			19	.05	4.9	390	7.6	130
AA Df 104	10-18-88	28	83	4.0	--	--	346	7.2	170
	04-26-89			4.4	--	--	360	7.0	170
AA Df 105	10-18-88	10	48	22	.06	3.5	177	5.6	7
	04-25-89			18	<.01	--	91	5.2	5
AA Df 107	10-19-88	39	88	12	--	--	315	7.0	150
	04-26-89			11	--	--	322	6.7	140
AA Df 108	11-29-88	46	43	170	.25	3.7	600	4.4	2
	05-05-89			160	.26	3.4	668	4.6	1
AA Df 109	10-18-88	6	57	6.6	--	--	378	7.4	190
	04-27-89			7.0	<.01	--	395	7.3	190

[1] Field determination.
[2] Monmouth aquifer.
[3] Laboratory determination.

Appendix D. Chloride, bromide, and nitrogen concentrations and other selected chemical constituents in water representative of the Aquia aquifer in east-central Anne Arundel County, Maryland—Continued

Well number (plate 1)	Date sampled	Altitude (ft above sea level)	Depth to top of screen (ft below land surface)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Nitrogen, NO_2+NO_3 total (mg/L)	Specific conductance, field (µS/cm)	pH field (standard units)	Alkalinity, laboratory (mg/L as ($CaCO_3$)
AA Df 110	10-25-88	28	62	5.2	--	--	380	7.2	210
	05-01-89			5.0	--	--	422	7.5	220
AA Df 111	10-19-88	30	89	3.7	--	--	111	7.2	200
	04-26-89			3.5	--	--	440	7.3	200
AA Df 112	10-26-88	35	50	28	.10	2.8	312	6.8	100
	05-05-89			21	<.01	2.6	300	6.0	100
AA Df 114	10-19-88	18	55	29	.10	<0.10	412	7.0	180
	04-28-89			27	--	--	450	6.7	180
AA Df 117	10-20-88	22	104	4.8	--	--	360	7.4	200
	05-02-89			3.9	--	--	415	8.0	200
AA Df 118	10-21-88	10	35	26	.15	--	455	7.0	200
	05-16-89			30	.12	--	470	7.8	200
AA Df 119	10-21-88	18	65	24	.18	.20	364	7.5	150
	04-28-89			23	.15	--	370	7.6	150
AA Df 121	10-20-88	48	53	140	.15	.200	970	6.6	280
	05-02-89			130	.14	.10	1,000	6.3	290
AA Df 123	11-22-88	10	43	88	.45	.900	540	6.7	120
AA Df 124	10-26-88	8	22	120	.39	1.2000	425	5.6	11
	04-25-89			240	.71	2.1000	817	4.5	8
AA Df 126	10-19-88	9	83	3.6	.02	<.100	355	7.9	190
	04-28-89			3.1	--	--	360	7.6	190
AA Df 134	10-19-88	25	94	3.4	--	--	400	7.6[3/]	220
AA Df 136	10-18-88	5	51	11	.08	<.100	510	7.0	230
	04-28-89			11	<.01	--	473	7.1	290
AA Df 137	10-20-88	9	76	4.5	--	--	398	7.1	200
	05-02-89			3.9	--	--	440	7.3	210
AA Df 138	10-26-88	19	52	7.7	--	--	427	7.2	220
	04-26-89			21	<.01	--	480	7.2	200
AA Df 139	10-20-88	38	85	14	.07	1.3000	439	7.2	210
	05-01-89			13	<.01	1.7000	478	7.7	210
AA Df 143	04-26-89	37	80	11	<.01	--	42	7.4	200
AA Df 144	10-27-88	47	78	9.0	--	--	272	7.3	140
	04-28-89			7.5	--	--	280	6.8	150
AA Df 145	04-25-89	26	49	14	<.01	11.000	350	6.0	100
AA Df 146	10-20-88	19	85	3.8	.02	<.100	439	7.4	200
	05-17-89			3.7	.02	--	460	7.6[3/]	230
AA Df 147	10-26-88	20	43	19	.05	15.000	199	5.1	6
	04-26-89			20	<.01	--	248	4.4	4
	09-19-91					1.0[1/]			
AA Df 148	11-03-88	5	22	1,100	3.3	1.0000	5,000	6.7	140
AA Df 150	11-19-90	37	80	300	.09	.5	1,100	6.5	170
AA Ee 49	11-09-88	45	101	15	--	--	315	7.8[3/]	170
AA Ee 70	11-22-88	11	65	8.8	--	--	395	7.6	190
AA Ee 71	11-22-88	15	52	11	.03	--	370	6.9	180
AA Ee 73	11-02-88	5	90	3.0	--	--	282	7.6	150
	05-15-89			2.5	--	--	323	7.8	150
AA Ee 74	11-02-88	114	203	4.9	--	--	435	7.3	240
	05-15-89			3.3	--	--	500	7.4	250
AA Ee 77	11-03-88	28	75	40	.13	--	225	6.3	76
	05-17-89			15	.08	--	260	7.4	85
AA Ee 78	11-22-88	18	88	11	.02	--	420	7.6	220
	05-15-89			9.3	--	<.10	410	6.8	210
AA Ee 80	05-15-89	5	36	3.5	--	<.10	370	7.4[3/]	180
AA Ef 17	11-09-88	20	37	48	.07	--	250	5.8	24
AA Ef 20	10-19-88	12	27	110	.14	1.5	440	6.8	16
AA Ef 22	10-21-88	5	35	1,000	4.3	<.10	3,800	7.0	310
	04-27-89			1,200	4.3	--	3,700	6.9	340
AA Ef 23	11-03-88	17	55	73	.19	--	582	6.7	180
AA Ef 24	11-18-88	24	59	65	.24	<.10	510	6.6	120
	05-17-89			63	.18	--	628	6.9	140
AA Ef 26	11-09-88	15	40	11	--	--	355	7.3[3/]	170
	05-15-89			9.7	--	--	400	8.0	200

Appendix D. Chloride, bromide, and nitrogen concentrations and other selected chemical constituents in water representative of the Aquia aquifer in east-central Anne Arundel County, Maryland—Continued

Well number (plate 1)	Date sampled	Altitude (ft above sea level)	Depth to top of screen (ft below land surface)	Chloride, dissolved (mg/L)	Bromide, dissolved (mg/L)	Nitrogen, NO_2+NO_3 total (mg/L)	Specific conductance, field (µS/cm)	pH field (standard units)	Alkalinity, laboratory (mg/L as $CaCO_3$)
AA Ef 27	11-09-88	15	35	190	0.6	--	725	4.1	<1
	05-17-89			190	.56	--	820	4.9	<1
AA Ef 28	11-09-88	15	68	770	2.3	--	2,225	6.5	40
	05-17-89		68	860	2.8	.40	2,800	6.6	56
AA Ef 36	05-25-90	7	88	480	1.8	--	2,030[3/]	7.0	140
AA Ef 37	12-02-88	4	19	200	.83	<0.10	860	4.3	<1
	04-28-89	--	--	190	.73	--	1,020	4.4	<1

Appendix E. Lithologic logs from wells drilled during this study

Well AA Ce 126 -- Mago Vista

(Altitude of land surface: 6 feet)

Description of cuttings	Depth, in feet below land surface
Sand, coarse, brown, quartzose	0-10
Sand, as above, with some pebbles; layer of gray clay from 10 to 11 feet	10-20
Clay, black, carbonaceous, lignitic, with interbedded lenses of medium-to-coarse sand	20-30
Clay, as above; hard layer at 39 feet	30-40
Clay, as above, with large (as much as 0.39 inch) pieces of lignite	40-50
Sand and gravel, with some lignite; interval drilled "hard"	50-60
Sand, medium to coarse, tan, with some gravel and lignite	60-70
Sand, as above, with some black clay; geophysical logs show a clay between 76 and 89 feet	70-80
Clay, description based on geophysical logs	80-90
Sand, coarse, feldspathic; interbedded clay layers--especially towards bottom of interval	90-120
Sand, as above; driller reports thin lenses of white and red clay between 187 and 200 feet; small pieces of red clay noted from 200 feet to bottom of hole	120-204
Clay, red	204-216
Sand	216-230

Well AA Ce 129 -- Sherwood Forest

(Altitude of land surface: 5 feet)

