Department of Natural Resources
Resource Assessment Service
MARYLAND GEOLOGICAL SURVEY
Jeffrey P. Halka, Acting Director

REPORT OF INVESTIGATIONS NO. 77

OPTIMIZATION OF GROUND-WATER WITHDRAWALS IN ANNE ARUNDEL COUNTY, MARYLAND, FROM THE UPPER PATAPSCO, LOWER PATAPSCO, AND PATUXENT AQUIFERS PROJECTED THROUGH 2044

by

David C. Andreasen

Prepared in cooperation with the
Anne Arundel County Department of Public Works

2007

State of Maryland

Martin O’Malley
Governor

Anthony G. Brown
Lieutenant Governor

Maryland Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Resource Assessment Service
2300 St. Paul Street
Baltimore, Maryland 21218-5210
(410) 554-5500
TTY users call via the Maryland Relay
www.mgs.md.gov

Maryland Department of Natural Resources

John R. Griffin
Secretary

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KEY RESULTS

Withdrawals from public-supply wells operated by the Anne Arundel County Department of Public Works on average totaled approximately 26 million gallons per day in 2002. Of that amount 2.2, 17.2, and 6.2 million gallons per day were pumped from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively. The Anne Arundel County Department of Public Works operates five major well fields in those aquifers located in four pressure zones in the central and northern portions of the county. In response to pumping, water levels in Anne Arundel County have declined to as much as 90 feet below sea level. Currently there is adequate available drawdown to sustain the withdrawals. Average-day water demand, however, is projected to increase nearly three-fold to 73 million gallons per day by 2040, with an estimated maximum-day withdrawal of 140 million gallons per day. An increase of that magnitude could cause significant drawdown resulting in water levels falling below the regulatory management level in some areas, well operational problems, increased pumping costs, and reduced stream baseflow. To minimize the regional drawdown effect of the increased demand, withdrawals from Anne Arundel County's public-supply wells were optimized using a numerical, three-dimensional ground-water-flow model (MODFLOW code) constructed for this study in conjunction with an optimization algorithm (MODMAN and SuperLINDO codes) for the period 2005 to 2044. Water demands for Anne Arundel County's well fields were based on the 2003 *Comprehensive Water Strategic Plan* prepared by O'Brien and Gere. The simulation period was extended to 2044 in order to model the effects of the projected 2040 water demand. Additionally, the effects of projected maximum-day withdrawals were evaluated.

Optimized Withdrawals from Anne Arundel County Department of Public Works Supply Wells to Meet Projected 2040 Average-Day Demand of 73 Million Gallons Per Day (pgs. 56 to 69)

The projected average-day demand, optimized to reduce regional drawdown, could be withdrawn without causing water levels to fall below the management level near the well fields. However, the increased withdrawals resulted in relatively deep water levels that increased pumping lift, which would lead to greater energy costs. In addition, the increased withdrawals could eventually result in some reductions in baseflow to streams within the recharge (outcrop) areas of the pumped aquifers.

- Optimized average-day withdrawals increased by approximately 18, 21, and 9 million gallons per day from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively, by 2040.

- To meet demand, new well fields were modeled at Withernsea, Millersville, and Chesterfield with average-day supply capacities of 3.5, 12, and 8.2 million gallons per day and maximum-day supply capacities of 12, 20, and 15.6 million gallons per day by 2040, respectively. Additional wells would be required at the existing Broad Creek (five wells), Arnold (five wells), Severndale (one well), Dorsey Road (two wells), Crofton Meadows (four wells), and Ft. Meade (two wells) well fields.

- Available drawdown (or the difference between the pumping water level and the management level) in the Upper Patapsco aquifer near the Broad Creek, Withernsea, Arnold, Severndale, and Chesterfield well fields was reduced to 90, 301, 94, 20, and 56 feet, respectively, by 2044. Available drawdown in the Lower Patapsco aquifer near the Broad Creek, Withernsea, Arnold, Severndale, Millersville, Crofton Meadows, and Chesterfield well fields was reduced to 407, 680, 464, 164, 48, 160, and 259 feet, respectively, by 2044. Available drawdown in the Lower Patapsco aquifer at a location central to wells at Harundale, Crain Highway, Glendale, Quarterfield Road, Telegraph Road, and Stevenson Road was reduced to 40 feet by 2044. Available drawdown in the Patuxent aquifer near the Broad Creek, Arnold, Dorsey Road, Millersville, Crofton Meadows, Chesterfield, and Ft. Meade well fields was reduced to 768, 800, 198, 325, 512, 625, and 188 feet, respectively, by 2044. These numbers indicate the relative drawdown “buffer” remaining by 2044 before water levels would reach the management level.

- Simulated model-cell heads, adjusted to represent true heads immediately outside pumping wells, ranged from 29 to 227 feet below sea level in the Upper Patapsco aquifer, 107 to 203 feet below sea level in the Lower Patapsco aquifer, and 97 to 305 feet below sea level in the Patuxent aquifer, by 2044. The lowest water level (205 ft below sea level) occurred in the Dorsey Road well field. Depending on the efficiency of the well, water levels inside the pumping well would be even deeper. Based on the adjusted heads immediately outside pumping wells, pumping lift (or the distance required to pump water to the surface) ranged from 114 to 347 feet in the Upper Patapsco aquifer, 195 to 320 feet in the Lower Patapsco aquifer, and 226 to 373 feet in the Patuxent aquifer, by 2044. The greatest pumping lift occurred in the Dorsey Road well field at 373 feet. Again, depending on the efficiency of the well, pumping lift could be even greater. The greater lift heights would increase pumping costs. Careful well-field design could help to lessen the deep water levels by reducing the drawdown effects caused by well interference and inefficient wells.

- By 2044, simulated baseflow in Sawmill Creek in northern Anne Arundel County, North River in central Anne Arundel County, Northwest Branch of the Anacostia River at Riverdale in northern Prince George’s County, and Western Branch at Upper Marlboro in east-central Prince George’s County decreased on average approximately 6 percent from the simulated 2002 amounts as a result of the increased withdrawals. In response to a simulated 5-year drought occurring during the period of greatest withdrawals (2040 to 2044) with recharge reduced by 30 percent, simulated baseflow decreased on average approximately 22 percent from the simulated 2002 amounts in the four basins. While not of immediate concern, the reduction of baseflow might eventually affect stream and wetland ecology. Further research would be required to investigate the potential for baseflow reduction and its possible effects on stream ecosystems.

Effects of Projected 2040 Maximum-Day Withdrawals from Anne Arundel County Department of Public Works Supply Wells (pgs. 69 to 71)

While ground-water supply sustainability is more related to the response of the aquifer system to long-term withdrawals, the effects of short-term withdrawals are also important considerations especially as it pertains to well operations. Withdrawals during the day of maximum use—projected to increase to 140 million gallons per day by 2040—might cause significant drawdown resulting in isolated well-operational problems.

- Simulated model-cell heads resulting from maximum-day withdrawals in 2044 were as low as 165 feet below sea level in the Upper Patapsco aquifer at Chesterfield, 177 feet below sea level in the Lower Patapsco aquifer at Arnold, and 203 feet below sea level in the Patuxent aquifer at Dorsey Road.

- When simulated model-cell heads are adjusted to represent true heads immediately outside pumping wells, water levels were as low as 254 feet below sea level in the Upper Patapsco aquifer at Chesterfield, 242 feet below sea level in the Lower Patapsco aquifer at Millersville, and 437 feet below sea level in the Patuxent aquifer at Dorsey Road in 2044. The additional drawdown increased pumping lift to as much as

517 feet (Patuxent aquifer at Dorsey Road). The adjusted water levels fell below well screens in two Patuxent wells at Dorsey Road. To avoid this problem, withdrawals could be redistributed to other wells.

INTRODUCTION

BACKGROUND

Ground-water use in Anne Arundel County is primarily from the Aquia, Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers. Approximately 46 million gallons per day (Mgal/d) were withdrawn from these aquifers by major users—public, industrial, commercial, and agricultural use appropriated for greater than 10,000 gallons per day (gal/d)—in 2002. Of that amount, a total of 26 Mgal/d (or 56 percent) was pumped from the Upper and Lower Patapsco aquifers and Patuxent aquifer by public-supply wells operated by the Anne Arundel County Department of Public Works. The Anne Arundel County Department of Public Works does not withdraw water from the Magothy aquifer, but does operate an independent well field tapping the Aquia aquifer in southern Anne Arundel County at Rose Haven. The Anne Arundel County Department of Public Works operates five major well fields in the central and northern parts of the county at Arnold (Upper and Lower Patapsco aquifers), Broad Creek (Upper and Lower Patapsco aquifers), Crofton Meadows (Lower Patapsco and Patuxent aquifers), Dorsey Road (Patuxent aquifer) and Severndale (Lower Patapsco and Patuxent aquifers) (fig. 1; app. A). A production well completed in the Patuxent aquifer at Severndale is presently not being used because of excessive iron levels. The Anne Arundel County Department of Public Works also operates individual wells in the Lower Patapsco aquifer at Crain Highway, Glendale, Elvaton, Quarterfield Road, Telegraph Road, and Stevenson Road, in addition to a Lower Patapsco well field at Harundale (pl. 1), a Lower Patapsco well field at Herald Harbor, an Upper Patapsco well field at Gibson Island, and an Aquia well field at Rose Haven.

Pumpage from the well fields has caused significant cones-of-depression to develop at Arnold, Broad Creek, Crofton Meadows, and Severndale (Curtin and others, 2005a and 2005b). Temporal water-level trends in the Upper Patapsco, Lower Patapsco, and Patuxent aquifers are either flat or decline at rates of up to 1.5 feet per year (ft/yr) (Andreasen, 2005). Water levels measured in observation wells generally do not exceed 75 feet (ft) below sea level in any of the aquifers; however, pumping levels in production wells may be significantly deeper. The combination of relatively deep aquifers and shallow water levels results in substantial amounts of available drawdown, especially in the southern parts of the county where the Lower Patapsco and Patuxent aquifers are deepest. Average-day withdrawals from all Anne Arundel County Department of Public Works-operated well fields (not including Gibson Island, Herald Harbor, and Rose Haven) may increase to as much as 73 Mgal/d by 2040, with maximum-day withdrawals increasing to as much as 140 Mgal/d. Projected Ft. Meade (U.S. Army) water demands were included in the Anne Arundel County Department of Public Work's *Comprehensive Water Strategic Plan* (O'Brien and Gere, Inc., 2003). For the purposes of this study the withdrawals from existing and hypothetical wells screened in the Patuxent aquifer within the Ft. Meade well field were included as supplying part of Anne Arundel County's projected water demand. The projected average-day withdrawal rate (73 Mgal/d) could potentially cause water levels to exceed regulatory management levels at production well sites and near the outcrop areas. Previous estimates of the effect of increased production from the major aquifers underlying Anne Arundel County have been made utilizing numerical ground-water-flow models (Mack and Achmad, 1986; Achmad, 1991). Those models were developed based on the hydrogeologic data and water-use projections available at the time. However, revised water-use projections, refinements in the hydrogeology of the aquifer system, and advancements in modeling technology necessitated developing a new ground-water-flow model to reassess water-supply potential and effects on water levels from increased pumpage. In addition, an updated model can be used to develop optimum well withdrawal rates that minimize drawdown. The recharge capacity of the aquifers can also be evaluated, as well as potential effects on stream baseflow.

PURPOSE AND SCOPE

The purpose of this study is to determine the effects of projected (2040) withdrawals on water levels and recharge for the Upper Patapsco, Lower Patapsco, and Patuxent aquifers pumped for public supply by the Anne Arundel County Department of Public Works. In addition, optimum withdrawal rates from existing and hypothetical production wells were determined that minimize water-level decline (drawdown). By constructing and utilizing a numerical ground-water-flow model, this study optimized a pumping scenario provided by the Anne Arundel County Department of Public Works that projects water demands for the period 2005 to 2040. The study also estimated the increase in recharge from the aquifer outcrop area resulting from increased well production, and the possible effect that may have on stream baseflow. To adequately simulate the ground-water-flow system, the flow model also included the Magothy, Aquia and water-table aquifers.

Several smaller, independent well fields operated by the Anne Arundel County Department of Public Works (Herald Harbor, Gibson Island, and Rose Haven) were not included in the analysis.

LOCATION OF THE STUDY AREA

The study area includes the well fields of the Anne Arundel County Department of Public Works located in the central and northern portions of Anne Arundel County (fig. 1). The existing major well fields are Dorsey Road near Glen Burnie, Severndale at Severna Park, Arnold, Broad Creek near Annapolis, and Crofton Meadows at Crofton. To simulate ground-water flow in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers, a larger area was included in the ground-water-flow model. The model area includes Anne Arundel County and portions of Baltimore City and Baltimore, Calvert, Howard, Kent, Prince George’s, Queen Anne’s, and Talbot Counties.

PREVIOUS INVESTIGATIONS

The water-supply potential of the Potomac Group aquifers (Patapsco and Patuxent aquifers) in Anne Arundel County was previously investigated by Mack and Achmad (1986). Their study utilized a numerical ground-water-flow model to estimate the effects on water levels of projected withdrawals from the Potomac Group aquifers and the Magothy aquifer in Anne Arundel County and portions of surrounding counties by the Anne Arundel County Department of Public Works, other governmental agencies, and industry. Results of the study provided, in part, the technical basis for the strategic development of ground-water supplies by the Anne Arundel County Department of Public Works. Other important studies pertaining to either the hydrogeology or ground-water supply in Anne Arundel County include an analysis of brackish-water intrusion in the Aquia and Magothy aquifers in central Anne Arundel County (Fleck and Andreasen, 1996), hydraulic and water-quality characteristics of the Magothy, Patapsco, and Patuxent aquifers on Broadneck Peninsula (Mack and Andreasen, 1991), well-head protection areas for supply wells in the Glen Burnie area (Wilson and Achmad, 1995), surface water/ground-water interactions in northern Anne Arundel County (Achmad, 1991), and water-supply potential of the Aquia and Magothy aquifers in southern Anne Arundel County (Andreasen, 2002). Chapelle and Kean (1985) investigated the potential for the migration of brackish water in the Patuxent aquifer toward the Glen Burnie area. O’Brien and Gere, Inc. prepared a report entitled *Comprehensive Water Strategic Plan* (2003) that assessed future water demand requirements, well-field capacity, and capital improvements to distribution and treatment infrastructure. That plan provided a basis for the projected future well-field expansions used in this investigation. Water-level trends in the major aquifers in Anne Arundel County are compiled yearly by the Maryland Geological Survey from a network of observation wells maintained by the Maryland Geological Survey and U.S. Geological Survey (Andreasen, 2005). The potentiometric surfaces of the Magothy, Upper Patapsco, and Lower Patapsco aquifers (i.e., Curtin and others, 2005a, 2005b, and 2005c; Achmad and Hansen, 2001) and the Patuxent aquifer (Achmad and Hansen, 2001) have been mapped for various time periods for the Anne Arundel County–southern Maryland area.

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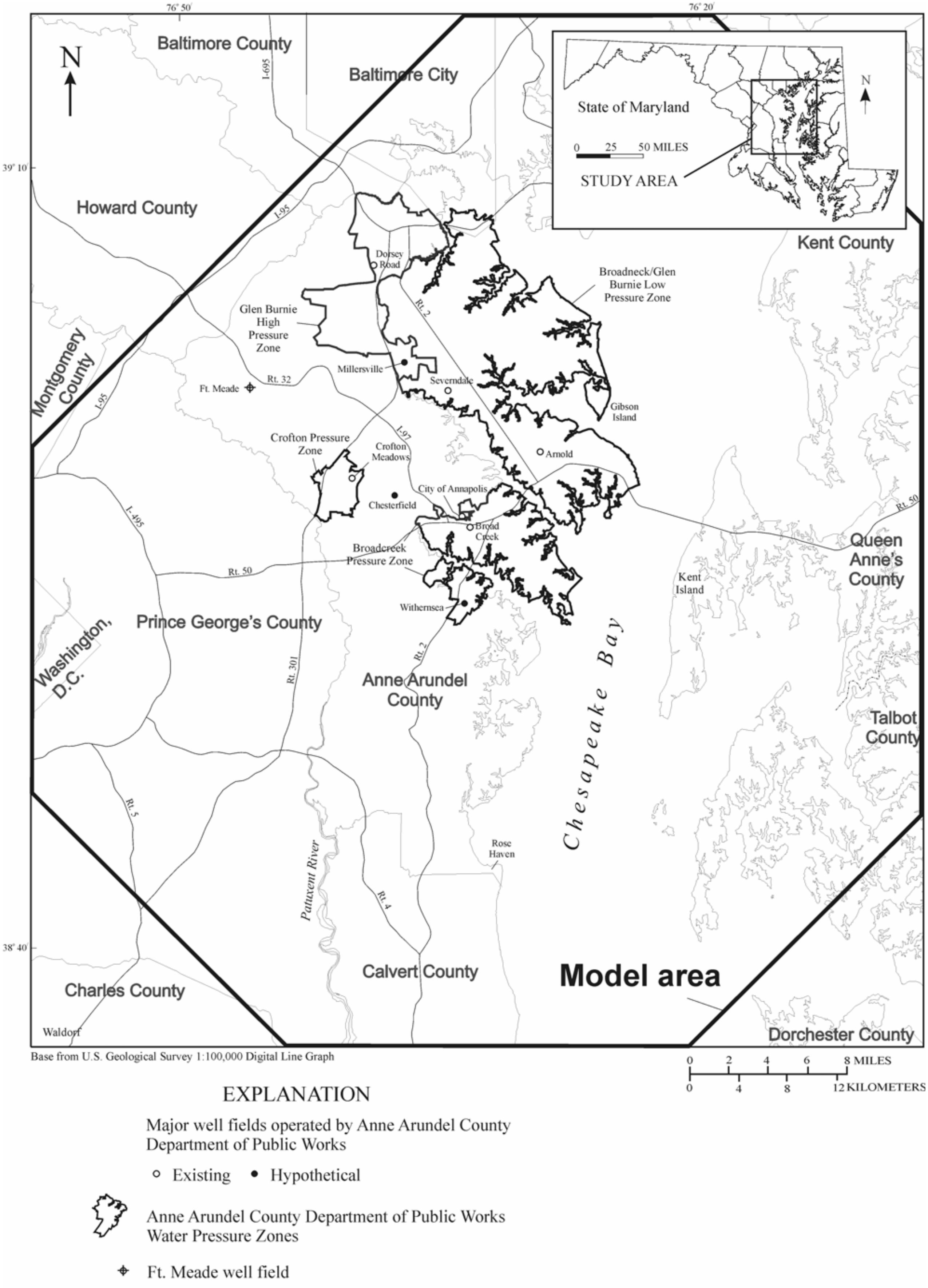


Figure 1. Location of the study area.

manuscript was typed, edited and formatted for publication by Donajean Appel, with additional editorial review by Claire Richardson, both of the Maryland Geological Survey.

HYDROGEOLOGY OF THE UPPER PATAPSCO, LOWER PATAPSCO, AND PATUXENT AQUIFERS IN ANNE ARUNDEL COUNTY

HYDROGEOLOGIC FRAMEWORK

Anne Arundel County is part of the mid-Atlantic Coastal Plain, which is comprised chiefly of unconsolidated deposits of gravel, sand, silt, and clay. The sediments are complexly stratified, forming a sequence of aquifers and confining beds that extend from Virginia to New Jersey (Leahy and Martin, 1993). In Anne Arundel County the Coastal Plain deposits range in thickness from a few tens of feet along its northwestern boundary with Howard County to as much as 2,500 ft at Rose Haven (Vroblesky and Fleck, 1991) (tab. 1). The Potomac Group of Lower Cretaceous age occurs at the base of the Coastal Plain and comprises over half of its total thickness. In Anne Arundel County the Potomac Group can be subdivided into the Patapsco Formation, Arundel Clay, and Patuxent Formation (Hansen, 1968; Glaser, 1969). Sandy strata comprising parts of these formations transmit water and form aquifers. In this report three Potomac Group aquifers (Upper Patapsco, Lower Patapsco, and Patuxent) are evaluated. The Patuxent aquifer, deepest of the Coastal Plain aquifers, is confined at its base by consolidated rock of suspected Triassic, Lower Paleozoic, and/or Precambrian age (Hansen and Edwards, 1986). The Arundel Clay separates the Patuxent and Lower Patapsco aquifers and is an effective confining bed. Clays within the Patapsco Formation divide it into an upper and lower aquifer. The Magothy aquifer overlies the Upper Patapsco aquifer. Although not a focus of this study, it is discussed because there is a direct hydraulic connection with the Upper Patapsco aquifer in part of the study area.

Sediment of the Potomac Group was deposited in a fluvio-deltaic environment by meandering or braided river systems (Glaser, 1969; Hansen, 1969). This form of deposition resulted in a complex array of lenticular and interfingering layers of gravel, sand, silt, and clay. Aquifers formed by these sediments consist of multiple sand and gravel layers interbedded with silt and clay. While correlation of individual sand layers based on lithologic or geophysical logs over even relatively short distances is difficult, the hydraulic connection of “sand systems” within each of the Potomac Group aquifers is established through the correlation of water-level fluctuations and well withdrawals (Achmad and Hansen, 2001; Curtin and others, 2005a and 2005b). Although not performed in this study, statistical analyses based on “percolation theory” suggest that overlapping sands in a three-dimensional aquifer layer become increasingly connected when net sand (and gravel) content reaches a threshold of 27.6 percent (King, 1990, p. 359) to 31.2 percent (Berkowitz and Balberg, 1993, p. 786).

Two hydrogeologic cross sections, A-A/ (fig. 2) and B-B/ (fig. 3), trending approximately along strike (perpendicular to the dip of the aquifers) and downdip (parallel to the dip of the aquifers), respectively, were prepared with a set of structure contour maps (fig. 4) to illustrate the altitude, thickness, and sand distribution characteristics of the aquifers and confining beds of the associated Potomac Group and Magothy Formation.

The Magothy aquifer, part of the Upper Cretaceous-age Magothy Formation, consists of light gray to white sand, interbedded with layers of black and gray lignitic clay. Pyrite is a common accessory mineral. Massive beds of well-sorted, coarse-grained sands characterize the Magothy aquifer. In the Annapolis area of Anne Arundel County, the Magothy aquifer consists predominantly of one continuous sand layer, whereas in southern Anne Arundel County two discrete sand layers are present (Andreasen, 2002). The Matawan Clay overlying the Magothy aquifer is an effective confining unit restricting flow between the Magothy and the shallower Aquia aquifer, although some inter-aquifer flow may occur with increased hydraulic gradient between these aquifers (Andreasen, 2002). The confining bed occurring between the Magothy and Upper Patapsco aquifers also is effective at restricting inter-aquifer flow. However, on Broadneck Peninsula, and perhaps elsewhere, the contact between the Magothy and Upper Patapsco aquifers is sand-on-sand, resulting in a direct hydraulic connection (Mack and Andreasen, 1991). In Anne Arundel County, the altitude of the top of the Magothy aquifer ranges from approximately 70 ft above sea level in central

Table 1. Stratigraphy and hydrologic and lithologic characteristics of geologic formations in Anne Arundel County

[modified from Mack and Achmad, 1986]

System	Series	Group	Formation		Thickness (feet)	Hydrologic character	General lithology
QUATERNARY	HOLOCENE and PLEISTOCENE		Alluvium and terrace deposits		30	Confining bed in most places. Poor aquifer in some places.	Sand, gravel, silt, and clay.
TERTIARY	EOCENE	PAMUNKEY	Nanjemoy		80	Confining bed	Sand, with clayey layers, glauconitic.
			Marlboro Clay		30	Confining bed	Clay, plastic, pale red to silvery gray.
	PALEOCENE		Aquia		100	Aquifer	Glauconitic, greenish to brown sand with indurated or “rock” layers in middle and basal parts.
			Brightseat		40	Confining bed in most places. Poor aquifer in some places.	Sand, silt, and clay, olive gray to black, glauconitic.
CRETACEOUS	UPPER CRETACEOUS		Severn		90	Poor aquifer in places.	Sand, silty to fine, with some glauconite.
			Matawan		30	Confining bed	Silt and fine sand, clayey, dark gray to black, glauconitic.
			Magothy		100	Aquifer	Sand, light gray to white, with interbedded thin layers of organic black clay.
	LOWER CRETACEOUS	POTOMAC	Patapsco	Upper	250	Confining bed	Clay, tough, variegated color; occasional sand layers.
						Aquifer	Sand, fine to medium, brown color interbedded with clay.
				Lower	250	Confining bed	Clay, tough, variegated color; occasional sand layers.
						Aquifer	Sand, fine to medium, brown color interbedded with clay.
			Arundel Clay		250 (?)	Confining bed	Clay, red, brown, and gray, contains some ironstone nodules and plant remains.
			Patuxent		250 (?)	Aquifer	Sand, gray and yellow, with interbedded clay; kaolinized feldspar and lignite common. Locally clay layers predominate.
TRIASSIC (?)[1]			“Red Beds”		Unknown	Confining bed	Consolidated red shale
LOWER PALEOZOIC (?) TO PRECAMBRIAN (?)			Basement Complex		Unknown	Confining bed	Probably gneiss, granite, gabbro, metagabbro, quartz diorite and granitized schist.

[1] Drilled in one well (AA Cg 22) at Sandy Point State Park.

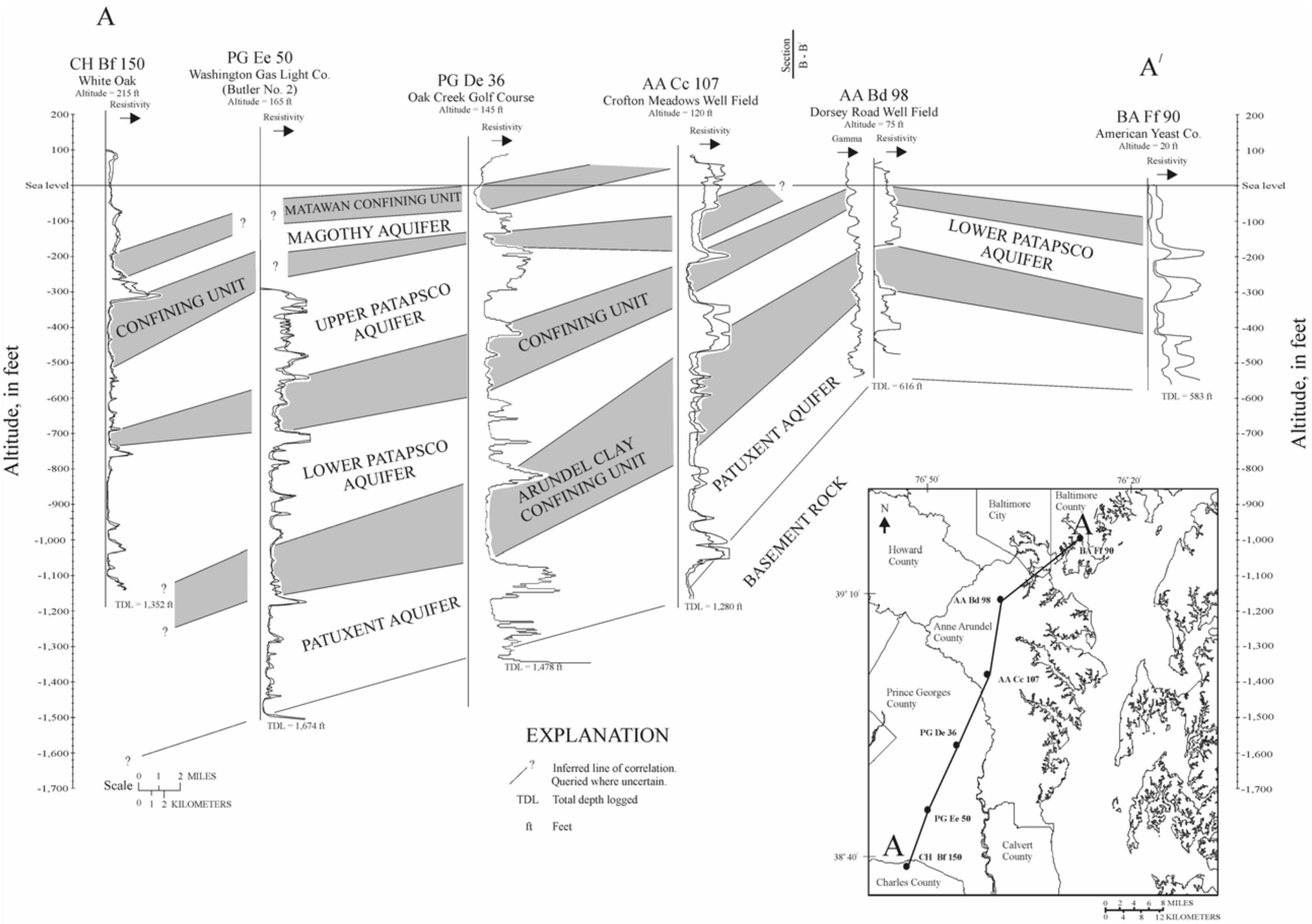


Figure 2. Hydrogeologic section A-A/ from northern Charles County to southeastern Baltimore County.

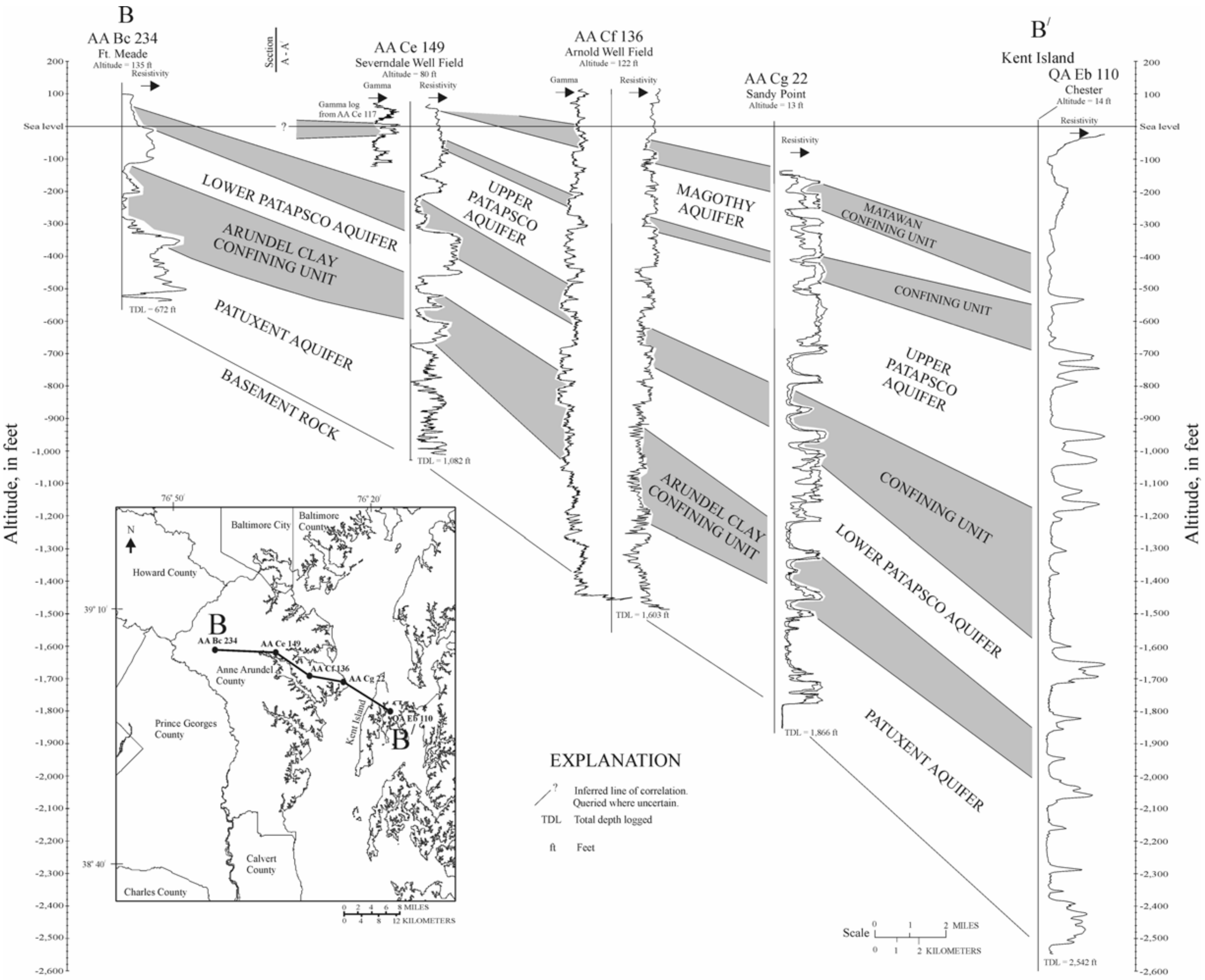


Figure 3. Hydrogeologic section B-B′ from Ft. Meade, Anne Arundel County, to Kent Island, Queen Anne's County.

Anne Arundel County to approximately 500 ft below sea level at Rose Haven (fig. 4). The aquifer dips to the southeast at approximately 30 feet per mile (ft/mi).

The Upper Patapsco aquifer, part of the Lower Cretaceous-age Patapsco Formation, is composed of fine- to coarse-grained, moderately iron-stained, gray, white, and red quartz with trace amounts of lignite and spherical sandstone grains (Mack and Andreasen, 1991). The sands are interbedded with tough gray, red, and mottled clays. The number and thickness of clay layers increase to the southeast and downdip (figs. 2 and 3). In Anne Arundel County, the altitude of the top of the Upper Patapsco aquifer ranges from approximately 40 ft above sea level in central Anne Arundel County to approximately 650 ft below sea level at Rose Haven (fig. 4). The aquifer dips to the southeast at approximately 40 ft/mi.

The lithologic character of the Lower Patapsco aquifer is similar to the Upper Patapsco aquifer. The number and thickness of clay layers increase to the southeast and downdip (figs. 2 and 3). In Anne Arundel County, the altitude of the top of the Lower Patapsco aquifer ranges from approximately 65 ft above sea level in north-central Anne Arundel County to approximately 1,300 ft below sea level at Rose Haven (fig. 4). The aquifer dips to the southeast at approximately 60 ft/mi.

The Patuxent aquifer, part of the Lower Cretaceous-age Patuxent Formation, consists of gray and yellow sand interbedded with dense reddish-brown and gray clay. The number and thickness of clay layers increase to the southeast (fig. 3). In Anne Arundel County, the altitude of the top of the Patuxent aquifer ranges from approximately sea level in north-central Anne Arundel County to approximately 1,750 ft below sea level at Rose Haven (fig. 4). The aquifer dips to the southeast at approximately 70 ft/mi.

HYDRAULIC PROPERTIES

Transmissivity is the measure of an aquifer's ability to transmit water—the higher the value, the better the ability to transmit water. Values from published reports and data on file at the Maryland Geological Survey were compiled and used to create maps of transmissivity distribution in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers (fig. 5). Included on the maps are contours of simulated transmissivity used in the ground-water-flow model discussed later in this report.

In the Magothy aquifer, a tract of high transmissivity occurs in the central part of Anne Arundel County (fig. 5). The tract, aligned along the dip of the Magothy Formation, ranges from 540 feet squared per day (ft^2/d) to 12,433 ft^2/d (fig. 5). The difference in transmissivity values may in part be a function of the portion of the aquifer that was screened. In some locations the upper part of the Magothy aquifer has a lower transmissivity than the lower part of the aquifer, where coarser sands typically occur. For example, the transmissivity value 12,433 ft^2/d was determined in a well screened in the lower portion of the aquifer, whereas the value 540 ft^2/d was determined in a well screened in the upper portion of the aquifer. Another factor that may affect transmissivity distribution is the local absence of a confining bed separating the Magothy and Upper Patapsco aquifers.

In Anne Arundel County calculated transmissivity values for the Upper Patapsco aquifer range from 2,406 ft^2/d to 16,068 ft^2/d (fig. 5). In part, the difference in transmissivity is a function of the variation in the horizontal hydraulic conductivity of the aquifer, which depends on sand-particle size and sorting. For instance, at the sites with values of 16,068 ft^2/d and 9,375 ft^2/d, the length of well screens (112 and 107 ft, respectively) and aquifer thickness (120 and 100 ft, respectively) are about the same. Therefore, the lower transmissivity is likely a result of a lower horizontal hydraulic conductivity of the sands. Transmissivity values at Anne Arundel County well fields range from 9,375 ft^2/d to 9,970 ft^2/d (tab. 2). No data were available for the Severndale well field.

Lower Patapsco transmissivity values in Anne Arundel County range from 2,264 ft^2/d to 10,214 ft^2/d (fig. 5). Transmissivity values at Anne Arundel County well fields range from 2,264 ft^2/d to 10,214 ft^2/d (tab. 2). No data were available for the Elvaton, Glendale, Meade Village, Phillip Drive, and Quarterfield Road well fields.

Transmissivity values of the Patuxent aquifer in Anne Arundel County range from 950 ft^2/d to 8,690 ft^2/d (fig. 5). Transmissivity values range from 1,410 ft^2/d to 8,690 ft^2/d (tab. 2) at Anne Arundel County well fields.

Storage coefficient is a measure of the ability of a water-bearing material (aquifer) to store water. It is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (Heath, 1983; p. 28). Storage coefficients of the Magothy,

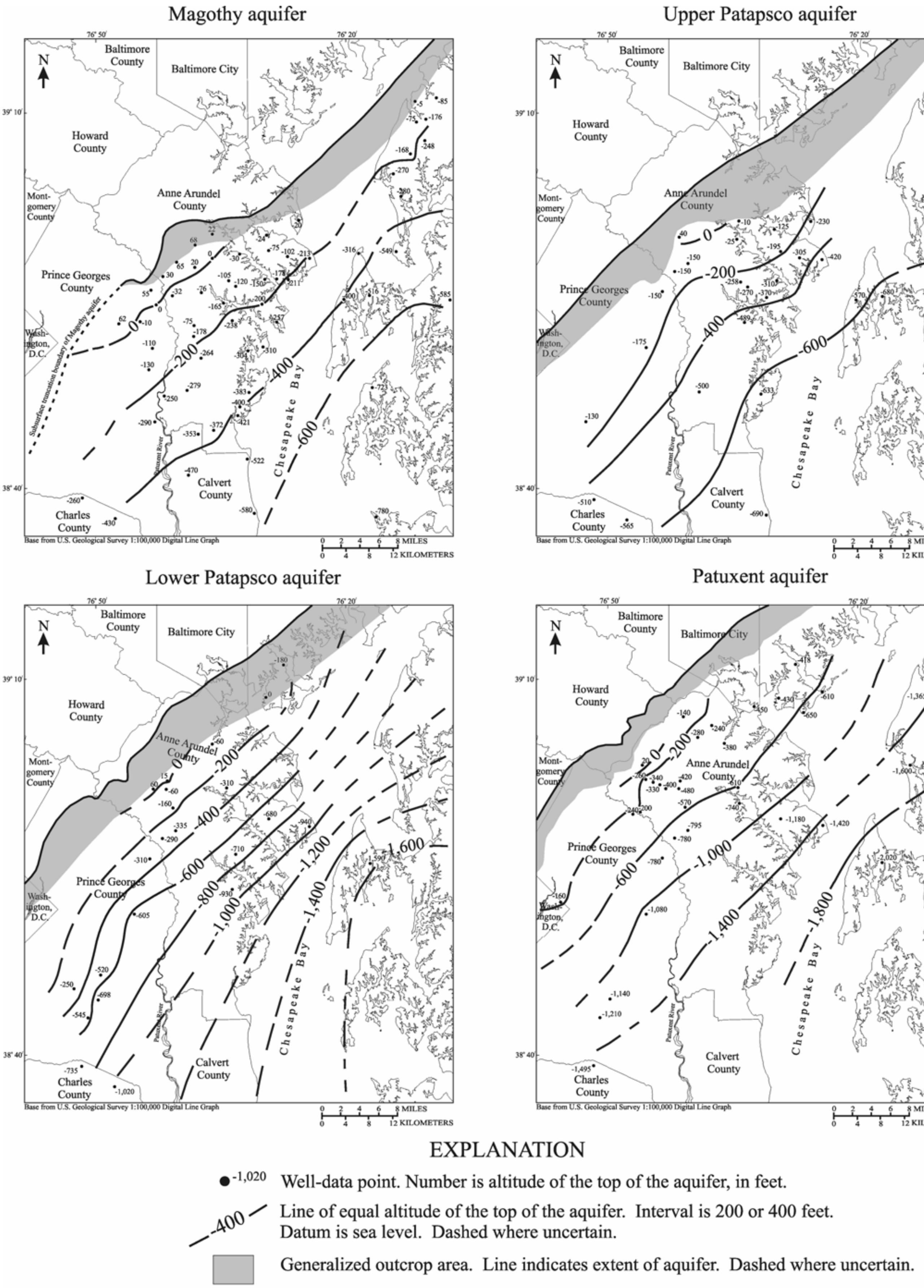
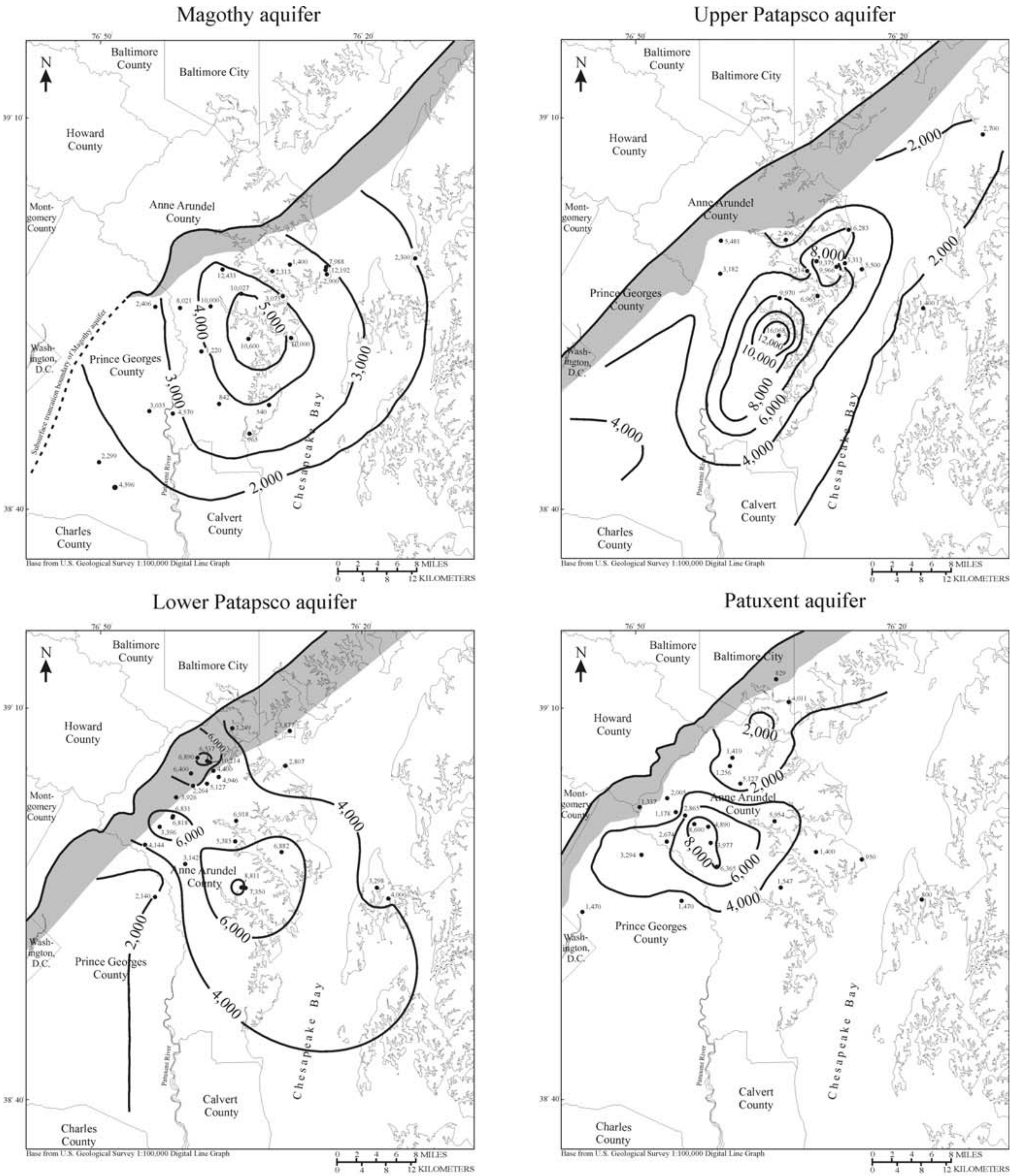


Figure 4. Altitude of the top of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers.