Description of cuttings	Depth, in feet below land surface
Sand, fine, glauconitic, dark-green, with pieces of soft, black, organic clay	0-9
Sand, fine, quartzose, gray, with some lignite and soft, gray and black clay	9-18
Sand, fine, quartzose, dark-gray, with layers of soft, black clay and trace amounts of mica	18-30
Sand and clay, as above, with some partially indurated, reddish-orange silt (last 2 feet)	30-38
Sand, coarse, white with some fine, gray sand; driller reported a coarse sand at 45 feet	38-50
Sand, as above, with layers of lignite	50-58
Sand, very fine, dark-gray, with some flakes of muscovite	58-70
Sand, fine to medium, dark-gray, with some muscovite and lignite; driller reported hard drilling between 76 and 78 feet	70-78
Sand, as above, with some iron-stained grains	78-90
Sand, coarse	90-98
Sand, coarse, white, with some purple, pink, and orange grains and lignite; trace amounts of white clay and pyrite; geophysical logs indicate a clay from 100 to 145 feet	98-118
Sand, very fine to fine, brown, with abundant fine-grained spherical concretions and trace amounts of pink clay; geophysical logs indicate a clay from 100 to 145 feet	118-145
Sand, very fine, light-brown	145-150
Sand, medium, light-brown	150-158

Appendix E. Lithologic logs from wells drilled during this study—Continued

Well AA Ce 133 -- Moorings-on-the-Bay

(Altitude of land surface: 15 feet)

Description of cuttings	Depth, in feet below land surface
Sand, medium, brown, well-sorted	0-15
Sand, medium, reddish-brown; driller reported "hardpan" between 18 and 21 feet	15-21
Clay, black, organic; color of drilling fluid turned black	21-22
Clay, as above, with some fine, gray sand and abundant lignite	22-39
Clay, as above, with a few hard layers, very coarse white, quartz sand and small pieces of lightly micaceous clay	39-49
Silt, black and gray, with some layers of black clay and lignite; hard drilling between 57 and 59 feet	49-59
Sand, fine to medium, white and gray, with some small amounts of white clay; hard drilling throughout interval; geophysical logs show mostly clay	59-69
Sand, as above, with more white clay	69-79
Sand, medium, white and gray, with some pink-colored grains; also some white clay; geophysical logs show a sand from 80 to 85 feet and a clay from 85 to 102 feet	79-102
Sand, fine, gray, with white clay layers	102-119
Sand, as above, with small pieces of white and red clay; geophysical logs show a clay from 131 to 136 feet	119-139
Clay, red and white, with layers of coarse white sand	139-179

Well AA Cf 141 -- Belvedere Heights

(Altitude of land surface: 62 feet)

Description of cuttings	Depth, in feet below land surface
Sand, medium, quartzose, brown, iron-stained, with lesser amounts of glauconite; also, some sandy, reddish-brown clay and hard, iron-oxide cemented layers	0-10
Sand, fine, gray, moderately glauconitic	10-30
Sand, as above, with lesser amounts of glauconite	30-40
Clay, silty, dark greenish-gray; small pieces of white, silty clay	40-50
Clay, dark greenish-gray	50-58
Sand; description based on geophysical logs	58-74
Clay, dark greenish-gray	74-80
Sand, very coarse, white and purple, with dark greenish-gray clay towards the top of the interval	80-90
Sand, medium to coarse, white, with some minor amounts of lignite	90-100
Sand, coarse, white, lignitic	100-110
Sand, medium to coarse, micaceous, lignitic, with subordinate amounts of gray clay	110-130
Clay, black, organic, lignitic; borehole log shows clay in lower half of interval	130-140
Sand, medium to coarse, white, with thick layer of gray clay towards middle of interval	140-150
Sand, very coarse, feldspathic, with some small pieces of white clay	150-160
Sand, fine to medium, orange, with some pieces of white clay	160-170
Sandstone layers composed of hard, iron-oxide cemented quartz interbedded with white clay and white and reddish sand	170-180
Sandstone, red, very hard, with pyrite and very coarse sand; geophysical log indicates a clay	180-190
Clay, gray and white	190-200

Appendix E. Lithologic logs from wells drilled during this study—Continued

Well AA De 193 -- Londontown Public House Park

(Altitude of land surface: 37 feet)

Description of cuttings	Depth, in feet below land surface
No sample collected	0-10
Sand, silty, dark-green glauconite and lightly iron-stained quartz	10-20
Sand, as above, with increased glauconite content	20-30
Sand, medium to coarse, quartzose, iron-stained, with minor amounts of limonite	30-40
Sand, as above, with "earthy," detrital limonite	40-50
Sand, as above, with thin layers of crusty limonite	50-60
Sand, medium to coarse, quartzose, iron-stained, with crusty limonite at times forming hard-cemented sandstone; also, weathered glauconite	60-70
Sand, medium to coarse, quartzose, iron-stained, reddish-yellow, with hard, crusty, limonite	70-80
Sand, as above	80-90
Sand, as above; medium to very coarse	90-100
Sand, fine, predominantly clean quartz, with fresh, dark-green glauconite	100-110
Sand, as above; silty	110-120
Sand, as above; some flakes of muscovite	120-130
Silt, dark-gray, moderately micaceous, composed of clear quartz and dark-green glauconite, with some coarse quartz grains noted	130-140
Sand, very fine, silty, predominantly quartzose	140-150
Sand, as above	150-160
Silt, dark-gray, predominantly quartzose	160-170
Silt, as above	170-180
Clay, silty, black, slightly micaceous, glauconitic	180-190
Clay, as above	190-210
Clay, stiff, black, slightly micaceous	210-220

Well AA De 196 -- Quiet Waters Park

(Altitude of land surface: 41 feet)

Description of cuttings	Depth, in feet below land surface
Clay, silty, brown	0-10
Clay, green, with layers of very fine, brown sand	10-18
Clay, green, glauconitic, with interbedded layers of very fine, iron-stained sand, partially cemented	18-28
Clay, as above, with dark-green glauconitic sand	28-35
Sand, fine to coarse, quartzose, brown; indurated layer at 35 feet	35-38
Sand, fine, glauconitic, dark-green, with some iron-oxide cemented layers	38-58
Sand, medium to coarse, brown and green, iron-stained	58-88
Sand, as above, with abundant chalky, white, calcareous-cemented glauconitic silt	88-98
Sand, medium to coarse, quartzose, glauconitic, with cemented silt as above	98-118
Sand, as above, becoming harder to drill	118-128
Sand, fine, glauconitic; thin bed of silty, dark-gray clay at 137 feet	128-138
Sand, as above, with more clay; drilled very smooth	138-158
Core at 148 feet: Silt, sandy, glauconitic, dark-green, lightly micaceous; core recovery = 2 inches	
Clay, silty, glauconitic, dark-green; driller reported a clay at 162 feet	158-174
Sand, fine, quartzose, glauconitic, light-green	174-190
Core at 175 feet: Sand, silty, glauconitic, dark-green; core recovery = 12 inches	
Sand, as above, grading downwards from a silt to a black clay	190-238

Appendix E. Lithologic logs from wells drilled during this study—Continued

Well AA De 200 -- Quiet Waters Park

(Altitude of land surface: 42 feet)
(Driller's log = 0 to 78 feet; Geologist's log = 78 to 238 feet)

Description of cuttings	Depth, in feet below land surface
Clay, silty, brown	0-18
Clay, silty, gray, with brown clay lenses	18-25
Clay, silty, gray and white, with fine, brown sand layers and glauconite	25-43
Sand, fine to medium, brownish-green, with glauconite and thin, white clay layers	43-65
Sand, fine to medium, brownish-green, with glauconite and "hardpan" layers	65-78
Sand, medium, brown; echnoid spines noted in sample	78-88
Sand, as above, iron-stained, with some "crusty" limonite	88-98
Sand, medium to coarse, grayish-green, partially cemented with calcareous, chalky, white matrix; some phosphate grains	98-108
Sand, as above, increased cementation, phosphate grains, and some glauconitic clay	108-118
Sand, fine, glauconitic, black, with some mica	118-141
Clay, dark-gray, micaceous	141-143
No sample collected	143-148
Sand, very fine to fine, dark-green, glauconitic; geophysical log indicates a clay	148-188
Core at 163 feet: Clay, silty, dark-green, micaceous; Recovery = 11 inches	
Sand, medium, dark-green, glauconitic	188-198
Sand, as above, very fine	198-208
Sand, as above, some fine particles of lignite noted	208-218
Sand, very fine, dark-green, glauconitic	218-238
Clay, black, micaceous	228-238

Well AA Df 151 -- Annapolis Roads

(Altitude of land surface: 22 feet)