Magothy aquifer

Upper Patapsco aquifer

Lower Patapsco aquifer

Patuxent aquifer

EXPLANATION

- • 2,140 Calculated transmissivity, in feet squared per day.
- —2,000— Contour of simulated transmissivity, in feet squared per day. Contour interval is 1,000 or 2,000 feet squared per day.
- ▨ Generalized outcrop area. Line indicates extent of aquifer. Dashed where uncertain.

Figure 5. Calculated and simulated transmissivity of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers.

Table 2. Hydraulic properties of the Upper Patapsco, Lower Patapsco, and Patuxent aquifers at major well fields operated by Anne Arundel County

Well field	Transmissivity, feet squared per day	Specific capacity, gallons per minute per foot[1]
Upper Patapsco aquifer		
Amberly	9,966	11 to 16
Arnold	9,375	10.3 to 13.2
Broad Creek	9,970	8.6 to 17.6
Central Avenue[2]	16,068	25.4
Severndale	[3]	6.5
Lower Patapsco aquifer		
Arnold	6,882	13 to 27
Broad Creek	7,350 to 8,881	18 to 33
Crain Highway	5,127	10 to 15
Crofton Meadows	3,142	9 to 20
Elvaton	[3]	10
Glendale	[3]	6.5
Harundale	4,946	4.5 to 16
Kings Heights	3,396	5.5 to 9.1
Meade Village	[3]	6.6 to 8.8
Phillip Drive[4]	[3]	9.7
Quarterfield Road	[3]	8.4
Sawmill Creek[4]	6,537 to 10,214	3.6 to 8.6
Severndale	5,768 to 6,918	7 to 21
Stevenson Road	2,264	3.4
Telegraph Road	6,890	9.8
Patuxent aquifer		
Arnold	1,500	2.9
Broad Creek	3,140	3.6
Crofton Meadows	4,128 to 6,365	5.3 to 16
Dorsey Road	1,410 to 1,256	2.6 to 10
Ft. Meade[5]	1,178 to 4,890	8 to 24
Kings Heights[4]	8,690	4.7 to 19.6
Severndale	5,954	11

[1] Specific capacity is a measure of the hydraulic characteristics of the aquifer and the well.
[2] The Central Avenue well field was constructed and tested during the late 1970's, but not put into production.
[3] No data available.
[4] Taken out of production.
[5] Currently operated by the U.S. Army.

Patapsco (Upper and Lower units undifferentiated), and Patuxent aquifers in the study area range from 0.0001 to 0.0003, 0.00005 to 0.0003, and 0.0001 to 0.0007, respectively (Hansen, 1972).

Specific capacity of a well is a measure of both the hydraulic characteristics of the aquifer, or the portion of an aquifer in which the well is screened, and the design, construction, and development of the well itself. Specific capacity is typically measured as well yield (gallons per minute) per unit drawdown (feet). In general, larger diameter wells with longer screen intervals designed for high capacity supply tend to have higher specific capacity values. This is likely a result of proper well design and greater effort made toward developing well efficiency of the larger supply well. In the major well fields operated by the Anne Arundel County Department of Public Works specific capacity ranges from 2.6 to 33 gallons per minute per foot (gal/min/ft) (tab. 2). In the Upper Patapsco aquifer, specific capacity ranges from 6.5 gal/min/ft at Severndale to 25.4 gal/min/ft at Central Avenue. The Central Avenue well field was constructed and tested during the late 1970's, but was not put into production. In the Lower Patapsco aquifer, specific capacity ranges from 3.4 gal/min/ft at Stevenson Road to as high as 33 gal/min/ft at Broad Creek. In the Patuxent aquifer, specific capacity ranges between 2.6 and 10 gal/min/ft at Dorsey Road to as high as 19.6 gal/min/ft at Kings Heights.

GROUND-WATER WITHDRAWALS

Combined ground-water withdrawals from the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers in the entire model area have increased from approximately 2 Mgal/d between 1900 and 1920 to 46 Mgal/d in 2002 (fig. 6). These figures reflect withdrawals from users appropriated for more than 10,000 gal/d. Records for the periods 1900-1970 and 1970-2002 show 10-year and 1-year averages, respectively (Wheeler and Wilde, 1989; Judith Wheeler, U.S. Geological Survey, personal communication, 2004) (app. B). Prior to about 1930, most of the major ground-water withdrawals were from the Upper Patapsco aquifer at the U.S. Naval Academy in Annapolis and from the Patuxent aquifer at the Bethlehem Steel plant in Baltimore County (app. B). Beginning in about 1930 water was withdrawn from all four aquifers as municipal, institutional, and industrial well fields were developed. Anne Arundel County started its first major public-water supply with the construction of the Sawmill Creek well field in Glen Burnie (Mack and Achmad, 1986). During the next three decades, from 1930 to 1960, ground-water withdrawals were dominated by water use from the Patuxent aquifer, attributed mainly to withdrawals at the Bethlehem Steel plant and other industrial users in Baltimore County and Baltimore City (app. B). Within this period the City of Annapolis constructed a well field in the Magothy aquifer, and Anne Arundel County developed well fields in the Upper Patapsco, Lower Patapsco, and Patuxent aquifers at Dorsey Road, Gibson Island, Harundale, Kings Heights, Maryland City, Meade Village, Phillip Drive, and Severna Park (Mack and Achmad, 1986). With the exception of a Magothy well field constructed in 1959 at Pines-on-the Severn, the Anne Arundel County Department of Public Works has never operated a major well field in that aquifer. Between 1960 and 1969 Anne Arundel County added well fields at Broad Creek, Crain Highway, Crofton, Crofton Meadows, Elvaton, Glendale, and Herald Harbor. During the period 1970 to 2002, withdrawals from the Magothy and Upper Patapsco aquifers within the model area, while fluctuating, show a relatively stable trend. Withdrawals from the Lower Patapsco and Patuxent aquifers over the same period, however, increased significantly. By 2002 about 53 and 30 percent of the total amount of water pumped by major users in the study area was attributed to the Lower Patapsco and Patuxent aquifers, respectively. Between 1970 and 2002 Anne Arundel County added well fields at Amberly, Arnold, Quarterfield Road, Telegraph Road, Thelma Avenue, Severndale, and Stevenson Road (Mack and Achmad, 1986). In 2002, the major well fields operated by the Anne Arundel County Department of Public Works pumped on an average-daily basis a total of approximately 26 Mgal/d, of which 2.2, 17.2, and 6.2 Mgal/d were withdrawn from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively (fig. 7; tab. 3). Withdrawals from all other major users in Anne Arundel County totaled 9.4 Mgal/d (average day) in 2002, with the City of Annapolis pumping the greatest amount (2.4 Mgal/d from the Magothy and 2 Mgal/d from the Lower Patapsco aquifer) (tab. 3). Water withdrawn by users appropriated for greater than 10,000 gal/d in other counties within the model area totaled 1.3, 0.2, 1.6, and 7.7 Mgal/d from the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively, in 2002 (tab. 3). These figures exclude Howard and Talbot Counties where little or no water

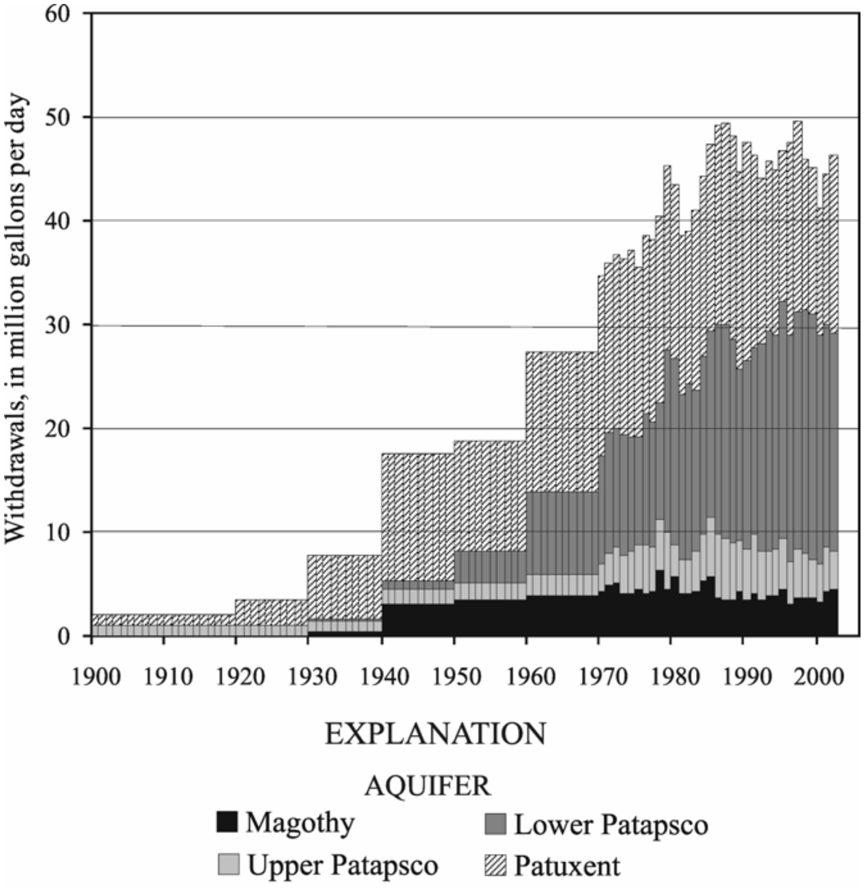


Figure 6. Withdrawals by users pumping greater than 10,000 gallons per day in the model area.

Table 3. Average-day withdrawal rates within the model area in 2002

User or supplier	Average-daily withdrawal rates by aquifer, million gallons per day				
	Magothy	Upper Patapsco	Lower Patapsco	Patuxent	Total
I. Anne Arundel County:					
Department of Public Works[1]	0	2.2	17.2	6.2	25.6
City of Annapolis	2.4	0	2.0	0	4.4
Other users in Anne Arundel County	0.7	1.04	0.43	2.8	4.97
II. Counties other than Anne Arundel County[2] (includes Baltimore City)	1.3	0.2	1.6	7.7	10.8
Total for model area	4.4	3.44	21.2	16.7	45.8

[1] Does not include Rose Haven.

[2] Includes Baltimore, Calvert, Kent, Prince George’s, and Queen Anne’s Counties.

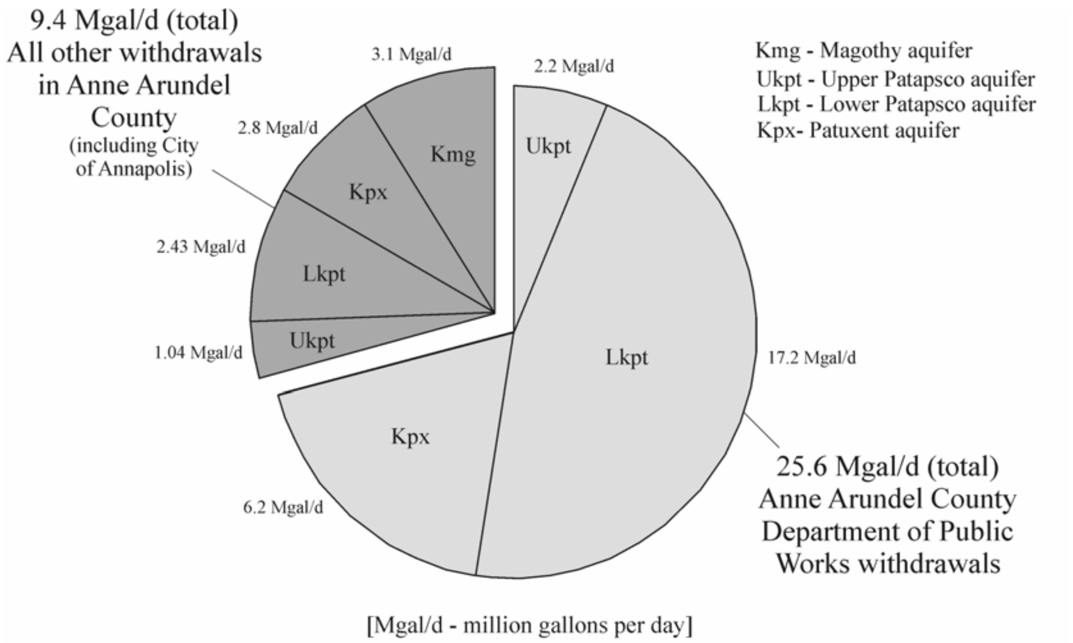


Figure 7. Average-day withdrawals from users that have an appropriated water use greater than 10,000 gallons per day in Anne Arundel County, by aquifer, in 2002.

is withdrawn from the four aquifers within the model area. The location of production wells or well fields supplying water to users pumping greater than 10,000 gal/d from the Magothy, Upper Patapsco, Lower Patapsco and Patuxent aquifers in 2002 are shown in figures 8 through 11.

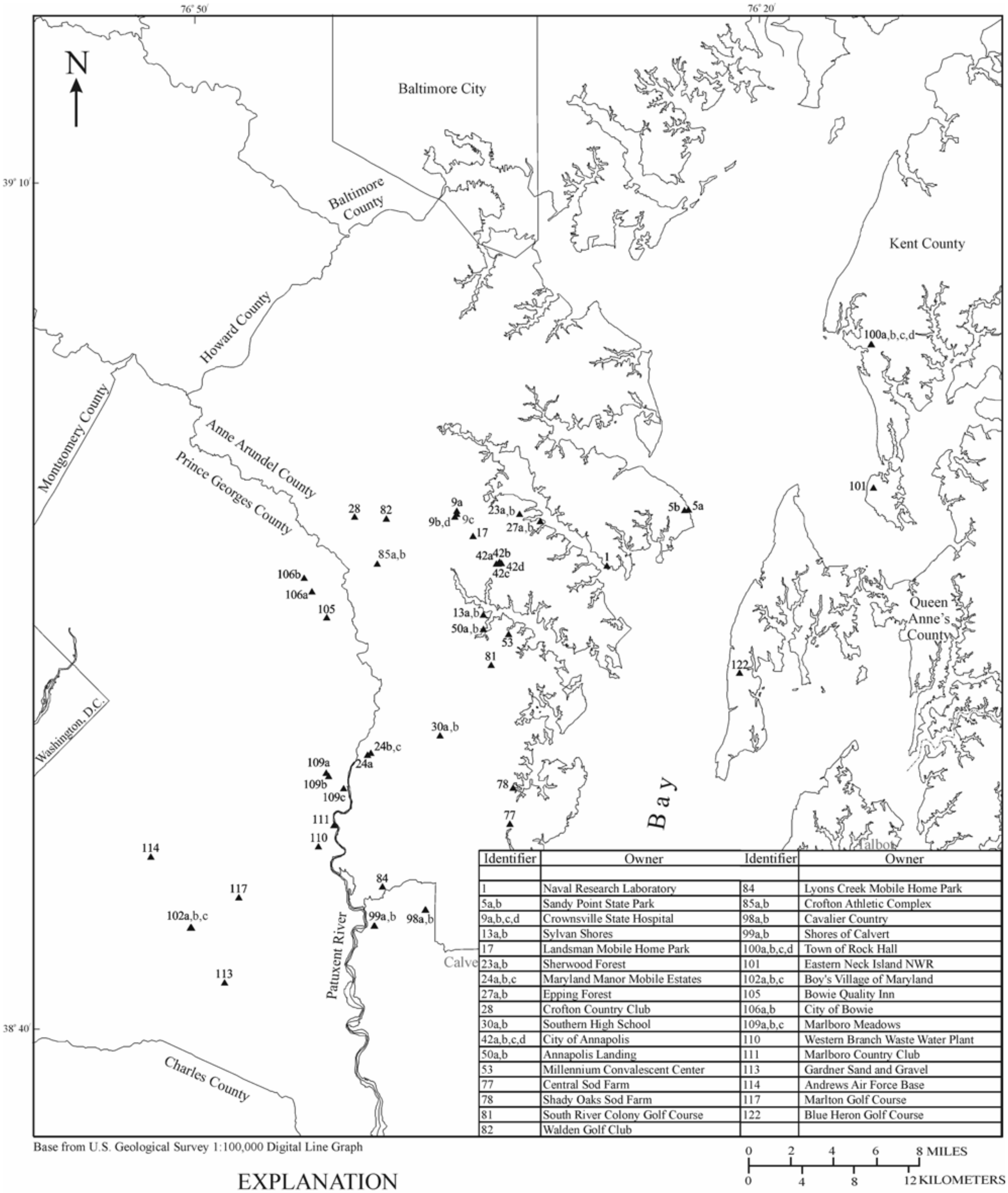
In 2000, an estimated 2.7 Mgal/d were withdrawn by individual, domestic wells screened in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers. This rate was estimated by multiplying a population of 127,000 not served by public water in 2000 (Judith Wheeler, U.S. Geological Survey, personal communication, 2004) by a per capita water-use rate of 80 gal/d, and subtracting the domestic withdrawals from the Aquia aquifer in southern Anne Arundel County and Annapolis Neck (Andreasen, 2002). Typically, the shallow portions of those aquifers are utilized for domestic supply, and therefore, are not affected by the deeper public-supply wells.

WATER-LEVEL TRENDS AND AVAILABLE DRAWDOWN

Water levels in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers have all responded to generally increased withdrawals that have occurred in these aquifers since the start of development in the early 1900’s. For the most part, water levels have declined from pre-development highs in each of the aquifers. Figures 12 through 17 show selected hydrographs and pumpage trends (average-day withdrawals) from some of the major well fields in Anne Arundel County. The hydrographs were constructed using intermittent water-level measurements, which may include low values caused by short-term withdrawals from nearby production wells.

The Magothy aquifer is pumped at its highest rate in Anne Arundel County at the City of Annapolis well field (approximately 2.4 Mgal/d in 2002). Water levels in the Magothy aquifer at the City of Annapolis well field, while responding to the short-term cycling of nearby production wells, show very little downward trend (fig. 12). This is, in part, a result of the proximity of the well field to the recharge area of the aquifer and to a general reduction of withdrawals by the city. Withdrawals from the Magothy aquifer decreased as more water was pumped from Lower Patapsco wells operated by the City of Annapolis. Water levels in observation well AA De 1 fluctuated between approximately 4 ft above sea level to 40 ft below sea level during the period 1969-2004.

Water levels in the Upper Patapsco aquifer in Anne Arundel County declined from approximately sea level to 35 ft below sea level at Arnold between



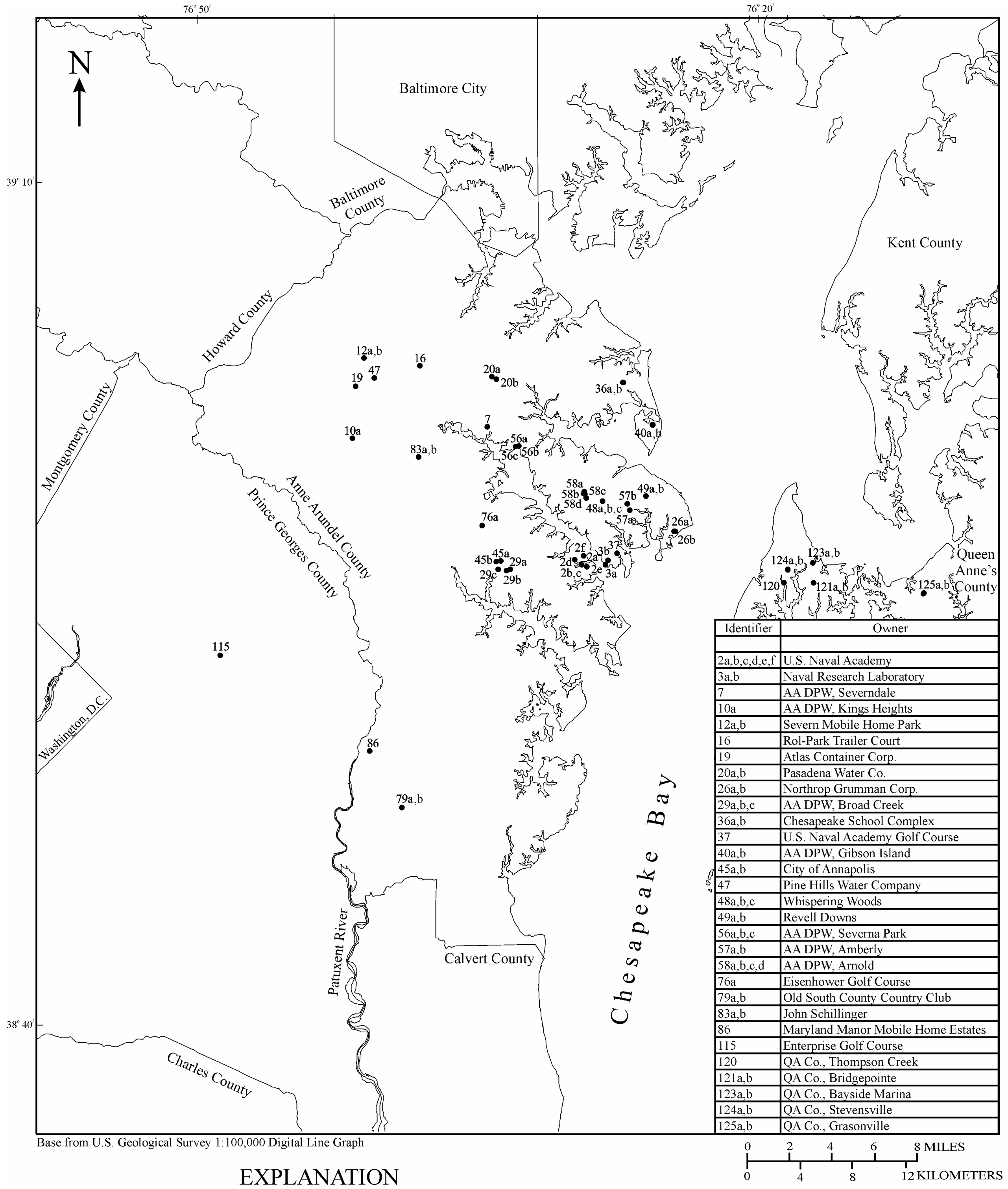
Identifier	Owner	Identifier	Owner
1	Naval Research Laboratory	84	Lyons Creek Mobile Home Park
5a,b	Sandy Point State Park	85a,b	Crofton Athletic Complex
9a,b,c,d	Crownsville State Hospital	98a,b	Cavalier Country
13a,b	Sylvan Shores	99a,b	Shores of Calvert
17	Landsman Mobile Home Park	100a,b,c,d	Town of Rock Hall
23a,b	Sherwood Forest	101	Eastern Neck Island NWR
24a,b,c	Maryland Manor Mobile Estates	102a,b,c	Boy's Village of Maryland
27a,b	Epping Forest	105	Bowie Quality Inn
28	Crofton Country Club	106a,b	City of Bowie
30a,b	Southern High School	109a,b,c	Marlboro Meadows
42a,b,c,d	City of Annapolis	110	Western Branch Waste Water Plant
50a,b	Annapolis Landing	111	Marlboro Country Club
53	Millennium Convalescent Center	113	Gardner Sand and Gravel
77	Central Sod Farm	114	Andrews Air Force Base
78	Shady Oaks Sod Farm	117	Marlton Golf Course
81	South River Colony Golf Course	122	Blue Heron Golf Course
82	Walden Golf Club		

Base from U.S. Geological Survey 1:100,000 Digital Line Graph

EXPLANATION

113 ▲ Production well screened in the Magothy aquifer. Number next to symbol is the identifier (see app. B).

Figure 8. Location of production wells or well fields in the Magothy aquifer supplying water to users pumping greater than 10,000 gallons per day.



Identifier	Owner
2a,b,c,d,e,f	U.S. Naval Academy
3a,b	Naval Research Laboratory
7	AA DPW, Severndale
10a	AA DPW, Kings Heights
12a,b	Severn Mobile Home Park
16	Rol-Park Trailer Court
19	Atlas Container Corp.
20a,b	Pasadena Water Co.
26a,b	Northrop Grumman Corp.
29a,b,c	AA DPW, Broad Creek
36a,b	Chesapeake School Complex
37	U.S. Naval Academy Golf Course
40a,b	AA DPW, Gibson Island
45a,b	City of Annapolis
47	Pine Hills Water Company
48a,b,c	Whispering Woods
49a,b	Revell Downs
56a,b,c	AA DPW, Severna Park
57a,b	AA DPW, Amberly
58a,b,c,d	AA DPW, Arnold
76a	Eisenhower Golf Course
79a,b	Old South County Country Club
83a,b	John Schillinger
86	Maryland Manor Mobile Home Estates
115	Enterprise Golf Course
120	QA Co., Thompson Creek
121a,b	QA Co., Bridgepointe
123a,b	QA Co., Bayside Marina
124a,b	QA Co., Stevensville
125a,b	QA Co., Grasonville

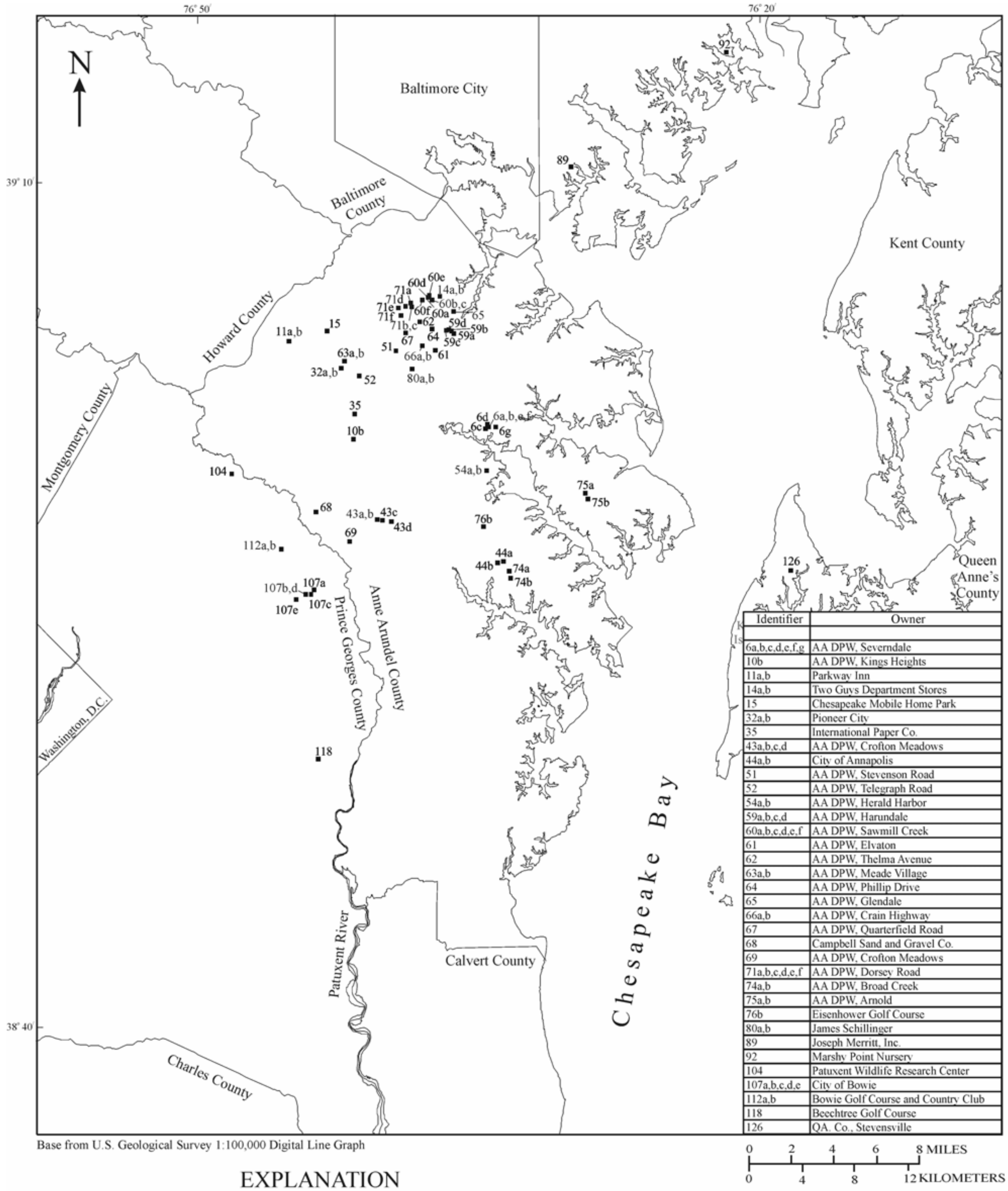
Base from U.S. Geological Survey 1:100,000 Digital Line Graph

EXPLANATION

●86 Production well screened in the Upper Patapsco aquifer. Number next to symbol is the identifier (see app. B).

AA DPW, Anne Arundel County Department of Public Works
QA Co., Queen Anne's County

Figure 9. Location of production wells or well fields in the Upper Patapsco aquifer supplying water to users pumping greater than 10,000 gallons per day.



Identifier	Owner
6a,b,c,d,e,f,g	AA DPW, Severndale
10b	AA DPW, Kings Heights
11a,b	Parkway Inn
14a,b	Two Guys Department Stores
15	Chesapeake Mobile Home Park
32a,b	Pioneer City
35	International Paper Co.
43a,b,c,d	AA DPW, Crofton Meadows
44a,b	City of Annapolis
51	AA DPW, Stevenson Road
52	AA DPW, Telegraph Road
54a,b	AA DPW, Herald Harbor
59a,b,c,d	AA DPW, Harundale
60a,b,c,d,e,f	AA DPW, Sawmill Creek
61	AA DPW, Elvaton
62	AA DPW, Thelma Avenue
63a,b	AA DPW, Meade Village
64	AA DPW, Phillip Drive
65	AA DPW, Glendale
66a,b	AA DPW, Crain Highway
67	AA DPW, Quarterfield Road
68	Campbell Sand and Gravel Co.
69	AA DPW, Crofton Meadows
71a,b,c,d,e,f	AA DPW, Dorsey Road
74a,b	AA DPW, Broad Creek
75a,b	AA DPW, Arnold
76b	Eisenhower Golf Course
80a,b	James Schillinger
89	Joseph Merritt, Inc.
92	Marshy Point Nursery
104	Patuxent Wildlife Research Center
107a,b,c,d,e	City of Bowie
112a,b	Bowie Golf Course and Country Club
118	Beechtree Golf Course
126	QA. Co., Stevensville

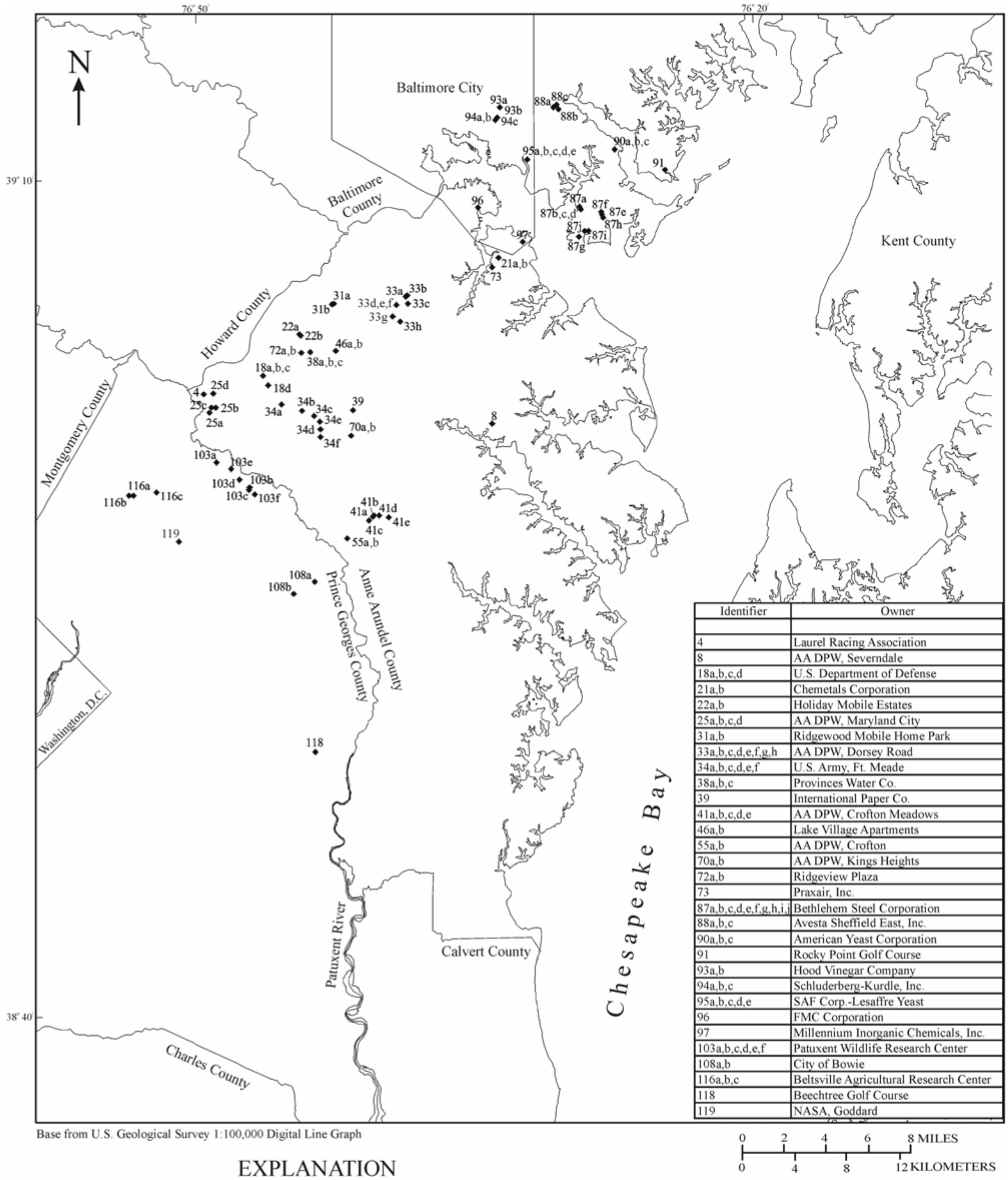
Base from U.S. Geological Survey 1:100,000 Digital Line Graph

EXPLANATION

■ 118 Production well screened in the Lower Patapsco aquifer. Number next to symbol is the identifier (see app. B).

AA DPW, Anne Arundel County Department of Public Works
QA Co., Queen Anne's County

Figure 10. Location of production wells or well fields in the Lower Patapsco aquifer supplying water to users pumping greater than 10,000 gallons per day.



Identifier	Owner
4	Laurel Racing Association
8	AA DPW, Severndale
18a,b,c,d	U.S. Department of Defense
21a,b	Chemetals Corporation
22a,b	Holiday Mobile Estates
25a,b,c,d	AA DPW, Maryland City
31a,b	Ridgewood Mobile Home Park
33a,b,c,d,e,f,g,h	AA DPW, Dorsey Road
34a,b,c,d,e,f	U.S. Army, Ft. Meade
38a,b,c	Provinces Water Co.
39	International Paper Co.
41a,b,c,d,e	AA DPW, Crofton Meadows
46a,b	Lake Village Apartments
55a,b	AA DPW, Crofton
70a,b	AA DPW, Kings Heights
72a,b	Ridgeview Plaza
73	Praxair, Inc.
87a,b,c,d,e,f,g,h,i,j	Bethlehem Steel Corporation
88a,b,c	Avesta Sheffield East, Inc.
90a,b,c	American Yeast Corporation
91	Rocky Point Golf Course
93a,b	Hood Vinegar Company
94a,b,c	Schluderberg-Kurdle, Inc.
95a,b,c,d,e	SAF Corp.-Lesaffre Yeast
96	FMC Corporation
97	Millennium Inorganic Chemicals, Inc.
103a,b,c,d,e,f	Patuxent Wildlife Research Center
108a,b	City of Bowie
116a,b,c	Beltsville Agricultural Research Center
118	Beechtree Golf Course
119	NASA, Goddard

Base from U.S. Geological Survey 1:100,000 Digital Line Graph

EXPLANATION

118 ◆ Production well screened in the Patuxent aquifer. Number next to symbol is the identifier (see app. B).

AA DPW, Anne Arundel County Department of Public Works
NASA, National Aeronautics and Space Administration

Figure 11. Location of production wells or well fields in the Patuxent aquifer supplying water to users pumping greater than 10,000 gallons per day.

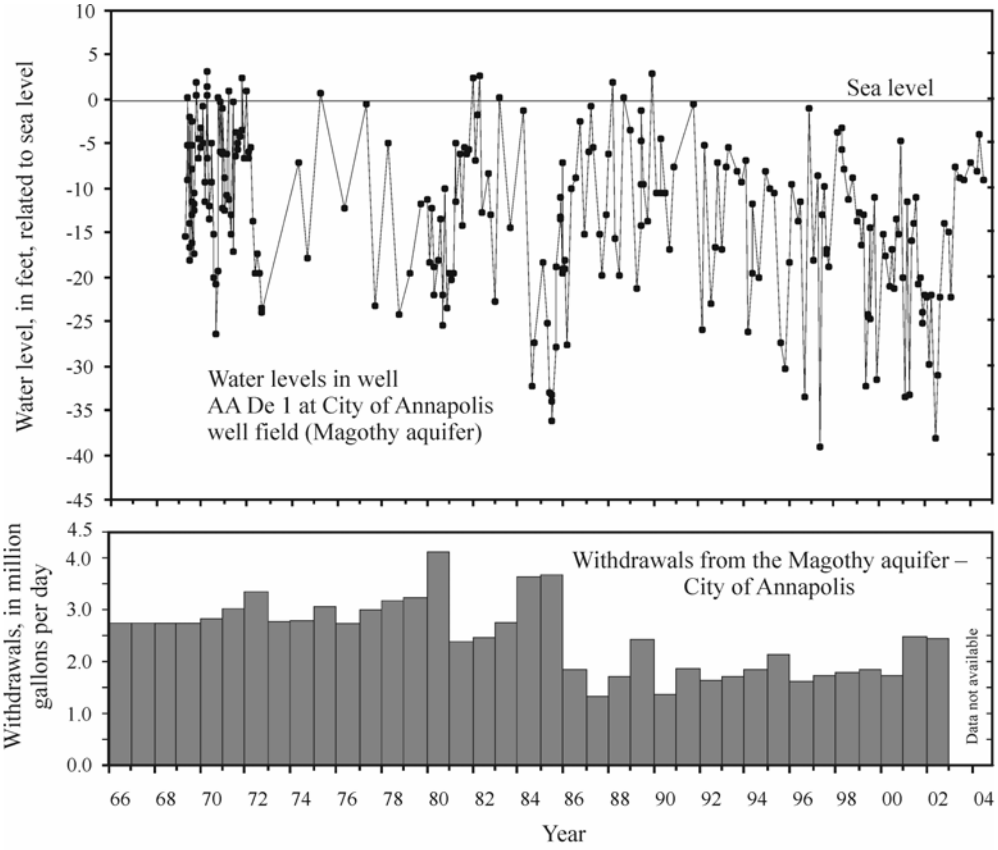


Figure 12. Water-level and pumpage trends in the Magothy aquifer in the City of Annapolis well field, 1966-2002.

1976 and 2002 (fig. 13). Water levels reached their lowest level at Arnold in 1988 (approximately 48 ft below sea level) when approximately 2 Mgal/d were pumped from the Upper Patapsco aquifer. Water levels recovered in the early to mid-1990's as some pumpage in the Arnold well field was shifted to the deeper Lower Patapsco aquifer. Since about 1997, however, withdrawals have increased in the Upper Patapsco aquifer causing a resumption in drawdown. Water levels in the Upper Patapsco aquifer declined from approximately 5 ft above sea level to 3 ft below sea level at Broad Creek between 1967 and 2004 (fig. 13). During that period, water levels fluctuated by as much as 30 ft as a result of cycling of the production wells. Water levels reached their lowest level in 1995 (approximately 35 ft below sea level) as a result of the steady increase in pumpage from approximately 0.1 Mgal/d in 1969 to 1.8 Mgal/d in 1995 (fig. 13). Withdrawals decreased significantly after 1997.

Water levels in the Lower Patapsco aquifer at the Severndale well field have declined approximately 120 ft during the period 1961 to 2004 (fig. 14). The lowest levels recorded (approximately 105 ft below sea level in 1980) were likely caused by a brief period of large withdrawals. Since 1978, when the well field first began production, withdrawals have increased from approximately 0.2 Mgal/d to a high of approximately 6.5 Mgal/d in 1999. As a result, water levels overall have shown a downward trend. Water levels in the Lower Patapsco aquifer at the Crofton Meadows well field have declined from a high of approximately 50 ft above sea level in 1979 to 15 ft below sea level in 2004 (fig. 14). Prior to the start of withdrawals from the Lower Patapsco aquifer at Crofton Meadows in 1988, water levels were declining at a rate of approximately 1.5 ft/yr. This decline is a result of a regional lowering of heads in the Lower Patapsco aquifer. While the Patuxent aquifer was being pumped at rates ranging from 1.2 Mgal/d in 1978 to 2.1 Mgal/d in 1987 at Crofton Meadows, downward leakage from the Lower Patapsco aquifer to the Patuxent aquifer is not a likely cause for the decline,

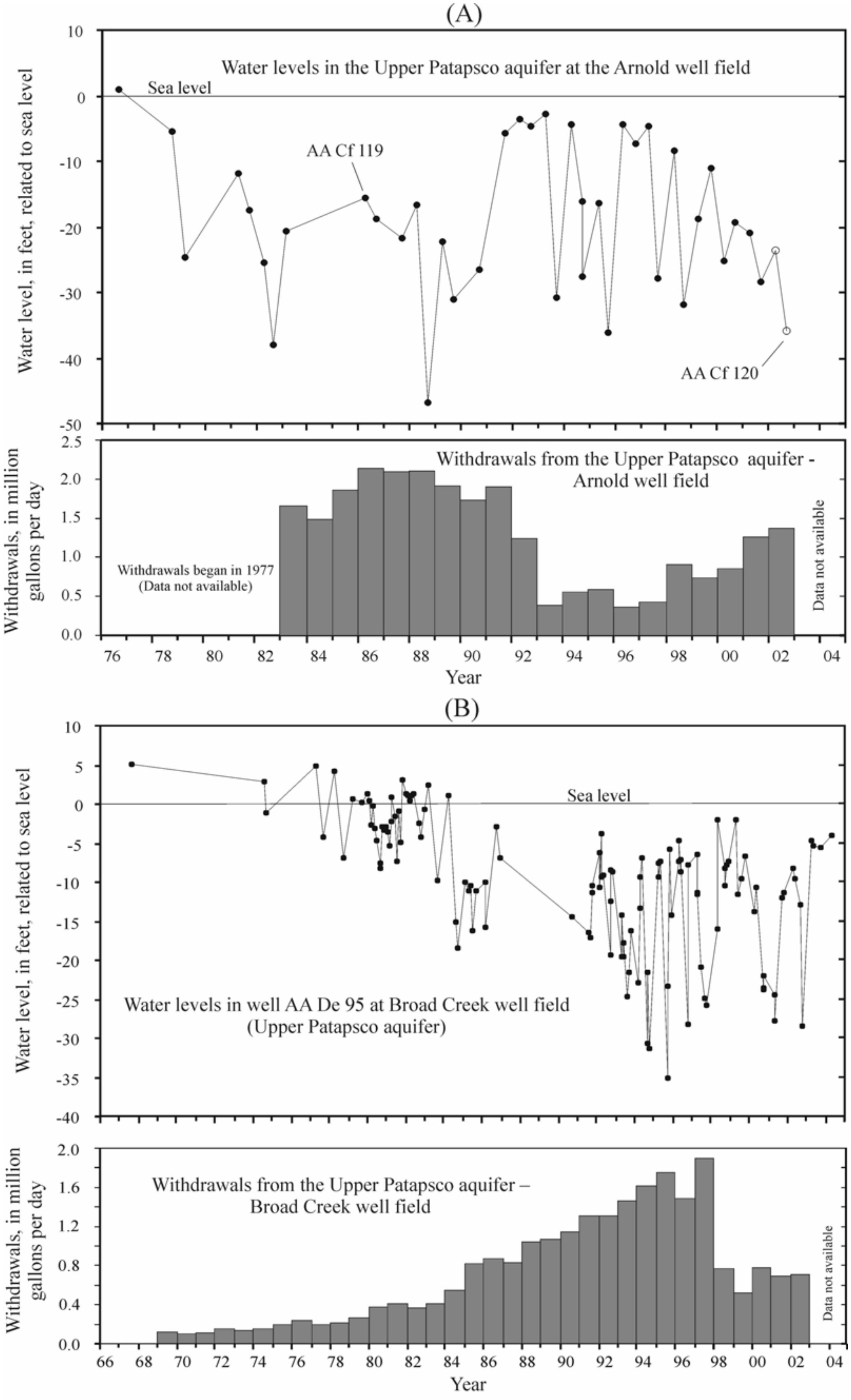


Figure 13. Water-level and pumpage trends in the Upper Patapsco aquifer in the (A) Arnold (1976-2002) and (B) Broad Creek well fields (1967-2004).

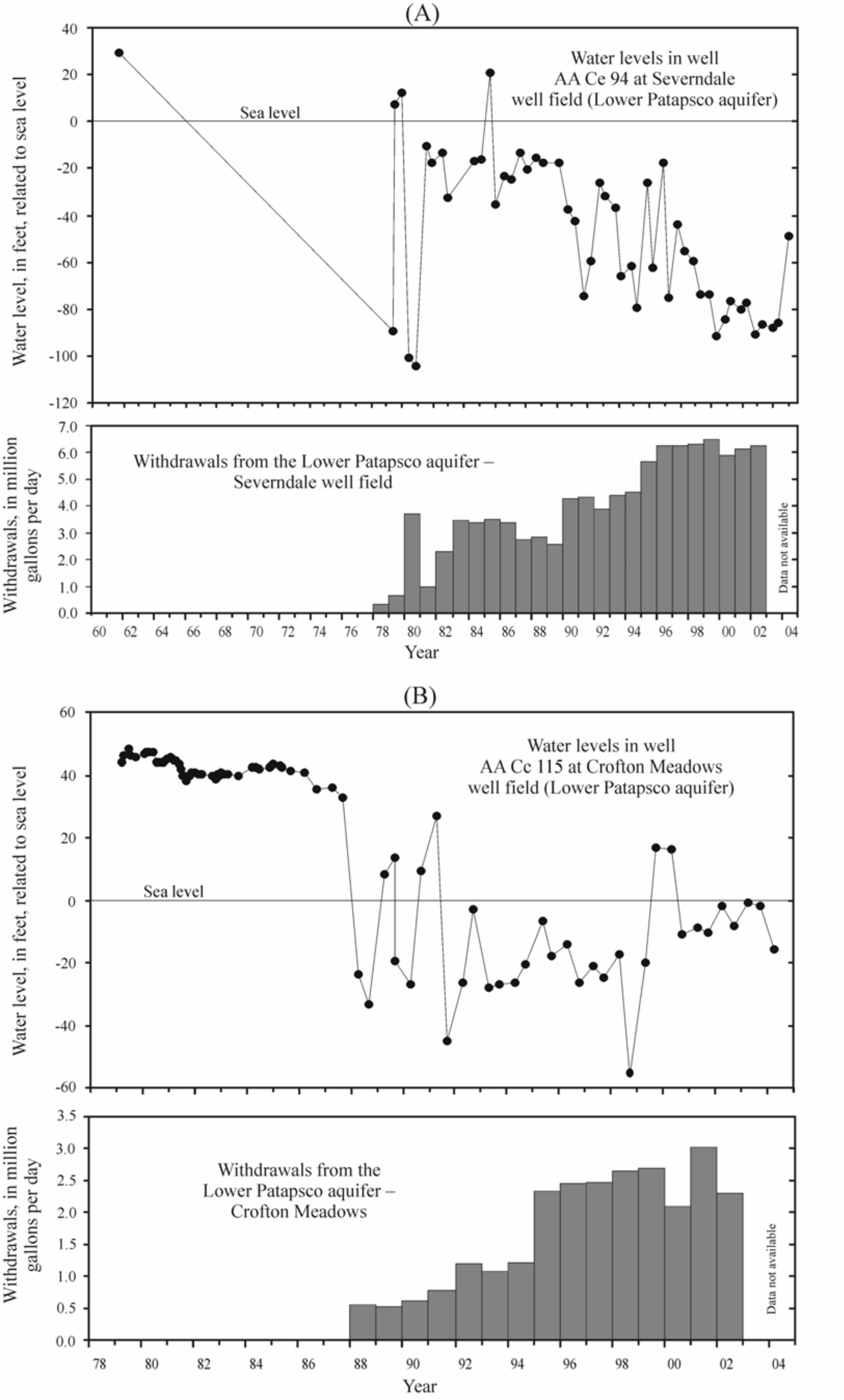


Figure 14. Water-level and pumpage trends in the Lower Patapsco aquifer in the (A) Severndale (1961-2004) and (B) Crofton Meadows well fields (1979-2004).

given the relatively thick (approximately 125 ft) low-permeability clay that separates the two aquifers. Water levels in the Lower Patapsco aquifer at the Arnold well field have declined from a high of approximately 4 ft above sea level in 1989 to 45 ft below sea level in 2004 (fig. 15). When withdrawals from the Lower Patapsco aquifer began in 1992, water levels declined approximately 50 to 60 ft, then stabilized. The brief periods of drawdown prior to 1992 are a result of aquifer tests. Since about 2002, water levels show a slight recovery. The earliest water level measured in Lower Patapsco aquifer observation well AA Bd 91 in the Dorsey Road well field was approximately 68 ft above sea level in 1961 (fig. 15). As withdrawals increased in the Lower Patapsco aquifer in the Dorsey Road and Sawmill Creek well fields, water levels declined to approximately 8 ft above sea level in 1982, then began recovering as withdrawals stopped in the 1990's (Sawmill Creek in 1990; Dorsey Road in 1996). Use of the Lower Patapsco aquifer at these well fields has been shown to significantly reduce baseflow in Sawmill Creek (Achmad, 1991). As a result, the Sawmill Creek well field was abandoned and pumpage in the Dorsey Road well field was shifted entirely to the deeper Patuxent aquifer to prevent any potential harm to the ecology of Sawmill Creek. The discontinuation of withdrawals from the Lower Patapsco aquifer have caused water levels in the aquifer and baseflow in Sawmill Creek to recover (Andreasen, 2005).

The City of Annapolis and Broad Creek well fields are located approximately 0.5 mile from one another. Pumpage from the Lower Patapsco aquifer in either well field affects water levels at both sites. The City of Annapolis began pumping water from one well screened in the Lower Patapsco aquifer in the mid-1960's (fig. 16). The water-level record from observation well AA De 94 shows a decline of about 10 ft between 1965 and 1984. In 1986 the withdrawals increased significantly with the addition of a second production well. The Anne Arundel County Department of Public Works began pumping from the Lower Patapsco aquifer in the Broad Creek well field in 1995. Withdrawals from the city's well field and later from the Broad Creek well field caused water levels to decline from approximately 10 ft below sea level in 1988 to 35 ft below sea level in 2003.

Water levels in the Patuxent aquifer at Crofton Meadows have declined from approximately 42 ft above sea level in 1973 to 20 ft below sea level in 2002 in response to pumping within the well field (fig. 17). Withdrawals from the well field have increased from approximately 0.11 Mgal/d in 1964 to 3.3 Mgal/d in 2002. An increase in withdrawals from the Lower Patapsco aquifer in the Crofton Meadows well field resulted in a reduction in Patuxent withdrawals in 1994. Water levels in the Patuxent aquifer in the Dorsey Road well field have declined from approximately sea level in 1978 to as much as 80 ft below sea level in 2002 (fig. 17). Withdrawals from the well field have increased from approximately 0.4 Mgal/d in 1950 to 2.9 Mgal/d in 2002. Water levels continued to decline during the period 1999 to 2002 despite the stabilization of withdrawals during that period. This may be caused by a lag-time before steady-state conditions are reached or a re-distribution of withdrawals within the well field whereby production wells closer to the observation well (AA Ad 90) were pumped at a higher rate.

The potentiometric surfaces of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers for the fall of 2004 are shown in figure 18. In the Magothy aquifer the highest measured head (90 ft above sea level) occurs in the outcrop area of central Anne Arundel County. An outcrop area is the area in which a geologic formation (or aquifer) is exposed at the surface. The deepest measured head in Anne Arundel County is 17 ft below sea level at the southern end of Annapolis Neck. Heads decrease south and east with the lowest heads occurring in northern Charles County where the Magothy is pumped for public supply at Waldorf. Heads in northern Charles County are as deep as approximately 70 ft below sea level. In the Upper Patapsco aquifer the highest measured head (121 ft above sea level) occurs in the outcrop area of central Anne Arundel County. The deepest measured head in Anne Arundel County is 21 ft below sea level on Broadneck Peninsula. Heads also decrease south and east with the lowest readings occurring in northern Charles County (70 ft below sea level). The Upper Patapsco aquifer is also pumped for public supply in the Waldorf area south of the area shown in figure 18. In the Lower Patapsco aquifer the highest measured head (113 ft above sea level) occurs in the outcrop area in northeastern Prince George's County. The deepest measured head in Anne Arundel County is 90 ft below sea level at Severndale. Similar to the Magothy and Upper Patapsco aquifers, heads decrease south and east with the lowest readings occurring in northern Charles County (113 ft below sea level). The Lower Patapsco aquifer is pumped for public supply in the Waldorf area. In the Patuxent aquifer the highest measured water level (170 ft above sea level) occurs

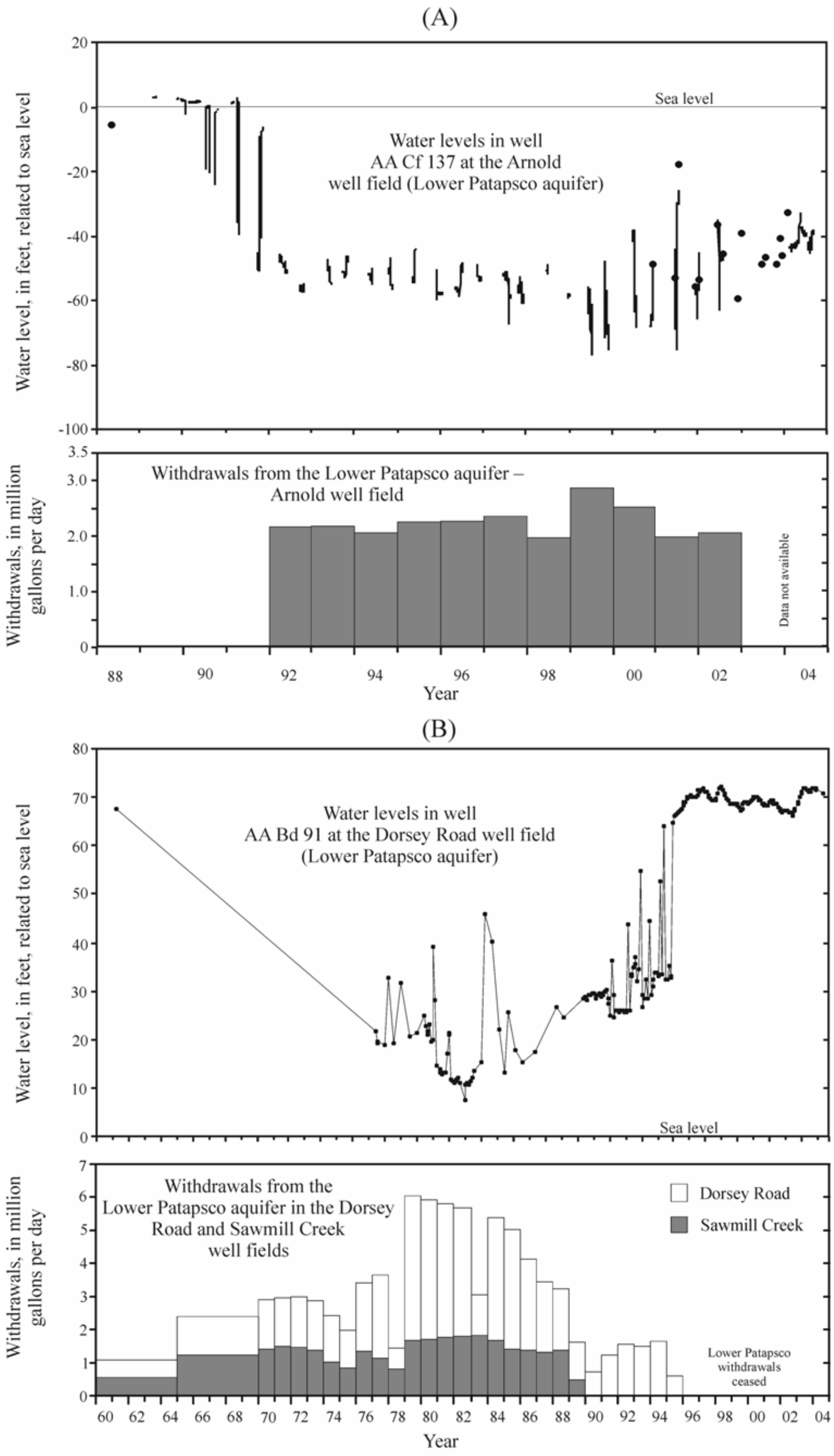


Figure 15. Water-level and pumpage trends in the Lower Patapsco aquifer in the (A) Arnold (1988-2004) and (B) Dorsey Road-Sawmill Creek well fields (1960-2004).

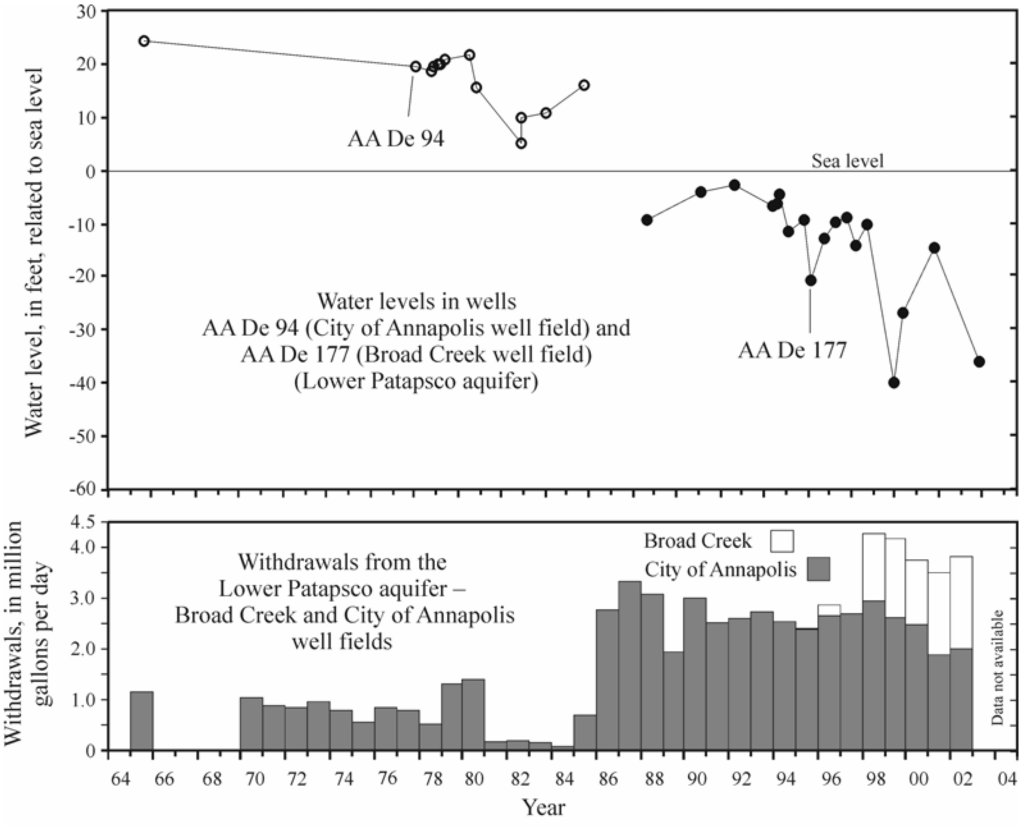


Figure 16. Water-level and pumpage trends in the Lower Patapsco aquifer in the Broad Creek and City of Annapolis well fields (1965-2003).

in the outcrop area of northwestern Prince George's County. The deepest measured head in Anne Arundel County is 72 ft below sea level at Dorsey Road. Cones-of-depression are formed at Crofton Meadows (40 ft below sea level), Dorsey Road (72 ft below sea level), and southeastern Baltimore County (31 ft below sea level). Heads decrease to the southeast.

Permitted withdrawals of ground water from Maryland's confined aquifers are regulated in order to assure a continued supply of water and to prevent dewatering of the confined aquifer. Applications for ground-water appropriation permits (GAPs) are evaluated by the Maryland Department of the Environment to determine whether the water-level decline (drawdown) resulting from those withdrawals exceeds a management level. This level, referred to as the 80-percent management level, is defined as 80 percent of the difference between the pre-pumping water level and the top of the aquifer (fig. 19). Drawdown associated with permitted average-day withdrawals is not allowed to fall below the management level in an area common to the well or wells associated with the appropriation permit. The management level provides a buffer before the confined aquifer begins to dewater. Available drawdown (equal to the difference between the water level and the 80-percent management level) in 2002 for aquifers in Anne Arundel County is as follows: Magothy, 0 to 300 ft; Upper Patapsco, 0 to 500 ft; Lower Patapsco, 0 to 1,000 ft; and Patuxent, 0 to 1,400 ft (fig. 20).

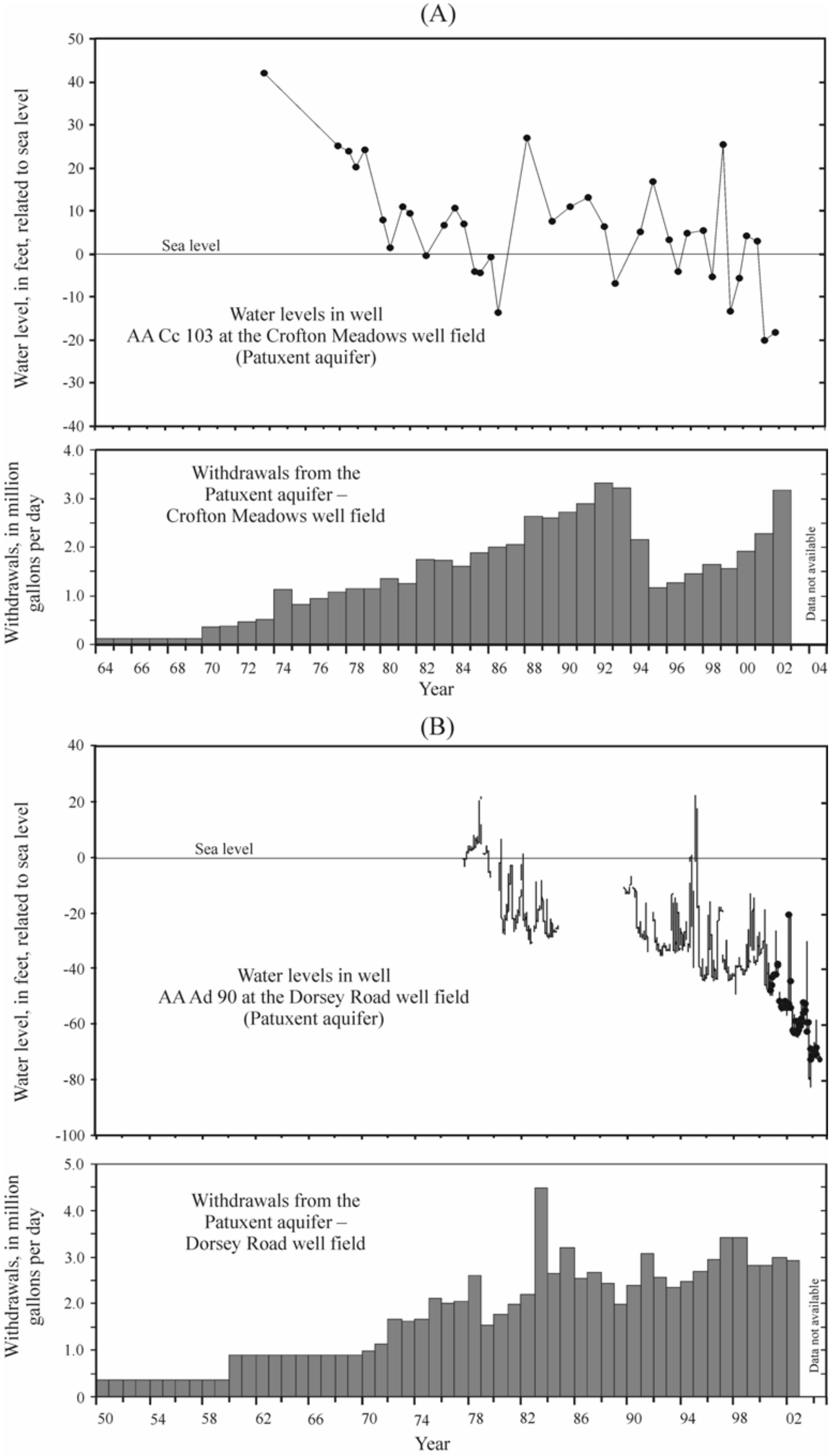


Figure 17. Water-level and pumpage trends in the Patuxent aquifer in the (A) Crofton Meadows (1964-2002) and (B) Dorsey Road well fields (1950-2004).

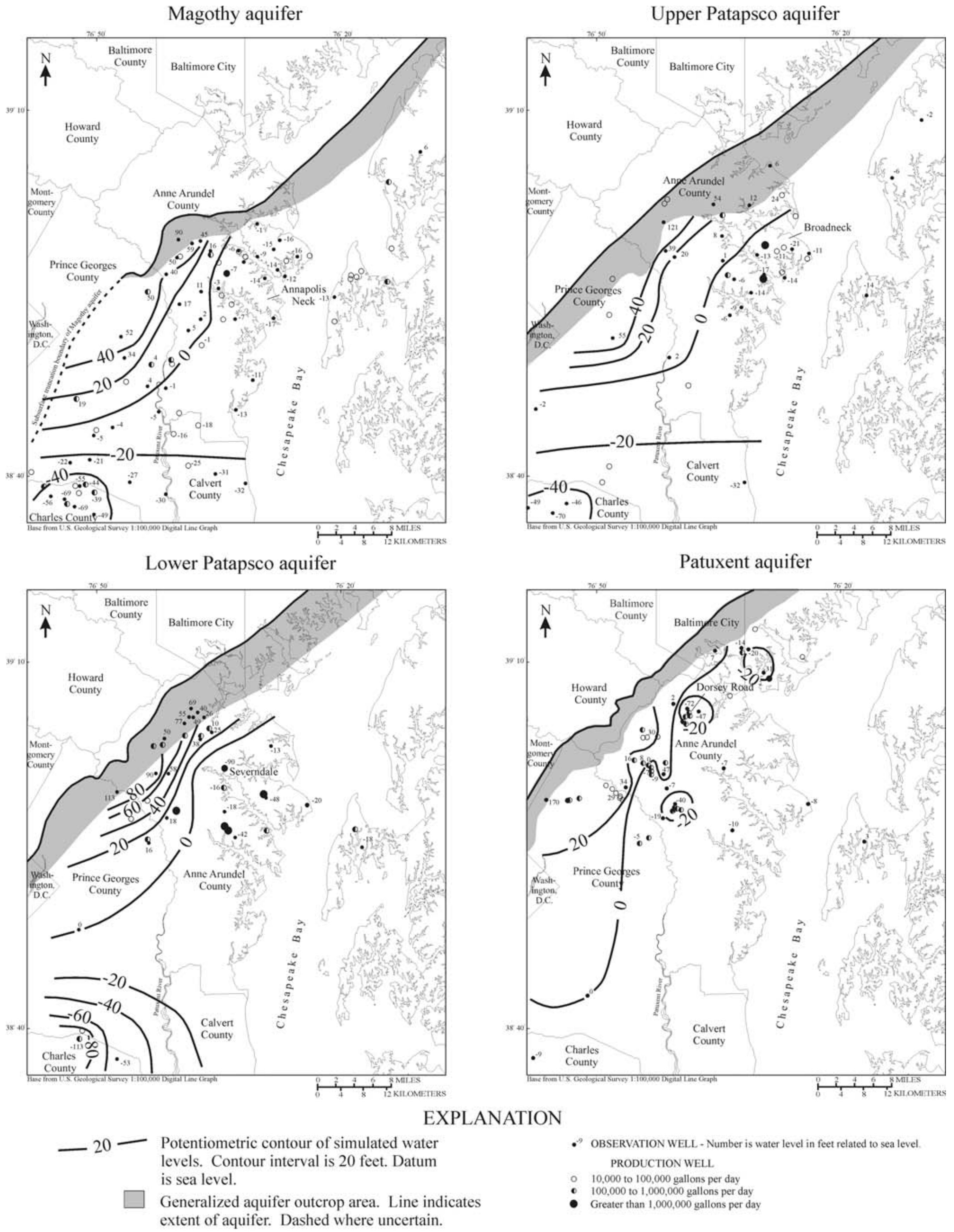


Figure 18. Potentiometric surfaces of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers during the fall, 2004.

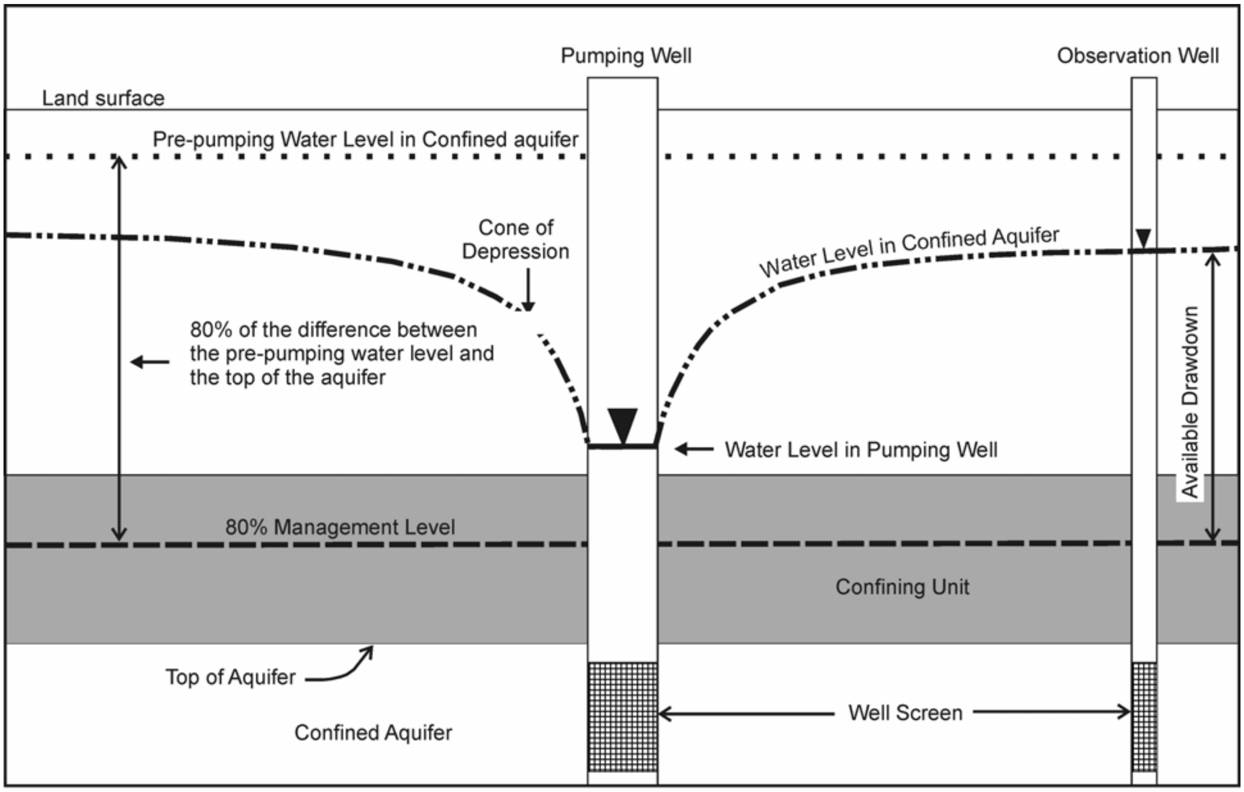


Figure 19. Schematic defining available drawdown and 80-percent management water level. [Source: State of Maryland, 2004].

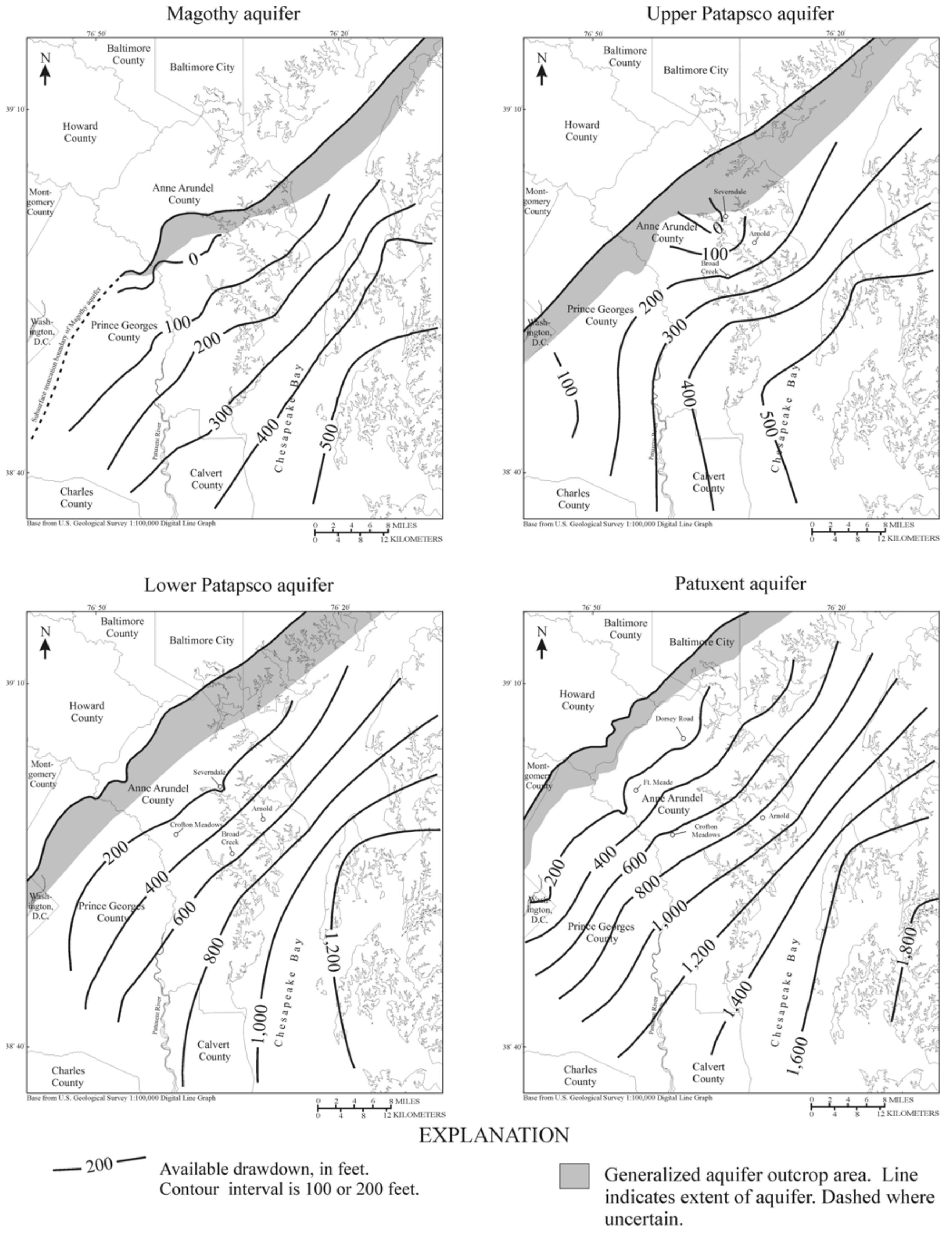
WATER-SUPPLY POTENTIAL OF THE UPPER PATAPSCO, LOWER PATAPSCO, AND PATUXENT AQUIFERS

SIMULATION OF GROUND-WATER FLOW

The water-supply potential of the Upper Patapsco, Lower Patapsco, and Patuxent aquifers was evaluated by simulating ground-water flow using the numerical, finite-difference ground-water-flow model MODFLOW (McDonald and Harbaugh, 1988). The model was constructed using the preprocessing software Processing MODFLOW (Chiang and Kinzelbach, 1993). The model simulated flow in the Upper Patapsco, Lower Patapsco, and Patuxent aquifers as well as in the Magothy aquifer. The water-table aquifer, a portion of which included the outcrop areas of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers, was also simulated in the model. The Aquia aquifer was represented in the model as a constant-head layer. The ground-water-flow model, constructed based on a conceptual model of flow, was calibrated using historical ground-water levels and stream baseflow data. The calibrated model was then used in conjunction with a linear-programming algorithm to optimize future withdrawals from Anne Arundel County's well fields.

Conceptual Model

A conceptual model of the ground-water-flow system was developed to provide a framework for construction of the flow model. The conceptual model describes in general terms the geometry of the aquifer system, the lateral and vertical direction of flow, boundaries, sources of recharge, and areas of



Magothy aquifer

Upper Patapsco aquifer

Lower Patapsco aquifer

Patuxent aquifer

EXPLANATION

200 Available drawdown, in feet. Contour interval is 100 or 200 feet.

Generalized aquifer outcrop area. Line indicates extent of aquifer. Dashed where uncertain.

Figure 20. Approximate available drawdown remaining in 2002 in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers.

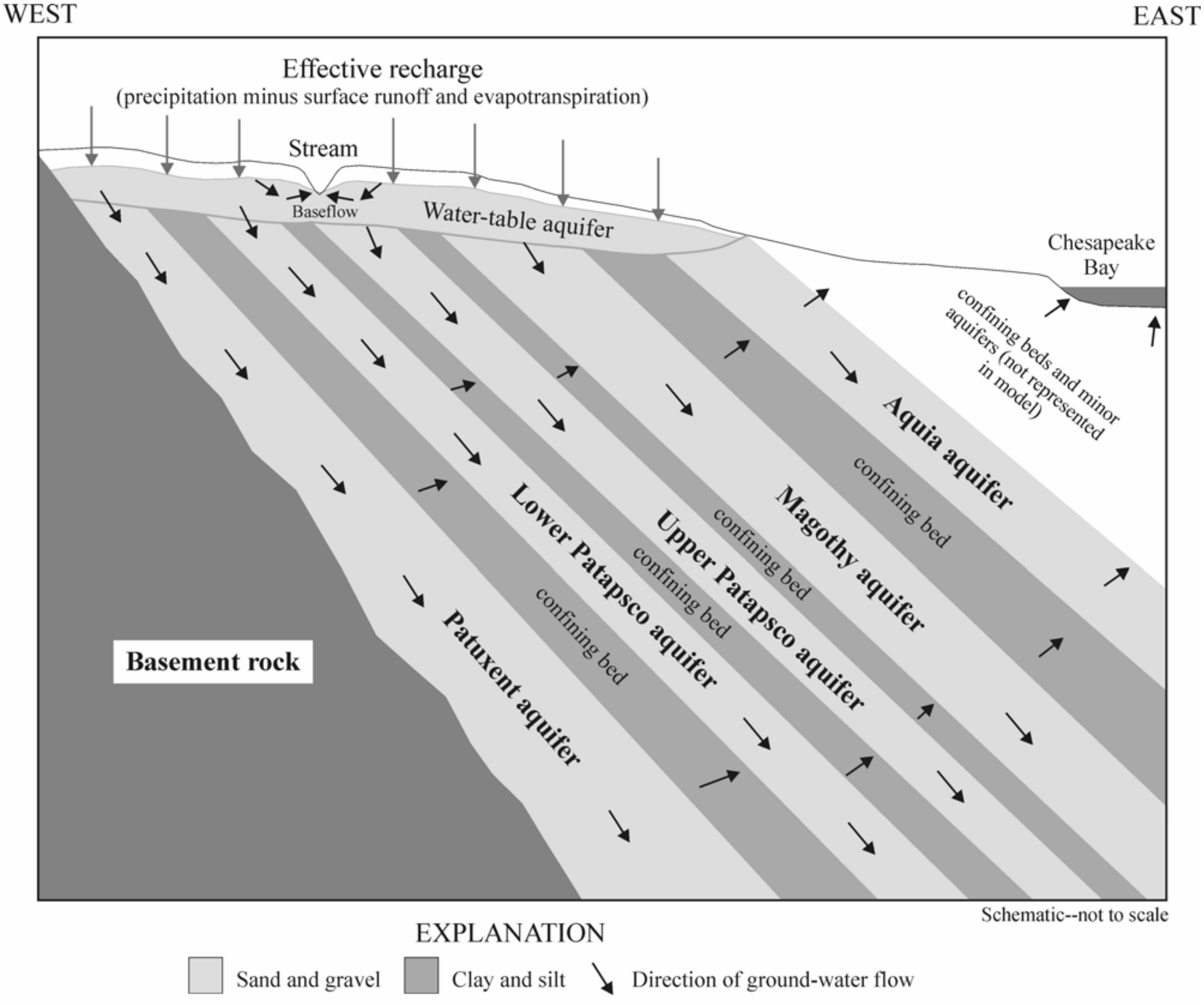


Figure 21. Conceptual model of the ground-water-flow system modeled in Anne Arundel County and surrounding areas.

discharge. Figure 21 shows a schematic cross section of the conceptual model trending from west to east across Anne Arundel County. The model includes the five major confined aquifers in Anne Arundel County—the Aquia, Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers—in addition to the water-table aquifer. The relatively minor aquifers overlying the Aquia aquifer were excluded from the model. The aquifers are separated by clay confining beds. Although the schematic cross-section portrays both aquifers and confining beds as homogeneous and structurally uniform, in reality, the aquifer system is a complex, heterogeneous array of complexly interbedded sands and clays (figs. 2 and 3). The aquifer system is bound below by the relatively low permeability crystalline basement rock, and above by the water table, tidal water bodies, or the relatively low permeability clays overlying the Aquia aquifer. Recharge from precipitation enters the water-table aquifer. In the model, only effective recharge, or that portion of infiltrating water that recharges the water-table aquifer after evapotranspiration, is considered. Within the water-table aquifer, ground water flows from high to low elevations and discharges to streams and rivers. The remainder of the water in the water-table aquifer enters the deep flow system to recharge the confined aquifers. The southeastwardly flow of ground water in the confined aquifers depicted in figure 21 is representative of pre-pumping conditions; however, ground-water withdrawals have significantly altered the flow regime, causing reversal of flow directions in many areas. Water not captured by wells eventually flows upwards and discharges beneath the Chesapeake Bay and Atlantic Ocean.

Model Grid, Layers, and Boundary Conditions

The model grid consists of 119 columns and 108 rows. The grid is oriented in a northeasterly direction with model rows aligned parallel to the Fall Line (the western extent of Coastal Plain sediments) (fig. 22). The orientation of the model columns is roughly parallel to the primary direction of ground-water flow. The total area covered by the grid is 2,446 square miles. Natural flow boundaries for the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers are too distant to model effectively. The size of the model area was, therefore, selected to satisfy the study objectives while minimizing potentially unrealistic boundary effects on the flow system. The model edges are located far enough from the main pumpage centers in the study area to minimize adverse boundary effects. Variable grid spacing was used so that individual wells or well fields could be represented in the model. Grid spacing increases away from the well fields towards the model boundaries. The smallest cell size within the grid is 360 by 390 ft.

The model consists of six layers (fig. 23). The layers, from top to bottom, include the water-table aquifer (model layer 1), the Aquia aquifer and water-table aquifer (model layer 2), the Magothy aquifer (model layer 3), the Upper Patapsco aquifer (model layer 4), the Lower Patapsco aquifer (model layer 5), and the Patuxent aquifer (model layer 6) (fig. 23). The water-table aquifer was spilt into two model layers (model layers 1 and 2) in order to include the Aquia aquifer. Model layer 1 was modeled as an active water-table layer (transmissivity variable through time), while model layers 2 (portion underlying the water-table aquifer), 3, 4, 5, and 6 were modeled as confined aquifers (transmissivity constant through time). All six model layers contain constant-head cells representing tidal rivers and Chesapeake Bay. The portion of model layer 2 representing the Aquia aquifer is a constant-head layer. Heads assigned to model layer 2 are discussed in a later section of the report pertaining to temporal boundary conditions. The model is a quasi three-dimensional representation of flow where vertical leakage between aquifers through confining beds is simulated by a leakance term assigned to each model layer. Since the Patuxent aquifer overlies impermeable basement rock, the base of model layer 6 is represented as a no-flow boundary.

The location and type of model boundaries assigned to each active model layer were selected, where possible, to coincide with natural flow boundaries. The water-table aquifer (model layer 1) was represented in the model in an area that includes the outcrop areas of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers (fig. 24). The boundaries of model layer 1 are represented either as no flow coinciding with surface-water divides and the Fall Line, or constant head coinciding with tidal rivers or Chesapeake Bay. Boundaries in model layers 3 (Magothy aquifer), 4 (Upper Patapsco aquifer), 5 (Lower Patapsco aquifer), and 6 (Patuxent aquifer) are represented either as no flow coinciding with their updip extent or as constant head coinciding with tidal rivers or Chesapeake Bay (fig. 25). The east, south, and west sides of model layers 3, 4, 5, and 6 lack natural flow boundaries. To simulate flow in those areas, general-head boundaries were used. A general-head boundary allows flow across the boundary to vary as a function of the head gradient. Flow into or out of a cell containing the boundary is proportional to: (1) the difference between the simulated head in the cell and the head assigned to an external specified-head source, and (2) the hydraulic conductance between the head and the source (McDonald and Harbaugh, 1988). Heads assigned to the general-head boundaries were adjusted during the transient simulation (1900-2002) to represent temporal changes in head outside the model area.