Description of cuttings	Depth, in feet below land surface
Clay, stiff, reddish-brown and green, with some fine glauconitic sand	0-10
Clay, stiff, as above, with some thin lenses of medium-to-coarse quartzose sand and some fine glauconitic sand	10-20
Sand, coarse to very coarse, clear and lightly iron-stained, with some pebbles -- as much as 0.24 inch in diameter, and trace amount of very fine glauconite	20-30
Sand, medium to coarse, composed mainly of lightly iron-stained quartz with minor amounts of very fine, dark-green to black glauconite; gamma log indicates a downward gradation to a siltier facies	30-40
Sand, medium, quartzose, iron-stained, partially cemented, with some limonite nodules and fragments; single point electric log suggests several thin indurated layers	40-50
Sand, fine, quartzose, iron-stained, with several hard layers of limonite-cemented sand; gamma log suggests a clay at the base	50-60
Clay, silty, reddish-brown; gamma log indicates a coarse sand at 65 feet	60-70
Clay, as above	70-80
Clay, silty, iron-stained quartz, and glauconite; echnoderm spine -- 0.39 inch in length noted	80-90
Sand, fine to medium, quartzose, lightly iron-stained, with minor amounts of glauconite, and occasional limonite fragments; gamma log indicates a 3-foot sandy layer at the top grading downward to a clay	90-120
Silt, white to light-brown, chalky, partially cemented to form crusty, hard layers; gamma log indicates a sandy layer at 125 feet; trace amounts of muscovite	120-130
Silt, as above, lead-gray	130-150
Silt, as above; geophysical log indicates a sand from 150-153 feet	150-160
Silt, clayey, lead-gray, with sparse amounts of black, silty glauconite	160-180
Silt, as above, more black clay content	180-190
Clay, silty, black	190-210
Clay, as above, trace mica	210-220

Appendix E. Lithologic logs from wells drilled during this study—Continued

Well AA Df 154 -- Hillsmere

(Altitude of land surface: 5 feet)

Description of cuttings	Depth, in feet below land surface
Sand, medium, brown, iron-stained, quartzose with lesser amounts of olive-green glauconite; thin layer of green clay near surface	0-10
Sand, coarse, brown, iron-stained, with some green glauconite	10-20
Sand, coarse, tan, quartzose, lesser amounts of iron staining, minor amounts of black to dark-green glauconite; some crusty cemented sand	20-30
Sand, fine to medium, light-brown, increasing amounts of black glauconite; very fine shell detritus	30-40
Sand, fine, calcareous, glauconitic, some fine shell fragments	40-50
Sand, silty to medium, glauconitic, partially cemented with chalky, white calcareous matrix	50-60
Sandstone, tan, crusty, slightly glauconitic, some weathered shell and shell clasts	60-70
Sandstone, as above 60-70	
Sand, fine, quartz and goethite, calcareous, with weathered shell fragments	70-80
Sand, as above; indurated zones throughout interval	80-90
Sand, coarse, quartz and goethite, with chalky, white clay flecked with fresh glauconite; very hard, indurated layer at 102 feet	90-100
Sand, silty, glauconitic, dark greenish-brown, with some weathered shell	100-110
Sand, silty, well-sorted, glauconitic, dark-green, with clear quartz and sparse amounts of mica	110-120
Sand, medium, dark-green glauconite and clear quartz	120-130
Sand, fine to medium, glauconitic, dark-green, with minor amounts of clear quartz	130-140
Sand, silty to fine, glauconitic, dark-green, with sparse amounts of muscovite	140-150
Sand, as above, with lesser amounts of glauconite; indurated layers throughout interval	150-160
Sand, as above, with the addition of chalky, hard, clay flecked with glauconite; also, some weathered shell and coarse, iron-stained quartz (probably originating from 164-169 feet	160-170
Clay; description based on gamma log	170-180
Sand, very coarse, quartzose, iron-stained, with chalky, hard, calcareous clay flecked with glauconite; also, minor amounts of shell fragments	180-190
Sand, as above, with more chalky clay, and shell, some limonite	190-200
Silt, gray, with hard, chalky clay and coarse iron-stained quartz sand (probably originating from 204 to 208 feet)	200-210
Silt, lead-gray, composed or clear quartz and fresh glauconite	210-220
Clay, silty, lead-gray	220-230
Clay, dark-gray, silty	230-240
Clay, as above (248-250 feet); sand, coarse, quartz, iron stained (242-248 feet)	240-250

Appendix E. Lithologic logs from wells drilled during this study—Continued

Well AA Df 155 -- Bay Ridge

(Altitude of land surface: 39 feet)

Description of cuttings	Depth, in feet below land surface
Sand, brown, fine, quartzose; grades downward to a light, olive-green clay	0-10
Sand, fine to medium, light-tan, quartzose, clear; thin layers of green clay appearing mostly toward top of interval; some hard indurated layers	10-20
Clay, silty; description based on driller's log and geophysical logs	20-30
Clay, brown; grades downward to a fine, iron-stained, quartz sand; indurated zones between 36 and 40 feet	30-40
Sand, fine to medium, tan, quartzose, clear, very little iron staining	40-50
Sand, fine to medium, tan, predominantly quartzose, with light iron staining, and crusty limonite; thin interbedded layers of green clay and coarse, quartz pebbles -- possibly originating from uphole; hard drilling between 57 and 60 feet	50-60
Sand, medium to coarse, reddish-brown, iron-stained, predominantly quartzose; hard drilling throughout interval--probably due to limonite cementation	60-70
Sand, silty, clayey, tan to reddish-brown	70-80
Clay, sandy, reddish-brown, moderately glauconitic, with small chips of limonite	80-90
Sand, silty, reddish-brown, with indurated limonite layers--exceptionally hard at 98 feet; goethite, dark-green to black, radiating, splintery crystals	90-100
Sand, fine, tan, crusty; sample contains fine-grained goethite, and occasional fresh and partially weathered shall fragments; thin layers of silty, green clay appear within interval	100-110
Sand, silty, predominantly quartzose, with glauconitic silt; partially lithified zone between 117 and 119 feet composed of calcite and limonite-cemented sand	110-120
Sand, tan, silty, iron-stained, with some shell, and interbedded lenses of chalky, calcareous clay	120-130
Sand; description based on driller's log and geophysical logs	130-140
Sand, fine, light tan, glauconitic and quartzose, with some iron staining on quartz grains	140-150
Sand, silty to medium, clear quartz, and glauconite; blebs of gray, silty clay, and fine shell fragments and mica noted in sample	150-160
Sand, fine to medium, black, boytroidal dark-green glauconite, and clear quartz; gray, silty clay with occasional flakes of muscovite; gamma log indicates a silty clay throughout interval	160-170
Clay, silty, lead-gray	170-175
Sand, very fine, light olive-gray, moderately glauconitic, well-sorted, with some flakes of muscovite	175-180
Sand, very fine, light greenish-gray, lightly glauconitic, with small pods of gray to pale-red, silty, micaceous clay	180-190
Sand, very fine, gray, very little glauconite, with some blebs of darker gray, silty clay	190-200
Sand, silty, gray, lightly glauconitic	200-210
Clay, sandy, dark-gray to black, with some white, chalky, calcareous cementation	210-220
Clay, silty, black	220-230
Clay, silty, dark-gray (black when wet), with some flakes of muscovite	230-240

Appendix E. Lithologic logs from wells drilled during this study—Continued

Well AA Ee 81 -- South River Farms Park

(Altitude of land surface: 11 feet)

Description of cuttings	Depth, in feet below land surface
Sand, fine, brown, quartzose, iron-stained, moderately glauconitic; several feet of greenish-brown clay -- probably occurring at base of interval	0-10
Sand, fine, brown, quartzose, less iron staining than previous sample, moderately glauconitic, with several cemented, limonite layers (less than 1 foot thick) near base of interval	10-20
Sand, fine, reddish-brown, with some dark-green glauconite, and medium-to-coarse, quartz sand	20-30
Sand, fine, tan, composed of clear quartz and dark-green glauconite	30-40
Sandstone, composed of silt-size dark-green to brown glauconite and clear quartz grains in calcareous matrix; hard, white weathered shell fragments, echnoid spines, and clam valves noted	40-50
Sand, as above, with shell fragments, fish spines, echnoid spines, clam valves, and porifera fragments noted; also thin layers of small pebbles and coarse quartz sand	50-60
Sand, fine to silty, light-brown, partially cemented by white, chalky, calcareous material; glauconite--mostly altered to goethite, and some shell fragments	60-70
Sand, as above, fine-grained, with less cementation and shell material	70-80
Sand, medium to very coarse, light-brown, with abundant goethite and hard, chalky pods	80-90
Sand, fine, clear quartz and olive-green glauconite, with thin lenses of very coarse quartz sand and chalky material	90-100
Sand, as above	100-110
Sand, fine to medium, gray, with some very coarse sand, hard chalky material and gray silt	110-120
Sand, fine to medium, black and white, composed mostly of black to dark-green glauconite with lesser amounts of clear quartz, well-sorted	120-130
Sand, as above, finer grained	130-140
Sand, as above	140-150
Sand, fine, tan, less glauconite than previous sample, with some gray silt	150-160
Sand, fine, black and white, equal amounts of quartz and glauconite, well-sorted	160-170
Sand, fine to silty, gray, quartzose, lightly glauconitic, with lenses of coarse quartz	170-180
Sand, as above	180-190
Sand, as above, grading to a silt	190-200
Silt, dark-gray, slightly clayey	200-210
Silt, as above	210-220