Rivers

Streams and non-tidal rivers were simulated in model layer 1 using the river package of MODFLOW (fig. 26). Four of the rivers and creeks represented in the model—Sawmill Creek, North River, Northwest Branch of the Anacostia River at Riverdale, and Western Branch at Upper Marlboro—have historical base-flow records. The length, width, and bottom thickness of each river reach contained in a model cell was input into the river package. During model simulations, flow between river cells and model layer 1 is controlled by the head gradient established between the defined stage of the river cells and simulated head in model layer 1, and the vertical hydraulic conductivity of the river-bottom material. An estimate of the vertical

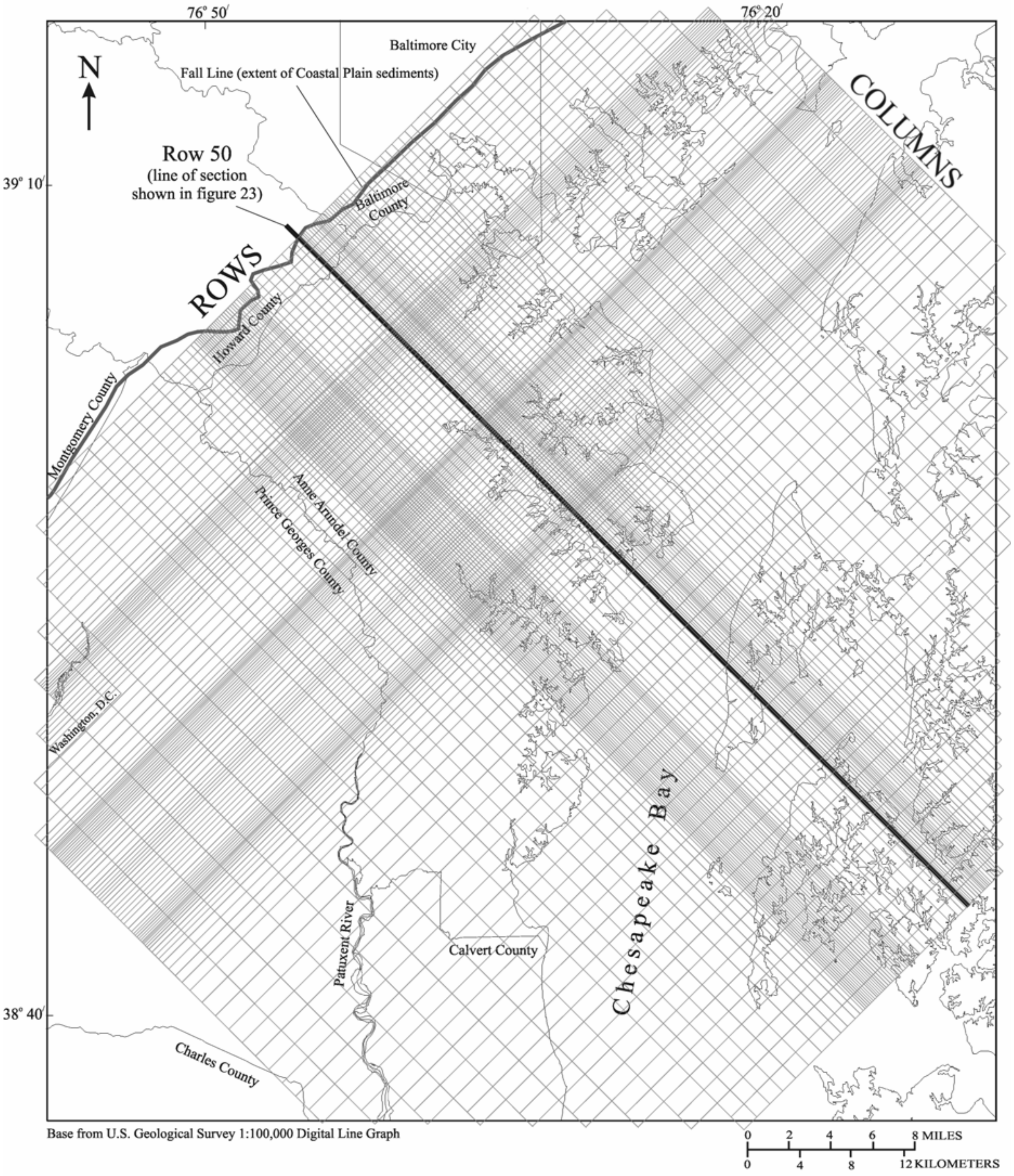


Figure 22. Finite-difference model grid.

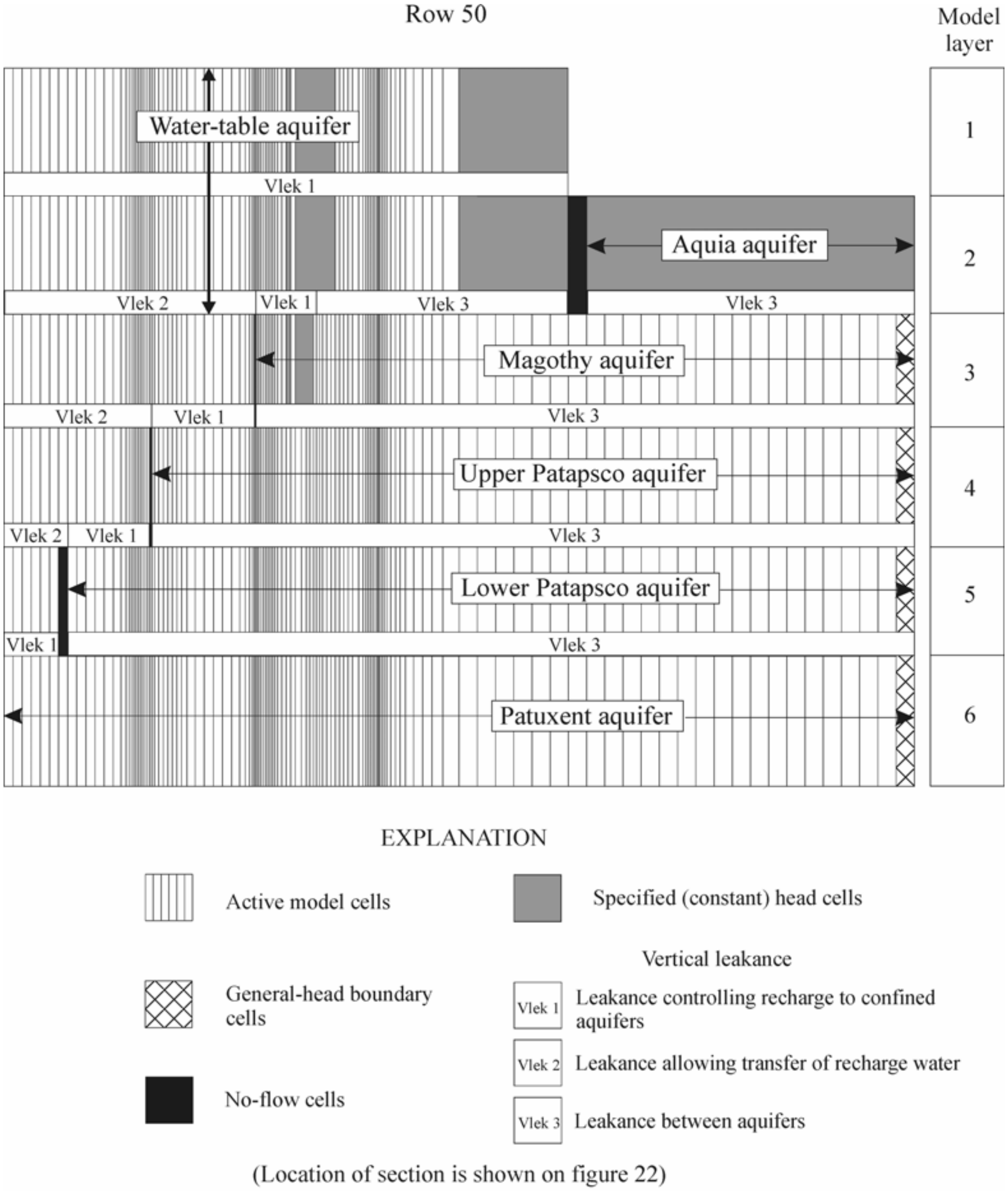


Figure 23. Cross section along model row 50 showing model layers and boundaries.

hydraulic conductivity of the river-bottom material was multiplied by the area of the river bottom within each river cell, and divided by the river-bottom thickness. The resulting hydraulic conductance term was assigned to each river cell. The vertical hydraulic conductivity of the river-bottom material was set to 1 foot per day (ft/d), which is within the range of values for a silty to clean sand (Freeze and Cherry, 1979, p. 29). Average river stage and bottom altitudes were also assigned for each river cell. The river stage was estimated at 1 ft above the stream bottom and remained constant throughout the transient model simulation. River-bottom altitudes and lengths of river reaches were estimated using U.S. Geological Survey 1:24,000- and 1:100,000-scale topographic maps. The river-conductance term was adjusted during model calibration.

Hydraulic Parameters

In a water-table aquifer, transmissivity is a product of the horizontal hydraulic conductivity of the aquifer and its saturated thickness. In model layer 1 (water-table aquifer), the horizontal

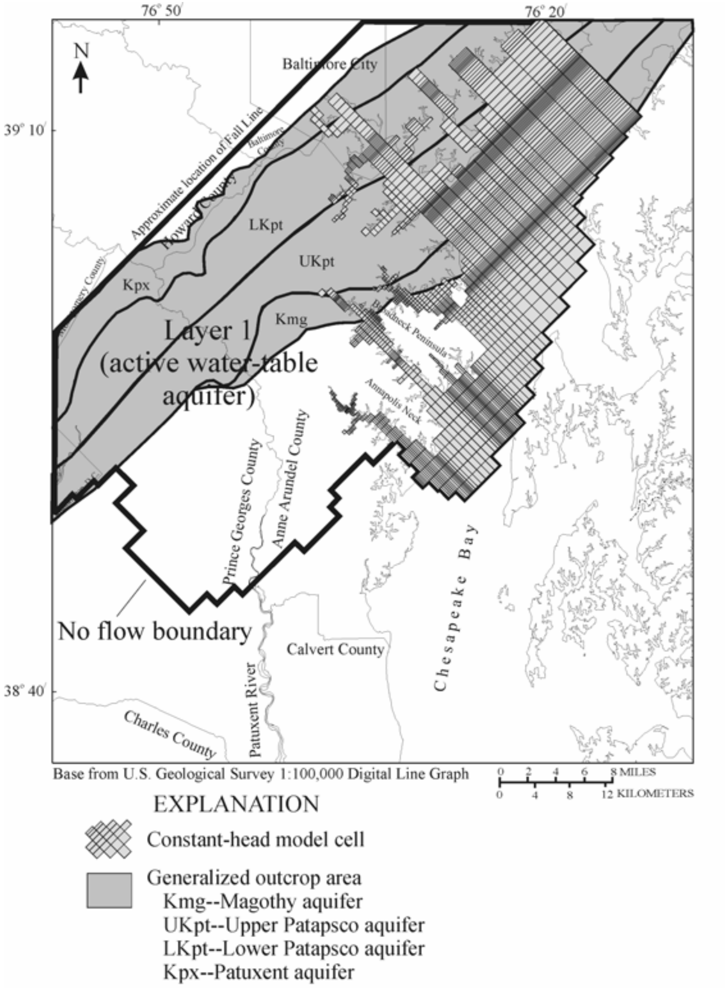


Figure 24. Boundaries in model layer 1 (water-table aquifer).

hydraulic conductivity was set at 35 ft/d. This value, selected through model calibration, is within a typical range for a sand aquifer (Freeze and Cherry, 1979). Model layer 2, underlying the water-table aquifer represented in model layer 1, was assigned a transmissivity value of 1,000 ft^2/d as determined through model calibration. In the confined aquifers (model layers 3, 4, 5, and 6), transmissivity is constant in time. Transmissivity arrays were developed for model input first from measured field data and then adjusted through model calibration (fig. 5). In the Magothy aquifer the simulated transmissivity ranges from less than 1,500 ft^2/d to more than 5,000 ft^2/d (fig. 5). An area of relatively high transmissivity occurs in east-central Anne Arundel County. The higher values in this area are generally supported by the field data. In the Upper Patapsco aquifer simulated transmissivity ranges from less than 2,000 ft^2/d to as much as 14,000 ft^2/d (fig. 5). An area of relatively high transmissivity occurs across east-central and south-central Anne Arundel County. There is relatively good agreement between the simulated and field data. In the Lower Patapsco aquifer, simulated transmissivity ranges from less than 2,000 ft^2/d to as much as 8,000 ft^2/d (fig. 5). In general, an area of high transmissivity extends from the northwestern part of Anne Arundel County where the aquifer is in outcrop through the east-central part of the county. Simulated values generally agree with the field data. In the Patuxent aquifer simulated transmissivity ranges from less than 2,000 ft^2/d to more than 8,000 ft^2/d (fig. 5). Transmissivity is highest in the northwestern part of Anne Arundel County. The simulated values are generally in agreement with the field data. The general absence of deep wells in the southern part of the model area (southern Anne Arundel and Prince George's Counties and northern Calvert County)

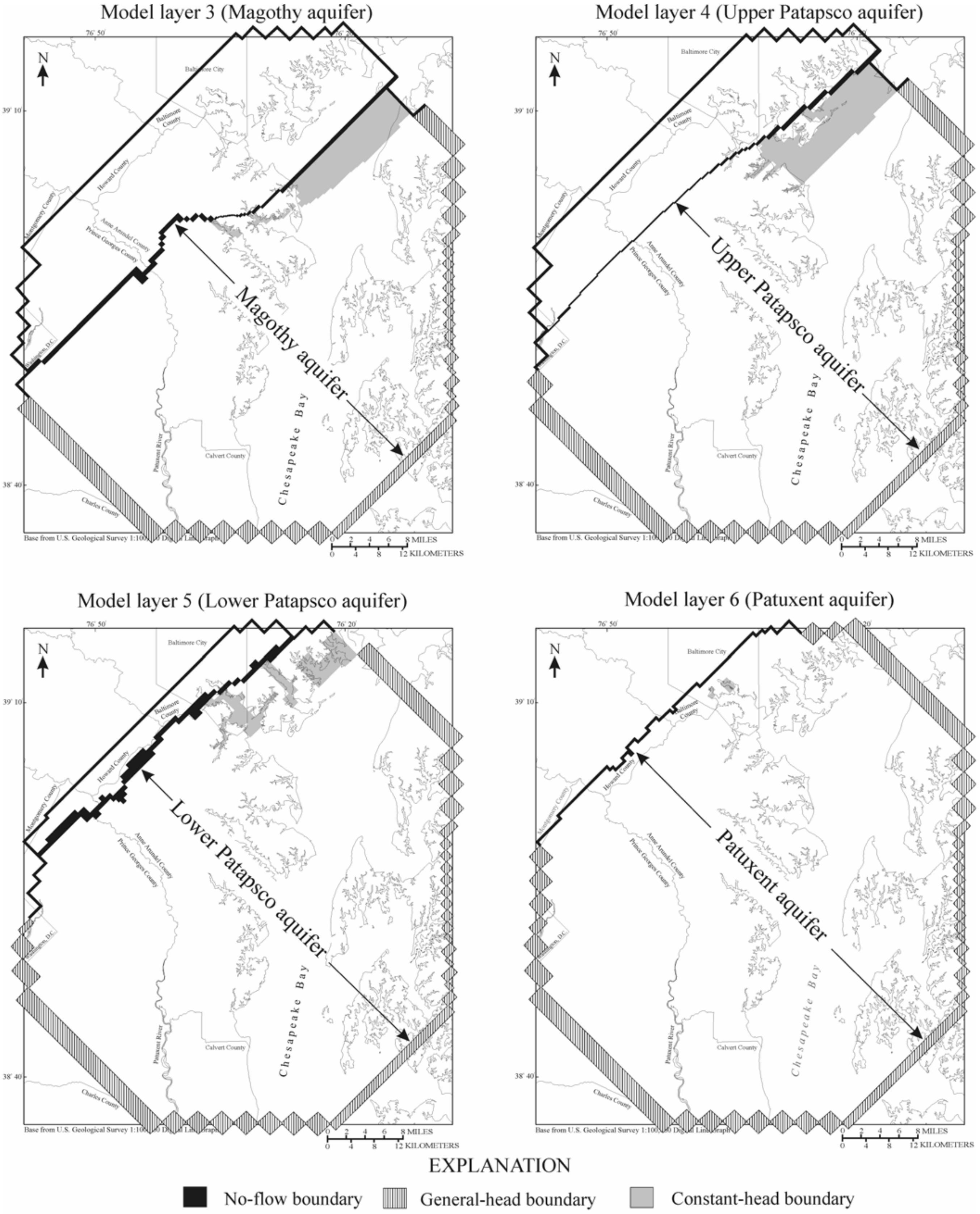


Figure 25. Boundaries in model layers 3 (Magothy aquifer), 4 (Upper Patapsco aquifer), 5 (Lower Patapsco aquifer), and 6 (Patuxent aquifer).

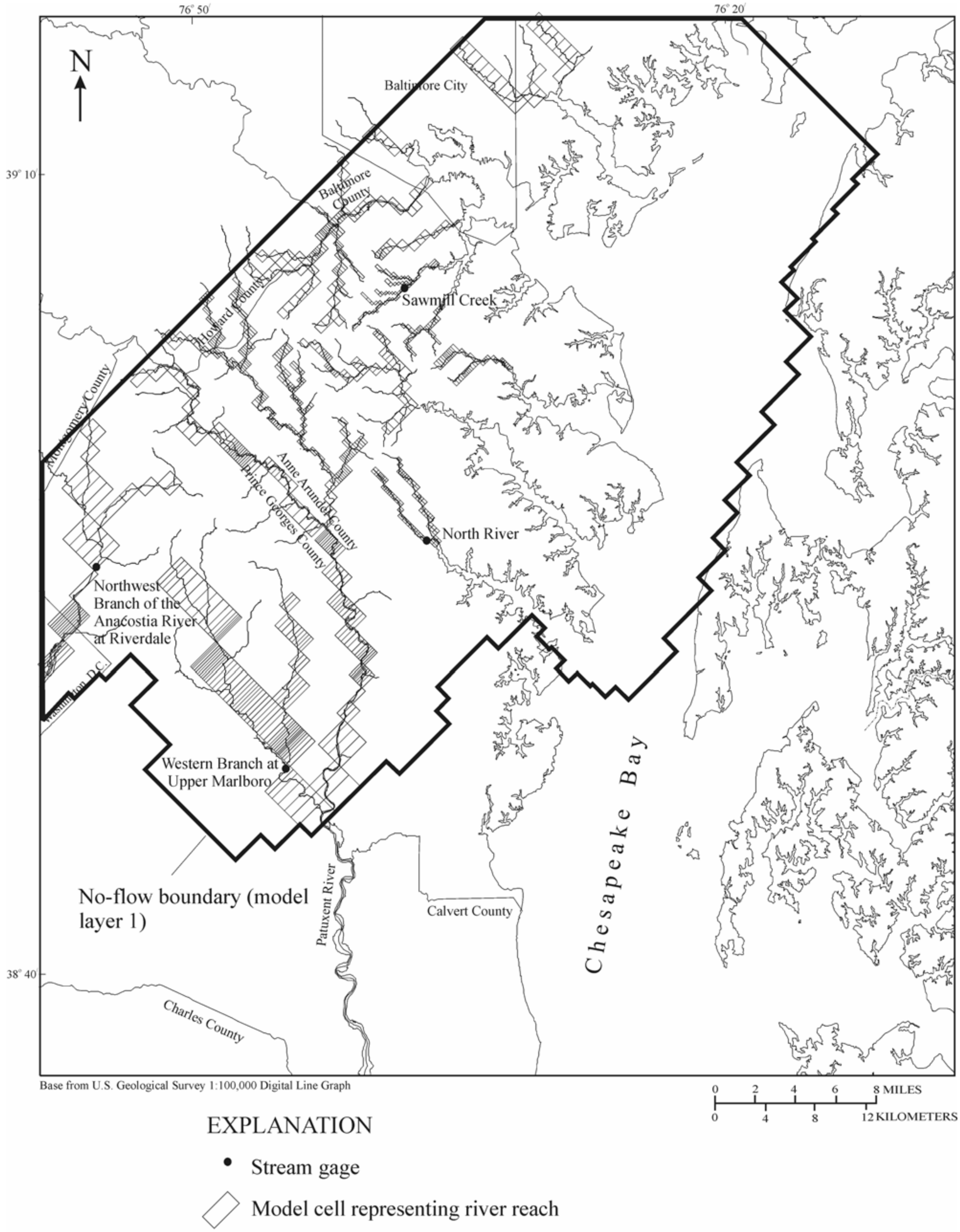


Figure 26. Location of rivers represented in the ground-water-flow model and stream gages used in model calibration.

results in a significant data gap. The accuracy of simulated transmissivity arrays in those areas, therefore, is uncertain.

Storage coefficients assigned to the model for the confined aquifers were 0.0001 for model layers 3, 4, and 5, and 0.0009 for model layer 6. These values are within the range of measured storage coefficients for the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers (Hansen, 1972). A storage coefficient of 0.25 was used for the unconfined aquifer in model layer 1. This value is within the range of storage coefficients for unconfined aquifers (Fetter, 1980, p. 97).

Vertical leakance is a mathematical expression used to calculate the volume of flow of water between model layers. Vertical leakance between model layers was calculated using the following equation (McDonald and Harbaugh, 1988, p. 5-16):

$$L = \frac{1}{\frac{bu/2}{Ku} + \frac{bc}{Kc} + \frac{bl/2}{Kl}}$$

where

L = vertical leakance, d^{-1};
K = vertical hydraulic conductivity, ft/d;
b = thickness, ft/d;
u = upper aquifer;
c = confining bed;
l = lower aquifer.

Initially, vertical leakance was calculated using average model-layer thickness and estimates of vertical hydraulic conductivity. Because the clay confining beds are significantly less permeable than the sandy aquifers, vertical leakance is controlled mostly by the vertical hydraulic conductivity of the confining beds. During model calibration the vertical leakance was adjusted.

Vertical leakance values assigned to model layer 1 occur in three zones expressed in cubic feet per day per cubic foot (1/d): zone 1 (1 x 10^{-8} 1/d), zone 2 (1 x 10^{-4} 1/d), and zone 3 (9 x 10^{1} 1/d). Zone 1 represents the low-permeability Marlboro Clay overlying the Aquia aquifer, zone 2 in part controls the amount of recharge entering the confined aquifers, and zone 3 represents the window in the confining bed overlying the Lower Patapsco aquifer in the Glen Burnie area (Wilson and Achmad, 1995). Vertical leakance values assigned to model layer 2 are: 9 x 10^{-6} 1/d, representing the Matawan Clay separating the Aquia and Magothy aquifers; 1 x 10^{-4} 1/d, representing the recharge area of the Magothy aquifer; and 8 x 10^{-5} 1/d, representing the subcrop area of the Magothy aquifer. Vertical leakance values assigned to model layer 3 are: 1 x 10^{-4} 1/d, representing the confining bed separating the Magothy and Upper Patapsco aquifers; 1 x 10^{-3} 1/d, representing the sand-on-sand contact between the Magothy and Upper Patapsco aquifers on Broadneck Peninsula (Mack and Andreasen, 1991); and 1 x 10^{-3} to 5 x 10^{-4}1/d, representing the recharge area of the Upper Patapsco aquifer. Vertical leakance values assigned to model layer 4 are: 2 x 10^{-5} 1/d, representing the confining bed separating the Upper and Lower Patapsco aquifers; 1 x 10^{-1} 1/d, representing the window in the confining bed overlying the Lower Patapsco aquifer in the Glen Burnie area; and 9 x 10^{-4} 1/d, representing the recharge area of the Lower Patapsco aquifer. Vertical leakance values assigned to model layer 5 are: 2 x 10^{-5} to 4.5 x 10^{-12} 1/d, representing the confining bed separating the Lower Patapsco and Patuxent aquifers; 2 x 10^{-4} 1/d, representing a paleochannel penetrating the Arundel Clay confining bed separating the Lower Patapsco and Patuxent aquifers at Baltimore City (Chapelle and Kean, 1985); and 1 x 10^{-5} l/d, representing the recharge area of the Patuxent aquifer. A value of 1 x 10^{2} 1/d was assigned to the active areas of model layers 2, 3, and 4 northwest of the areas representing the Aquia, Magothy, and Upper Patapsco aquifers, respectively. This relatively high value allows the transfer of recharge water from model layers 1 and 2 (water-table aquifer) to the deeper confined aquifers.

Recharge

Recharge was calculated from baseflow records in four basins within the active portion of model layer 1 (water-table aquifer). The four basins are Sawmill Creek (northern Anne Arundel County), North River (head of South River in central Anne Arundel County), Northwest Branch of the Anacostia River at Riverdale (northern Prince George’s County), and Western Branch at Upper Marlboro (east-central Prince George’s County) (tab. 4). Baseflow was separated from the stream-flow record using two techniques—fixed interval and local-minimum (Pettyjohn and Henning, 1979). The median baseflow for the four basins during the period of stream-flow record are 2.85 x 10^{5}, 6.74 x 10^{5}, 33.6 x 10^{5}, and 39.1 x 10^{5} cubic feet per day (ft^{3}/d) for Sawmill Creek, North River, Northwest

Branch, and Western Branch, respectively. While baseflow fluctuates during the period of record there is no obvious indication of increasing or decreasing trends. Linear recharge rates were estimated by dividing the median baseflow by the approximate drainage area. The resulting recharge rates were as follows: Sawmill Creek, 9.0 inches per year (in/yr); North River, 12.4 in/yr; Northwest Branch of the Anacostia River at Riverdale, 7.2 in/yr; and Western Branch at Upper Marlboro, 6.8 in/yr (tab. 4). Ground-water withdrawals from the Lower Patapsco aquifer in the Sawmill Creek basin can reduce baseflow to Sawmill Creek (Achmad, 1991). Achmad (1991) estimated recharge in the Sawmill Creek basin to be approximately 20.1 in/yr for the period 1944-1952 unaffected by ground-water withdrawals. Baseflow separated using the fixed interval and local-minimum methods for periods 1945-1952 and 1989-2003 unaffected by ground-water withdrawals resulted in median values of 6.28 x 10^5 and 2.79 x 10^5 ft^3/d, respectively, or 19.8 and 8.8 in/yr of recharge (tab. 4).

Recharge was applied to the top of the active portion of model layer 1 (water-table aquifer) (fig. 27). The rate of simulated recharge, adjusted during model calibration, ranges from 9 in/yr in southern Anne Arundel County and eastern Prince George's County to approximately 18 in/yr in northern Anne Arundel County. The rate of recharge was held constant during model simulations.

Table 4. Basins with calculated baseflow and recharge

Basin	U.S. Geological Survey stream gage station identification number	Basin area, square miles	Period of record	Median baseflow, cubic feet per day (x 10^5)	Recharge rate, inch per year
Sawmill Creek	1589500	4.97	1945-2003	2.85	9.0
			1945-1952; 1989-2003	6.28; 2.79	19.8; 8.8
North River (Head of South River)	1590000	8.5	1932-1973	6.74	12.4
Northwest Branch of the Anacostia River at Riverdale	1649500	72.8	1938-2003	33.6	7.2
Western Branch at Upper Marlboro	1594526	89.7	1986-2003	39.1	6.8

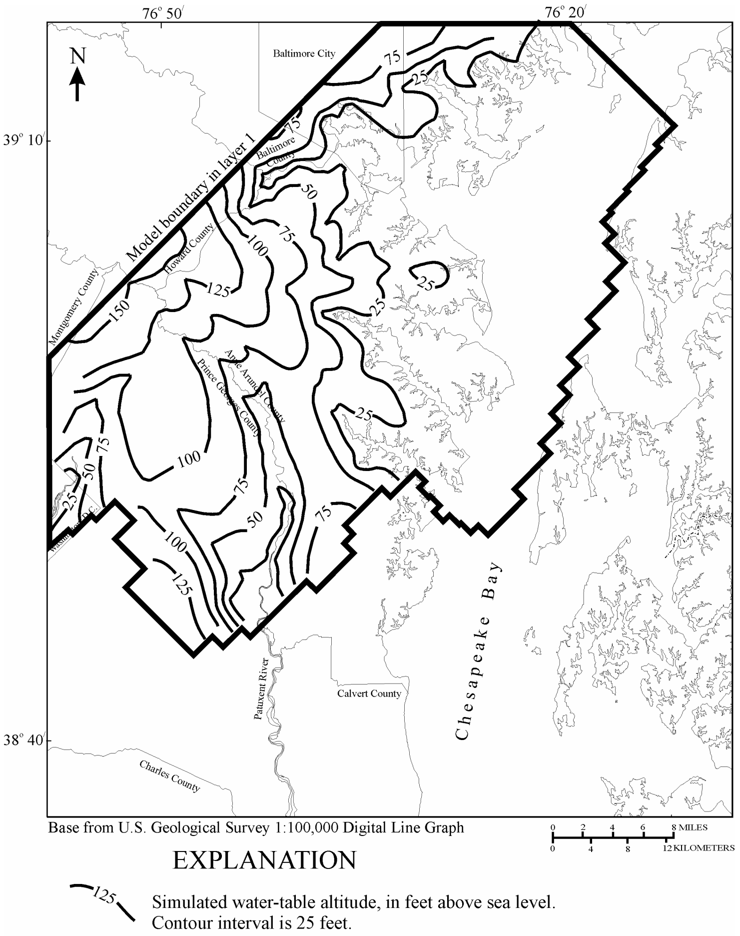


Figure 27. Simulated steady-state, pre-pumping water-table altitude of model layer 1.

Pumpage

Ground-water withdrawals from the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers by users permitted to withdraw more than 10,000 gal/d were simulated in the model. Where model-cell size was sufficiently small, individual pumping wells in well fields were simulated. In those instances withdrawals were divided amongst the individual wells based on the number of pumping wells and the number of model cells used. Withdrawals for appropriated users are given in Appendix B. Withdrawals for the period 1900 to 1969 are estimated average daily withdrawals for 10-year periods, and from 1970 to 1979 are estimated average daily withdrawals for 1-year periods (Wheeler and Wilde, 1989). Beginning in 1979 users having appropriations of more than 10,000 gal/d were required to report monthly withdrawals to the Maryland Department of the Environment. Withdrawals for the period 1979 to 2002 are average daily withdrawals calculated from yearly totals of reported monthly withdrawals.

Most of the water withdrawn from the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers was by public-water suppliers appropriated for more than 10,000 gal/d. A relatively small amount was withdrawn for domestic supply by individual wells. In 2000, approximately 2.7 Mgal/d were withdrawn from individual, domestic wells screened in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers (Judith Wheeler, U.S. Geological Survey, personal communication, 2004). Because domestic withdrawals are relatively small, they were not simulated in the model. The effect of excluding domestic withdrawals on model performance is discussed in the section of this report entitled “Model Calibration and Sensitivity Analysis.”

STEADY-STATE FLOW SIMULATION

A steady-state flow simulation was made to obtain initial water levels for use in the transient-flow model. The steady-state simulation represents pre-pumping (non-pumping) conditions. The simulation also provides information on the overall performance of the model relative to the conceptual model of flow. Parameters assigned to the model, including transmissivity, horizontal hydraulic conductivity, recharge, river-bed conductance, vertical leakance, and general-head boundary heads and conductance, were adjusted until a reasonable head distribution was attained in the water-table and confined aquifers. A lack of pre-pumping head data prevented a more rigorous quantitative model calibration. Simulated pre-pumping water levels in model layer 1 (water-table aquifer) range from as much as 150 ft above sea level in northwestern Anne Arundel County to sea level along the tidal rivers and Chesapeake Bay (fig. 27). Simulated pre-pumping, steady-state potentiometric surfaces of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers range from 80 to 100 ft above sea level near their outcrop areas to less than 20 ft above sea level on the Eastern Shore (fig. 28). The principal direction of natural ground-water flow is toward the southeast. The pre-pumping head distribution in the four aquifers is consistent with other regional ground-water-flow models of these aquifers (Mack and Achmad, 1986; Fleck and Vroblesky, 1996).

TRANSIENT-FLOW SIMULATION

In order to develop a predictive flow model for water-supply analysis, a transient-flow model simulating past withdrawals was constructed and calibrated using historical water-level and baseflow data. The transient model, based initially on the steady-state model, was modified to simulate the period 1900 to 2002. This period was selected because it spans virtually the entire period of ground-water development within the model area. This provided the opportunity to assess the ability of the model to simulate a range of pumping conditions. Also, because ground-water withdrawals were relatively low in 1900, water levels at the start of the transient simulation very likely match those simulated by the non-pumping, steady-state model.

Time Discretization, Initial Heads, and Temporal Boundary Conditions

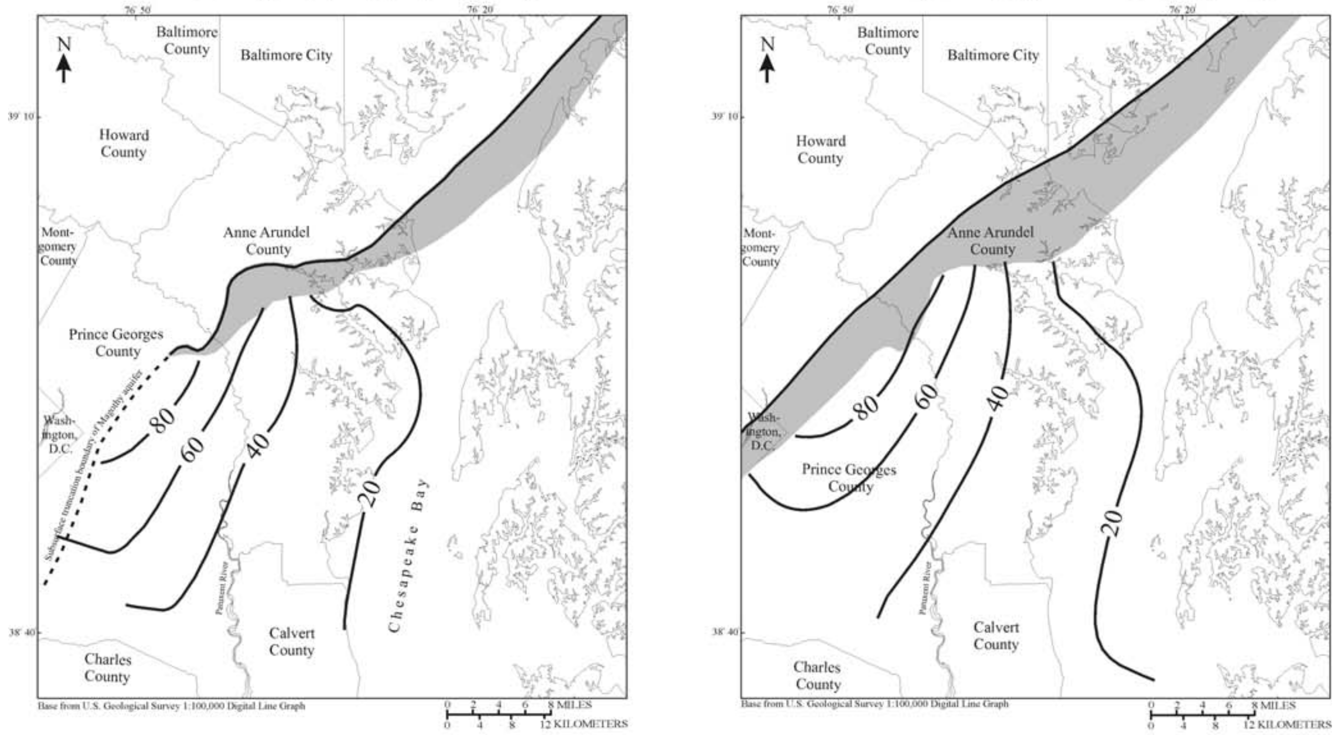
The transient model simulated the historical development of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers from 1900 to 2002. Over that time interval, the transient model was divided into 39 stress periods (tab. 5). The duration of the stress periods was variable. Stress period 1 spanned 20 years, stress periods 2 through 6 spanned 10 years each, and stress periods 7 through 39 spanned 1 year each. Each stress period included the average withdrawals that occurred during that period. The stress periods were divided into two time steps, at the end of which the model solved a set of ground-water-flow equations that produced head output and volumetric budget values. The duration of the stress periods was reduced to 1 year after 1970 because of the increased availability of pumpage records and more frequent water-level data to calibrate the model.

Initial conditions for the transient model—including starting heads in model layers 3 (Magothy aquifer), 4 (Upper Patapsco aquifer), 5 (Lower Patapsco aquifer), and 6 (Patuxent aquifer) and heads along the general-head boundaries in those layers—were taken from the steady-state model.

Boundary conditions that change with time, including specified heads in model layer 2 and general-head boundary heads in layers 3, 4, 5, and 6, were assigned to the transient model. Constant heads representing the Aquia aquifer were specified for stress periods 1 (1900-1919), 4 (1940-1949), 17 (1980), 22 (1985), 27 (1990), 32 (1995), and 39 (2002). Water levels for the following periods were obtained from previous studies: stress periods 4 and 17—Chapelle and Drummond (1983); stress period 22—Mack and others (1987); stress period 27—Mack and others (1992); stress period 32—Curtin and others (1996); and stress period 39—Curtin and others (2003). Water levels for stress period 1 were obtained from the pre-pumping, steady-state model. Water levels were assigned to the general-head boundaries in model layers 3, 4, 5, and 6 for stress periods 1 (1900), 12 (1975), 19 (1982), 23 (1986), 27 (1990), 31 (1994), 35 (1998), and 39 (2002). In general, the changes to the boundary heads reflect declining water levels resulting from increased ground-water withdrawals over the simulation period.

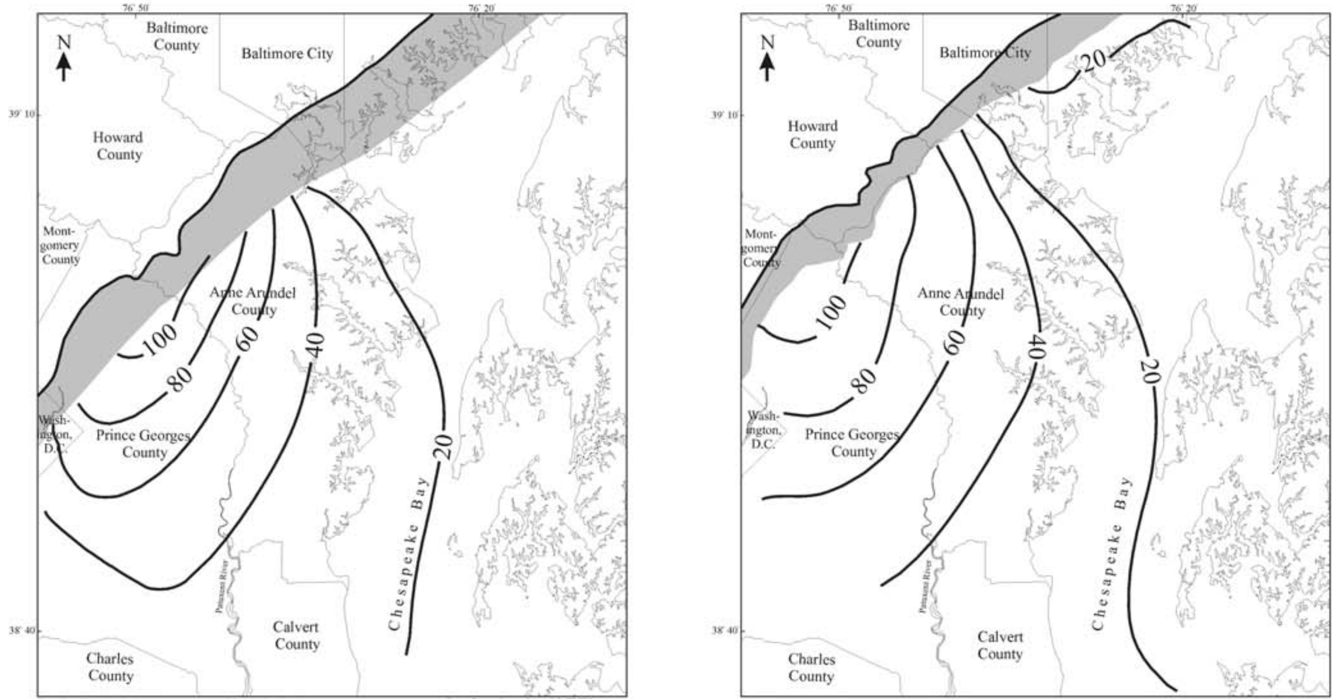
Model layer 3 (Magothy aquifer)

Model layer 4 (Upper Patapsco aquifer)



Model layer 5 (Lower Patapsco aquifer)

Model layer 6 (Patuxent aquifer)



EXPLANATION

— 80 — Potentiometric contour of simulated water levels. Contour interval is 20 feet. Datum is sea level.

▨ Generalized aquifer outcrop area. Line indicates extent of aquifer. Dashed where uncertain.

Figure 28. Simulated potentiometric surfaces of model layers 3 (Magothy aquifer), 4 (Upper Patapsco aquifer), 5 (Lower Patapsco aquifer), and 6 (Patuxent aquifer) for steady-state, pre-pumping conditions.

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

Stress period	Period	Duration of stress period, years
1	1900-1919	20
2	1920-1929	10
3	1930-1939	10
4	1940-1949	10
5	1950-1959	10
6	1960-1969	10
7 - 39	1970-2002	1

Model Calibration and Sensitivity Analysis

Model parameters were varied systematically in an iterative process until simulated heads and baseflow reasonably matched observed heads and baseflow. Successive model runs were completed after independently varying recharge to model layer 1, river-bottom vertical hydraulic conductivity in model layer 1, horizontal hydraulic conductivity and storage coefficient of model layer 1, transmissivity of model layers 2 through 6, general-head boundary conductance in model layers 3 through 6, vertical leakance between model layers 1 through 6, and storage coefficient of model layers 2 through 6. The steady-state model, which simulated pre-pumping conditions, was periodically re-run to verify the results using the adjusted parameters.

The model was considered calibrated when the lowest value of the root-mean-square error was obtained between the simulated and observed water levels (Anderson and Woessner, 1992). Simulated water levels were compared to observed water levels from 62 observation wells (20 Magothy wells, 15 Upper Patapsco wells, 14 Lower Patapsco wells, and 13 Patuxent wells) (tab. 6). The wells are located throughout the model area; however, the greatest concentration occurs in Anne Arundel County (fig. 29). The lowest root-mean-square error obtained was 9.34 ft. Simulated water levels at the end of the simulation period (1900-2002) were compared to water levels measured during the Fall of 2002 in the 62 observation wells (fig. 30). The slope of the first order linear regression (Y= mX + b) was 0.93. The correlation coefficient of the simulated and observed water levels was 0.96, which is considered a good fit. The mean of the absolute difference between simulated and observed water levels was 5.3, 5.6, 7.8, and 10.1 ft in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively. The median of the absolute difference between simulated and observed water levels was 4.6, 4.8, 7.8, and 5.1 ft in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively.

Simulated water levels were plotted along with observed water levels for eight observation wells in each of the four aquifers (figs. 31 through 34). Simulated water levels matched the general water-level trends in most of the observation wells. The stair-step pattern visible on some hydrographs resulted from changes in water levels assigned to the general-head boundaries. In general, the greatest difference between simulated and observed water levels occurred in central Prince George’s County (PG De 33 and PG Ed 34) where information regarding the hydraulic characteristics (primarily transmissivity and vertical leakance) of the aquifers is relatively sparse, and, therefore, model calibration may be less accurate (figs. 32 and 33).

Simulated baseflow at the end of stress period 39 (2002) in four basins were compared to the median baseflow calculated from the stream-flow records. In general, simulated baseflow was in fairly good agreement with measured baseflow. However, the relative absence of head data in the water-table aquifer prevents a full calibration of baseflow. Simulated baseflow was 8 percent greater at Sawmill Creek, 2 percent greater at Northwest Branch of the Anacostia River at Riverdate, and 14 percent lower at Western Branch at Upper Marlboro compared to measured baseflow (fig. 35). Simulated baseflow matched measured baseflow at North River (fig. 35). Lower Patapsco pumpage in the Dorsey Road and Sawmill Creek well fields in northern Anne Arundel County significantly affect baseflow in Sawmill Creek (Achmad, 1991). To restore baseflow in Sawmill Creek to natural levels, withdrawals from the Lower Patapsco aquifer in those well fields were stopped in 1989. Therefore, simulated baseflow in Sawmill Creek for stress period 39 (2002) was compared to available measured baseflow unaffected by withdrawals from the Lower Patapsco aquifer. The periods of record for measured baseflow unaffected by withdrawals are 1945-1951 and 1989-2003. The simulated baseflow in 2002 equaled 3.00 x 10^5 ft^3/d compared to median values of 6.28 x 10^5 and 2.79 x 10^5 ft^3/d for the measured data. The simulated data matched fairly well with the more recent baseflow data, but was significantly lower than the earlier data. The discrepancy may, in part, be attributed to differences in recharge from precipitation between the two periods.