Appendix E. Lithologic logs from wells drilled during this study—Continued

Well AA Ef 29 -- Arundel-on-the-Bay

(Altitude of land surface: 5 feet)

Description of cuttings	Depth, in feet below land surface
No sample collected	0-10
Clay, olive-green, stiff, glauconitic; sand, fine, quartzose, lightly iron-stained, with subordinate amounts of fresh glauconite (18 to 20 feet)	10-20
Sand, fine, quartzose, lightly iron-stained; moderate amounts of olive-green glauconite	20-30
Sand, medium, composed of dark-green, polylobate glauconite, and lightly iron-stained quartz, minor amounts of goethite, well-sorted	30-40
Sand, as above	40-50
Sand, as above; trace amounts of white, chalky clay	50-60
Sand, medium to coarse, equal amounts of dark-green, polylobate glauconite--some altered to goethite and lightly iron-stained quartz; gamma log indicates a silt; several fine shell fragments noted; indurated shell layer occurring at 69 feet	60-70
Sand, fine, quartz and goethite, calcareous, with weathered shell fragments	70-80
Sand, as above; indurated zones throughout interval	80-90
Sand, coarse, quartz and goethite, with chalky, white clay flecked with fresh glauconite; very hard, indurated layer at 102 feet	90-100
Sand, silty, glauconitic, dark greenish-brown, with some weathered shell	100-110
Sand, silty, well-sorted, glauconitic, dark-green, with clear quartz and sparse amounts of mica	110-120
Sand, medium, dark-green glauconite and clear quartz	120-130
Sand, fine to medium, glauconitic, dark-green, with minor amounts of clear quartz	130-140
Sand, silty to fine, glauconitic, dark-green, with sparse amounts of muscovite	140-150
Sand, as above, with lesser amounts of glauconite; indurated layers throughout interval	150-160
Sand, as above, with the addition of chalky, hard, clay flecked with glauconite; also, some weathered shell and coarse, iron-stained quartz (probably originating from 164-169 feet	160-170
Clay; description based on gamma log	170-180
Sand, very coarse, quartzose, iron-stained, with chalky, hard, calcareous clay flecked with glauconite; also, minor amounts of shell fragments	180-190
Sand, as above, with more chalky clay, and shell, some limonite	190-200
Silt, gray, with hard, chalky clay and coarse iron-stained quartz sand (probably originating from 204 to 208 feet)	200-210
Silt, lead-gray, composed of clear quartz and fresh glauconite	210-220
Clay, silty, lead-gray	220-230
Clay, dark-gray, silty	230-240
Clay, as above (248-250 feet); sand, coarse, quartz, iron-stained (242-248 feet)	240-250

Appendix E. Lithologic logs from wells drilled during this study—Continued

Well AA Ef 32 -- Mayo Beach Park

(Altitude of land surface: 8 feet)

Description of cuttings	Depth, in feet below land surface
Sand, medium, light-tan, quartzose, some light-purple quartz grains	0-10
Clay, silty, light-tan (10-14 feet); sand, fine, light-tan, with some flakes of mica (14-20 feet)	10-20
Sand, fine to medium, light-tan, mostly quartzose with small amounts of dark-green glauconite	20-30
Sand, fine, greenish-brown, equal amounts of fresh glauconite and clear to lightly iron-stained quartz	30-40
Sand, as above, with some coarse grains	40-50
Sand, as above	50-60
Sand, medium, brown, iron-stained, with some limonite	60-70
Sand, as above, with less limonite and iron staining; some weathered shell	70-80
Sand, medium, dark-brown, composed predominantly of brown glauconite, with lesser amounts of iron-stained quartz, and weathered shell	80-90
Sand, very fine, composed of quartz, weathered glauconite, and abundant weathered calcareous granules	90-100
Sand, white, calcareous, with weathered glauconite, and brown quartz grains	100-110
Sand, as above	110-120
Sand, as above	120-130
Sand, as above; with the addition of quartz, calcareous silt, abundant weathered shell debris, and calcareous sandstone	130-140
Sand, as above	140-150
Sand, fine, black, predominantly dark-green to black glauconite with sparse amount of clear quartz	150-160
Sand, as above, with increasing quartz content	160-170
Sand, as above	170-180
Sand, fine, light-gray, quartzose, with occasional black glauconite, shell material, and dark-gray silt	180-190
Sand, as above	190-200
Sand, fine, light-brown, with some weathered glauconite	200-210
Sand, fine, light-gray, with some weathered glauconite	210-220
Sand, as above, with less glauconite, and sparse amounts of mica	220-230
Silt, black, sparse amounts of mica	230-240
Silt, as above	240-250
Clay, black, silty	250-260

Appendix F. Palynological analyses of selected core samples from wells AA De 144, AA De 155, AA De 159, and AA De 200 (by Gilbert J. Brenner, State University of New York at New Paltz)

Well AA De 144
(Altitude of land surface: 85 feet)

Depth[1/]: 99 - 100.5 feet

Stage determination: Paleocene-Eocene
Stratigraphic correlation: Brightseat Formation-Nanjemoy Formation
Paleoecology: Marine

Diagnostic Palynomorphs	Range Atlantic Coastal Plain (ACP)	Frequency[2/]
Distephanus cf. speculum	Paleocene-Recent	O

Discussion:

The above species was the only microfossil that was found in this sample. D. speculum is a silicoflagellate that has been found by me in the Brightseat Formation in well QA-Db 80 and in the Nanjemoy Formation in well QA-Ea 79 on Kent Island, Maryland. The total biozone for this species ranges from Paleocene to Recent. It is not known from the Cretaceous.

Well AA De 155
(Altitude of land surface: 56 feet)

Depth[1/] : 71 - 72.5 feet

Stage determination: Paleocene
Stratigraphic correlation: Brightseat Formation
Paleoecology: Marine

Diagnostic Palynomorphs	Range ACP	Frequency[2/]
Castanea types	Paleocene-Recent	C
Momipites flexus	Paleocene	O
Momipites microfoveolatus	Paleocene-Eocene	O
Pinuspollenites sp.	Triassic-Recent	A
Triatriopollenites triangulatus	Paleocene-Eocene	R
Dinoflagellates		
Baltispaeridium nanum	Eocene	R
Danea californica	Paleocene	O

Discussion:

Danea californica (Drugg, 1976) had been described in the Brightseat Formation (Whitney, 1984). The common occurrence of small, prolate, smooth, and tricolporate castanea types is typical of the Paleocene to Lower Eocene in the Atlantic Coastal Plain.

Well AA De 159
(Altitude of land surface: 70 feet)

Depth[1/]: 98.5 - 100 feet

Stage determination: Paleocene
Stratigraphic correlation: Brightseat Formation
Paleoecology: Marine

Diagnostic Palynomorphs	Range ACP	Frequency[2/]
Betulaceapollenites sp.	Cretaceous-Recent	O
Pinuspollenites sp.	Triassic-Recent	A
Dinoflagellates		
Danea californica	Paleocene	O
Deflandrea pulchra	Paleocene	O
Fibrocysta bipolare	Paleocene	O

Discussion:

Dinoflagellates found in this sample have been reported from the Brightseat Formation (Whitney, 1984).

1/ Datum is land surface.

2/ R = Rare (less than 1 percent); O = Occasional (1-5 percent); C = Common (6-10 percent); A = Abundant (greater than 10 percent).

Well AA De 200
(Altitude of land surface: 42 feet)

Depth[1/]: 143 feet

Stage determination: Thanetian (Upper Paleocene)
Stratigraphic correlation: Aquia Formation
Paleoecology: Marine
Palynomorph Recovery: Poor

Diagnostic Palynomorphs	Range ACP	Frequency[2/]
Pollen and Spores		
Acanthotriletes sp. (Found previously at 93 ft in PG-Df 35)	Upper Paleocene, Aquia Formation	R
Caryapollenites sp. <29μm	Upper Paleocene-Lower Eocene	R
Momipites coryloides	Paleocene-Eocene	R
Reworked Potomac Group Spores		
Densoisporites sp.	Zones I - III	O
Taurocusporites reduncus	Zones I - III	C
Dinoflagellate Cysts		
Phelodinium magnificum - complex	Upper Paleocene, Aquia Formation	R

Discussion:

The presence of small, juglandaceous pollen under 29 micrometers in maximum diameter with the pores on one pole as in Caryapollenites sp. have been reported in Zone P4 (Upper Paleocene) in the Fort Union Formation of Wyoming (Nichols and Ott, 1978) and the Lower Sabinian (Thanetian, Upper Paleocene) of South Carolina (Frederiksen and Christopher, 1978). I have only seen the above-mentioned spore, Acanthotriles sp. in the Aquia Formation of well PG-Df 35 in a core at 93 feet. There are many degraded spores from the Potomac Group (Brenner, 1963) in this sample. These reworked spores have an amber color, which is of a higher thermal maturation grade than the Paleocene types. The dinoflagellate cyst P. magnificum has been previously reported from the Upper Paleocene of Virginia (Edwards, 1989).

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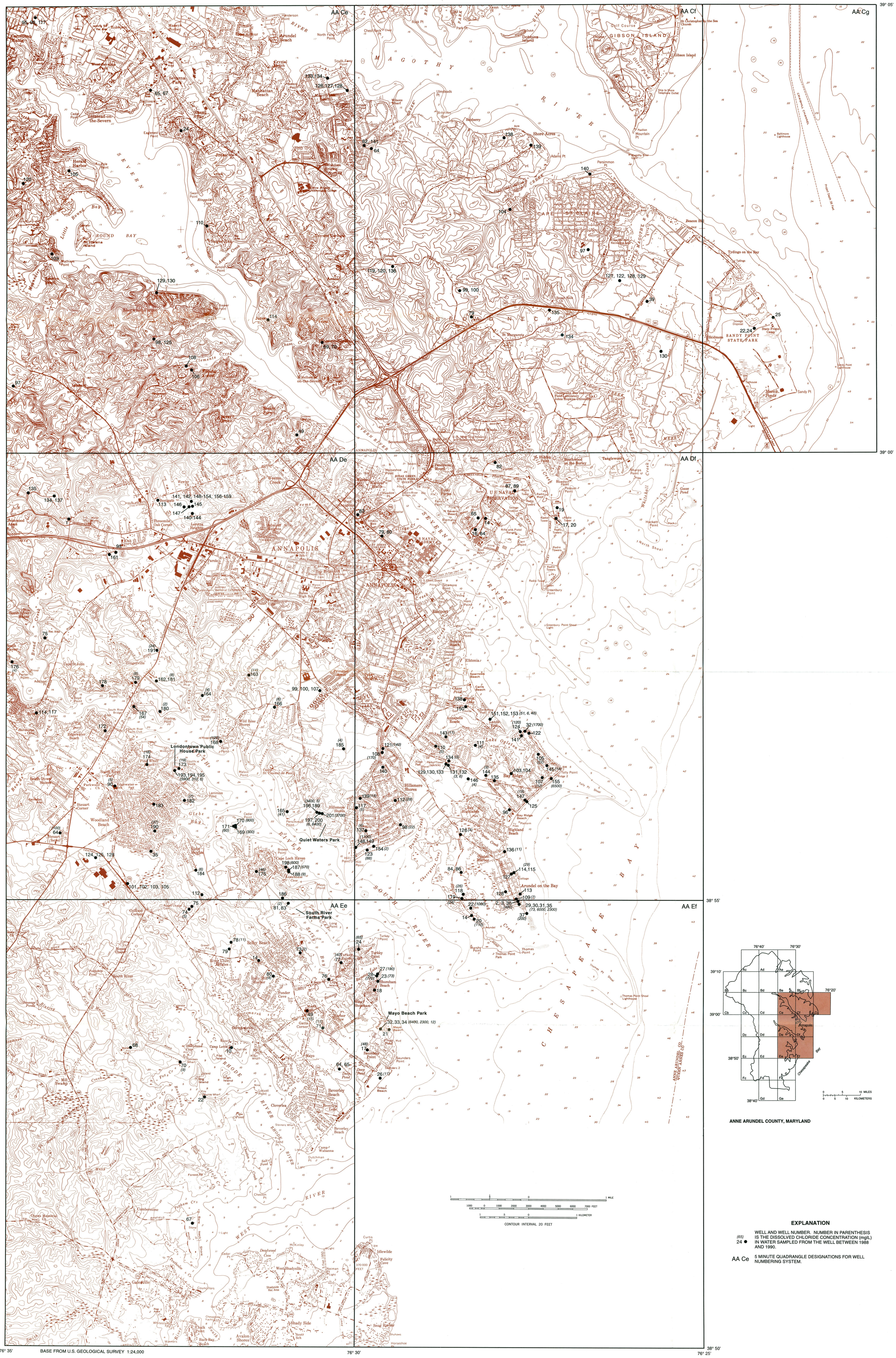


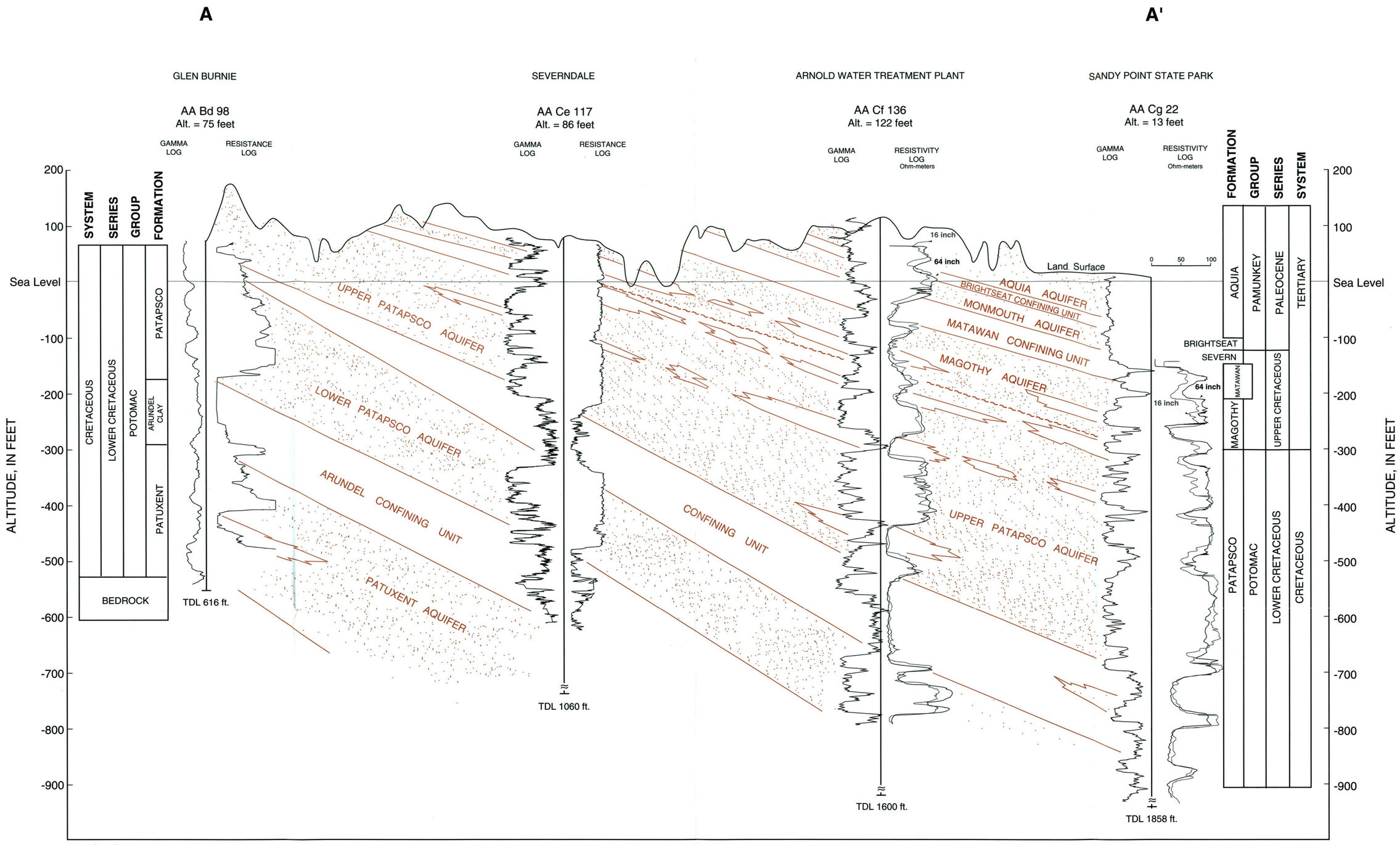
ANNE ARUNDEL COUNTY, MARYLAND

BASE FROM U.S. GEOLOGICAL SURVEY 1:24,000

EXPLANATION

(65) 24 ● WELL AND WELL NUMBER. NUMBER IN PARENTHESIS IS THE DISSOLVED CHLORIDE CONCENTRATION (mg/L) IN WATER SAMPLED FROM THE WELL BETWEEN 1988 AND 1990.