Table 6. Comparison of observed and simulated water levels (2002)

[County abbreviations are listed on abbreviations for appendixes, p. 81]

Well number	Model cell (row, column, layer)	Observed water level, feet related to sea level	Simulated water level, feet related to sea level	Absolute difference between observed and simulated water levels, feet
Magothy aquifer				
AA Cc 117	84,44,3	48.52	49.02	0.50
AA Cd 78	59,49,3	37.46	35.95	1.51
AA Ce 114	52,74,3	-8.86	-12.29	3.43
AA Cf 99	35,87,3	-10.04	-16.07	6.03
AA Cg 8	24,94,3	-11.35	-13.66	2.31
AA Dd 42	88,69,3	9.81	8.22	1.59
AA De 103	85,93,3	-6.14	-8.64	2.50
AA Df 79	54,92,3	-9.75	-15.59	5.84
AA Ed 39	96,93,3	-0.72	-1.45	0.73
AA Fe 47	95,100,3	-9.65	-17.82	8.17
CA Bb 10	103,105,3	-30.56	-34.41	3.85
CA Bb 23	102,99,3	-17.44	-23.08	5.64
CA Cc 56	102,108,3	-32.07	-34.22	2.15
KE Cb 97	2,95,3	7.23	2.03	5.20
PG Cf 33	96,47,3	47.56	51.55	3.99
PG De 21	102,67,3	35.23	24.27	10.96
PG Ed 50	106,67,3	19.74	-0.60	20.34
PG Fe 30	106,91,3	-3.68	-12.01	8.33
PG Gf 35	106,102,3	-29.07	-34.61	5.54
QA Ea 27	28,100,3	-12.44	-18.91	6.47
Upper Patapsco aquifer				
AA Bd 159	46,33,4	38.79	51.43	12.64
AA Bd 99	46,39,4	49.96	37.23	12.73
AA Be 102	26,57,4	11.24	17.07	5.83
AA Bf 3	14,46,4	7.60	2.80	4.80
AA Ce 120	54,58,4	7.96	7.34	0.62
AA Ce 70	51,80,4	-12.28	-14.86	2.58
AA Cf 121	27,91,4	-16.18	-13.78	2.40
AA De 128	86,92,4	-5.28	-7.01	1.73
AA De 95	63,81,4	-5.32	-13.41	8.09
AA Df 19	45,94,4	-10.38	-16.64	6.26
AA Ec 12	100,90,4	2.21	3.34	1.13
KE Cb 36	1,91,4	-1.95	-0.82	1.13
KE Db 40	5,95,4	-5.69	-5.81	0.12
PG De 33	102,58,4	55.17	39.21	15.96
QA Eb 111	19,102,4	-12.91	-20.86	7.95
Lower Patapsco aquifer				
AA Ad 102	33,13,5	70.21	60.58	9.63
AA Ad 109	31,20,5	40.27	49.34	9.07
AA Bd 109	45,24,5	66.02	56.84	9.18
AA Bd 157	46,33,5	39.37	30.45	8.92
AA Cc 115	84,44,5	2.98	0.25	2.73
AA Cc 40	76,29,5	90.51	75.87	14.64
AA Ce 94	48,50,5	-85.76	-77.23	8.53
AA Cf 137	39,80,5	-31.80	-33.87	2.07
AA Cg 23	24,94,5	-16.68	-14.38	2.30
AA De 177	63,80,5	-37.21	-32.64	4.57
PG Be 14	95,18,5	112.18	105.18	7.00
PG Cf 44	94,39,5	41.32	46.06	4.74
PG Ed 34	105,56,5	1.05	24.81	23.76
QA Eb 112	19,102,5	-17.54	-19.59	2.05
Patuxent aquifer				
BC 5S2E24	17,12,6	14.21	7.90	6.31
AA Ac 11	38,10,6	4.00	0.95	3.05
AA Ad 29	28,21,6	-43.11	-38.00	5.11
AA Cb 1	93,23,6	36.23	40.38	4.15
AA Cc 102	92,42,6	-16.83	4.38	21.21
AA Cc 80	69,33,6	42.89	15.65	27.24
AA Ce 117	48,50,6	-6.04	-1.70	4.34
AA Cg 22	24,94,6	-8.09	-7.79	0.30
AA De 203	63,80,6	-9.10	-4.20	4.90
BA Gf 11	11,33,6	-34.37	-35.39	1.02
PG Be 23	94,25,6	22.90	46.47	23.57
PG Cf 66	97,43,6	-1.22	16.97	18.19
QA Eb 110	19,102,6	3.61	-8.09	11.70

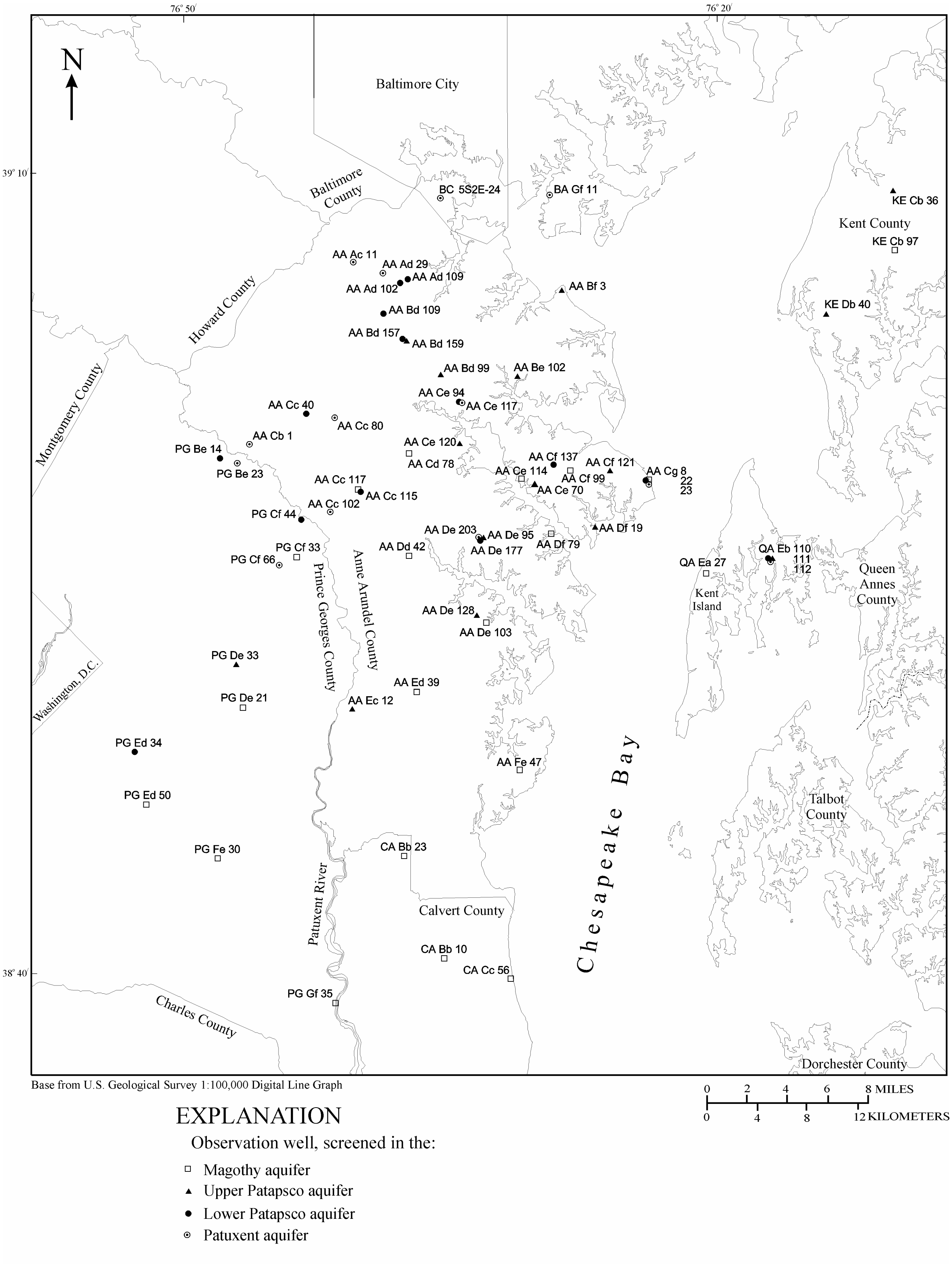


Figure 29. Location of wells with long-term water-level record used in model calibration.

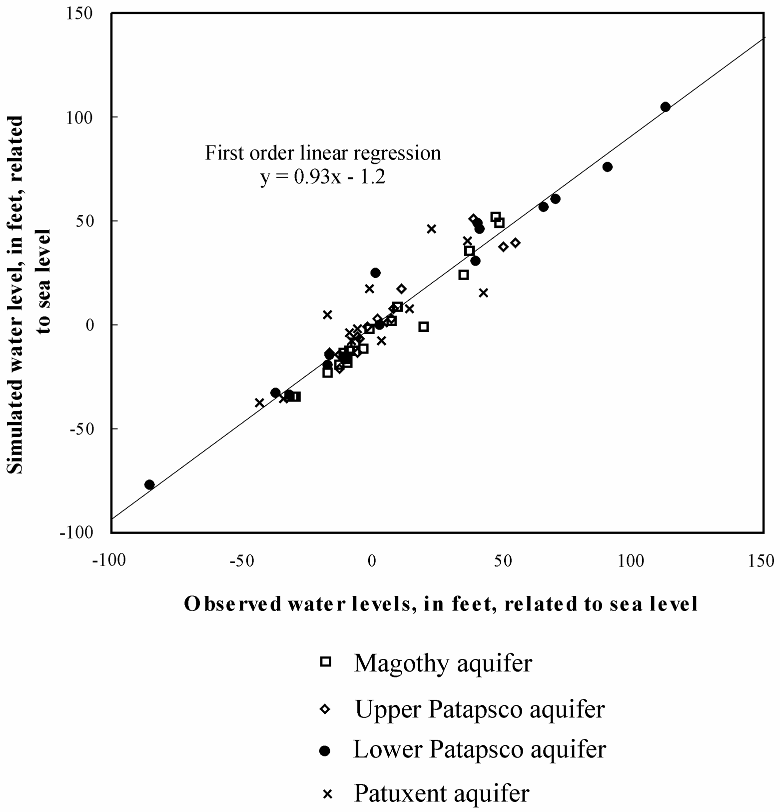


Figure 30. Relation between observed and simulated water levels in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers at the end of the simulation period 1900-2002.

Under pre-pumping, steady-state conditions, recharge to the confined aquifers from the outcrop areas was approximately 0.03, 0.2, 0.2, and 0.3 in/yr for the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively. The rate increased to 0.4, 0.7, 0.8, and 0.9 in/yr in 1950, and to 1.8, 1.6, 1.6, and 1.7 in/yr at the end of the transient simulation period (2002) caused by increased withdrawals from the confined aquifers.

The sensitivity of the model to global changes in model input parameters was tested by running the calibrated model with each changed parameter and comparing its affect on model output (fig. 36). Model output was measured in terms of the root-mean-square error between the simulated and observed water levels at observation wells in model layers 3, 4, 5, and 6. The purpose of the sensitivity analysis was to determine the degree to which uncertainty in model input parameters affect simulated water levels. The model was most sensitive to transmissivity and pumpage (model layers 3, 4, 5, and 6) and less sensitive to leakance between aquifers, horizontal hydraulic conductivity of model layer 1 (water-table aquifer), general-head boundary hydraulic conductance (model layers 3, 4, 5, and 6), river-bottom vertical hydraulic conductivity, applied recharge in model layer 1, and storage coefficient of model layers 3, 4, 5, and 6.

Self-supplied, domestic withdrawals from the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers were not included in the model because the effects of those withdrawals on the flow system were considered minimal. To determine the effect that domestic withdrawals have on simulated head, the calibrated model was run with an additional 2.7 Mgal/d pumped from the Magothy, Upper Patapsco, and Lower Patapsco aquifers. The domestic withdrawals were evenly divided between the three aquifers and assigned to the model in areas not served by public water in central and northern

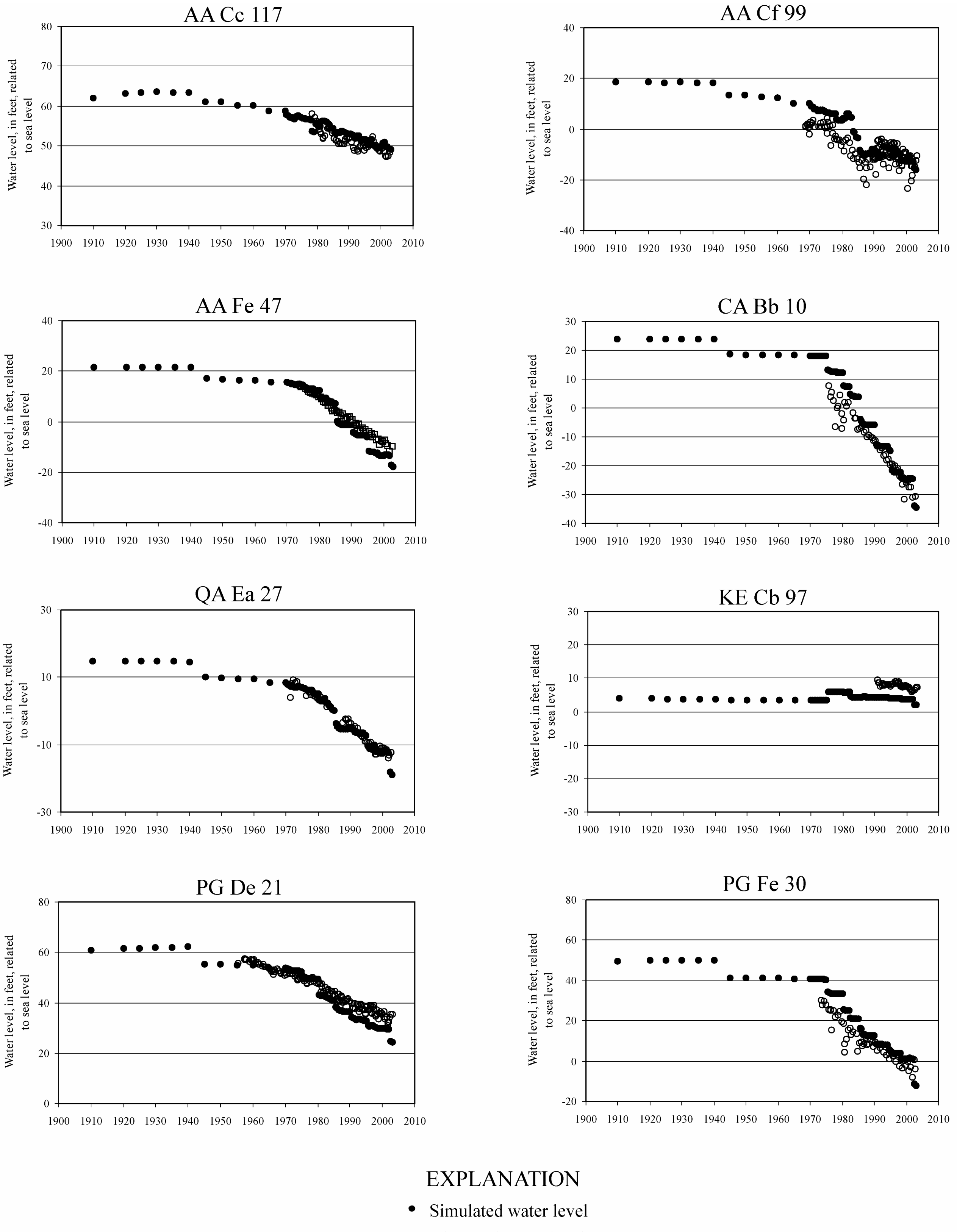


Figure 31. Hydrographs of observed and simulated water levels in wells screened in the Magothy aquifer, 1900-2002.

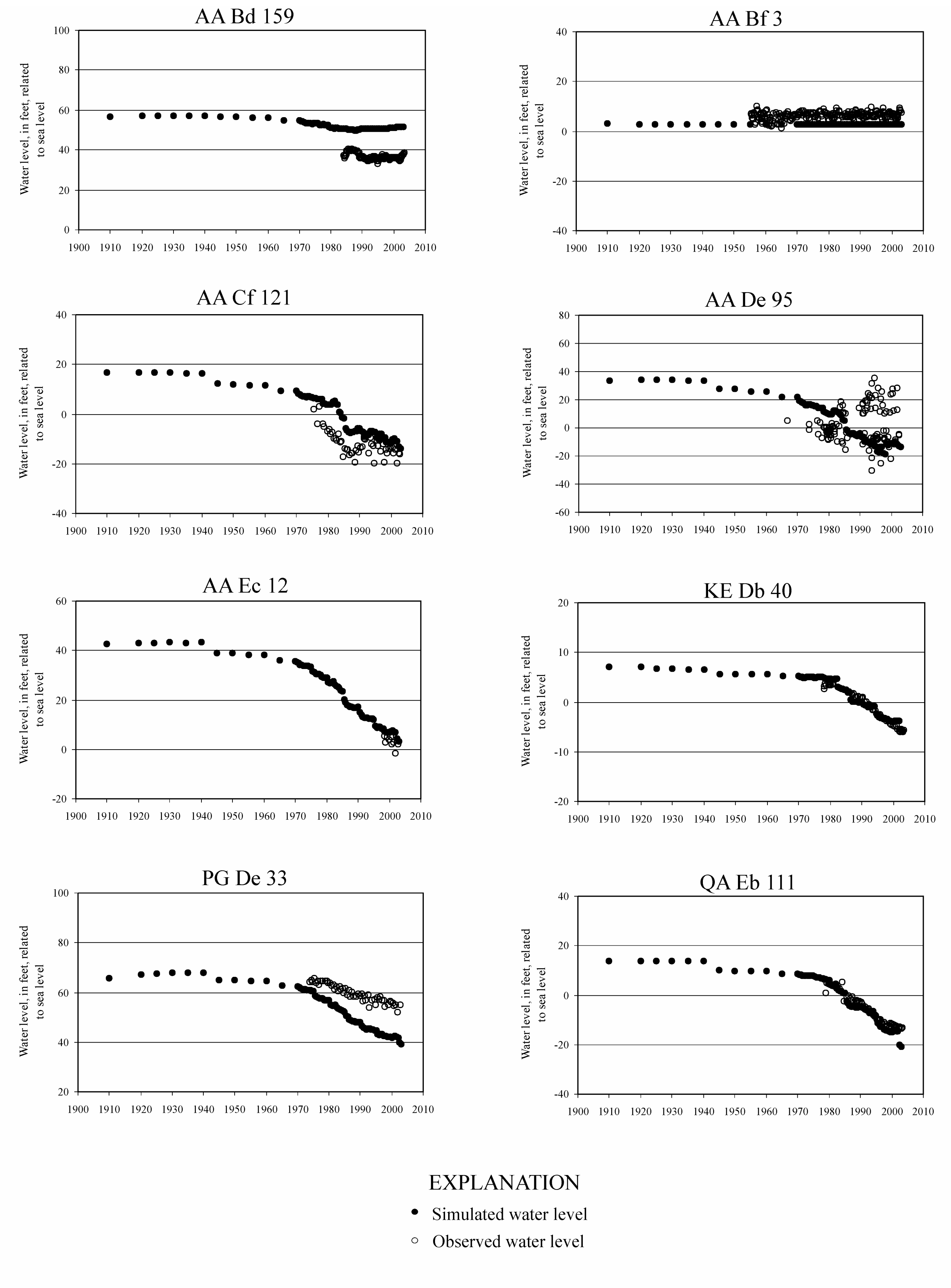


Figure 32. Hydrographs of observed and simulated water levels in wells screened in the Upper Patapsco aquifer, 1900-2002.

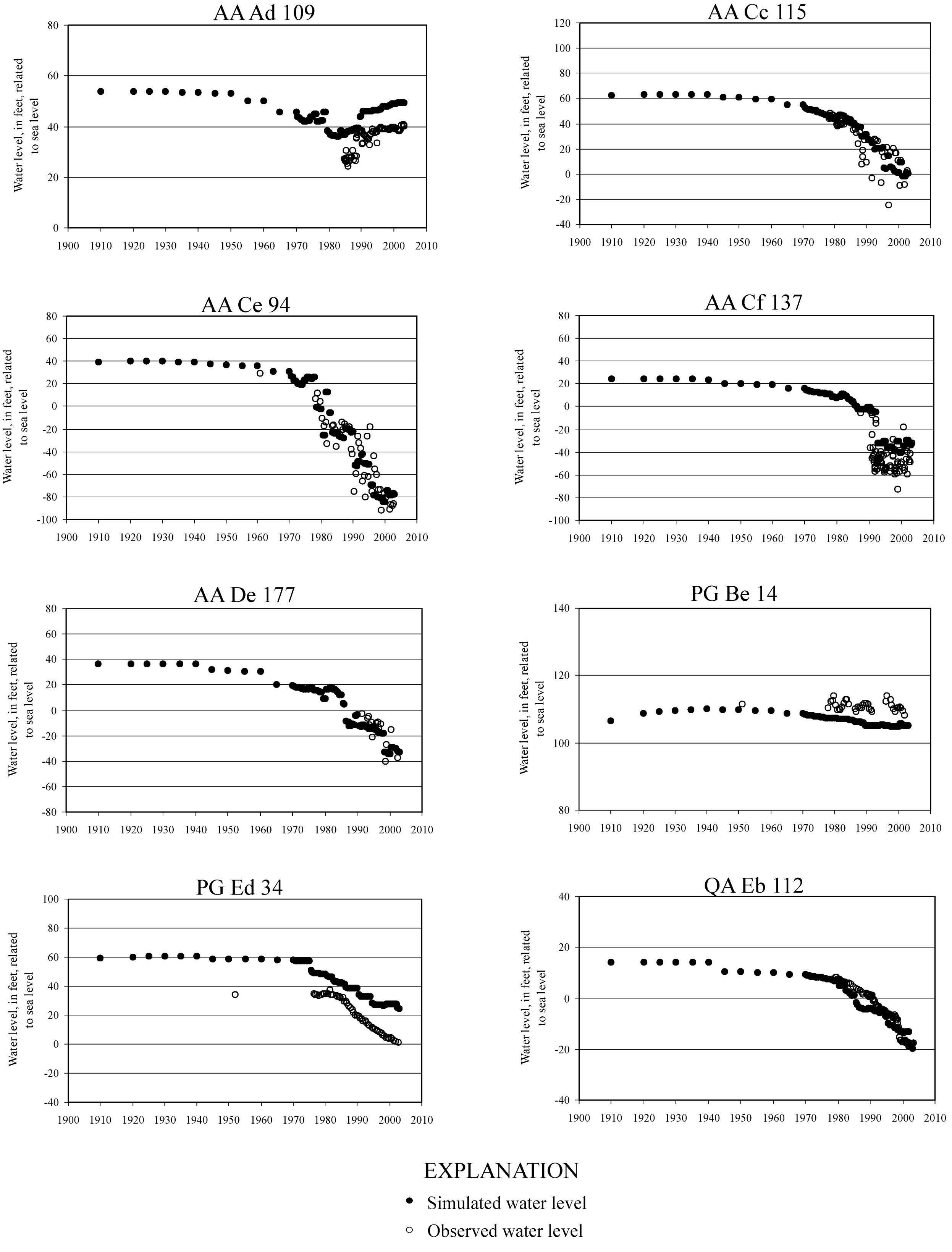


Figure 33. Hydrographs of observed and simulated water levels in wells screened in the Lower Patapsco aquifer, 1900-2002.

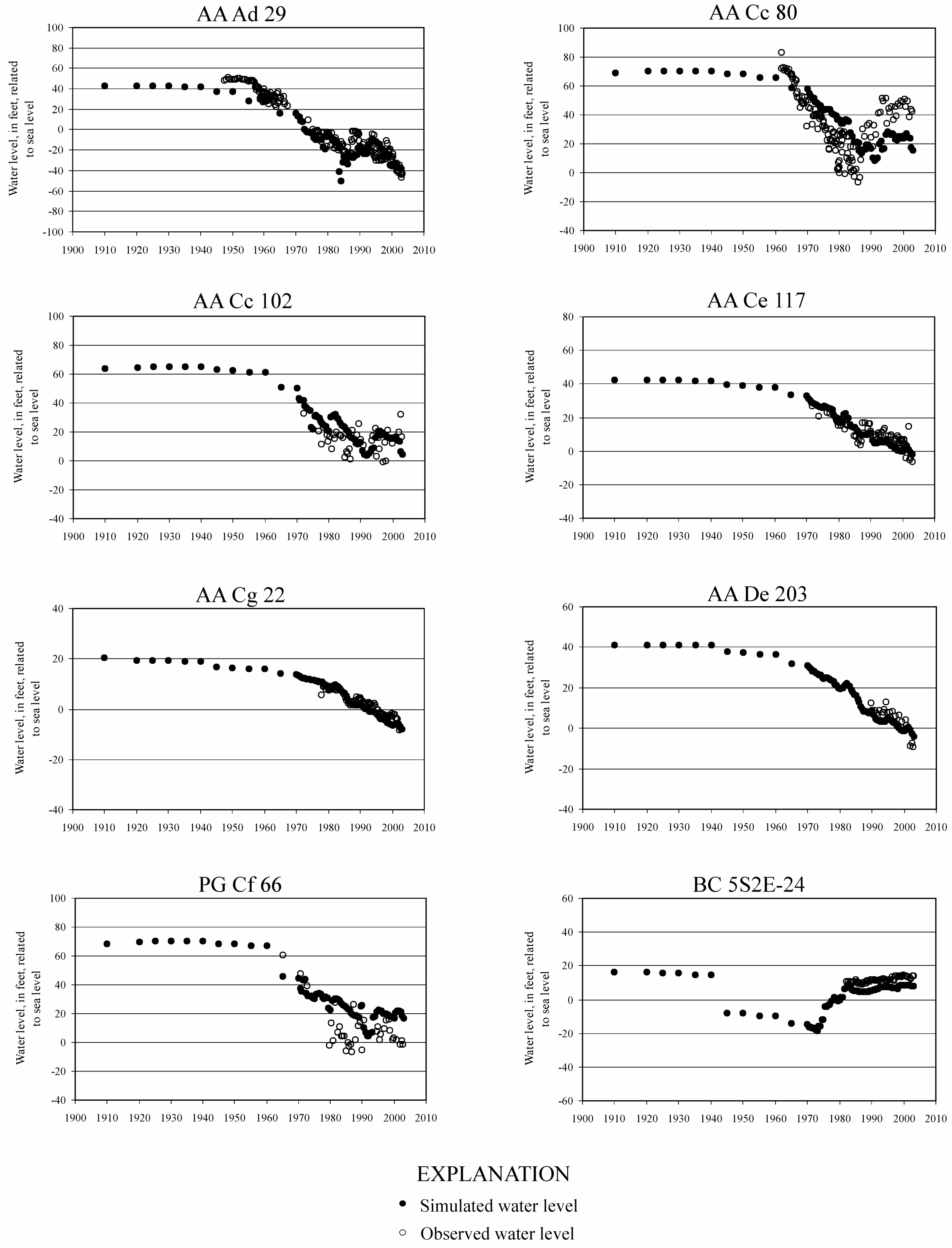


Figure 34. Hydrographs of observed and simulated water levels in wells screened in the Patuxent aquifer, 1900-2002.

Stream gage	Measured baseflow, ft³/d	Simulated annual average baseflow (2002), ft³/d	Percent difference
Sawmill Creek	2.79×10^5	3.00×10^5	8
North River	6.74×10^5	6.76×10^5	0
Northwest Branch of Anacostia River at Riverdale	3.36×10^6	3.30×10^6	2
Western Branch at Upper Marlboro	3.91×10^6	4.44×10^6	14

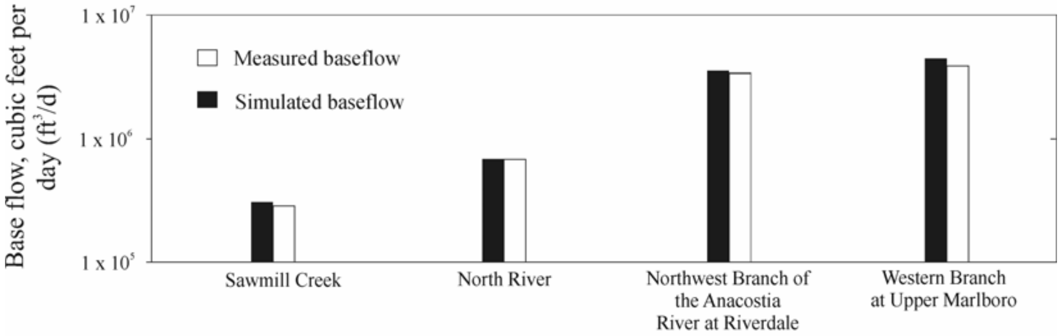


Figure 35. Comparison of simulated and measured annual average baseflow in 2002 in four streams.

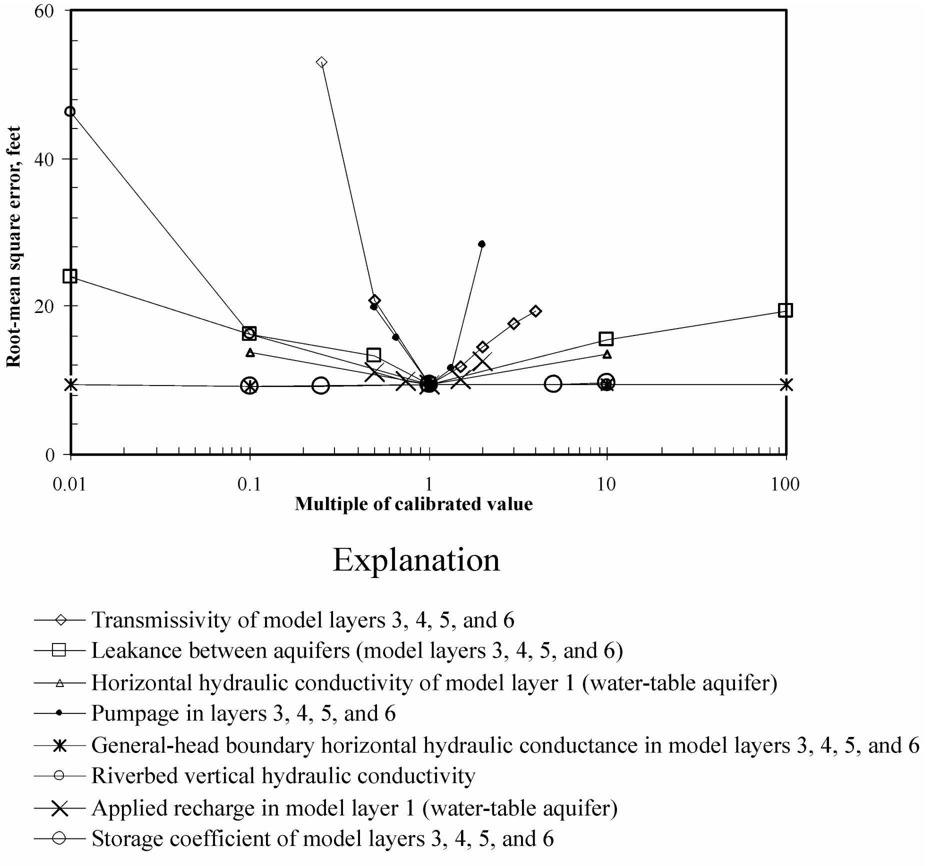


Figure 36. Effects of varying model parameters on simulated water-level match.

Anne Arundel County. No domestic withdrawals were simulated in the Patuxent aquifer because most of the area where the Patuxent aquifer is shallow enough to be utilized for domestic supply is served by public water. A comparison of both the root-mean-square error and the slope of the first order linear regression with and without the domestic withdrawals showed negligible differences.

Water Budget

The budget for each model layer was calculated at the end of the transient simulation period 1900-2002 (stress period 39) (fig. 37). The budget describes the movement of water into and out of each model layer. Sources of flow into the model included recharge, general-head boundaries, and aquifer storage. Sinks or flow out of the model included wells, general-head boundaries, rivers, and constant-head boundaries. Constant-head boundaries consisted of tidal rivers and the Chesapeake Bay.

In model layer 1 and part of model layer 2 representing the water-table aquifer, total inflow from recharge equaled 6.35 x 10^7 ft^3/d. Of that amount, approximately 58 percent discharged to rivers, 29 percent discharged to constant-head boundaries, and 12.9 percent recharged the deep confined aquifers. A relatively small percentage entered storage, resulting mostly from a few model cells representing rivers that had simulated model-cell heads slightly below the specified river stage.

In model layer 3 (Magothy aquifer), net inflow from recharge through the outcrop area, general-head boundaries, upward leakage from model layer 4 (Upper Patapsco aquifer), and storage equaled 2.42 x 10^6 ft^3/d. Of the total amount of net inflow approximately 57 percent entered as recharge, 23 percent flowed upward from model layer 4 (Upper Patapsco aquifer), 20 percent entered from general-head boundaries, and 0.4 percent entered from storage. The net inflow was balanced by an equal amount of net outflow. Of the total amount of net outflow approximately 76.5 percent flowed upward to the part of model layer 2 representing the Aquia aquifer, and 23.5 percent discharged to wells.

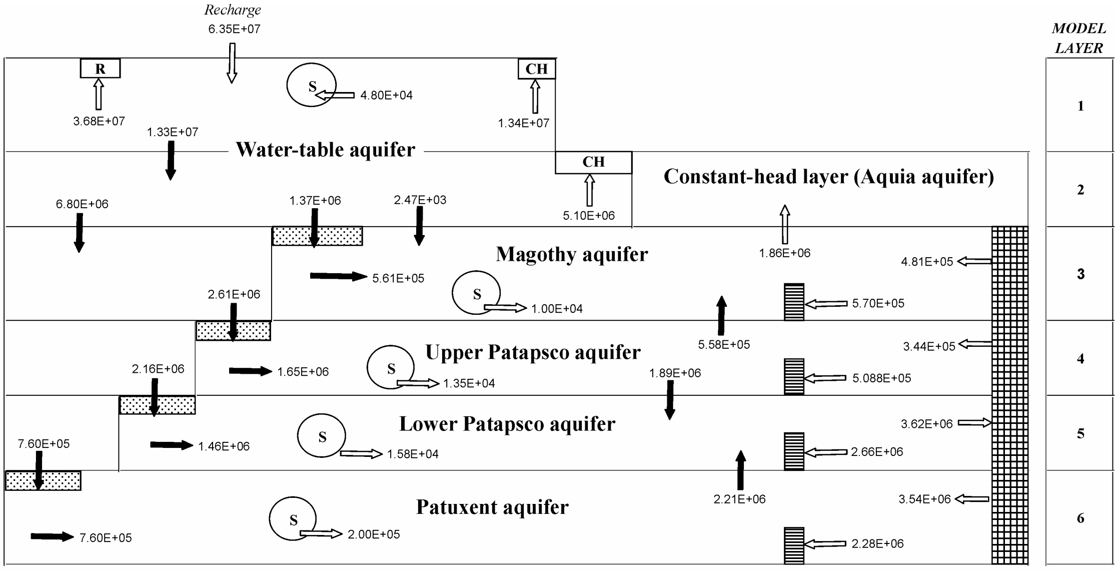
In model layer 4 (Upper Patapsco aquifer), net inflow from recharge through the outcrop area, general-head boundaries, and storage equaled 2.97 x 10^6 ft^3/d. Out of the total amount of net inflow approximately 88 percent entered from recharge, 11.6 percent entered from general-head boundaries, and 0.5 percent entered from storage. The net inflow was balanced by an equal amount of net outflow. Of the total amount of net outflow approximately 63.0 percent flowed downward to model layer 5 (Lower Patapsco aquifer), 18.9 percent flowed upward to model layer 3 (Magothy aquifer), and 17.2 percent discharged to wells.

In model layer 5 (Lower Patapsco aquifer), net inflow from recharge through the outcrop area, downward leakage from model layer 4 (Lower Patapsco aquifer), upward leakage from model layer 6 (Patuxent aquifer), and storage equaled 6.26 x 10^6 ft^3/d. Of the total amount of net inflow approximately 34 percent entered from recharge, 35 percent flowed upward from model layer 6 (Patuxent aquifer), 30 percent flowed downward from model layer 4 (Upper Patapsco aquifer), and 0.3 percent entered from storage. The net inflow was balanced by an equal amount of net outflow. Of the total amount of net outflow approximately 57.6 percent flowed to general-head boundaries and 42.4 percent flowed to wells.

In model layer 6 (Patuxent aquifer), net inflow from recharge through the outcrop area, general-head boundaries, and storage equaled 4.5 x 10^6 ft^3/d. Of the total amount of net inflow approximately 78.7 percent entered from general-head boundaries, 16.9 percent entered from recharge, and 4.4 percent entered from storage. The net inflow was balanced by an equal amount of net outflow. Of the total amount of net outflow approximately 50.8 percent discharged to wells, and 49.2 percent flowed upward to model layer 5 (Lower Patapsco aquifer).

OPTIMIZED WITHDRAWALS FROM ANNE ARUNDEL COUNTY PUBLIC-SUPPLY WELLS IN THE UPPER PATAPSCO, LOWER PATAPSCO, AND PATUXENT AQUIFERS

A withdrawal scenario for the period 2005-2044 was modeled that minimized regional drawdown near the Anne Arundel County Department of Public Works' well fields while supplying projected average-day demands. To determine the effect of maximum-day withdrawals on water levels, a second scenario was modeled using the optimized 2040 withdrawals over a 1-year period. The *Comprehensive Water Strategic Plan* (O'Brien and Gere, 2003) formed the basis of the demand projections. In the *Comprehensive Water Strategic*



WATER BUDGET

Model layer	Flow, cubic feet per day		Difference, in percent
1 and 2 (Water-table aquifer)	IN	6.35E+07	0.0
	OUT	6.35E+07	
3	IN	2.42E+06	-0.4
	OUT	2.43E+06	
4	IN	2.97E+06	0.4
	OUT	2.96E+06	
5	IN	6.26E+06	-0.3
	OUT	6.28E+06	
6	IN	4.50E+06	0.2
	OUT	4.49E+06	

EXPLANATION

- ⇩ Net Inflow
- ⇧ Net Outflow
- ⬇ Net flow between model layers
- CH Constant-head boundary
- ▦ General-head boundary
- Ⓢ Storage
- ▨ Recharge area -- confined aquifer
- ▤ Well
- R River

E, exponential notation (x10)

Figure 37. Water budget at the end of transient simulation period 1900-2002.

Plan, the total projected 2043 water demand supplied by the Anne Arundel County Department of Public Works was 67.2 Mgal/d (average day) and 130.7 Mgal/d (maximum day), which included Gibson Island and Herald Harbor, but not Rose Haven. The total projected 2043 water demand was approximately 66.7 Mgal/d (average day) and 129.7 Mgal/d (maximum day), excluding Gibson Island, Herald Harbor, and Rose Haven. In the *Comprehensive Water Strategic Plan,* the maximum-day demand by 2043 supplied by the county's well fields (excluding Gibson Island, Herald Harbor, and Rose Haven) was 110.0 Mgal/d (maximum day), and water purchased from the City of Baltimore by 2043 was 19.7 Mgal/d (maximum day). An earlier water-supply study of the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers in Anne Arundel County by Mack and Achmad (1986) evaluated the potential for increased development of those aquifers. That study addressed only average-day demands. However, more recent information regarding aquifer characteristics, combined with more robust modeling techniques, provided an opportunity to reevaluate the water-supply capacity. To ensure that the aquifers in Anne Arundel County are capable of meeting demand, the Baltimore City supply was replaced by ground-water supply after 2025. The total demand by 2040 used in this ground-water study from the county's well fields (excluding Gibson Island, Herald Harbor, and Rose Haven) was 73 Mgal/d (average day) and 140 Mgal/d (maximum day), which is slightly greater than the *Comprehensive Water Strategic Plan* projection to account for 10 percent leakage in the distribution system.

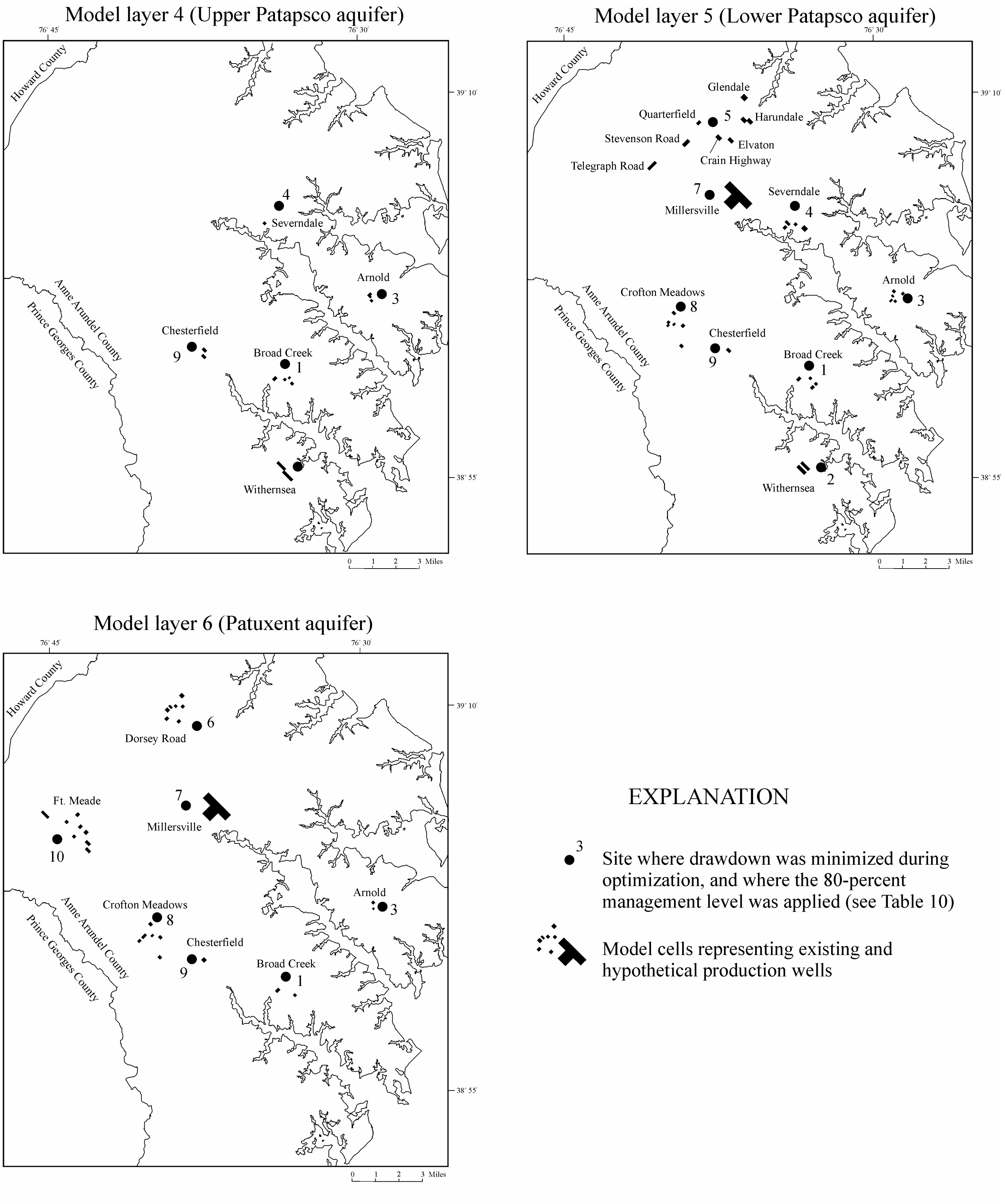
To include withdrawals both from within Anne Arundel County and from the neighboring counties and Baltimore City, a relatively large area was modeled. As a result, the level of finite-difference discretization of the model prevented the precise simulation of ground-water flow between closely spaced pumping wells. The model, therefore, was not intended for site-specific well-field design. Optimizing well, water treatment, and distribution system construction costs were also beyond the scope of this study. Optimization was performed using the three-dimensional, numerical ground-water-flow model developed for this study in conjunction with the ground-water management code MODMAN (Greenwald, 1998) and linear programming code SuperLINDO (SuperLINDO, 2002). The optimization method is discussed in detail in Greenwald (1998). While the ground-water-flow model used in this study optimized withdrawals based on specific water-demand projections, it could be modified in the future to test alternate withdrawal scenarios.

Optimized Withdrawals to Meet Projected 2040 Average-Day Demand

Optimizing Withdrawals to Minimize Regional Drawdown

The objective of this scenario was to supply the projected water demand during the period 2005 to 2044 while minimizing the maximum regional drawdown in the Anne Arundel County Department of Public Works' well fields. The projected demands were based on the 2003 *Comprehensive Water Strategic Plan* (O'Brien and Gere, 2003), but with the exception of assuming independence from the Baltimore City water supply by 2025. Approximately 7 Mgal/d (average day) was obtained from Baltimore City for use in the northern part of the county in 2004. The simulation period was divided evenly into eight 5-year stress periods. Drawdown was minimized in each of the eight stress periods (5-year intervals) from 2005 to 2044 in selected model cells near each well field (fig. 38). The locations were chosen to represent the cumulative, regional effect of drawdown resulting from the individual production wells within each well field. The greatest amount of drawdown at those locations was 106 ft by 2044; that is to say, water levels declined by as much as 106 ft between 2005 and 2044. During optimization each well or well field was required to pump a specified amount identified by the *Comprehensive Water Strategic Plan* based on distribution and water-treatment plant capacities (tab. 7). Hypothetical wells were added as both average-day and maximum-day demand requirements increased. To minimize the maximum regional drawdown while pumping the projected withdrawal rates, pumpage from the individual production wells was optimized. A series of balance constraints were applied in each stress period, such that each well or well field pumped the required amount. In this scenario, a total of 73 Mgal/d (average day) was withdrawn by 2040 from well fields located in four of Anne Arundel County's pressure zones: Broad Creek, Broadneck/Glen Burnie Low, Glen Burnie High, and Crofton (fig. 1). With the exception of Broad Creek, Gibson Island, Herald Harbor, and Rose Haven pressure zones, the county's water-distribution system is interconnected, and water can be transferred between zones. Gibson Island, Herald Harbor, and Rose Haven were not included in this study.

To meet projected average-day and maximum-day demands without supply from Baltimore City, hypothetical wells were added to existing well fields in the Broad Creek, Broadneck/Glen Burnie Low, and Crofton pressure zones (tab. 7; pl. 1). Additionally, a well field was added in the vicinity of the Millersville Central Water Facility (Millersville well field) in the Glen Burnie High zone (fig. 1; pl. 1). This well field consolidates the smaller Brookfield, Marley Creek, Olde Mill, and New Cut well fields that were proposed in the 2003 *Comprehensive Water Strategic Plan*. The Millersville well field is similar in location to the hypothetical New Cut well field discussed in the 2003 *Comprehensive Water Strategic Plan*. It was located further to the south from the New Cut location to lessen interference with the Dorsey Road well field, and because there is more available drawdown at that site. Aquifer hydraulic properties would need to be determined at this site to verify its suitability for a well field. The well field consists of eight wells (four in the Lower Patapsco aquifer and four in the Patuxent aquifer). Remote well fields also were added to the Broad Creek zone near Edgewater (Withernsea well field) and to the Crofton zone near the existing Crofton Meadows well field (Chesterfield well field) (fig. 1; pl. 1). While the model was capable of selecting well locations that would result in the least amount of drawdown, the locations of the hypothetical wells were based primarily on practical considerations, such as available public property and distance to water-distribution lines. To allow for a standby well, the highest yielding well within each pressure zone was assumed to be turned off when calculating

 Model layer 4 (Upper Patapsco aquifer)

Model layer 5 (Lower Patapsco aquifer)

Model layer 6 (Patuxent aquifer)

EXPLANATION

3 ● Site where drawdown was minimized during optimization, and where the 80-percent management level was applied (see Table 10)

Model cells representing existing and hypothetical production wells

Figure 38. Location of model cells representing existing and hypothetical production wells and sites where drawdown was minimized during optimization, and where the 80-precent management level was applied.

Table 7. Average-day withdrawal demands used in optimization simulation

[County abbreviations are listed on abbreviations for appendixes, p. 81]

Design rate, million gallons per day	Water pressure zone	Well field (see Plate 1 for location)	Well	Aquifer	Model cell (row, column, layer)	Average-day withdrawal demand in stress period, million gallons per day (number in parentheses is maximum-day withdrawal)							
						1 2005-2009	2 2010-2014	3 2015-2019	4 2020-2024	5 2025-2029	6 2030-2034	7 2035-2039	8 2040-2044
0.87	Broad Creek	Broad Creek	AA De 96	Upper Patapsco	62,81,4	3.9 (6.1)	3.9 (6.1)	3.9 (8)	7.9 (12)	12 (20)	12 (20)	12 (20)	12 (20)
1.15			AA De 97		64,80,4								
1.44			AA De 136		66,77,4								
3.10			AA De 177	Lower Patapsco	63,80,5								
3.60			AA De 208		65,84,5								
1.15			Hypothetical well 1	Upper Patapsco	63,84,4	▨	▨						
3.10			Hypothetical well 2	Lower Patapsco	63,84,5	▨	▨						
3.10			Hypothetical well 4		66,77,5	▨	▨	▨					
3.10			Hypothetical well 3	Patuxent	63,84,6	▨	▨	▨	▨				
3.10			Hypothetical well 5		66,77,6	▨	▨	▨	▨				
3.10		Withernsea	Hypothetical well 1	Upper Patapsco	86,92,4	▨	▨	▨	▨	▨	▨	1.5 (5)	3.5 (12)
3.10			Hypothetical well 3		86,92,5	▨	▨	▨	▨	▨	▨		
3.10			Hypothetical well 4	Lower Patapsco	87,93,4	▨	▨	▨	▨	▨	▨	▨	
3.10			Hypothetical well 2		88,92,5	▨	▨	▨	▨	▨	▨	▨	
					Total	**3.9**	**3.9**	**3.9**	**12**	**12**	**12**	**13.5**	**15.5**
1.08	Broadneck/ Glen Burnie Low	Arnold	AA Cf 118	Upper Patapsco	39,80,4	3.7 (8)	9.6 (16)	9.6 (16)	9.6 (16)	9.6 (16)	9.6 (16)	12 (20)	12 (20)
1.29			AA Cf 119		40,80,4								
1.29			AA Cf 120		40,81,4								
1.44			AA Cf 155		41,83,4								
2.88			AA Cf 142	Lower Patapsco	40,80,5								
3.46			AA Cf 150		41,83,5								
3.17			Hypothetical well 1	Lower Patapsco	42,81,5	▨							
3.17			Hypothetical well 2		38,79,5	▨							
3.17			Hypothetical well 4		36,83,5	▨							
1.50			Hypothetical well 5	Patuxent	40,81,6								
1.50			Hypothetical well 3		38,79,6	▨							
					Total	**3.7**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**12**	**12**
0.43	Broadneck/ Glen Burnie Low	Severndale	AA Ce 96	Upper Patapsco	48,50,4	5 (8)	5 (8)	5 (8)	4.8 (8)	4.8 (8)	4.8 (8)	4.8 (8)	4.8 (8)
2.30			AA Ce 131	Lower Patapsco	48,50,5								
			AA Ce 132										
1.73			AA Ce 121		50,50,5								
2.45			AA Ce 122		48,49,5								
1.87			AA Ce 139		46,52,5								
2.70			Hypothetical well 1		45,56,5								
0.83		Harundale	AA Bd 36		32,32,5	1.8 (1.8)	1.8 (1.8)	1.8 (1.8)	1.8 (1.8)	0 (3)	0 (3)	0 (3)	0 (3)
			AA Bd 37										
1.37			AA Bd 162		33,31,5								
			AA Bd 63										
1.10		Crain Highway	AA Bd 174		44,30,5	▨	0 (1.8)	0 (1.8)	0 (1.8)	0 (1.8)	0 (1.8)	0 (1.8)	0 (1.8)
1.08		Glendale	AA Bd 103		28,28,5	0.6 (.6)	0.6 (.6)	0.6 (.6)	0 (.6)	0 (.6)	0 (.6)	0 (.6)	0 (.6)
0.94		Elvaton	AA Bd 107		42,32,5	0.9 (.9)	0.9 (.9)	0.9 (.9)	0 (.9)	0 (.9)	0 (.9)	0 (.9)	0 (.9)
					Total	**8.3**	**8.3**	**8.3**	**6.6**	**4.8**	**4.8**	**4.8**	**4.8**

the required number of hypothetical wells. The design pumping well rates for the hypothetical wells were estimated based on nearby production wells screened in the same aquifer. Locations of all existing and hypothetical wells used in the optimization model are shown on Plate 1. The hypothetical wells are plotted as model cells in which they were represented in the flow model. The differences in cell size are attributed to the variable-spaced, finite-difference model grid (fig. 22). In this scenario it was assumed that the Ft. Meade (U.S. Army) well field would be utilized to supply part of the water demand included in the Crofton pressure zone (fig. 1).

The projected average-day demands from the Broad Creek and Crofton zones increased from 3.9 to 15.5 Mgal/d and 5.7 to 27 Mgal/d, respectively, over the simulation period (2005 to 2040) (tab. 7). Demands in the Broadneck/Glen Burnie Low zone increased from 12 to 16.8 Mgal/d over the simulation period (tab. 7). Demands in the Glen Burnie High zone increased from 4.6 to 14 Mgal/d over the simulation period (tab. 7).

During the optimization simulation, the Glendale, Elvaton, Stevenson Road, and Telegraph Road wells were available for average-day pumping conditions between 2005 and 2015 and were retained only to meet maximum-day demands after

Table 7. Average-day withdrawal demands used in optimization simulation—Continued

Design rate, million gallons per day	Water pressure zone	Well field (see Plate 1 for location)	Well	Aquifer	Model cell (row, column, layer)	Average-day withdrawal demand in stress period, million gallons per day (number in parentheses is maximum-day withdrawal)							
						1 2005-2009	2 2010-2014	3 2015-2019	4 2020-2024	5 2025-2029	6 2030-2034	7 2035-2039	8 2040-2044
0.90	Glen Burnie High	Quarterfield Road	AA Bd 109	Lower Patapsco	45,24,5	▨	0 (.9)	0 (.9)	0 (.9)	0 (.9)	0 (.9)	0 (.9)	0 (.9)
0.94		Telegraph Road	AA Bc 215		56,23,6	0.9 (.9)	0.9 (.9)	0.9 (.9)	0 (.9)	0 (.9)	0 (.9)	0 (.9)	0 (.9)
0.72		Stevenson Road	AA Bd 121		52,26,5	0.7 (.7)	0.7 (.7)	0.7 (.7)	0 (.7)	0 (.7)	0 (.7)	0 (.7)	0 (.7)
1.01		Dorsey Road	AA Ad 111	Patuxent	34,15,6	3 (3)	3 (3)	3 (3)	3 (6)	2 (6)	2 (6)	2 (6)	2 (6)
0.75			AA Bd 161		36,18,6								
1.66			AA Bd 177		40,15,6								
			AA Bd 178										
0.72			AA Bd 97		44,17,6								
1.01			AA Bd 98		44,21,6								
1.01			Hypothetical well 1		42,15,6	▨	▨	▨					
1.01			Hypothetical well 2		38,16,6	▨	▨	▨					
3.00		Millersville	Hypothetical well 1	Lower Patapsco	52,36,5	▨	▨						12 (20)
3.00			Hypothetical well 3		53,37,5	▨	▨	▨	▨				
3.00			Hypothetical well 5		52,37,5	▨	▨	▨	▨				
3.00			Hypothetical well 7		52,38,5	▨	▨	▨	▨	▨	▨	▨	
3.00			Hypothetical well 2	Patuxent	52,36,6	▨	▨	2.4 (4)	2.4 (4)	7.8 (13)	9.6 (16)	9.6 (16)	
3.00			Hypothetical well 4		53,37,6	▨	▨						
3.00			Hypothetical well 6		52,37,6	▨	▨	▨	▨				
3.00			Hypothetical well 8		52,38,6	▨	▨	▨	▨	▨	▨		
					Total	**4.6**	**4.6**	**7**	**5.4**	**9.8**	**11.6**	**11.6**	**14**
1.44	Crofton	Crofton Meadows	AA Cc 128	Lower Patapsco	84,43,5	5.7 (9.2)	15 (25)	15 (28)	19.8 (40)	19.8 (40)	21 (45)	21 (45)	21 (45)
1.44			AA Cc 129		85,44,5								
2.16			AA Cc 140		83,46,5								
2.16			AA Cd 106		81,49,5								
0.87			AA Cc 103	Patuxent	86,43,6								
1.29			AA Cc 105		85,43,6								
1.15			AA Cc 107		88,43,6								
1.87			AA Cc 138		83,46,6								
1.87			AA Cd 107		81,49,6								
1.80			Hypothetical well 1	Lower Patapsco	80,42,5	▨							
1.80			Hypothetical well 3		87,54,5	▨							
1.50			Hypothetical well 2	Patuxent	80,42,6	▨							
1.50			Hypothetical well 4		87,54,6	▨							
4.00		Chesterfield	Hypothetical well 1	Upper Patapsco	75,61,4	▨							
4.00			Hypothetical well 2	Lower Patapsco	75,61,5	▨							
4.00			Hypothetical well 3	Patuxent	75,61,6	▨	▨	▨					
4.00			Hypothetical well 4	Upper Patapsco	77,62,4	▨	▨	▨					
1.50		Ft. Meade	AA Bb 68	Patuxent	79,13,6	▨	▨	1.8 (3)	4.2 (7)	4.2 (7)	6 (10)	6 (10)	6 (10)
1.50			AA Bc 164		75,18,6	▨	▨						
1.50			AA Bc 234		73,23,6	▨	▨						
1.50			AA Cc 144		75,28,6	▨	▨						
1.50			AA Cc 120		73,26,6	▨	▨						
1.50			AA Cc 123		77,29,4	▨	▨						
1.50			Hypothetical well 1		77,24,6	▨	▨	▨	▨	▨			
1.50			Hypothetical well 2		71,19,6	▨	▨	▨	▨	▨			
					Total	**5.7**	**15**	**16.8**	**24**	**24**	**27**	**27**	**27**

2015. The Crain Highway well was retained only for maximum-day demands throughout the simulation. After 2020, the Harundale well field was retained only to supply maximum-day demands.

Over the simulation period, withdrawals from wells within the model area other than those operated by the Anne Arundel County Department of Public Works were increased to the permitted average-day appropriation amount (app. C). By 2040, the amount pumped from those wells totaled approximately 30 Mgal/d. Withdrawals from those wells were not optimized. In the City of Annapolis well field, Magothy withdrawals were decreased approximately 20 percent over the simulation period with a subsequent 20-percent increase in Lower Patapsco withdrawals. Long-term plans for the City of Annapolis well field indicates a further shifting of Magothy withdrawals to the deeper aquifers to avoid potential interference with local domestic users (Whitman, Requardt & Associates, 2003).

Over the simulation period, heads assigned to the general-head boundaries in model layers 3 (Magothy aquifer), 4 (Upper Patapsco aquifer), 5 (Lower Patapsco aquifer), and 6 (Patuxent aquifer) were lowered at rates approximately one-half the rates observed during the period 1980 to 2002. The lesser rates were meant to represent a gradual equilibration of regional heads. Specified heads in model layer 2 (Aquia aquifer) were assigned using head data from a numerical ground-water-flow model of projected water use (Andreasen, 2002).

The optimization model determined optimum pumping rates for existing and hypothetical wells that minimized maximum regional drawdown at selected model cells near each well field, while meeting the pumpage demands shown in table 7. Withdrawals were optimized in each of the eight stress periods (5-year intervals) from 2005 to 2040. The optimized average-day withdrawals for each of the wells are shown in table 8. The optimized average-day amount withdrawn by 2040 from each aquifer in each well field is shown in table 9. Also shown in table 9 are average-day withdrawals represented in the model from sources other than the Anne Arundel County Department of Public Works. Those withdrawals were not optimized.

In the Broad Creek zone approximately 4.6, 5.7, and 1.7 Mgal/d were withdrawn from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively, by 2040 from the Broad Creek well field (tab. 9). Also in the Broad Creek zone, 3.5 Mgal/d were pumped from the Upper Patapsco aquifer by 2040 from the Withernsea well field. The optimization algorithm determined that pumping the Upper Patapsco aquifer results in less drawdown than pumping the Lower Patapsco aquifer at that

Table 8. Optimized withdrawals for the average-day withdrawal scenario

[County abbreviations are listed on abbreviations for appendixes, p. 81]

Design rate, million gallons per day	Water pressure zone	Well field	Well number (see Plate 1 for location)	Aquifer	Model cell (row, column, layer)	Average-day withdrawal rates in stress period (million gallons per day)							
						1 2005-2009	2 2010-2014	3 2015-2019	4 2020-2024	5 2025-2029	6 2030-2034	7 2035-2039	8 2040-2044
0.87	Broad Creek	Broad Creek	AA De 96	Upper Patapsco	62,81,4	0.87	0.87	0	0	0.87	0.87	0.87	0.87
1.15			AA De 97		64,80,4	0	0	0	0	1.15	0	1.15	1.15
1.44			AA De 136		66,77,4	0	0	0	0	1.44	0	1.44	1.44
3.10			AA De 177	Lower Patapsco	63,80,5	0	0	0	3.10	0	3.10	3.10	0
3.60			AA De 208		65,84,5	3.03	3.03	0	1.74	3.60	0.66	3.6	2.57
1.15			Hypothetical well 1	Upper Patapsco	63,84,4			0	0	1.15	1.15	1.15	1.15
3.10			Hypothetical well 2	Lower Patapsco	63,84,5			3.10	3.10	0	3.10	0.66	3.10
3.10			Hypothetical well 4		66,77,5				0	0.66	3.10	0	0
3.10			Hypothetical well 3	Patuxent	63,84,6					0	0	0	1.69
3.10			Hypothetical well 5		66,77,6					3.10	0	0	0
3.10		Withernsea	Hypothetical well 1	Upper Patapsco	86,92,4							1.50	0.40
3.10			Hypothetical well 3		87,93,4								3.10
3.10			Hypothetical well 4	Lower Patapsco	88,92,5								0
3.10			Hypothetical well 2		86,92,5							0	0
					Total	**3.9**	**3.9**	**3.9**	**7.9**	**12.0**	**12.0**	**13.5**	**15.5**
1.08	Broadneck/ Glen Burnie Low	Arnold	AA Cf 118	Upper Patapsco	39,80,4	0	0	1.08	0	0	1.08	1.08	1.08
1.29			AA Cf 119		40,80,4	0	0	1.29	0.79	0	0	1.29	1.29
1.29			AA Cf 120		40,81,4	0.25	0	1.29	1.29	1.29	1.29	1.29	1.29
1.44			AA Cf 155		41,83,4	0	0	1.44	1.44	1.44	0	1.44	1.44
2.88			AA Cf 142	Lower Patapsco	40,80,5	0	0	0	2.88	0.49	0	0.52	2.88
3.46			AA Cf 150		41,83,5	3.46	3.46	0	0	0	3.46	0	0.37
3.17			Hypothetical well 1		42,81,5		0	0	0	0	3.17	0	0
3.17			Hypothetical well 2		38,79,5		1.45	1.29	3.17	3.17	0	3.17	3.17
3.17			Hypothetical well 4		36,83,5		3.17	3.17	0	3.17	0.58	3.17	0.44
1.50			Hypothetical well 5	Patuxent	40,81,6	0	0	0	0	0	0	0	0
1.50			Hypothetical well 3		38,79,6		1.50	0	0	0	0	0	0
					Total	**3.7**	**9.6**	**9.6**	**9.6**	**9.6**	**9.6**	**12.0**	**12.0**
0.43		Severndale	AA Ce 96	Upper Patapsco	48,50,4	0	0	0.43	0.43	0.43	0	0.43	0.43
2.30			AA Ce 131 AA Ce 132	Lower Patapsco	48,50,5	0.43	0	1.86	0	0	0	0	0
1.73			AA Ce 121		50,50,5	0	0	0	0	0	0	0	0
2.45			AA Ce 122		48,49,5	0	2.30	0	0	2.45	2.10	0	0
1.87			AA Ce 139		46,52,5	1.87	0	0	1.87	1.87	0	1.67	1.67
2.70			Hypothetical well 1		45,56,5	2.70	2.70	2.70	2.50	0.05	2.70	2.70	2.70
0.83		Harundale	AA Bd 36 AA Bd 37		32,32,5	0.43	0.43	0.83	0.83	0	0	0	0
1.37			AA Bd 162 AA Bd 63		33,31,5	1.37	1.37	0.97	0.97	0	0	0	0
1.80		Crain Highway	AA Bd 174		44,30,5		0	0	0	0	0	0	0
1.08		Glendale	AA Bd 103		28,28,5	0.60	0.60	0.60	0	0	0	0	0
0.94		Elvaton	AA Bd 107		42,32,5	0.90	0.90	0.90	0	0	0	0	0
					Total	**8.3**	**8.3**	**8.3**	**6.6**	**4.8**	**4.8**	**4.8**	**4.8**

location. This was largely caused by a greater simulated transmissivity of the Upper Patapsco aquifer as compared to the Lower Patapsco aquifer at that site. The Magothy aquifer was not pumped at Withernsea because of the possibility that drawdown resulting from a high-capacity production well could interfere with nearby domestic users. An alternative pumping scheme was tested for the Broad Creek zone in which the optimization algorithm was allowed to select wells from both the Broad Creek and Withernsea well fields that resulted in the least amount of drawdown, while supplying a combined rate of 15.5 Mgal/d. The optimization code chose to withdraw 12.4 Mgal/d by 2040 from the Withernsea well field—approximately evenly divided between the Upper and Lower Patapsco aquifers—while 3.1 Mgal/d was withdrawn from the Upper Patapsco aquifer from the Broad Creek well field. The greater rate pumped at the Withernsea well field was likely the result of the greater simulated transmissivity of the Upper Patapsco aquifer at that site as compared to Broad Creek, and because there is less interference with withdrawals from the City of Annapolis well field. Results of the model simulations indicate that the aquifers have sufficient capacity at the Broad Creek and Withernsea well fields to meet the well withdrawals under both pumping alternatives.

In the Broadneck/Glen Burnie Low zone approximately 5.1 and 6.9 Mgal/d were withdrawn

Table 8. Optimized withdrawals for the average-day withdrawal scenario—Continued

Design rate, million gallons per day	Water pressure zone	Well field	Well number (see Plate 1 for location)	Aquifer	Model cell (row, column, layer)	Average-day withdrawal rates in stress period (million gallons per day)							
						1 2005-2009	2 2010-2014	3 2015-2019	4 2020-2024	5 2025-2029	6 2030-2034	7 2035-2039	8 2040-2044
0.90	Glen Burnie High	Quarterfield Road	AA Bd 109	Lower Patapsco	45,24,5		0	0	0	0	0	0	0
0.94		Telegraph Road	AA Bc 215		56,23,6	0.90	0.90	0.90	0	0	0	0	0
0.72		Stevenson Road	AA Bd 121		52,26,5	0.70	0.70	0.70	0	0	0	0	0
1.01		Dorsey Road	AA Ad 111	Patuxent	34,15,6	1.01	1.01	1.01	1.01	0	1.01	1.01	1.01
0.75			AA Bd 161		36,18,6	0.32	0	0.75	0.75	0	0	0	0.75
1.66			AA Bd 177 AA Bd 178		40,15,6	1.66	1.66	1.23	1.23	1.66	0	0.99	0
0.72			AA Bd 97		44,17,6	0	0	0	0	0	0.72	0	0
1.01			AA Bd 98		44,21,6	0	0.32	0	0	0	0	0	0
1.01			Hypothetical well 1		42,15,6				0	0	0.27	0	0
1.01			Hypothetical well 2		38,16,6				0	0	0	0	0.24
3.00		Millersville	Hypothetical well 1	Lower Patapsco	52,36,5			2.40	2.40	3.00	3.00	3.00	3.00
3.00			Hypothetical well 3		53,37,5					1.80	3.00	3.00	3.00
3.00			Hypothetical well 5		52,37,5					3.0	3.00	3.00	3.00
3.00			Hypothetical well 7		52,38,5								3.00
3.00			Hypothetical well 2	Patuxent	52,36,6			0	0	0	0	0	0
3.00			Hypothetical well 4		53,37,6			0	0	0	0	0	0
3.00			Hypothetical well 6		52,37,6					0	0.60	0.60	0
3.00			Hypothetical well 8		52,38,6							0	0
					Total	**4.6**	**4.6**	**7.0**	**5.4**	**9.8**	**11.6**	**11.6**	**14.0**
1.44	Crofton	Crofton Meadows	AA Cc 128	Lower Patapsco	84,43,5	1.44	1.44	0	0	1.44	1.44	1.44	1.44
1.44			AA Cc 129		85,44,5	0	0	0	0	1.44	1.44	1.44	1.44
2.16			AA Cc 140		83,46,5	2.09	2.16	0	2.16	2.16	2.16	2.16	2.16
2.16			AA Cd 106		81,49,5	2.16	2.16	2.16	0	2.16	2.16	2.16	1.51
0.87			AA Cc 103	Patuxent	86,43,6	0	0	0	0.87	0	0	0	0.87
1.29			AA Cc 105		85,43,6	0	0	0	1.29	0	0	0	0.90
1.15			AA Cc 107		88,43,6	0	0	0	0	1.15	0	0	1.15
1.87			AA Cc 138		83,46,6	0	0	0	1.87	1.65	0	0	0
1.87			AA Cd 107		81,49,6	0	0	1.87	1.62	0	0	0	0
1.80			Hypothetical well 1	Lower Patapsco	80,42,5		0	0	0	0	0	1.80	0
1.80			Hypothetical well 3		87,54,5		1.19	1.43	0	1.80	1.80	1.80	1.80
1.50			Hypothetical well 2	Patuxent	80,42,6		0	0	0	0	0	0	0
1.50			Hypothetical well 4		87,54,6		0	1.50	0	0	0	0	1.50
4.00		Chesterfield	Hypothetical well 1	Upper Patapsco	75,61,4		4.00	4.00	4.00	4.00	4.00	4.00	2.48
4.00			Hypothetical well 2	Lower Patapsco	75,61,5		4.00	4.00	4.00	0	4.00	2.20	0.86
4.00			Hypothetical well 3	Patuxent	75,61,6				4.00	0	0	0	0.91
4.00			Hypothetical well 4	Upper Patapsco	77,62,4				0	4.00	4.00	4.00	4.00
1.50		Ft. Meade	AA Bb 68	Patuxent	79,13,6			0	0	0	0	1.50	1.50
1.50			AA Bc 164		75,18,6			0	0	0	0	0	1.50
1.50			AA Bc 234		73,23,6			0.30	1.20	1.20	1.50	1.50	1.50
1.50			AA Cc 144		75,28,6			0	0	1.50	0	1.50	0
1.50			AA Cc 120		73,26,6			1.50	1.50	1.50	1.50	1.50	0
1.50			AA Cc 123		77,29,4			0	1.50	0	1.50	0	0
1.50			Hypothetical well 1		77,24,6						1.50	0	0
1.50			Hypothetical well 2		71,19,6						0	0	1.50
					Total	**5.7**	**15.0**	**16.8**	**24.0**	**24.0**	**27.0**	**27.0**	**27.0**

Table 9. Optimized withdrawals, and other withdrawals in the model not optimized, for the average-day withdrawal scenario (2040)

User or supplier	Average-daily withdrawal rates by aquifer, million gallons per day				
	Magothy	Upper Patapsco	Lower Patapsco	Patuxent	Total
OPTIMIZED AVERAGE-DAY WITHDRAWALS					
I. Anne Arundel County					
A. Department of Public Works[1]					
Broad Creek zone					
Broad Creek well field	0	4.6	5.7	1.7	12.0
Withernsea well field	0	3.5	0	0	3.5
sub-total	0	8.1	5.7	1.7	15.5
Broadneck/Glen Burnie Low zone					
Arnold well field	0	5.1	6.9	0	12.0
Severndale well field	0	0.43	4.4	0	4.8
sub-total	0	5.5	11.3	0	16.8
Glen Burnie High					
Dorsey well field	0	0	0	2.0	2.0
Millersville well field	0	0	12.0	0	12.0
sub-total	0	0	12.0	2.0	14.0
Crofton					
Crofton Meadows well field	0	0	8.4	4.4	12.8
Chesterfield well field	0	6.5	0.9	0.9	8.3
Ft. Meade well field	0	0	0	6.0	6.0
sub-total	0	6.5	9.3	11.3	27.1
TOTAL	0	20.1	38.3	15.0	73.4
OTHER WITHDRAWALS IN THE MODEL THAT WERE NOT OPTIMIZED					
B. City of Annapolis	1.7	1.5	2.4	0	5.6
C. Other users in Anne Arundel County	1.0	2.3	0.7	0.85	4.8
II. Counties other than Anne Arundel County[2] (includes Baltimore City)	1.5	0.66	2.6	14.2	19
TOTAL FOR MODEL AREA	4.2	24	44	30	103

[1] Does not include Gibson Island, Herald Harbor, and Rose Haven.

[2] Includes portions of Baltimore, Calvert, Kent, Prince George's, and Queen Anne's Counties.

from the Upper and Lower Patapsco aquifers, respectively, by 2040 from the Arnold well field (tab. 8). There were no withdrawals from the Patuxent aquifer over most of the simulation period; however, given its relatively large amount of available drawdown—greater than 800 ft in 2002 (fig. 20)—it could serve as a future water supply. Initial testing of the Patuxent aquifer at Arnold indicated that it is less transmissive than both the Upper and Lower Patapsco aquifers (Mack and Andreasen, 1991). In the Severndale well field, 0.43 and 4.4 Mgal/d were pumped from the Upper and Lower Patapsco aquifers, respectively, by 2040. The Patuxent aquifer at Severndale was not included in the optimization analysis because of high iron concentrations in that area.

In the Glen Burnie High zone, the majority of withdrawals were from the hypothetical well field at Millersville. Withdrawals from the well field were simulated beginning in 2015 (stress period 3) (tab. 8). By 2040, 12.0 Mgal/d were withdrawn from the Lower Patapsco aquifer at that site. The optimization algorithm selected the Lower Patapsco aquifer over the Patuxent aquifer at Millersville because it resulted in less drawdown, in part because of the higher simulated transmissivity of the Lower Patapsco aquifer at that site. However, because the Lower Patapsco aquifer is shallower, and, therefore, has less available drawdown than the Patuxent aquifer, some of the withdrawals could be shifted to the Patuxent aquifer. To demonstrate this, the model was re-run with withdrawals evenly divided between the Lower Patapsco and Patuxent aquifers at Millersville. While not an optimal solution in terms of drawdown, the results showed that the amount of available drawdown in the Patuxent aquifer at Millersville could more than adequately support half of the demand requirement. The remainder of the projected withdrawal for the Glen Burnie High zone (2 Mgal/d) was supplied by the Patuxent aquifer from the Dorsey Road well field; however, this rate could potentially be increased. An alternative pumping scenario was simulated in which 2 Mgal/d was shifted from the Millersville well field to the Dorsey Road well field for the period 2020 to 2040. The total average-day withdrawal rate from Dorsey Road for that period increased to 4 Mgal/d. This rate is equivalent to a maximum-day demand of 6 Mgal/d divided by 1.5. Results of the simulation indicate that 4 Mgal/d can be withdrawn from the Patuxent aquifer at Dorsey Road; however, increased withdrawals would result in deep water levels that might affect pump operations. A more precise well-field analysis would be required to identify potential well-interference problems.

In the Crofton zone, approximately 8.4 and 4.4 Mgal/d were withdrawn from the Lower Patapsco and Patuxent aquifers, respectively, by 2040 from the Crofton Meadows well field (tab. 8). The Upper Patapsco aquifer is too shallow and too thin to be utilized for major water supply at Crofton Meadows. At the Chesterfield well field, approximately 6.5, 0.9, and 0.9 Mgal/d were withdrawn from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively, by 2040. The Chesterfield well field is centrally located between the Crofton Meadows and Broad Creek well fields to reduce well interference. The location of the well field is consistent with the location identified in the *Comprehensive Water Strategic Plan* (O'Brien and Gere, 2003). The exact location would depend on practical concerns, such as available public property and costs of water-transmission lines. The remote well field could potentially be located closer to Crofton Meadows; however, a more detailed well-field study would be required to determine with greater accuracy the possible effects a closer location would have on well interference. Obtaining all of the projected water demand from the Crofton Meadows well field would result in significant drawdown that could lower water levels below management levels. The Ft. Meade well field pumped a total of 6 Mgal/d by 2040 from the Patuxent aquifer. The Lower Patapsco aquifer, while present at Ft. Meade, was not provided as an alternative because of its shallower depth.

By the end of the simulation period, total withdrawals from the major Anne Arundel County Department of Public Works' well fields increased by approximately 47 Mgal/d from 2002 levels (25.6 Mgal/d in 2002 to 73.0 Mgal/d in 2040). Withdrawals from the individual aquifers increased by approximately 18 Mgal/d from the Upper Patapsco aquifer, 21 Mgal/d from the Lower Patapsco aquifer, and 9 Mgal/d from the Patuxent aquifer.

Relation to Management Level

The relation of water levels to the State-mandated 80-percent management level is critical in assessing the sustainability of projected water demands. The management level provides a buffer before the confined aquifer begins to dewater. The 80-percent management level regulation does not apply at a pumping well, but rather in an area common to the well or wells associated with the appropriation permit under average-day pumping conditions. In this study, the 80-percent management level was applied at the model cells near each well field where drawdown was minimized during optimization (fig. 38). During the model simulation (2005-2044), simulated water levels in each stress period in the model cells near the well fields remained above the 80-percent management level. In the Upper Patapsco aquifer, by 2044, available drawdown (difference between water level and the 80-percent management level) in those model cells near the Broad Creek, Withernsea, Arnold, Severndale, and Chesterfield well fields was reduced to 90, 301, 94, 20, and 56 ft, respectively (tab. 10; fig. 39). The Upper Patapsco aquifer at Severndale has the least amount of remaining available drawdown by 2044 (20 ft). However, since there was only one well pumping from the Upper Patapsco aquifer at Severndale, withdrawals from that well (0.43 Mgal/d in 2040) could be shifted to the deeper Lower Patapsco aquifer.

In the Lower Patapsco aquifer, by 2044, available drawdown in those model cells near the Broad Creek, Withernsea, Arnold, Severndale, Millersville, Crofton Meadows, and Chesterfield well fields was reduced to 407, 680, 464, 164, 48, 160, and 259 ft, respectively (tab. 10; fig. 39). Available drawdown in the model cell near Lower Patapsco wells at Harundale, Crain Highway, Glendale, Quarterfield Road, Telegraph Road, and Stevenson Road was reduced to 40 ft by 2044 (tab. 10). Those wells, however, were not pumped after 2025. A model simulation was made with withdrawals from those wells continued to the end of the simulation period (2044). Available drawdown under that pumping scenario was reduced to 20 ft.

In the Patuxent aquifer, by 2044, available drawdown in those model cells near the Broad Creek, Arnold, Dorsey Road, Millersville, Crofton Meadows, Chesterfield, and Ft. Meade well fields was reduced to 768, 800, 198, 325, 512, 625, and 188 ft, respectively (tab. 10; fig. 39).

Figure 39 shows the amount of available drawdown for the Upper Patapsco, Lower Patapsco, and Patuxent aquifers in 2044 for the entire model area. The least amount of available drawdown occurs near the outcrop areas of each aquifer. In the Upper Patapsco and Patuxent aquifers, no available drawdown remains (water levels have reached or fallen below the management level) in relatively small areas near the outcrop. These areas are particularly sensitive to drawdown because the aquifers are very shallow near the outcrop. In the Lower Patapsco aquifer, water levels remained above the 80-percent management level by 2044.

Water Levels and Pumping Lift

Simulated potentiometric surfaces by 2044 for the Upper Patapsco, Lower Patapsco, and Patuxent aquifers show significant cones-of-depression around the major pumping centers in Anne Arundel County (fig. 40). A cone-of-depression associated with industrial withdrawals is also formed in the Patuxent aquifer in southeastern Baltimore County. Despite the relatively deep simulated water levels in the Patuxent aquifer in the Glen Burnie area combined with the relatively close proximity to the Patapsco River, the possibility of brackish water from the Patapsco River reaching the well fields is low. Chapelle and Kean (1985) modeled the movement of brackish water from the Patapsco River toward the Glen Burnie area using a head gradient similar to that shown in figure 40. Their model showed only a slight movement of brackish water from the Patapsco River over a 50-year period. The potential for brackish-water intrusion affecting the other well fields would be even less probable, given the significantly greater distances to brackish-water bodies, and generally greater aquifer depths.

By 2040, the lowest model-cell water levels were 140 ft below sea level in the Upper Patapsco aquifer in the Chesterfield well field, 153 ft below sea level in the Lower Patapsco aquifer in the Broad Creek well field, and 164 ft below sea level in the Patuxent aquifer in the Dorsey Road well field (tab. 11). Model-cell water levels are averages over the model-cell areas; therefore, water levels are deeper closer to actual pumping wells within the model cells. To more accurately determine water levels immediately outside pumping wells, water levels were estimated using the Thiem equation (Trescott, and others, 1976; Pritchett and Garg, 1980) for simulated water levels at the end of the simulation period (2044). Depending on the efficiency of the well, water levels inside the pumping well will be even deeper. No attempt was made to estimate pumping levels based on well efficiency. Water levels immediately outside pumping wells ranged from 29 to 227 ft below sea level in the Upper Patapsco aquifer, 107 to 203 ft below sea level in the Lower Patapsco aquifer, and 97 to 305 ft below

Table 10. Available drawdown in model cells near Anne Arundel County well fields in 2044 for the average-day withdrawal scenario

Sites where drawdown was minimized during optimization		Aquifer	Available drawdown, feet
Identification number (see figure 38)	Well field(s)		
1	Broad Creek well field	Upper Patapsco	90
		Lower Patapsco	407
		Patuxent	768
2	Withernsea well field	Upper Patapsco	301
		Lower Patapsco	680
3	Arnold well field	Upper Patapsco	94
		Lower Patapsco	464
		Patuxent	800
4	Severndale well field	Upper Patapsco	20
		Lower Patapsco	164
5	Harundale, Crain Highway, Glendale, Elvaton, Quarterfield Road, Telegraph Road, and Stevenson Road wells	Lower Patapsco	40
6	Dorsey Road well field	Patuxent	198
7	Millersville well field	Lower Patapsco	48
		Patuxent	325
8	Crofton Meadows well field	Lower Patapsco	160
		Patuxent	512
9	Chesterfield well field	Upper Patapsco	56
		Lower Patapsco	259
		Patuxent	625
10	Ft. Meade well field	Patuxent	188

sea level in the Patuxent aquifer (tab. 11). The lowest water level occurred in the Dorsey Road well field at 305 ft below sea level. The adjusted water levels do not fall below either the top of well screens in wells with uniform casing diameter or below depths where the main casing diameter decreases because of the use of riser pipes in any of the county's production wells.

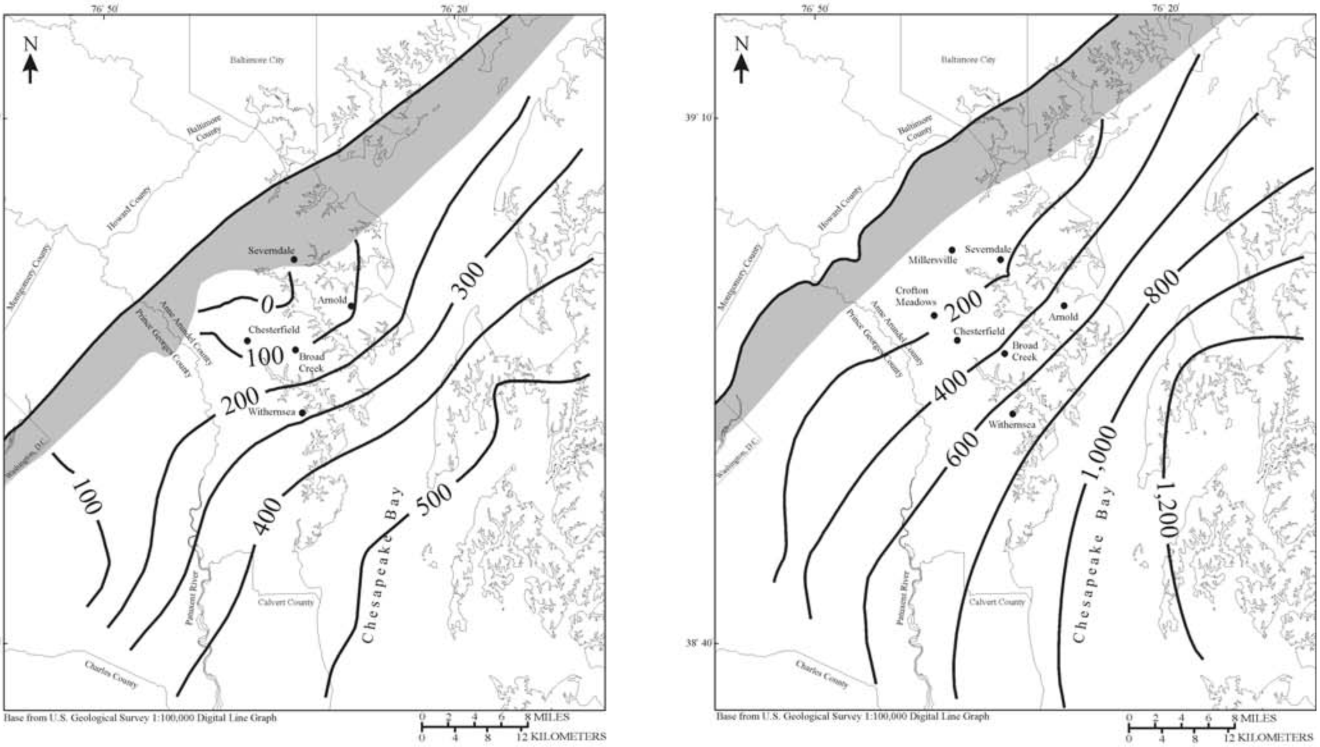
Pumping costs, in both energy consumption and pump maintenance, increase with deepening pumping water levels. Based on the adjusted heads immediately outside pumping wells, pumping lift (or distance required to pump water to the surface) ranged from 114 to 347 ft in the Upper Patapsco aquifer, 195 to 320 ft in the Lower Patapsco aquifer, and 226 to 373 ft in the Patuxent aquifer (tab. 11). The greatest pumping lift occurred in the Dorsey Road well field at 373 ft. Again, depending on the efficiency of the well, pumping lift could be even greater.

Effect on Recharge and Baseflow

The increase in withdrawals over the simulation period induced recharge from the outcrop areas. Recharge increased by 1.2, 0.8, and 0.6 in./yr in the Upper Patapsco, Lower Patapsco, and Patuxent aquifers by 2044, respectively, from simulated rates of 1.6, 1.7, and 1.7 in./yr in 2002. Simulated baseflow as measured in four streams within the outcrop areas of the Upper Patapsco, Lower Patapsco, and Patuxent aquifers decreased as a result of the increased recharge to the confined aquifers. Baseflow decreased by 9, 5, 7, and 4 percent from simulated 2002 levels in Sawmill Creek in northern Anne Arundel County, North River in central Anne Arundel County, Northwest Branch of the Anacostia River at Riverdale in northern Prince George's County, and Western Branch at Upper Marlboro in east-central Prince George's County.