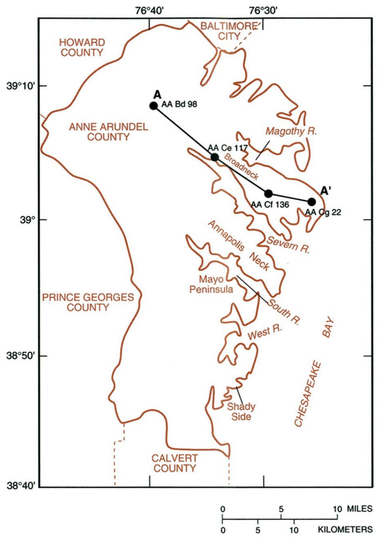
AA Ce 5 MINUTE QUADRANGLE DESIGNATIONS FOR WELL NUMBERING SYSTEM.



Vertical Scale Exaggerated x53.

(Geohydrology by David C. Andreasen, 1991)

0 1 2 MILES
0 1 2 3 KILOMETERS



EXPLANATION

AQUIFER - sand, sand and gravel, and silty sand

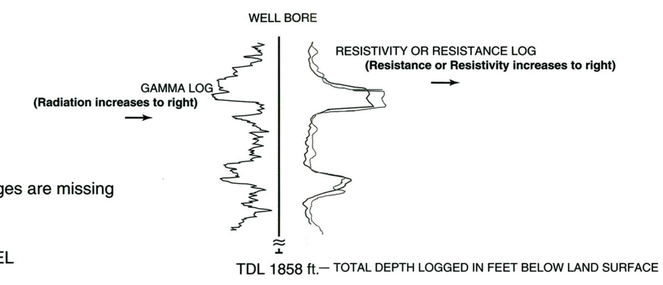
CONFINING UNIT - clay and silt

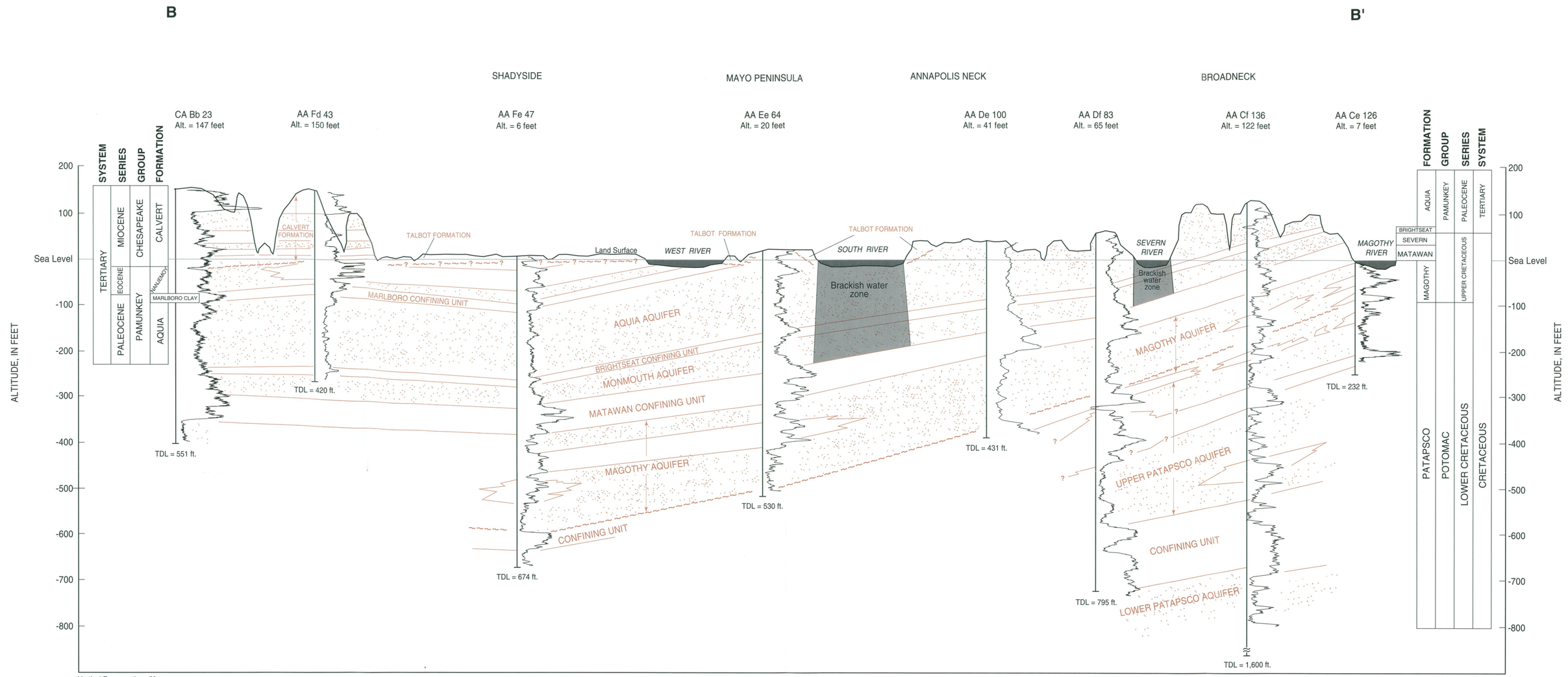
INFERRED LINE OF CORRELATION

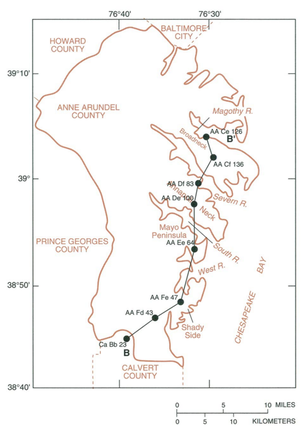
UNCONFORMITY - inferring that one or more stages are missing