Model layer 4 (Upper Patapsco aquifer)

Model layer 5 (Lower Patapsco aquifer)



Model layer 6 (Patuxent aquifer)

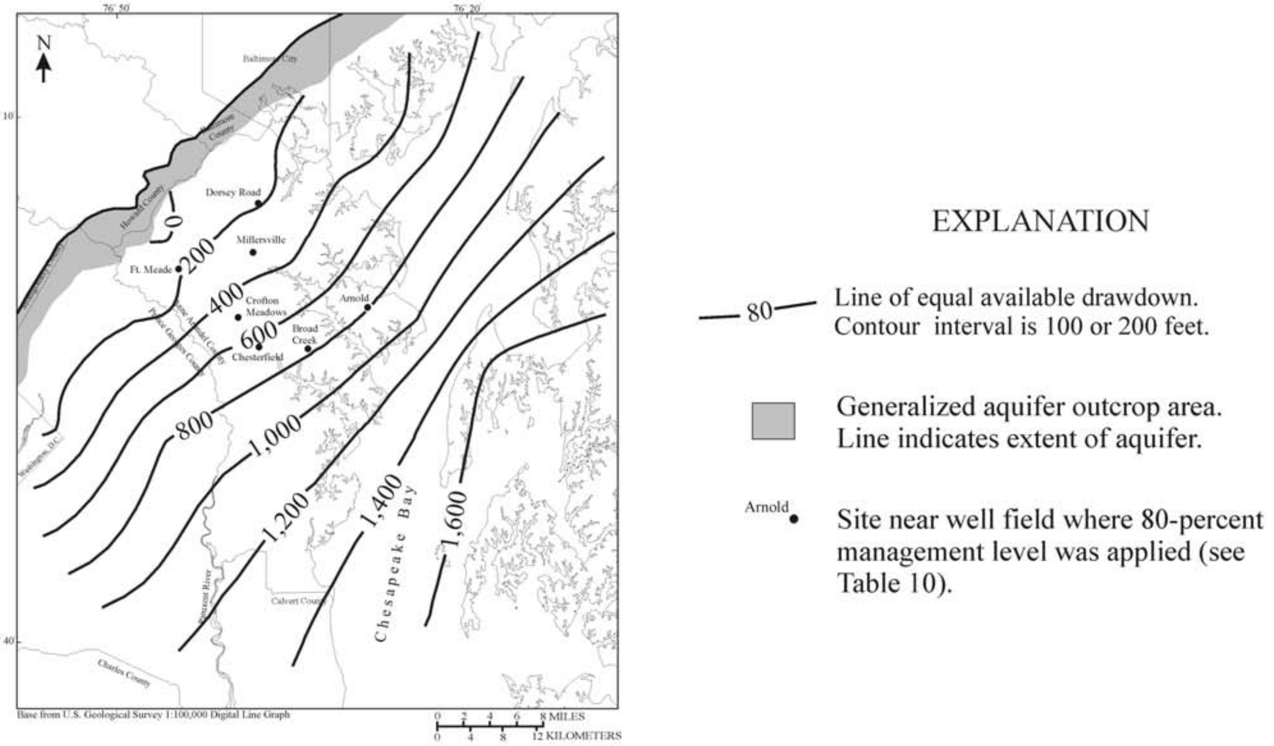
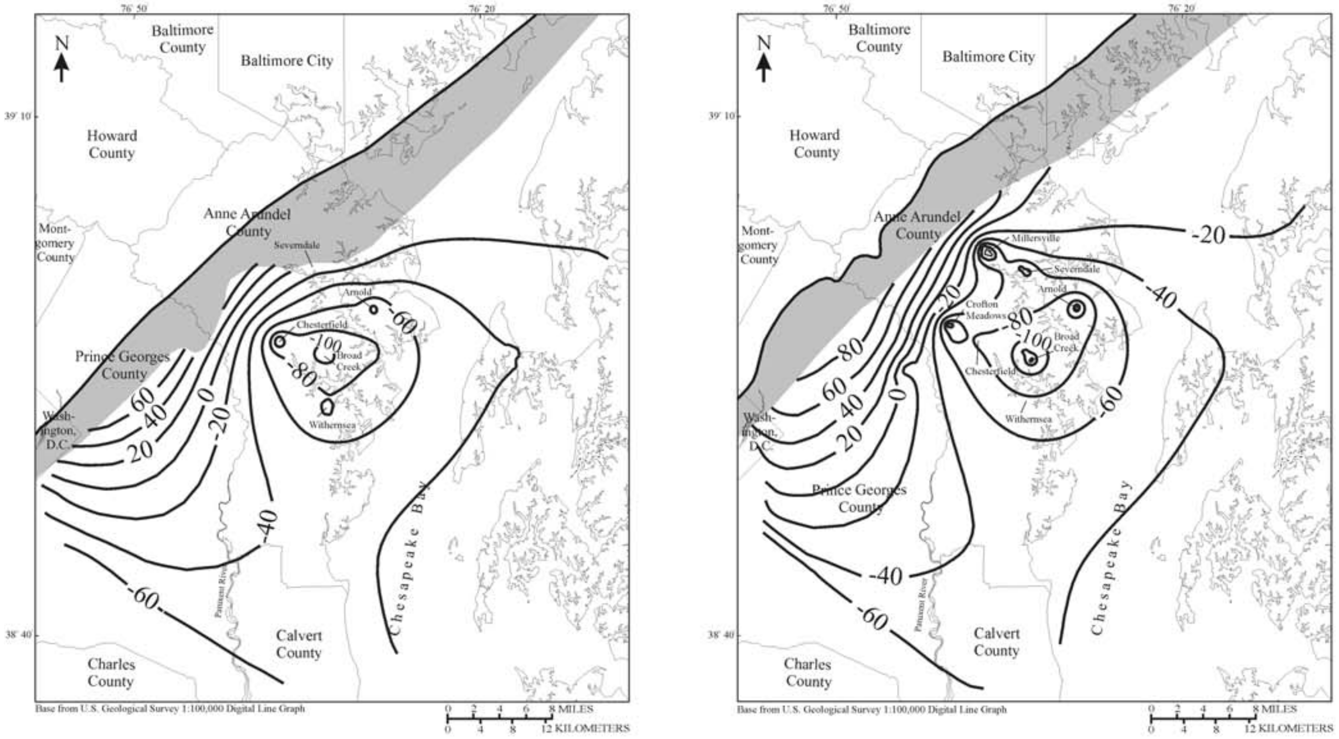


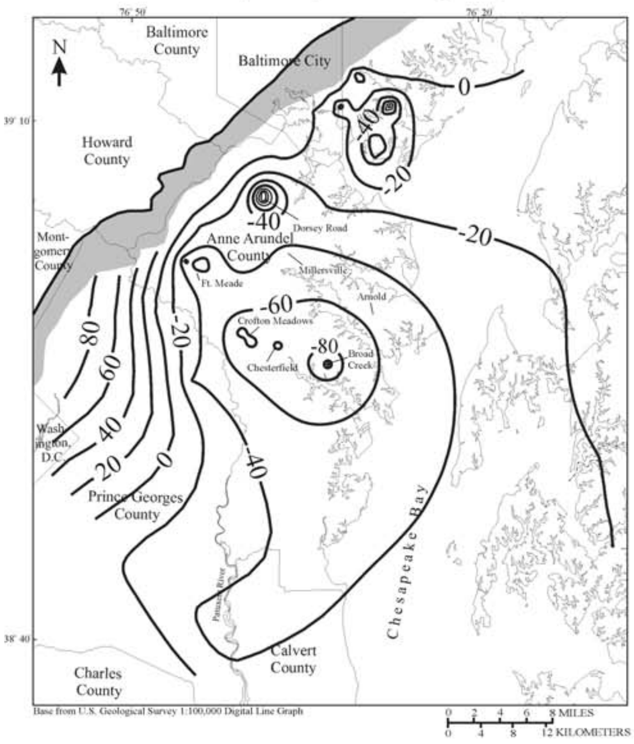
Figure 39. Simulated available drawdown in 2044 for model layers 4 (Upper Patapsco aquifer), 5 (Lower Patapsco aquifer), and 6 (Patuxent aquifer) for the average-day withdrawal optimization scenario.

Model layer 4 (Upper Patapsco aquifer)

Model layer 5 (Lower Patapsco aquifer)



Model layer 6 (Patuxent aquifer)



EXPLANATION

—80— Potentiometric contour of simulated water levels. Contour interval is 20 feet. Datum is sea level.

▨ Generalized aquifer outcrop area. Line indicates extent of aquifer.

Figure 40. Simulated 2044 potentiometric surface of model layers 4 (Upper Patapsco aquifer), 5 (Lower Patapsco aquifer), and 6 (Patuxent aquifer) for the average-day withdrawal optimization scenario.

Table 11. Model-cell heads converted to heads immediately outside pumping wells in 2044 for the average-day withdrawal scenario.

[County abbreviations are listed on abbreviations for appendixes, p. 81]

Pressure zone	Well field	Well number (see Plate 1 for location)	Aquifer	Altitude of land surface, feet	Pumping rate, million gallons per day	Cell-average head, related to sea level, feet	Additional drawdown, feet	Head adjusted to immediately outside well	
								Related to sea level, feet	Related to land surface, feet[1]
Broad Creek	Broad Creek	AA De 96	Upper Patapsco	65	0.87	-116	12	-128	-193
		AA De 97		90	1.15	-118	16	-134	-224
		AA De 136		80	1.44	-115	20	-135	-215
		AA De 208	Lower Patapsco	80	2.57	-147	36	-183	-263
		Hypothetical well 1	Upper Patapsco	80[2]	1.15	-114	17	-131	-211
		Hypothetical well 2	Lower Patapsco	80[2]	3.10	-153	50	-203	-283
		Hypothetical well 3	Patuxent	80[2]	1.69	-137	78	-215	-295
	Withernsea	Hypothetical well 1	Upper Patapsco	30[2]	0.40	-81	3	-84	-114
		Hypothetical well 3		30[2]	3.10	-88	29	-117	-147
Broadneck/ Glen Burnie Low	Arnold	AA Cf 118	Upper Patapsco	120	1.08	-90	13	-103	-223
		AA Cf 119		125	1.29	-94	15	-109	-234
		AA Cf 120		120	1.29	-95	14	-109	-229
		AA Cf 155		75	1.44	-90	17	-107	-182
		AA Cf 142	Lower Patapsco	120	2.88	-145	44	-189	-309
		AA Cf 150		75	0.37	-118	6	-124	-199
		Hypothetical well 2		120[2]	3.17	-144	56	-200	-320
		Hypothetical well 4		120[2]	0.44	-111	8	-119	-239
	Severndale	AA Ce 96	Upper Patapsco	89	0.43	-14	15	-29	-118
		AA Ce 139	Lower Patapsco	60	1.67	-95	40	-135	-195
		Hypothetical well 1		80[2]	2.70	-98	70	-168	-248

To illustrate how drought conditions might compound the problem of reduced baseflow, the model was re-run using the optimized withdrawal rates with a reduction in recharge during the last stress period (2040-2044). The drought was simulated during the final stress period to coincide with the greatest withdrawal rates. This scenario represents the greatest stress on the aquifer system. The annual average recharge rate was reduced by 30 percent. This value was arrived at by comparing a moving 5-year average baseflow to the average baseflow for the period of stream-flow record (1932 to 1973) in North River (U.S. Geological Survey gage 1590000). During the period of record the lowest baseflow readings occurred in the 1960's during an extended drought. Average baseflow during a 5-year period extending from 1966 to 1970 was approximately 5.47 cubic feet per second (ft^3/s), or 30 percent less than the median baseflow for the period of record of 7.8 ft^3/s. Applying the reduced recharge rate to the model caused baseflow to decrease by 33, 18, 19 and 20 percent from simulated 2002 levels in Sawmill Creek in northern Anne Arundel County, North River in central Anne Arundel County, Northwest Branch of the Anacostia River at Riverdale in northern Prince George's County, and Western Branch at Upper Marlboro in east-central Prince George's County. Therefore, imposition of drought conditions results in an additional 12 to 24 percent reduction in baseflow beyond the reduction resulting from withdrawals from the confined aquifers. By 2044, water levels in the water-table aquifer were as much as 7 ft lower under drought conditions compared to non-drought conditions. Water levels in the confined aquifers (Upper Patapsco, Lower Patapsco and Patuxent aquifers) declined up to 3 ft by 2044 as a result of the drought. The water-level decline was most pronounced near the outcrop (recharge) areas. The reduction in baseflow resulting from increased

Table 11. Model-cell heads converted to heads immediately outside pumping wells in 2044 for the average-day withdrawal scenario—Continued

Pressure zone	Well field	Well number (see Plate 1 for location)	Aquifer	Altitude of land surface, feet	Pumping rate, million gallons per day	Cell-average head, related to sea level, feet	Additional drawdown, feet	Head adjusted to immediately outside well	
								Related to sea level, feet	Related to land surface, feet[1]
Glen Burnie High	Dorsey Road	AA Ad 111	Patuxent	68	1.01	-162	143	-305	-373
		AA Bd 161		70	0.75	-164	123	-287	-357
		Hypothetical well 2		70[2]	0.24	-120	37	-157	-227
	Millersville	Hypothetical well 1	Lower Patapsco	100[2]	3.00	-88	84	-172	-272
		Hypothetical well 3		100[2]	3.00	-98	86	-184	-284
		Hypothetical well 5		100[2]	3.00	-110	85	-195	-295
		Hypothetical well 7		100[2]	3.00	-104	85	-189	-289
Crofton	Crofton Meadows	AA Cc 128	Lower Patapsco	134	1.44	-107	28	-135	-269
		AA Cc 129		134	1.44	-109	32	-141	-275
		AA Cc 140		135	2.16	-118	40	-158	-293
		AA Cd 106		148	1.51	-105	29	-133	-281
		AA Cc 103	Patuxent	125	0.87	-90	13	-103	-228
		AA Cc 105		130	0.90	-89	14	-103	-233
		AA Cc 107		120	1.15	-88	18	-106	-226
		Hypothetical well 3	Lower Patapsco	130[2]	1.80	-104	42	-146	-276
		Hypothetical well 4	Patuxent	130[2]	1.50	-93	26	-119	-249
	Chesterfield	Hypothetical well 1	Upper Patapsco	120[2]	2.48	-126	55	-181	-301
		Hypothetical well 2	Lower Patapsco	120[2]	0.86	-90	17	-107	-227
		Hypothetical well 3	Patuxent	120[2]	0.91	-88	20	-108	-228
		Hypothetical well 4	Upper Patapsco	120[2]	4.00	-140	87	-227	-347
	Ft. Meade	AA Bb 68	Patuxent	130	1.50	-69	75	-144	-274
		AA Bc 164		135	1.50	-78	30	-108	-243
		AA Bc 234		133	1.50	-72	25	-97	-230
		Hypothetical well 2		130[2]	1.50	-75	30	-105	-235

[1] Equivalent to pumping lift.
[2] Estimate of land surface altitude.

withdrawals and compounded by drought might, over time, affect stream and wetland ecology. It should be stressed, however, that this result, if it occurs, would develop over many years, and, therefore, does not pose an immediate concern.

Effects of Projected 2040 Maximum-Day Withdrawals

While ground-water supply sustainability is primarily dependent on the response of the aquifer system to long-term withdrawals, the effects of short-term withdrawals are also an important consideration because excessive localized drawdown caused by withdrawals may present problems to well operations. Withdrawals by the Anne Arundel County Department of Public Works during the day of maximum use are projected to increase to 140 Mgal/d by 2040. This figure is based on the 2003 *Comprehensive Water Strategic Plan* (O'Brien and Gere, 2003), with the following modifications:

(1) In the *Comprehensive Water Strategic Plan*, the Broad Creek zone supplied 23 Mgal/d (maximum day) by 2043, while in this study the Broad Creek zone supplied 32 Mgal/d (maximum

day) by 2040. A higher withdrawal rate was used because the greater amount of available drawdown in the aquifers as they deepen toward the southeast might provide an additional source of water that could potentially be transferred to other pressure zones.

(2) In the *Comprehensive Water Strategic Plan*, the Broadneck zone supplied 16 Mgal/d (maximum day) by 2043 from the Arnold well field, while in this study the Arnold well field supplied 20 Mgal/d by 2040. The higher rate was used to determine whether 16 Mgal/d was the maximum attainable rate at that site.

(3) In the *Comprehensive Water Strategic Plan*, the Glen Burnie Low zone (Severndale, Harundale, Crain Highway, Glendale, and Elvaton well fields) supplied 19.3 Mgal/d by 2043, and the Glen Burnie High zone (Dorsey Road, Quarterfield Road, Telegraph Road, and Stevenson Road well fields) supplied 14.8 Mgal/d by 2043. In this study, the Glen Burnie Low zone supplied approximately 14 Mgal/d by 2040, and the Glen Burnie High zone supplied approximately 28 Mgal/d by 2040. By 2040, 20 Mgal/d (maximum day) is supplied by a new well field and treatment plant at Millersville (Glen Burnie High zone). This provides Anne Arundel County with an option of eliminating the smaller Brookfield, Marley Creek, Olde Mill, and New Cut well fields that were proposed in the *Comprehensive Water Strategic Plan*, and consolidating them into a larger centralized facility at Millersville.

(4) In the *Comprehensive Water Strategic Plan*, the Crofton zone supplied 36.8 Mgal/d (maximum day) by 2043, where 33 Mgal/d was supplied by the Crofton well field, and 3.8 Mgal/d was supplied by the Kings Heights well field. In this study the Crofton Meadows zone supplied 44.6 Mgal/d by 2040, with 19.4 Mgal/d supplied by the Crofton Meadows well field, 15.6 Mgal/d supplied by a remote well field at Chesterfield, and 10 Mgal/d supplied by the Ft. Meade well field. The projected water demands for Ft. Meade are consistent with those used in the *Comprehensive Water Strategic Plan*. Also, in this study, it was assumed that a new Kings Heights water treatment plant was not constructed, and that the Crofton Meadows water treatment plant was designed with a capacity of 35 Mgal/d (maximum day) as opposed to 33 Mgal/d (maximum day) proposed on the *Comprehensive Water Strategic Plan*. The capacity of the Chesterfield well field was sufficient to eliminate the Crownsville well field proposed in the *Comprehensive Water Strategic Plan*.

To determine the effects of maximum-day withdrawals, a period of 1 year was simulated where withdrawals from the county's wells were held constant for 6 months (January to June) at 2040 average-day rates determined by the previous optimization scenario, increased for a period of 1 day (July 1st) to daily maximum levels, and returned to average-day levels for the remainder of the year (July 2nd to December). This was not an optimization simulation, but rather a simulation in which withdrawals were specified. The simulation consisted of 30 stress periods of variable duration. The duration of the stress periods are as follows: (1) stress periods 1 through 5 and 26 through 30: 1 month, (2) stress periods 6 through 8 and 23 through 25: 1 week, and (3) stress periods 9 through 22: 1 day. The day of maximum withdrawals occurred in stress period 15. The daily maximum demand for each well field was divided among the individual production wells. Withdrawals used in the simulation are shown in table 12. To realistically reflect probable operating conditions at the well fields, an operational constraint was applied in which the production well with the greatest pumping capacity in each well field was not used during the day of maximum withdrawal. Withdrawals from wells other than those operated by the Anne Arundel County Department of Public Works were held constant at the average-day rates used in stress period 8 (2040-2044) in the previous scenario. During the one day of maximum withdrawals, pumpage from those wells were increased by a factor of 1.5. This increase is within the range observed in withdrawals from Anne Arundel County's public-supply wells (O'Brien and Gere, 2003); however, it may not be representative of maximum-day withdrawals for other types of water use simulated in the model, such as industrial and commercial use.

During the day of maximum withdrawals, the deepest simulated model-cell water levels were 165 ft below sea level in the Upper Patapsco aquifer at Chesterfield, 177 ft below sea level in the Lower Patapsco aquifer at Arnold, and 203 ft below sea level in the Patuxent aquifer at Dorsey Road (tab. 13). Model-cell water levels adjusted to water levels immediately outside pumping wells using the Thiem equation (Trescott, and others, 1976; Pritchett and Garg, 1980) were as deep as 254 ft below sea level in the Upper Patapsco aquifer at Chesterfield, 242 ft below sea level in the Lower Patapsco aquifer at Millersville, and 437 ft below sea level in the Patuxent aquifer at Dorsey Road (tab. 13). Depending on the efficiency of the well, water levels inside the pumping well would be even deeper. No attempt was made to estimate pumping levels based on well efficiency. The adjusted water levels fell below well screens in two Patuxent wells at Dorsey Road (AA Bd 177–Well 19 and AA Bd 178–Well 20). To avoid this problem, withdrawals could be redistributed to other wells. In addition, careful well-field design could help to lessen drawdown by reducing well interference and increasing well efficiency. Based on the adjusted heads immediately outside pumping wells, pumping lift (or distance required to pump water to the surface) ranged from 128 to 374 ft in the Upper Patapsco aquifer, 87 to 346 ft in the Lower Patapsco aquifer, and 211 to 517 ft in the Patuxent aquifer (tab. 13).

Table 14 shows the maximum-daily withdrawals by aquifer for the entire model area by 2040. In Anne Arundel County Department of Public Works wells, withdrawals from the Lower Patapsco aquifer were the greatest (approximately 70 Mgal/d), followed by the Patuxent aquifer (approximately 46 Mgal/d), and the Upper Patapsco aquifer (approximately 24 Mgal/d). For all users in the entire model area, withdrawals from the Lower Patapsco aquifer were the greatest (approximately 78 Mgal/d), followed by the Patuxent aquifer (approximately 68 Mgal/d), the Upper Patapsco aquifer (approximately 31 Mgal/d), and the Magothy aquifer (approximately 6 Mgal/d). The total withdrawal during the day of maximum use was approximately 184 Mgal/d in 2040.

MODEL LIMITATIONS

Numerical ground-water-flow models (such as MODFLOW) are one of the most robust tools for simulating the effects of withdrawals on water levels; however, there are some important limitations that should be considered: (1) the accuracy of the model is limited by the validity of the conceptual model of ground-water flow, the hydrogeologic framework, and the input parameters such as aquifer transmissivity, confining-bed leakance, and pumpage; (2) while the accuracy of the model to simulate historical conditions can be determined using field data, the accuracy of the same model to simulate future conditions can be determined only at the end of the simulation period. However, model performance can be evaluated and improved at intermediate steps as more data on water-level trends and pumpage become available; (3) model-cell heads are averages over the cell areas; therefore, simulated heads are less representative of true heads in larger model cells, and (4) accurately simulating the effects of withdrawals from the confined aquifers on stream baseflow is limited since model calibration is less complete in the recharge (outcrop) areas resulting from a relative absence of head data in the water-table aquifer.

Since the ground-water management code (MODMAN) used in this study uses output from the numerical ground-water-flow model, its performance is constrained by the limitations of the flow model. In particular, accurately estimating aquifer transmissivity is critical because the selection of optimum withdrawal rates that minimize drawdown is highly dependent on aquifer transmissivity. Test wells and aquifer-test data, especially in existing or future well fields currently lacking field data, will be essential in applying the results of this study. Additionally, the validity of the optimization analysis is dependent on the selection of parameters that constrain the optimization problem, such as the design rates of both existing and hypothetical production wells, and projected withdrawal demands.

Table 12. Maximum-day withdrawals in 2040

[County abbreviations are listed on abbreviations for appendixes, p. 81]

Water pressure zone	Well field	Well number (see Plate 1 for location)	Aquifer	Model cell (row, column, layer)	Withdrawals, million gallons per day		
					Stress period		Maximum day, total
					1-14 and 16-30	15 (Maximum day)	
Broad Creek	Broad Creek	AA De 96	Upper Patapsco	62,81,4	0.87	0.87	20.0
		AA De 97		64,80,4	1.15	1.15	
		AA De 136		66,77,4	1.44	1.44	
		AA De 177	Lower Patapsco	63,80,5	0	3.10	
		AA De 208		65,84,5	2.57	0	
		Hypothetical well 1	Upper Patapsco	63,84,4	1.15	1.15	
		Hypothetical well 2	Lower Patapsco	63,84,5	3.10	3.10	
		Hypothetical well 4		66,77,5	0	3.10	
		Hypothetical well 3	Patuxent	63,84,6	1.69	3.10	
		Hypothetical well 5		66,77,6	0	3.10	
	Withernsea	Hypothetical well 1	Upper Patapsco	86,92,4	0.40	3.00	12.0
		Hypothetical well 3		87,93,4	3.10	3.00	
		Hypothetical well 4	Lower Patapsco	88,92,5	0	3.00	
		Hypothetical well 2		86,92,5	0	3.00	
				Total	**15.5**	**32.0**	**32.0**
Broadneck/ Glen Burnie Low	Arnold	AA Cf 118	Upper Patapsco	39,80,4	1.08	1.08	20.0
		AA Cf 119		40,80,4	1.29	1.29	
		AA Cf 120		40,81,4	1.29	1.29	
		AA Cf 155		41,83,4	1.44	1.44	
		AA Cf 142	Lower Patapsco	40,80,5	2.88	2.88	
		AA Cf 150		41,83,5	0.37	0	
		Hypothetical well 1		42,81,5	0	3.17	
		Hypothetical well 2		38,79,5	3.17	3.17	
		Hypothetical well 4		36,83,5	0.44	3.17	
		Hypothetical well 5	Patuxent	40,81,6	0	0.97	
		Hypothetical well 3		38,79,6	0	1.50	
				Total	**12.0**	**20.0**	**20.0**
	Severndale	AA Ce 96	Upper Patapsco	48,50,4	0.43	0.43	8.8
		AA Ce 131	Lower Patapsco	48,50,5	0	2.30	
		AA Ce 132					
		AA Ce 121		50,50,5	0	1.73	
		AA Ce 122		48,49,5	0	0	
		AA Ce 139		46,52,5	1.67	1.87	
		Hypothetical well 1		45,56,5	2.70	2.46	
	Harundale	AA Bd 36		32,32,5	0	0.83	2.2
		AA Bd 37					
		AA Bd 162		33,31,5	0	1.37	
		AA Bd 63					
	Crain Highway	AA Bd 174		44,30,5	0	1.80	1.8
	Glendale	AA Bd 103		28,28,5	0	0.60	0.6
	Elvaton	AA Bd 107		42,32,5	0	0.90	0.9
				Total	**4.80**	**14.3**	**14.3**

Table 12. Maximum-day withdrawals in 2040—Continued

Water pressure zone	Well field	Well number (see Plate 1 for location)	Aquifer	Model cell (row, column, layer)	Withdrawals, million gallons per day		
					Stress period		Maximum day, total
					1-14 and 16-30	15 (Maximum day)	
Glen Burnie High	Quarterfield Road	AA Bd 109	Lower Patapsco	45,24,5	0	0.90	0.9
	Telegraph Road	AA Bc 215		56,23,6	0	0.90	0.9
	Stevenson Road	AA Bd 121		52,26,5	0	0.70	0.7
	Dorsey Road	AA Ad 111	Patuxent	34,15,6	1.01	0	6.0
		AA Bd 161		36,18,6	0.75	0.75	
		AA Bd 177		40,15,6	0	1.66	
		AA Bd 178					
		AA Bd 97		44,17,6	0	0.72	
		AA Bd 98		44,21,6	0	0.85	
		Hypothetical well 1		42,15,6	0	1.01	
		Hypothetical well 2		38,16,6	0.24	1.01	
	Millersville	Hypothetical well 1	Lower Patapsco	52,36,5	3.00	3.00	20.0
		Hypothetical well 3		53,37,5	3.00	3.00	
		Hypothetical well 5		52,37,5	3.00	3.00	
		Hypothetical well 7		52,38,5	3.00	3.00	
		Hypothetical well 2	Patuxent	52,36,6	0	3.00	
		Hypothetical well 4		53,37,6	0	2.02	
		Hypothetical well 6		52,37,6	0	3.00	
		Hypothetical well 8		52,38,6	0	0	
				Total	**14.0**	**28.5**	**28.5**
Crofton	Crofton Meadows	AA Cc 128	Lower Patapsco	84,43,5	1.44	1.44	19.4
		AA Cc 129		85,44,5	1.44	1.44	
		AA Cc 140		83,46,5	2.16	0	
		AA Cd 106		81,49,5	1.51	2.16	
		AA Cc 103	Patuxent	86,43,6	0.87	0.87	
		AA Cc 105		85,43,6	0.90	1.29	
		AA Cc 107		88,43,6	1.15	1.15	
		AA Cc 138		83,46,6	0	1.87	
		AA Cd 107		81,49,6	0	1.87	
		Hypothetical well 1	Lower Patapsco	80,42,5	0	2.16	
		Hypothetical well 3		87,54,5	1.80	2.16	
		Hypothetical well 2	Patuxent	80,42,6	0	1.50	
		Hypothetical well 4		87,54,6	1.50	1.50	
	Chesterfield	Hypothetical well 1	Upper Patapsco	75,61,4	2.48	4.00	15.6
		Hypothetical well 2	Lower Patapsco	75,61,5	0.83	4.00	
		Hypothetical well 3	Patuxent	75,61,6	0.91	3.58	
		Hypothetical well 4	Upper Patapsco	77,62,4	4.00	4.00	
	Ft. Meade	AA Bb 68	Patuxent	79,13,6	1.50	1.50	10.0
		AA Bc 164		75,18,6	1.50	1.50	
		AA Bc 234		73,23,6	1.50	1.50	
		AA Cc 144		75,28,6	0	1.50	
		AA Cc 120		73,26,6	0	1.50	
		AA Cc 123		77,29,4	0	1.05	
		Hypothetical well 1		77,24,6	0	1.50	
		Hypothetical well 2		71,19,6	1.50	0	
				Total	**27.0**	**45.0**	**45.0**
				Grand total	**73**	**140**	**140**

Table 13. Model-cell heads converted to heads immediately outside pumping wells for the maximum-day withdrawal scenario

(County abbreviations are listed on abbreviations for appendixes, p. 81)

Water pressure zone	Well field	Well number (see Plate 1 for location)	Aquifer	Altitude of land surface, feet	Pumping rate, million gallons per day	Cell-average head, related to sea level, feet	Head adjusted to immediately outside well	
							Related to sea level, feet	Related to land surface,[1] feet
Broad Creek	Broad Creek	AA De 96	Upper Patapsco	65	0.87	-126	-138	-203
		AA De 97		90	1.15	-128	-144	-234
		AA De 136		80	1.44	-126	-146	-226
		AA De 177	Lower Patapsco	94	3.10	-175	-220	-314
		Hypothetical well 1	Upper Patapsco	80[2]	1.15	-122	-138	-218
		Hypothetical well 2	Lower Patapsco	80[2]	3.10	-167	-217	-297
		Hypothetical well 4		80[2]	3.10	-163	-208	-288
		Hypothetical well 3	Patuxent	80[2]	3.10	-156	-300	-380
		Hypothetical well 5		80[2]	3.10	-122	-253	-333
	Withernsea	Hypothetical well 1	Upper Patapsco	30[2]	3.10	-98	-125	-155
		Hypothetical well 4	Lower Patapsco	30[2]	3.10	-70	-98	-128
		Hypothetical well 3	Upper Patapsco	30[2]	3.10	-97	-126	-156
		Hypothetical well 2	Lower Patapsco	30[2]	3.10	-128	-194	-224
Broadneck/ Glen Burnie Low	Arnold	AA Cf 118	Upper Patapsco	120	1.08	-94	-107	-227
		AA Cf 119		125	1.29	-97	-112	-237
		AA Cf 120		120	1.29	-98	-112	-232
		AA Cf 155		75	1.44	-94	-110	-185
		AA Cf 142	Lower Patapsco	120	2.88	-177	-221	-341
		Hypothetical well 1		120[2]	3.17	-169	-223	-343
		Hypothetical well 2		120[2]	3.17	-170	-226	-346
		Hypothetical well 4		120[2]	3.17	-160	-216	-336
		Hypothetical well 5	Patuxent	120[2]	0.97	-76	-121	-241
		Hypothetical well 3		120[2]	1.50	-81	-154	-274
	Severndale	AA Ce 96	Upper Patapsco	89	0.43	-24	-39	-128
		AA Ce 131, 132	Lower Patapsco	80	2.30	-136	-187	-267
		AA Ce 122		62	1.73	-126	-166	-251
		AA Ce 139		60	1.87	-75	-120	-180
		Hypothetical well 1		80[2]	2.46	-115	-179	-259
	Harundale	AA Bd 36, 37		31	0.83	-36	-59	-90
		AA Bd 63, 162		38	1.37	-39	-78	-116
	Crain Highway	AA Bd 174		90	1.80	-44	-88	-178
	Glendale	AA Bd 103		80	0.60	-8	-23	-103
	Elvaton	AA Bd 107		20	0.90	-44	-67	-87
Glen Burnie High	Quarterfield Road	AA Bd 109	Lower Patapsco	190	0.90	-6	-24	-214
	Telegraph Road	AA Bc 215		124	0.90	-4	-32	-156
	Stevenson Road	AA Bd 121		108	0.70	-11	-29	-137
	Dorsey Road	AA Bd 161	Patuxent	70	0.75	-174	-297	-367
		AA Bd 177, 178		80	1.66	-203	-437	-517
		AA Bd 97		75	0.72	-107	-222	-297
		AA Bd 98		75	1.85	-107	-219	-294
		Hypothetical well 1		70[2]	1.01	-149	-308	-378
		Hypothetical well 2		70[2]	1.01	-187	-344	-414
	Millersville	Hypothetical well 1	Lower Patapsco	100[2]	3.00	-118	-202	-302
		Hypothetical well 3		100[2]	3.00	-125	-211	-311
		Hypothetical well 5		100[2]	3.00	-136	-242	-342
		Hypothetical well 7		100[2]	3.00	-127	-220	-320
		Hypothetical well 2	Patuxent	100[2]	3.00	-86	-192	-292
		Hypothetical well 4		100[2]	2.02	-78	-141	-241
		Hypothetical well 6		100[2]	3.00	-88	-185	-285
Crofton	Crofton Meadows	AA Cc 128	Lower Patapsco	134	1.44	-133	-161	-295
		AA Cc 129		134	1.44	-133	-165	-299
		AA Cd 106		148	2.16	-136	-178	-326
		AA Cc 103	Patuxent	125	0.87	-102	-115	-240
		AA Cc 105		130	1.29	-104	-123	-253
		AA Cc 107		120	1.15	-97	-115	-235
		AA Cc 138		134	1.87	-108	-136	-270
		AA Cd 107		148	1.87	-102	-133	-281
		Hypothetical well 1	Lower Patapsco	130[2]	2.16	-126	-173	-303
		Hypothetical well 3		130[2]	2.16	-132	-183	-313
		Hypothetical well 2	Patuxent	130[2]	1.50	-95	-118	-248
		Hypothetical well 4		130[2]	1.50	-97	-123	-253
	Chesterfield	Hypothetical well 1	Upper Patapsco	120[2]	4.00	-165	-254	-374
		Hypothetical well 2	Lower Patapsco	120[2]	4.00	-144	-222	-342
		Hypothetical well 3	Patuxent	120[2]	3.58	-117	-196	-316
		Hypothetical well 4	Upper Patapsco	120[2]	4.00	-164	-251	-371
	Ft. Meade	AA Bb 68	Patuxent	130	1.50	-92	-175	-305
		AA Bc 164		130	1.50	-98	-140	-270
		AA Bc 234		130	1.50	-94	-119	-249
		AA Cc 144		139	1.05	-83	-97	-236
		AA Cc 120		119	1.50	-89	-111	-230
		AA Cc 123		119	1.05	-77	-92	-211
		Hypothetical well 1		130[2]	1.50	-91	-114	-244

[1] Equivalent to pumping lift.

[2] Estimate of land surface altitude.

Table 14. Maximum-daily withdrawal rates in 2040 by aquifer.

User or supplier	Maximum-daily withdrawal rates by aquifer, million gallons per day				
	Magothy	Upper Patapsco	Lower Patapsco	Patuxent	Total
I. Anne Arundel County					
A. Department of Public Works[1]					
Broad Creek zone					
Broad Creek well field	0	4.6	9.3	6.2	20
Withernsea well field	0	6.0	6.0	0	12
sub-total	0	10.6	15.3	6.2	32
Broadneck/Glen Burnie Low zone					
Arnold well field	0	5.1	12.4	2.5	20
Severndale well field	0	0.43	8.4	0	8.8
Harundale, Crain Highway, Glendale, and Elvaton wells	0	0	5.5	0	5.5
sub-total	0	5.5	26.3	2.5	34
Glen Burnie High					
Dorsey well field	0	0	0	6.0	6.0
Millersville well field	0	0	12.0	8.0	20.0
Quarterfield Road, Telegraph Road, and Stevenson Road wells	0	0	2.5	0	2.5
sub-total	0	0	14.5	14.0	28.5
Crofton					
Crofton Meadows well field	0	0	9.4	10.0	19.4
Chesterfield well field	0	8.0	4.0	3.6	15.6
Ft. Meade well field	0	0	0	10	10
sub-total	0	8.0	13.4	23.6	45
TOTAL		24.1	69.5	45.7	140
B. City of Annapolis	2.6	2.2	3.6	0	8.4
C. Other users in Anne Arundel County	1.5	3.4	1.0	1.3	7.2
II. Counties other than Anne Arundel County[2] (includes Baltimore City)	2.3	1.0	3.9	21	28
TOTAL FOR MODEL AREA	6.4	31	78	68	184

[1] Does not include Gibson Island, Herald Harbor, and Rose Haven.

[2] Includes portions of Baltimore, Calvert, Kent, Prince George’s, and Queen Anne’s Counties.

SUMMARY AND CONCLUSIONS

The results of this study indicate that sufficient ground water is available to supply the projected demand through 2040 (73 Mgal/d average day) from the Anne Arundel County Department of Public Works well fields, while at the same time supplying ground water to other users in Anne Arundel County and the surrounding counties (including Baltimore City) at permitted levels. Meeting the projected demand will require construction of new wells and well fields. When withdrawals were optimized to minimize drawdown, simulated water levels did not fall below the State-mandated management level near the well fields by the end of the simulation period (2044). However, the increased withdrawals resulted in relatively deep water levels that increased pumping lift, which would lead to greater energy costs. In addition, the increased withdrawals may eventually reduce baseflow to streams within the recharge (outcrop) areas of the aquifers pumped.

Combined average-day ground-water withdrawals from the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers in the model area (in Anne Arundel County, portions of Baltimore City, and portions of Baltimore, Calvert, Kent, Prince George's, and Queen Anne's Counties) have increased twenty-fold from approximately 2 Mgal/d between 1900 and 1920, to 46 Mgal/d in 2002. Of this amount, major well fields operated by the Anne Arundel County Department of Public Works pumped a total of approximately 25 Mgal/d, of which 2.1, 17.0, and 6.2 Mgal/d were withdrawn from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively. Water demand to be supplied by the Anne Arundel County Department of Public Works is projected to increase nearly three-fold to 73 Mgal/d (average day) by 2040, with an estimated maximum-day withdrawal of 140 Mgal/d. An increase of that magnitude could cause significant drawdown resulting in some water levels falling below the regulatory management level, well-operational problems, increased pumping costs, and reduced stream baseflow. To reduce the impact, withdrawals from the Anne Arundel County Department of Public Works supply wells were optimized using a three-dimensional ground-water-flow model (MODFLOW code) and optimization algorithm (MODMAN and SuperLINDO codes). The effects of projected maximum-day withdrawals were also evaluated.

The primary aquifers utilized by the Anne Arundel County Department of Public Works for public supply are the aquifers of the Potomac Group (Upper and Lower Patapsco aquifers and Patuxent aquifer). In Anne Arundel County, the altitude of the top of the Upper Patapsco aquifer ranges from approximately 40 ft above sea level in central Anne Arundel County to approximately 650 ft below sea level at Rose Haven. The aquifer dips to the southeast at approximately 40 ft/mi. The altitude of the top of the Lower Patapsco aquifer ranges from approximately 65 ft above sea level in north-central Anne Arundel County to approximately 1,300 ft below sea level at Rose Haven. The aquifer dips to the southeast at approximately 60 ft/mi. The altitude of the top of the Patuxent aquifer ranges from approximately sea level in north-central Anne Arundel County to approximately 1,750 ft below sea level at Rose Haven. The aquifer dips to the southeast at approximately 70 ft/mi.

In the Upper Patapsco aquifer in Anne Arundel County, calculated transmissivity ranges from 2,406 ft^2/d to 16,068 ft^2/d. In the Lower Patapsco aquifer in Anne Arundel County, calculated transmissivity ranges from 2,807 ft^2/d to 10,214 ft^2/d. In the Patuxent aquifer in Anne Arundel County, calculated transmissivity ranges from 950 ft^2/d to 8,690 ft^2/d. Storage coefficient of the Patapsco (Upper and Lower units undifferentiated) and Patuxent aquifers in the study area range from 0.00005 to 0.0003, and 0.0001 to 0.0007, respectively.

Water levels in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers all have responded to increased withdrawals from these aquifers since the start of development in the early 1900's. In the Magothy aquifer, the deepest head in 2004 in Anne Arundel County is 17 ft below sea level at the southern end of Annapolis Neck. Heads decrease to the south and east, with the lowest heads occurring in northern Charles County (70 ft below sea level) where the Magothy aquifer is pumped for public supply at Waldorf. In the Upper Patapsco aquifer, the deepest head in 2004 in Anne Arundel County is 21 ft below sea level on Broadneck Peninsula. Heads also decrease south and east, with the lowest readings occurring in northern Charles County (70 ft below sea level). In the Lower Patapsco aquifer, the deepest head in 2004 in Anne

Arundel County is 90 ft below sea level at Severndale. As in the Magothy and Upper Patapsco aquifers, heads decrease south and east with the lowest readings occurring in northern Charles County (113 ft below sea level). In the Patuxent aquifer, the deepest head in 2004 is 72 ft below sea level at Dorsey Road.

The amount of drawdown available before water levels reach the management level was calculated by taking the difference between the 2002 water level and the 80-percent management level. Available drawdown in 2002 in Anne Arundel County ranges from approximately 0 to 300 ft and 0 to 500 ft in the Magothy and Upper Patapsco aquifers, respectively, and up to 1,000 ft and 1,400 ft in the Lower Patapsco and Patuxent aquifers, respectively.

The water-supply potential of the Upper Patapsco, Lower Patapsco, and Patuxent aquifers was evaluated by simulating ground-water flow using a numerical, finite-difference ground-water-flow model (MODFLOW). The model simulated flow in the Upper Patapsco, Lower Patapsco, and Patuxent aquifers as well as the Magothy aquifer and water-table aquifer under steady-state, pre-pumping conditions for the period 1900 to 2002. The flow model was calibrated using historical pumpage data, ground-water levels and stream baseflow. The calibrated flow model was used in conjunction with an optimization algorithm (MODMAN and SuperLINDO/PC) to minimize maximum drawdown in the Anne Arundel County Department of Public Works' major well fields, while pumping the projected water demand during the period 2005 to 2040. In this simulation a total of 73 Mgal/d (average day) was withdrawn by 2040 from Anne Arundel County's four pressure zones containing well fields—Broad Creek, Broadneck/Glen Burnie Low, Glen Burnie High, and Crofton. The simulation assumed no water would be obtained from Baltimore City after 2025.

Average-day demands from the Broad Creek and Crofton zones increased from 3.9 to 15.5 Mgal/d, and from 5.7 to 27 Mgal/d, respectively, over the simulation period. Average-day demands from the Broadneck/Glen Burnie Low zone increased from 12 to 16.8 Mgal/d over the simulation period. Average-day demands from the Glen Burnie High zone increased from 4.6 to 14 Mgal/d over the simulation period. To meet the average- and maximum-day demands, hypothetical wells were added to existing well fields in the Broad Creek, Broadneck/Glen Burnie Low, and Crofton pressure zones, and to new well fields at Millersville (Millersville Central Water Facility), Withernsea (near Edgewater), and Chesterfield (near Crofton Meadows).

Average-day demand from the existing and hypothetical wells were optimized to minimize drawdown at model cells adjacent to each well field. In the Broad Creek zone approximately 4.6, 5.7, and 1.7 Mgal/d were withdrawn from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers by 2044 from the Broad Creek well field. Also in the Broad Creek zone, 3.5 Mgal/d were pumped from the Upper Patapsco aquifer in the Withernsea well field by 2044.

In the Broadneck/Glen Burnie Low zone withdrawals from the Arnold well field in 2044 were approximately 5.1 and 6.9 Mgal/d from the Upper and Lower Patapsco aquifers, respectively. In the Severndale well field 0.43 and 4.37 Mgal/d were pumped from the Upper and Lower Patapsco aquifers, respectively, by 2044. The Patuxent aquifer was not included in the optimization analysis because of the high iron concentrations at that site.