AA Cf 136 — WELL NUMBER

Alt. = 122 feet — ALTITUDE OF WELL IN FEET ABOVE SEA LEVEL







EXPLANATION

AQUIFER - sand, sand and gravel, and silty sand

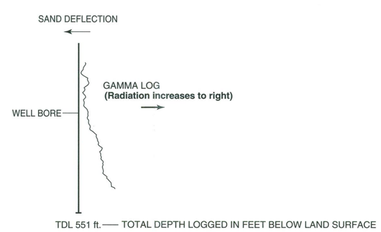
CONFINING UNIT - clay and silt

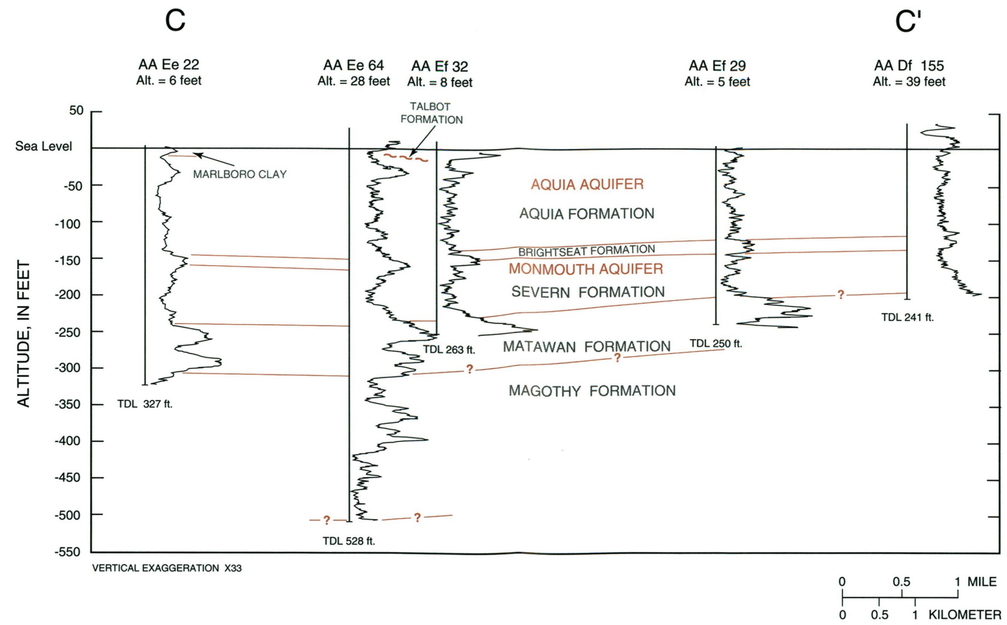
INFERRED LINE OF CORRELATION

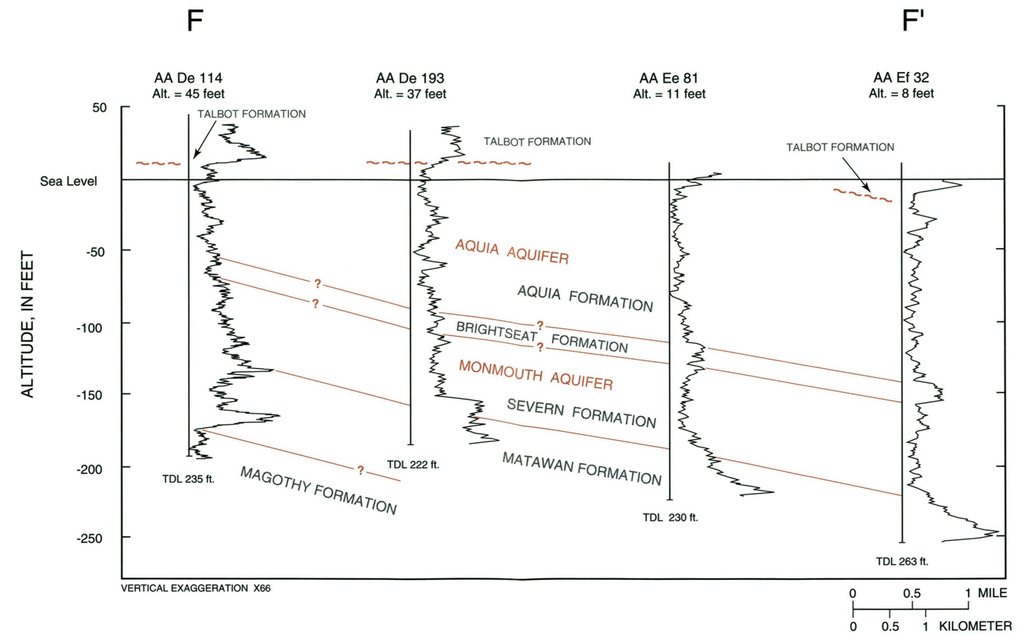
UNCONFORMITY - inferring that one or more stages are missing

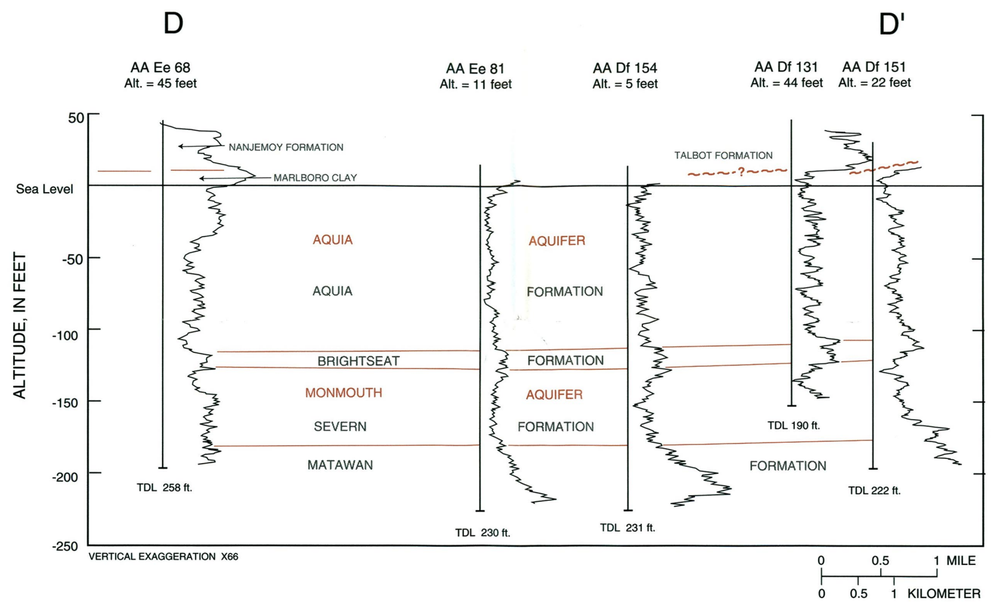
AA Cf 136 — WELL NUMBER

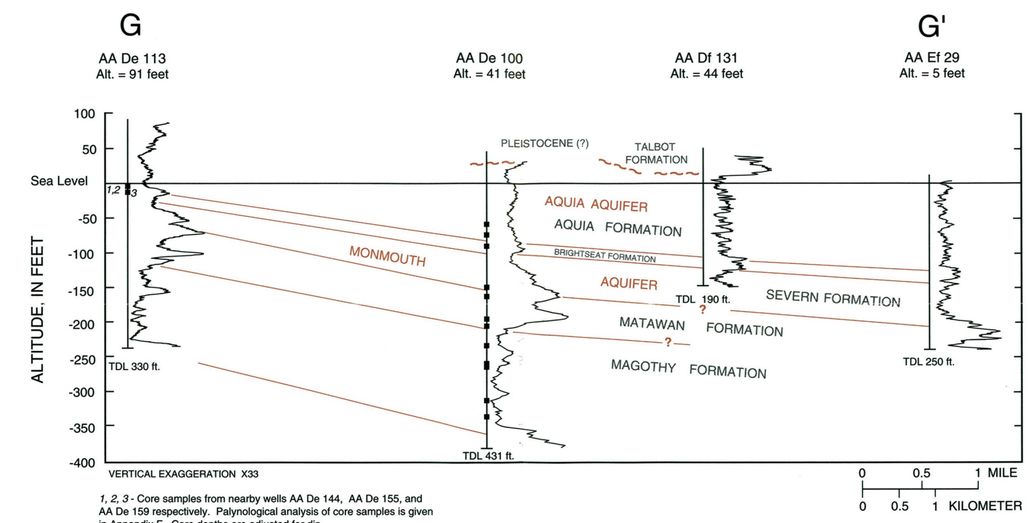
Alt. = 122 feet — ALTITUDE OF WELL IN FEET ABOVE SEA LEVEL





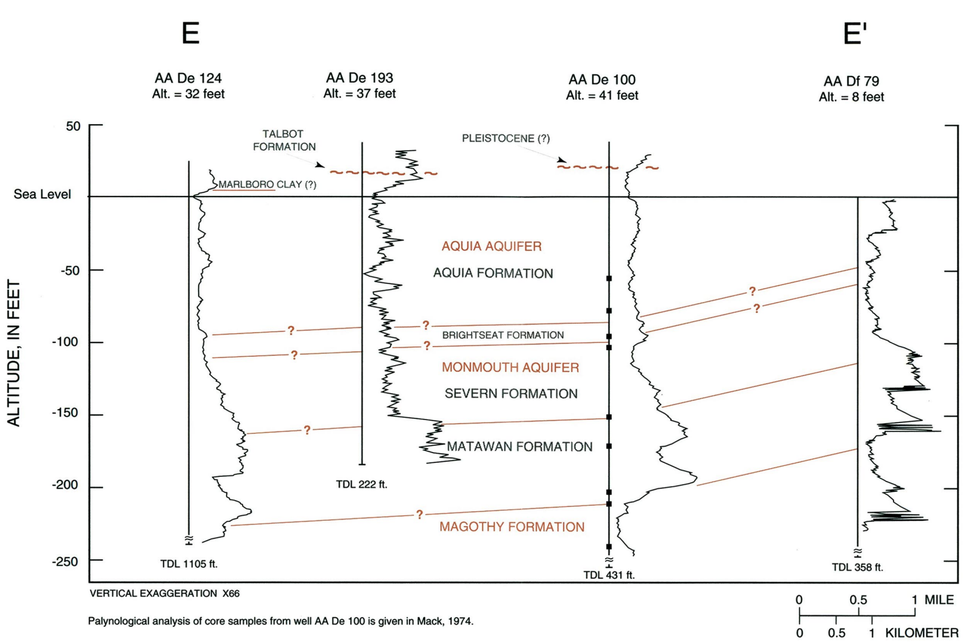






1, 2, 3 - Core samples from nearby wells AA De 144, AA De 155, and AA De 159 respectively. Palynological analysis of core samples is given in Appendix F. Core depths are adjusted for dip.

Palynological analysis of core samples from well AA De 100 is given in Mack, 1974.



Palynological analysis of core samples from well AA De 100 is given in Mack, 1974.

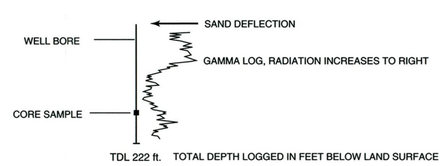
EXPLANATION

—?— INFERRED LINE OF CORRELATION, QUERIED WHERE UNCERTAIN.

~~~ UNCONFORMITY MARKING THE CONTACT BETWEEN TERTIARY AND QUATERNARY SEDIMENTS.

AA De 193 WELL NUMBER

Alt. = 37 feet ALTITUDE OF WELL IN FEET ABOVE SEA LEVEL



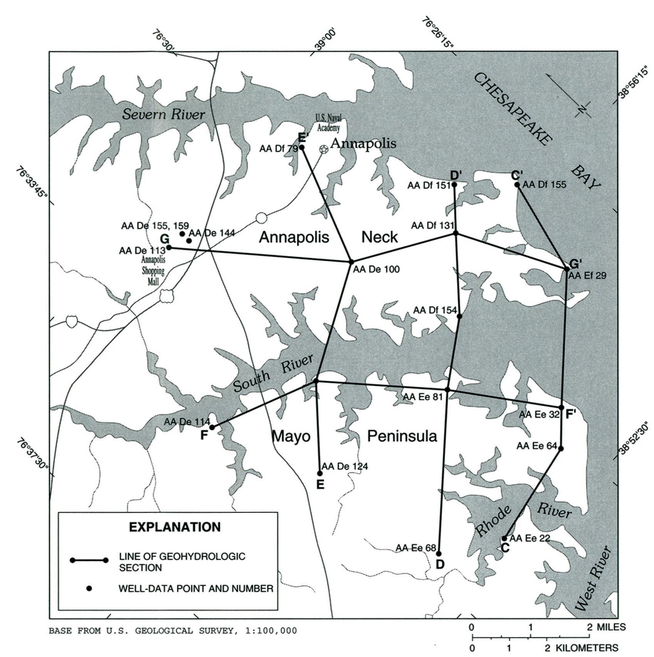

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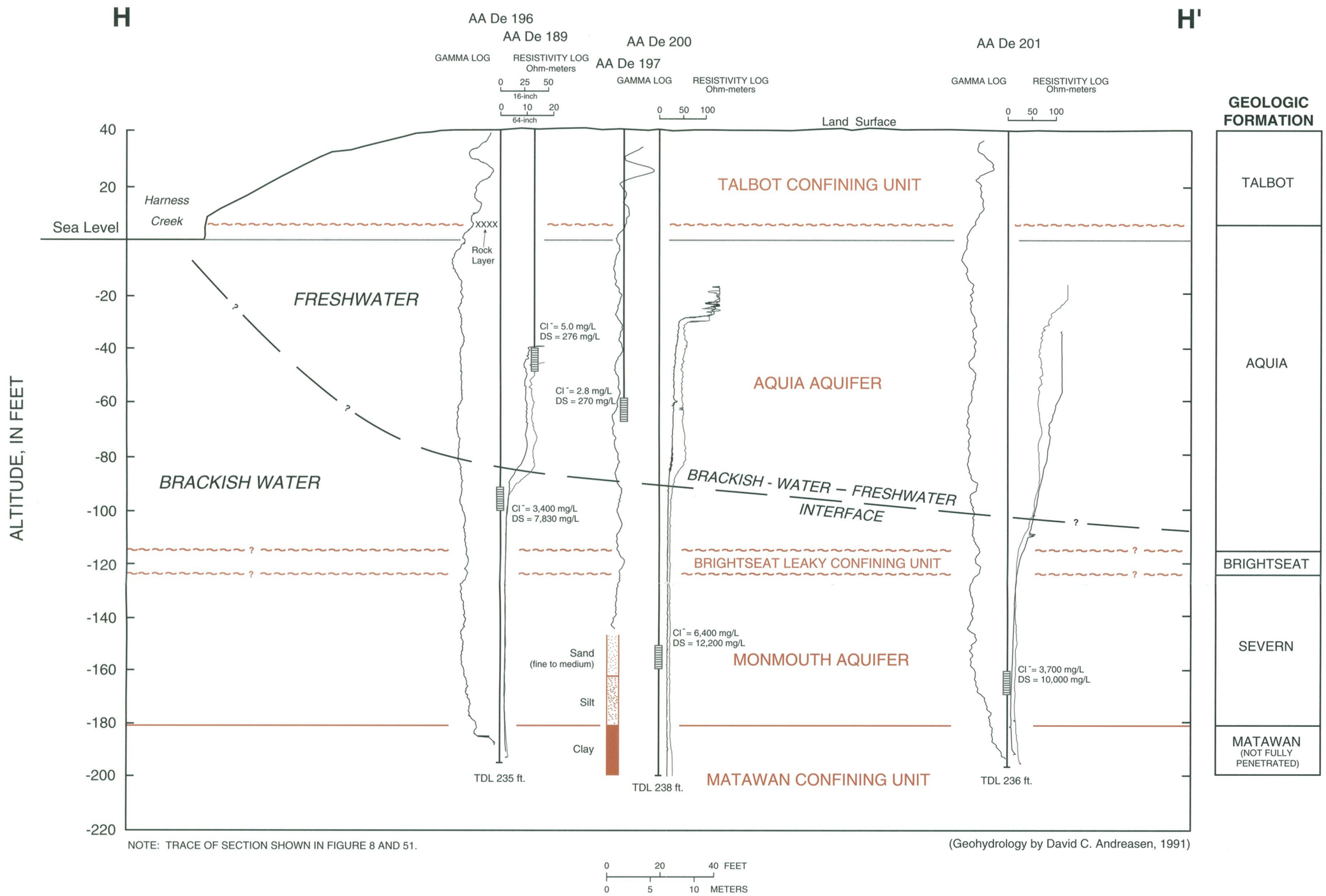
Plate 5.– Cross section of Quiet Waters Park showing geologic formations, geohydrologic units, location of wells, geophysical logs, and the interface of brackish water and freshwater in the Aquia and Monmouth aquifers, Anne Arundel County, Maryland.



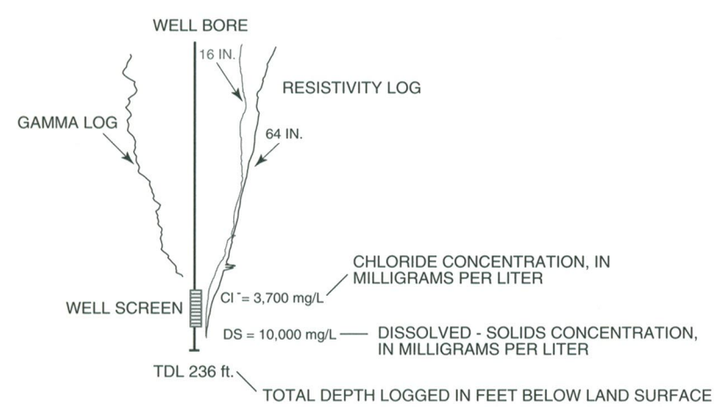
NOTE: TRACE OF SECTION SHOWN IN FIGURE 8 AND 51.

(Geohydrology by David C. Andreasen, 1991)

0 20 40 FEET
0 5 10 METERS

EXPLANATION

INFERRED LINE OF CORRELATION

UNCONFORMITY - Inferring that one or more stages are missing

AA De 201 WELL NUMBER