In the Glen Burnie High zone the majority of withdrawals were from a new well field (Millersville well field) located adjacent to the Millersville Central Water Facility. Withdrawals from the well field were simulated beginning in 2015. By 2044, 12.0 Mgal/d were withdrawn from the Lower Patapsco aquifer at that site. The remainder of the projected withdrawal for the Glen Burnie High zone (2 Mgal/d) was supplied by the Patuxent aquifer from the Dorsey Road well field.

In the Crofton zone withdrawals from the Crofton Meadows well field in 2044 were approximately 8.4 and 4.4 Mgal/d, respectively, from the Lower Patapsco and Patuxent aquifers. At the Chesterfield well field approximately 6.5, 0.86, and 0.91 Mgal/d were withdrawn from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively, by 2044. The Ft. Meade well field pumped a total of 6 Mgal/d by 2044 from the Patuxent aquifer.

A maximum drawdown of 106 ft occurred in selected model cells in the Upper Patapsco aquifer near the Chesterfield well field, in the Lower Patapsco aquifer near the Arnold, Broad Creek, Crofton Meadows, and Chesterfield well fields, and in the Patuxent aquifer near the Crofton Meadows and Chesterfield well fields by 2044. Simulated potentiometric surfaces in 2044 for the three aquifers show significant cones-of-depression around the major pumping centers in Anne Arundel County.

By 2044, available drawdown (difference between water level and the 80-percent management level) in the Upper Patapsco aquifer in selected model cells near the Broad Creek, Withernsea, Arnold, Severndale, and Chesterfield well fields was reduced to 90, 301, 94, 20, and 56 ft, respectively. By 2044, available drawdown in the Lower Patapsco aquifer in selected model cells near the Broad Creek, Withernsea, Arnold, Severndale, Millersville, Crofton Meadows, and Chesterfield well fields was reduced to 407, 680, 464, 164, 48, 160, and 259 ft, respectively. Available drawdown in the Lower Patapsco aquifer in a model cell near wells at Harundale, Crain Highway, Glendale, Quarterfield Road, Telegraph Road, and Stevenson Road was reduced to 40 ft by 2044. By 2044, available drawdown in the Patuxent aquifer in selected model cells near Broad Creek, Arnold, Dorsey Road, Millersville, Crofton Meadows, Chesterfield, and Ft. Meade well fields was reduced to 768, 800, 198, 325, 512, 625, and 188 ft, respectively.

Based on the optimized average-day withdrawals, the lowest model-cell water levels were 140 ft below sea level in the Upper Patapsco aquifer in the Chesterfield well field, 153 ft below sea level in the Lower Patapsco aquifer in the Broad Creek well field, and 164 ft below sea level in the Patuxent aquifer in the Dorsey Road well field. Model-cell water levels are averages over model-cell areas; therefore, water levels are deeper in pumping wells. Water levels immediately outside pumping wells estimated using the Thiem equation at the end of the simulation period (2044) ranged from 29 to 227 ft below sea level in the Upper Patapsco aquifer, 107 to 203 ft below sea level in the Lower Patapsco aquifer, and 97 to 305 ft below sea level in the Patuxent aquifer. Based on the adjusted heads immediately outside pumping wells, pumping lift (or distance required to pump water to the surface) ranged from 114 to 347 ft in the Upper Patapsco aquifer, 195 to 320 ft in the Lower Patapsco aquifer, and 226 to 373 ft in the Patuxent aquifer. The greatest pumping lift, 373 ft, occurred in the Dorsey Road well field.

As a result of the increased withdrawals over the simulation period, stream baseflow decreased from simulated 2002 levels in Sawmill Creek in northern Anne Arundel County (9 percent), North River in central Anne Arundel County (5 percent), Northwest Branch of the Anacostia River at Riverdale in northern Prince George’s County (7 percent), and Western Branch at Upper Marlboro in east-central Prince George’s County (4 percent).

Withdrawals from Anne Arundel County’s well fields during the day of maximum use are projected to increase to approximately 140 Mgal/d by 2040. During the day of maximum withdrawals, the deepest model-cell water levels were 165 ft below sea level in the Upper Patapsco aquifer at Chesterfield, 177 ft below sea level in the Lower Patapsco aquifer at Arnold, and 203 ft below sea level in the Patuxent aquifer at Dorsey Road. Model-cell water levels adjusted to water levels immediately outside pumping wells using the Thiem equation were as deep as 254 ft below sea level in the Upper Patapsco aquifer at Chesterfield, 242 ft below sea level in the Lower Patapsco aquifer at Millersville, and 437 ft below sea level in the Patuxent aquifer at Dorsey Road. The adjusted water levels fell below well screens in two Patuxent wells at Dorsey Road (AA Bd 177–Well 19 and AA Bd 178–Well 20). To avoid this problem, withdrawals could be redistributed to other wells. In addition, careful well-field design could help to lessen drawdown by reducing well interference and increasing well efficiency. Based on the adjusted heads immediately outside pumping wells, pumping lift (or distance required to pump water to the surface) ranged from 128 to 374 ft in the Upper Patapsco aquifer, 87 to 346 ft in the Lower Patapsco aquifer, and 211 to 517 ft in the Patuxent aquifer.

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APPENDIXES

ABBREVIATIONS FOR APPENDIXES

	Units of measurement
ft	feet
in	inches
gal/min	gallons per minute
(gal/min)/ft	gallons per minute per foot
Mgal/d	million gallons per day
	Counties
AA	Anne Arundel County
BA	Baltimore County
BC	Baltimore City
CA	Calvert County
KE	Kent County
PG	Prince George’s County
QA	Queen Anne’s County
	Aquifers
UKpt	Upper Patapsco aquifer
LKpt	Lower Patapsco aquifer
Kpx	Patuxent aquifer
Kmg	Magothy aquifer
	Well drillers
A C Schultes	A C Schultes of Maryland, Inc.
CZ Enterprises	CZ Enterprises
Delmarva	Delmarva Drilling, Inc.
Layne-Atlantic	Layne-Atlantic Co.
Shannahan	Shannahan Artesian Well Co.
Sydnor	Sydnor Hydrodynamics, Inc.
	Miscellaneous
DPW	Department of Public Works
NASA	National Aeronautics and Space Administration
Pl.	Plate
Rd.	Road

Appendix A. Construction records for production wells operated by the Anne Arundel County Department of Public Works and Ft. Meade (U.S. Army).

Well number (pl. 1)	State permit number	Owner and local well name	Well driller	Date completed	Altitude of land surface (ft above sea level)	Depth of well (ft)	Diameter of well (in.)		Depth to top screen (ft)	Total length of screen (ft)	Aquifer	Water levels below land surface (ft)		Date measured (month/year)	Pumping rate (gal/min)	Hours pumped	Specific capacity [(gal/min)/ft]
							Casing	Screen				Static	Pumping				
AA Ad 111	AA-94-1107	AA DPW, Dorsey 18	Layne-Atlantic	1998	68	500	18	8	455	40	Kpx	100	160	10/98	600	5	10
AA Bb 68	AA-68-0753	U.S. Army, Ft. Meade 1	Shannahan	1968	130	497	16,8	8	454	43	Kpx	65	225	4/68	700	4	4.4
AA Bc 164	AA-68-0754	U.S. Army, Ft. Meade 2	Shannahan	1968	130	594	16,8	8	495	101	Kpx	71	153	3/68	884	24	11
AA Bc 215	AA-81-1035	AA DPW, Telegraph Rd.	Sydnor	1982	124	325	16	10	250	62	LKpt	68	141	12/82	718	24	9.8
AA Bc 234	AA-81-3424	U.S. Army, Ft. Meade 3	A C Schultes	1984	130	672	18,12	12	480	122	Kpx	92	137	10/84	1,067	48	24
AA Bd 36	2803	AA DPW, Harundale 1	Layne-Atlantic	1948	31	123	20	10	98	25	LKpt	3	--	7/51	--	--	--
AA Bd 37	--	AA DPW, Harundale 2	Layne-Atlantic	1949	38	115	20	10	90	25	LKpt	7	67	1/49	450	48	7.5
AA Bd 63	20138	AA DPW, Harundale 3	Layne-Atlantic	1955	28	180	10	8	160	20	LKpt	0	110	9/55	500	5	4.5
AA Bd 97	49554	AA DPW, Dorsey 16	Layne-Atlantic	1962	75	534	10	10	504	30	Kpx	26	146	11/62	500	40	4.1
AA Bd 98	57226	AA DPW, Dorsey 17	Layne-Atlantic	1964	75	591	10	10	552	39	Kpx	58	205	8/64	907	8	6.2
AA Bd 103	AA-69-0954	AA DPW, Glendale	Layne-Atlantic	1969	80	221	10	10	176	35	LKpt	67	152	5/69	554	24	6.5
AA Bd 107	AA-69-1195	AA DPW, Elvaton	Layne-Atlantic	1969	20	240	10	10	185	35	LKpt	20	70	7/69	650	24	10
AA Bd 109	AA-71-0553	AA DPW, Quarterfield Rd.	Layne-Atlantic	1971	190	300	10	10	260	40	LKpt	125	164	7/71	326	24	8.4
AA Bd 121	AA-81-0368	AA DPW, Stevenson Rd.	A C Schultes	1982	108	346	6	6	326	20	Kpx	63	142	5/82	266	24	3.4
AA Bd 161	AA-88-4521	AA DPW, Dorsey 2	Delmarva	1990	70	516	16	8	478	38	Kpx	96	231	7/90	500	24	3.7
AA Bd 162	AA-88-7363	AA DPW, Harundale 4	A C Schultes	1992	42	215	14	10	185	30	LKpt	39	121	4/92	776	24	9.5
AA Bd 174	AA-94-8021	AA DPW, Crain Highway	Sydnor	2002	90	255	18	10	209	41	LKpt	53	128	8/02	750	24	10
AA Bd 177	AA-94-5643	AA DPW, Dorsey 19	A C Schultes	2001	80	515	18,8	8	480	30	Kpx	121	347	12/01	500	24	2.2
AA Bd 178	AA-94-7152	AA DPW, Dorsey 20	A C Schultes	2001	80	425	18,10	10	335	70	Kpx	114	250	12/01	700	24	5.1
AA Cc 103	AA-73-0086	AA DPW, Crofton Meadows 2	Layne-Atlantic	1973	125	1,150	10	10	1,030	100	Kpx	83	182	7/73	609	24	6.2
AA Cc 105	AA-73-0087	AA DPW, Crofton Meadows 3	Layne-Atlantic	1973	130	1,195	10	10	1,040	110	Kpx	103	239	8/73	726	24	5.3
AA Cc 107	AA-73-2802	AA DPW, Crofton Meadows 1	Layne-Atlantic	1974	120	1,000	10	10	1,035	100	Kpx	113	155	7/74	1,001	24	24
AA Cc 120	AA-81-3425	U.S. Army, Ft. Meade 4	A C Schultes	1984	119	685	18,12	12	581	89	Kpx	90	164	10/84	1,170	48	16
AA Cc 123	AA-81-3423	U.S. Army, Ft. Meade 6	A C Schultes	1984	130	747	18,12	12	611	81	Kpx	95	163	12/84	1,100	48	16
AA Cc 128	AA-81-7313	AA DPW, Crofton Meadows 4	Layne-Atlantic	1987	134	719	18	10	650	66	LKpt	101	212	3/87	1,000	24	9.0
AA Cc 129	AA-81-7314	AA DPW, Crofton Meadows 5	Layne-Atlantic	1987	134	577	18	10	519	38	LKpt	93	183	6/87	1,000	24	11
AA Cc 138	AA-94-1172	AA DPW, Crofton Meadows 7	A C Schultes	1997	134	1,195	20	10	930	190	Kpx	153	250	9/97	1,550	24	16
AA Cc 140	AA-94-1174	AA DPW, Crofton Meadows 6	A C Schultes	1998	135	530	24	10	510	117	LKpt	130	210	1/98	1,538	24	19
AA Cc 144	AA-94-8678	U.S. Army, Ft. Meade 5	A C Schultes	2003	139	733	18,12	12	604	104	Kpx	150	232	2/03	1,036	24	13

Appendix A. Continued.

Well number (pl. 1)	State permit number	Owner and local well name	Driller	Date completed	Altitude (ft above sea level)	Depth of well (ft)	Diameter of well (in.)		Depth to top screen (ft)	Total length of screen (ft)	Aquifer	Water levels below land surface (ft)		Date measured	Pumping rate (gal/min)	Hours pumped	Specific capacity [(gal/min)/ft]
							Casing	Screen				Static	Pumping				
AA Cd 106	AA-94-1173	AA DPW, Crofton Meadows 8	A C Schultes	1997	148	585	24	10	570	130	LKpt	135	236	11/97	2,000	6	20
AA Cd 107	AA-94-1175	AA DPW, Crofton Meadows 9	A C Schultes	1997	148	1,250	20	10	1,005	135	Kpx	150	247	11/97	1,553	6	16
AA Ce 96	43203	AA DPW, Severndale 3	Layne-Atlantic	1961	89	198	10	10	183	15	UKpt	63	125	10/61	400	24	6.5
AA Ce 121	AA-73-4129	AA DPW, Severndale 4	Layne-Atlantic	1976	85	575	16	16	410	130	LKpt	--	--	--	--	--	--
AA Ce 122	AA-73-4130	AA DPW, Severndale 5	Layne-Atlantic	1975	62	535	16	16	390	130	LKpt	72	131	8/75	1,218	24	21
AA Ce 131	AA-86-0110	AA DPW, Severndale 6	Sydnor	1988	80	559	10	10	522	23	LKpt	98	219	4/88	805	24	7.0
AA Ce 132	AA-86-0111	AA DPW, Severndale 7	Sydnor	1988	80	513	10	10	411	87	LKpt	102	151	4/88	805	24	16
AA Ce 139	AA-88-5792	AA DPW, Severndale 8	A C Schultes	1991	60	526	24	12	406	90	LKpt	81	202	9/91	1,050	24	8.7
AA Ce 149	AA-94-6681	AA DPW, Severndale 9	A C Schultes	2001	60	950	20	10	680	185	Kpx	65	222	10/01	1,650	24	11
AA Cf 118	AA-73-5564	AA DPW, Arnold 2	Sydnor	1976	120	551	18	12	387	113	UKpt	119	192	5/76	754	24	10
AA Cf 119	AA-73-5562	AA DPW, Arnold 1	Sydnor	1976	125	565	18	12	429	107	UKpt	130	187	8/76	754	24	13
AA Cf 120	AA-73-5563	AA DPW, Arnold 3A	Sydnor	1976	120	560	18	12	423	85	UKpt	124	186	10/76	754	24	12
AA Cf 142	AA-88-3644	AA DPW, Arnold 4	Sydnor	1990	120	975	18	18	786	153	LKpt	129	204	1/90	2,045	20	27
AA Cf 150	AA-94-1104	AA DPW, Arnold 5	Layne-Atlantic	1998	75	945	24	12	765	115	LKpt	96	287	2/98	2,400	24	13
AA Cf 155	AA-94-6680	AA DPW, Arnold 6	A C Schultes	2002	75	513	20	10	420	75	UKpt	98	178	5/02	1,062	24	13
AA De 96	AA-68-0188	AA DPW, Broad Creek 1	Layne-Atlantic	1967	65	492	12	10	447	45	UKpt	65	122	9/67	1,001	30	18
AA De 97	AA-68-0189	AA DPW, Broad Creek 2	Layne-Atlantic	1967	90	495	12	10	445	50	UKpt	84	150	10/67	1,001	30	15
AA De 136	AA-81-2588	AA DPW, Broad Creek 3	CZ Enterprises	1984	80	482	12	12	400	82	UKpt	85	202	8/84	1,007	24	8.6
AA De 177	AA-81-9213	AA DPW, Broad Creek 4	Sydnor	1988	94	974	18	12	836	92	LKpt	107	247	4/88	2,520	24	18
AA De 208	AA-88-9909	AA DPW, Broad Creek 5	A C Schultes	1993	80	1,022	24	12	760	157	LKpt	85	162	12/93	2,521	24	33

Appendix B. Appropriated ground-water use in the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers in the study area, 1900-2002.

Identification number (see figures 8, 9, 10, and 11)	Ground-water appropriation permit	Owner	Aquifer	Production wells	Average appropriation, Mgal/d	Model cell (row, column, layer)	Average withdrawals, million gallons per day					
							Year					
							1900-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969
1	AA32G001	Naval Research Laboratory	Kmg	AA Df 64	Inactive	52,93,3	0	0	0	0.150	0.188	0.190
2a,b	AA32G003	U.S. Naval Academy	UKpt	AA Df 12, 13	2.000	54,92,4	0.925	1.000	1.000	1.000	1.028	0.660
2c,d,e				AA Df 80, 83,160		54,91,4	0	0	0	0	0	0.325
2f				AA Df 101		53,91,4	0	0	0	0	0	0
						Total =	0.925	1.000	1.000	1.000	1.028	0.985
3a	AA32G101	Naval Research Laboratory	UKpt	AA Df 16	Inactive	52,93,4	0	0	0	0.307	0.192	0.192
3b				AA Df 65		51,93,4	0	0	0	0	0.192	0.192
						Total =	0	0	0	0.307	0.384	0.384
4	AA47G003	Laurel Racing Association	Kpx	AA Bb 22	0.043	92,6,6	0	0	0	0	0	0.070
5a,b	AA49G004	Sandy Point State Park	Kmg	AA Cg 6, 8	0.029	24,94,3	0	0	0	0	0.004	0.007
6a,b,e,f	AA53G008	AA DPW, Severndale	LKpt	AA Ce 94, 95, 131, 132	4.700	48,50,5	0	0	0	0	0	0
6c				AA Ce 121		50,50,5	0	0	0	0	0	0
6d				AA Ce 122		48,49,5	0	0	0	0	0	0
6g				AA Ce 139		46,52,5	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
7	AA53G108	AA DPW, Severndale	UKpt	AA Ce 96	0.300	48,50,4	0	0	0	0	0	0
8	AA53G208	AA DPW, Severndale	Kpx	AA Ce 149	1.6	46,52,6	0	0	0	0	0	0
9a	AA54G001	Crownsville State Hospital	Kmg	AA Cd 11	0.215	60,60,3	0	0	0.329	0.356	0.179	0.098
9b,d				AA Cd 43, 72		62,60,3	0	0	0	0	0.179	0.195
9c				AA Cd 50		61,60,3	0	0	0	0	0	0.098
						Total =	0	0	0.329	0.356	0.358	0.390
10a	AA54G018	AA DPW, Kings Heights	UKpt/ LKpt	AA Cc 43 (UKpt)	0.070	69,33,4	0	0	0	0	0.005	0.020
10b				AA Cc 79 (LKpt)		69,33,5	0.	0	0	0	0.005	0.020
						Total =	0	0	0	0	0.010	0.040
11a,b	AA54G019	Parkway Inn	LKpt	AA Bb 37, 71	0.015	60,8,5	0	0	0	0	0	0
12a,b	AA55G016	Severn Mobile Home Park	UKpt	AA Bc 88, 187	Inactive	55,19,4	0	0	0	0	0.004	0.012
13a,b	AA56G002	Sylvan Shores	Kmg	AA De 69, 122	0.055	80,86,3	0	0	0	0	0.035	0.038
14a,b	AA57G004	Two Guys Department Store	LKpt	AA Ad 69, 71	Inactive	27,24,5	0	0	0	0	0	0.200
15	AA57G007	Chesapeake Mobile Court	LKpt	AA Bc 72	Inactive	56,10,5	0	0	0	0	0.010	0.021
16	AA58G005	Rol-Park Trailer Village	UKpt	AA Bd 89	Inactive	50,32,4	0	0	0	0	0.003	0.008
17	AA60G021	Landsman Mobile Home Park	Kmg	AA Cd 93	0.025	63,67,3	0	0	0	0	0	0.003

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day															
	Year															
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
1	0.180	0.200	0.200	0.200	0.200	0.164	0.168	0.137	0.161	0.143	0.141	0.147	0.155	0.065	0.127	0.130
2a,b	0.637	0.657	0.675	0.628	0.685	0.683	0.629	0.700	0.731	0.707	0.802	0.876	0.950	1.185	1.060	0.915
2c,d,e	0.637	0.657	0.675	0.628	0.685	0.683	0.629	0.700	0.731	0.707	0.802	0.876	0.950	1.185	1.060	0.915
2f	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.382
Total	1.274	1.314	1.350	1.256	1.370	1.366	1.258	1.400	1.462	1.414	1.604	1.752	1.900	2.370	2.120	2.212
3a	0.158	0.157	0.145	0.183	0.148	0.165	0.195	0.165	0.170	0.165	0.156	0.157	0.149	0.073	0.017	0.223
3b	0.158	0.157	0.145	0.183	0.148	0.165	0.195	0.165	0.170	0.165	0.156	0.157	0.149	0.073	0.017	0.223
Total	0.316	0.314	0.290	0.366	0.296	0.330	0.390	0.330	0.340	0.330	0.312	0.314	0.298	0.146	0.034	0.446
4	0.060	0.044	0.066	0.068	0.074	0.084	0.085	0.087	0.087	0.087	0.071	0.075	0.094	0.073	0.067	0.083
5a,b	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.011	0.009	0.010	0.009	0.007	0.016
6a,b,e,f	0	0	0	0	0	0	0	0	0.202	0.397	2.230	0.585	1.381	2.078	2.032	2.104
6c	0	0	0	0	0	0	0	0	0.067	0.133	0.740	0.195	0.460	0.693	0.677	0.701
6d	0	0	0	0	0	0	0	0	0.067	0.133	0.740	0.195	0.460	0.693	0.677	0.701
6g	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0.336	0.663	3.710	0.975	2.301	3.464	3.386	3.506
7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9a	0.130	0.132	0.143	0.061	0.059	0.053	0.050	0.050	0.049	0.041	0.046	0.046	0.047	0.046	0.049	0.058
9b,d	0.260	0.264	0.287	0.122	0.118	0.105	0.099	0.101	0.098	0.083	0.092	0.092	0.094	0.091	0.098	0.115
9c	0.130	0.132	0.143	0.061	0.059	0.053	0.050	0.050	0.049	0.041	0.046	0.046	0.047	0.046	0.049	0.058
Total	0.520	0.527	0.573	0.244	0.235	0.211	0.199	0.202	0.197	0.165	0.184	0.184	0.187	0.183	0.196	0.230
10a	0.032	0.025	0.048	0.052	0.054	0.056	0.062	0.060	0.075	0.081	0.511	0.569	0.372	0.145	0.003	0.022
10b	0.032	0.025	0.048	0.052	0.054	0.056	0.062	0.060	0.075	0.081	0.511	0.569	0.372	0.145	0.003	0.022
Total	0.064	0.050	0.096	0.104	0.108	0.112	0.124	0.120	0.150	0.162	1.022	1.138	0.744	0.290	0.006	0.044
11a,b	0	0.008	0.008	0.008	0.006	0.006	0.005	0.008	0.008	0.008	0.010	0.007	0.013	0.015	0.013	0.018
12a,b	0.016	0.016	0.019	0.024	0.016	0.013	0.015	0.015	0.016	0.015	0.015	0.026	0.015	0.015	0.007	0
13a,b	0.041	0.043	0.052	0.047	0.043	0.034	0.038	0.044	0.041	0.042	0.039	0.042	0.043	0.045	0.042	0.047
14a,b	0.200	0.178	0.282	0.178	0.200	0.200	0.200	0	0	0	0	0	0	0	0	0
15	0.025	0.025	0.026	0.027	0.029	0.030	0.033	0.035	0.022	0.036	0.036	0.039	0.040	0.036	0	0
16	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.012	0.013	0.015	0.017	0.025	0.019	0.020	0.017	0.019
17	0.007	0.009	0.010	0.010	0.010	0.010	0.013	0.013	0.015	0.012	0.012	0.011	0.026	0.016	0.015	0.015

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day																
	Year																
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
1	0.045	0.045	0.188	0.188	0.482	0.335	0.335	0.335	0.427	0.427	0	0	0	0	0	0	0
2a,b	0.936	0.872	0.601	0.478	0.395	0.454	0.380	0.433	0.432	0.421	0.338	0.351	0.341	0.368	0.352	0.336	0.317
2c,d,e	0.936	0.872	0.601	0.478	0.598	0.688	0.575	0.656	0.654	0.638	0.513	0.531	0.516	0.558	0.534	0.509	0.480
2f	0.391	0.364	0.251	0.200	0.200	0.230	0.192	0.219	0.218	0.213	0.171	0.177	0.173	0.186	0.178	0.170	0.160
Total	2.263	2.108	1.453	1.156	1.193	1.372	1.147	1.308	1.304	1.272	1.022	1.059	1.030	1.112	1.064	1.015	0.957
3a	0.257	0.225	0.215	0.215	0.215	0.215	0.215	0.215	0.208	0.216	0.204	0.168	0.168	0.164	0	0	0
3b	0.257	0.225	0.215	0.215	0.215	0.215	0.215	0.215	0.208	0.216	0.204	0.168	0.168	0.164	0	0	0
Total	0.514	0.450	0.430	0.430	0.430	0.430	0.430	0.430	0.416	0.432	0.408	0.336	0.336	0.328	0	0	0
4	0.079	0.084	0.063	0.063	0.042	0.038	0.037	0.034	0.039	0.040	0.043	0.032	0.021	0.018	0.016	0.012	0
5a,b	0.021	0.026	0.041	0.047	0.053	0.070	0.022	0.014	0.014	0.035	0.018	0.019	0.028	0.025	0.039	0.019	0.019
6a,b,e,f	2.033	1.657	1.690	1.540	2.569	2.166	1.945	2.188	2.254	2.815	3.116	3.124	3.149	3.237	2.946	3.064	3.560
6c	0.678	0.550	0.570	0.513	0.856	0.725	0.651	0.732	0.754	0.942	1.043	1.046	1.054	1.083	0.986	1.025	0.890
6d	0.678	0.550	0.570	0.513	0.856	0.725	0.651	0.732	0.754	0.942	1.043	1.046	1.054	1.083	0.986	1.025	0.890
6g	0	0	0	0	0	0.725	0.651	0.732	0.754	0.942	1.043	1.046	1.054	1.083	0.986	1.025	0.890
Total	3.389	2.757	2.830	2.566	4.281	4.341	3.898	4.384	4.516	5.641	6.245	6.262	6.311	6.486	5.904	6.139	6.230
7	0	0	0	0	0	0	0	0.374	0.244	0.339	0.296	0.240	0.290	0.290	0.307	0.363	0
8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9a	0.054	0.041	0.041	0.033	0.060	0.039	0.033	0.041	0.047	0.046	0.041	0.035	0.034	0.035	0.043	0.060	0.062
9b,d	0.108	0.083	0.082	0.066	0.120	0.078	0.066	0.082	0.094	0.093	0.081	0.070	0.068	0.070	0.085	0.119	0.123
9c	0.054	0.041	0.041	0.033	0.060	0.039	0.033	0.041	0.047	0.046	0.041	0.035	0.034	0.035	0.043	0.060	0.062
Total	0.216	0.166	0.164	0.133	0.240	0.156	0.132	0.163	0.188	0.186	0.162	0.139	0.135	0.140	0.171	0.238	0.247
10a	0.011	0.048	0.007	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10b	0.011	0.048	0.007	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0.022	0.096	0.014	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11a,b	0.015	0.014	0.014	0.014	0.014	0.014	0.008	0.006	0.003	0.011	0.006	0.006	0.006	0.003	0.004	0.007	0
12a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13a,b	0.048	0.048	0.052	0.047	0.047	0.054	0.072	0.068	0.051	0.051	0.058	0.069	0.089	0.076	0.075	0.069	0.073
14a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0.017	0.010	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0.015	0.015	0.018	0.017	0.018	0.019	0.018	0.016	0.022	0.024	0.016	0.017	0.015	0.012	0.011	0.012	0.013

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Ground-water appropriation permit	Owner	Aquifer	Production wells	Average appropriation, Mgal/d	Model cell (row, column, layer)	Average withdrawals, million gallons per day					
							Year					
							1900-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969
18a,b,c	AA60G024	U.S. Department of Defense	Kpx	AA Bb 50, 54,70	0.018	76,9,6	0	0	0	0	0	0.015
18d				AA Bb 75		77,10,6	0	0	0	0	0	0.015
						Total =	0	0	0	0	0	0.030
19	AA62G003	Atlas Container Corp.	UKpt	AA Bc 182	0.030	57,26,4	0	0	0	0	0	0.002
20a	AA62G028	Pasadena Water Co.	UKpt	AA Be 104	Inactive	33,39,4	0	0	0	0	0	0.020
20b				AA Be 105		33,40,4	0	0	0	0	0	0.020
						Total =	0	0	0	0	0	0.40
21a,b	AA62G030	Chemetals Corp.	Kpx	AA Ae 35, 36	0.250	18,29,6	0	0	0	0	0	0.305
22a,b	AA63G008	Holiday Mobile Estates	Kpx	AA Bc 177, 178	0.125	58,9,6	0	0	0	0	0	0.040
23a,b	AA63G029	Sherwood Forest Water Co.	Kmg	AA Ce 98, 125	0.100	55,71,3	0	0	0	0	0	0.060
24a,b,c	AA65G032	Maryland Manor Mobile Estates	Kmg	AA Ec 6, 7, 8	0.080	100,89,3	0	0	0	0	0	0
25a,c	AA65G033	AA DPW, Maryland City	Kpx	AA Bb 64, 66	0.075	93,8,6	0	0	0	0	0.089	0.139
25b				AA Bb 65		92,8,6	0	0	0	0	0.089	0.139
25d				AA Bb 69		91,7,6	0	0	0	0	0	0
						Total =	0	0	0	0	0.178	0.278
26a,b	AA66G027	Northrop Grumman Corp.	UKpt	AA Cg 18, 19	0.060	27,95,4	0	0	0	0	0	0.027
27a,b	AA66G028	Epping Forest	Kmg	AA Ce 99, 119	0.042	54,75,3	0	0	0	0	0.005	0.011
28	AA66G048	Crofton Country Club	Kmg	AA Cc 62	0.060	89,39,3	0	0	0	0	0	0
29a	AA68G006	AA DPW, Broad Creek	UKpt	AA De 96	2.880	62,81,4	0	0	0	0	0	0.062
29b				AA De 97		64,80,4	0	0	0	0	0	0.062
29c				AA De 136		66,77,4	0	0	0	0	0	0
						Total =	0	0	0	0	0	0.124
30a,b	AA68G011	Southern High School	Kmg	AA Ed 39, 41	0.025	96,93,3	0	0	0	0	0	0
31a,b	AA69G006	Ridgewood Mobile Home Park	Kpx	AA Bc 199, 200	Inactive	53,9,6	0	0	0	0	0	0
32a,b	AA69G016	Pioneer City	LKpt	AA Bc 169, 195	0.560	57,15,5	0	0	0	0	0	0
33a,b	AA69G019	AA DPW, Dorsey Road	Kpx	AA Ad 76, 111	3.000	34,15,6	0	0	0	0	0.178	0.222
33c				AA Bd 161		36,18 6	0	0	0	0	0	0
33d,e,f				AA Bd 66, 177, 178		40,15,6	0	0	0	0	0.178	0.222
33g				AA Bd 97		44,17,6	0	0	0	0	0	0.222
33h				AA Bd 98		44,21,6	0	0	0	0	0	0.222
						Total =	0	0	0	0	0.356	0.888

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day															
	Year															
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
18a,b,c	0.015	0.014	0.016	0.014	0.012	0.013	0.014	0.013	0.015	0.014	0.014	0.014	0.013	0.013	0.013	0.014
18d	0.015	0.014	0.016	0.014	0.012	0.013	0.014	0.013	0.015	0.014	0.014	0.014	0.013	0.013	0.013	0.014
Total	0.030	0.028	0.032	0.028	0.024	0.026	0.028	0.026	0.030	0.028	0.028	0.028	0.026	0.026	0.026	0.028
19	0.003	0.004	0.004	0.005	0.008	0.011	0.014	0.015	0.014	0.014	0.011	0.012	0.011	0.012	0.015	0.014
20a	0.020	0.027	0.027	0.023	0.023	0.023	0.023	0.024	0	0	0	0	0	0	0	0
20b	0.020	0.027	0.027	0.023	0.023	0.023	0.023	0.024	0	0	0	0	0	0	0	0
Total	0.040	0.054	0.054	0.046	0.046	0.046	0.046	0.048	0	0	0	0	0	0	0	0
21a,b	0.398	0.483	0.520	0.685	0.744	0.725	0.916	0.908	0.778	0.580	0.781	0.948	0.500	0.352	0.804	0.781
22a,b	0.041	0.041	0.044	0.044	0.047	0.045	0.047	0.043	0.044	0.044	0.046	0.046	0.047	0.047	0.053	0.073
23a,b	0.070	0.047	0.053	0.055	0.051	0.048	0.055	0.066	0.058	0.057	0.059	0.064	0.035	0.067	0.066	0.069
24a,b,c	0	0.029	0.054	0.057	0.055	0.055	0.052	0.051	0.051	0.045	0.070	0.063	0.066	0.053	0.049	0.039
25a,c	0.256	0.239	0.261	0.266	0.274	0.265	0.270	0.267	0.256	0.269	0.282	0.290	0.293	0.324	0.318	0.312
25b	0.256	0.120	0.130	0.133	0.137	0.133	0.135	0.134	0.128	0.134	0.141	0.145	0.146	0.162	0.159	0.156
25d	0	0.120	0.130	0.133	0.137	0.133	0.135	0.134	0.128	0.134	0.141	0.145	0.146	0.162	0.159	0.156
Total	0.512	0.479	0.521	0.532	0.548	0.531	0.540	0.535	0.512	0.537	0.564	0.580	0.585	0.648	0.636	0.624
26a,b	0.061	0.090	0.043	0.033	0.028	0.035	0.029	0.019	0.022	0.023	0.023	0.029	0.023	0.030	0.041	0.033
27a,b	0.027	0.031	0.036	0.037	0.034	0.036	0.039	0.043	0.038	0.036	0.041	0.029	0.028	0.034	0.029	0.034
28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.010	0.001
29a	0.051	0.056	0.079	0.069	0.079	0.097	0.119	0.099	0.106	0.133	0.188	0.205	0.183	0.204	0.183	0.275
29b	0.051	0.056	0.079	0.069	0.079	0.097	0.119	0.099	0.106	0.133	0.188	0.205	0.183	0.204	0.183	0.275
29c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.183	0.275
Total	0.102	0.112	0.158	0.138	0.158	0.194	0.238	0.198	0.212	0.266	0.376	0.410	0.366	0.408	0.549	0.825
30a,b	0	0	0	0	0	0	0	0.014	0.020	0.032	0.033	0.032	0.023	0.023	0.022	0.022
31a,b	0.100	0.100	0.011	0.012	0.010	0.010	0.010	0.010	0.010	0.011	0.022	0.022	0.017	0.022	0.020	0.011
32a,b	0	0.035	0.132	0.174	0.225	0.255	0.304	0.332	0.380	0.388	0.406	0.429	0.436	0.440	0.452	0.453
33a,b	0.245	0.285	0.418	0.407	0.414	0.526	0.504	0.514	0.652	0.385	0.443	0.495	0.550	1.122	0.662	0.804
33c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33d,e,f	0.245	0.285	0.418	0.407	0.414	0.526	0.504	0.514	0.652	0.385	0.443	0.495	0.550	1.122	0.662	0.804
33g	0.245	0.285	0.418	0.407	0.414	0.526	0.504	0.514	0.652	0.385	0.443	0.495	0.550	1.122	0.662	0.804
33h	0.245	0.285	0.418	0.407	0.414	0.526	0.504	0.514	0.652	0.385	0.443	0.495	0.550	1.122	0.662	0.804
Total	0.980	1.140	1.672	1.628	1.656	2.104	2.016	2.056	2.608	1.540	1.772	1.980	2.200	4.488	2.648	3.216

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day																
	Year																
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
18a,b,c	0.014	0.014	0.013	0.013	0.013	0.009	0.007	0.006	0.005	0.006	0.007	0.007	0.007	0.005	0.008	0.005	0.003
18d	0.014	0.014	0.013	0.013	0.013	0.009	0.007	0.006	0.005	0.006	0.007	0.007	0.007	0.005	0.008	0.005	0.003
Total	0.028	0.028	0.026	0.026	0.026	0.018	0.014	0.012	0.010	0.012	0.014	0.014	0.014	0.010	0.016	0.010	0.006
19	0.012	0.013	0.016	0.016	0.023	0.019	0.022	0.028	0.026	0.020	0.006	0.022	0.016	0	0.008	0.020	0.009
20a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
20b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
21a,b	0.808	0.869	0.949	0.806	0.467	0.113	0.144	0.103	0.101	0.063	0.062	0.092	0.048	0.036	0.032	0.020	0.016
22a,b	0.068	0.072	0.076	0.067	0.066	0.081	0.080	0.077	0.073	0.081	0.089	0.100	0.103	0.106	0.097	0.102	0.106
23a,b	0.090	0.089	0.092	0.079	0.069	0.077	0.081	0.086	0.076	0.084	0.071	0.075	0.084	0.089	0.087	0.076	0.090
24a,b,c	0.054	0.080	0.080	0.071	0.077	0.086	0.087	0.094	0.100	0.111	0.100	0.110	0.123	0.084	0.089	0.154	0.079
25a,c	0.320	0.346	0.376	0.365	0.250	0	0	0	0	0	0	0	0	0	0	0	0
25b	0.160	0.173	0.188	0.182	0.125	0	0	0	0	0	0	0	0	0	0	0	0
25d	0.160	0.173	0.188	0.182	0.125	0	0	0	0	0	0	0	0	0	0	0	0
Total	0.640	0.692	0.752	0.729	0.500	0	0	0	0	0	0	0	0	0	0	0	0
26a,b	0.040	0.037	0.038	0.049	0.047	0.038	0.022	0.021	0.023	0.019	0.019	0.017	0.018	0.018	0.019	0.022	0.022
27a,b	0.040	0.037	0.034	0.035	0.037	0.037	0.037	0.044	0.044	0.043	0.039	0.046	0.046	0.054	0.048	0.041	0.035
28	0	0	0	0.001	0.017	0.028	0.013	0.017	0.003	0.008	0	0.016	0.009	0.029	0.004	0.001	0
29a	0.289	0.275	0.347	0.357	0.382	0.435	0.436	0.488	0.539	0.584	0.497	0.632	0.257	0.175	0.258	0.231	0.239
29b	0.289	0.275	0.347	0.357	0.382	0.436	0.436	0.488	0.539	0.584	0.497	0.632	0.257	0.175	0.258	0.231	0.237
29c	0.289	0.275	0.347	0.357	0.382	0.436	0.436	0.488	0.539	0.584	0.497	0.632	0.257	0.175	0.258	0.231	0.237
Total	0.867	0.825	1.041	1.071	1.146	1.307	1.308	1.464	1.617	1.752	1.491	1.896	0.771	0.525	0.774	0.693	0.713
30a,b	0.023	0.040	0.014	0.012	0.013	0.019	0.015	0.018	0.015	0.021	0.023	0.014	0.016	0.012	0.011	0.014	0.018
31a,b	0.010	0.010	0.011	0.011	0.012	0.014	0.013	0.014	0.025	0.035	0.035	0.039	0.013	0	0	0	0
32a,b	0.446	0.470	0.473	0.459	0.447	0.451	0.435	0.454	0.441	0.442	0.437	0.433	0.445	0.452	0.461	0.428	0.461
33a,b	0.638	0.668	0.609	0.393	0.600	0.766	0.640	0.588	0.622	0.675	0.739	0.852	0.853	0.564	0.564	0.598	0.587
33c	0	0	0	0	0	0	0	0	0	0	0	0	0	0.564	0.564	0.598	0.587
33d,e,f	0.638	0.668	0.609	0.393	0.600	0.766	0.640	0.588	0.622	0.675	0.739	0.852	0.853	0.564	0.564	0.598	0.587
33g	0.638	0.668	0.609	0.393	0.600	0.766	0.640	0.588	0.622	0.675	0.739	0.852	0.853	0.564	0.564	0.598	0.587
33h	0.638	0.668	0.609	0.393	0.600	0.766	0.640	0.588	0.622	0.675	0.739	0.852	0.853	0.564	0.564	0.598	0.587
Total	2.552	2.672	2.436	1.572	2.400	3.064	2.560	2.352	2.488	2.700	2.956	3.408	3.412	2.820	2.820	2.990	2.935

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Ground-water appropriation permit	Owner	Aquifer	Production wells	Average appropriation, Mgal/d	Model cell (row, column, layer)	Average withdrawals, million gallons per day					
							Year					
							1900-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969
34a	AA69G021	U.S. Army, Ft. Meade	Kpx	AA Bb 68	2.000	79,13,6	0	0	0	0	0	0
34b				AA Bc 164		75,18,6	0	0	0	0	0	0
34c				AA Bc 234		73,23,6	0	0	0	0	0	0
34d				AA Cc 144		75,28,6	0	0	0	0	0	0
34e				AA Cc 120		73,26,6	0	0	0	0	0	0
34f				AA Cc 123		77,29,6	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
35	AA70G012	International Paper Co.	LKpt	AA Bc 171	2.660	62,30,5	0	0	0	0.685	1.147	1.768
36a,b	AA70G013	Chesapeake School Complex	UKpt	AA Bf 50, 51	0.030	18,67,4	0	0	0	0.002	0.003	0.001
37	AA70G041	U.S. Naval Academy Golf Course	UKpt	AA Df 89	0.085	47,93,4	0	0	0	0.001	0.002	0.002
38a,b,c	AA70G046	Provinces Water Co.	Kpx	AA Bc 192, 193, 241	0.415	59,11,6	0	0	0	0	0	0
39	AA70G112	International Paper Co.	Kpx	AA Bc 173	0.576	62,30,6	0	0	0	0	0	0
40a,b	AA71G034	AA DPW, Gibson Island	UKpt	AA Cf 2, 123	0.110	19,80,4	0	0.014	0.027	0.068	0.067	0.085
41a	AA72G005	AA DPW, Crofton Meadows	Kpx	AA Cc 103	2.500	86,43,6	0	0	0	0	0	0.057
41b				AA Cc 105		85,43,6	0	0	0	0	0	0.057
41c				AA Cc 107		88,43,6	0	0	0	0	0	0
41d				AA Cc 138		83,46,6	0	0	0	0	0	0
41e				AA Cd 107		81,49,6	0	0	0	0	0	0
						Total =	0	0	0	0	0	0.114
42a	AA72G009	City of Annapolis	Kmg	AA De 2	2.000	64,75,3	0	0	0	0.681	0.671	0.646
42b				AA De 45		62,75,3	0	0	0	0.681	0.671	0.646
42c,d				AA De 46, 88		62,76,3	0	0	0	0.681	1.342	1.291
						Total =	0	0	0	2.043	2.684	2.583
43a	AA72G105	AA DPW, Crofton Meadows	LKpt	AA Cc 128	3.200	84,43,5	0	0	0	0	0	0
43b				AA Cc 129		85,44,5	0	0	0	0	0	0
43c				AA Cc 140		83,46,5	0	0	0	0	0	0
43d				AA Cd 106		81,49,5	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
44a	AA72G209	City of Annapolis	LKpt	AA De 94	1.850	62,76,5	0	0	0	0	0	1.156
44b				AA De 139		64,75,5	0	0	0	0	0	0
						Total =	0	0	0	0	0	1.156
45a	AA72G309	City of Annapolis	UKpt	AA De 219	1.850	62,76,4	0	0	0	0	0	0
45b				AA De 220		64,75,4	0	0	0	0	0	0
46a,b	AA73G025	Lake Village Apartments	Kpx	AA Bc 201, 202	0.160	56,13,6	0	0	0	0	0	0
47	AA74G002	Pine Hills Water Co.	UKpt	AA Bc 204	Inactive	55,27,4	0	0	0	0	0	0
48a,b,c	AA75G014	Whispering Woods	UKpt	AA Cf 117, 126, 127	Inactive	36,87,4	0	0	0	0	0	0
49a,b	AA76G001	Revell Downs	UKpt	AA Cf 121, 128	Inactive	26,91,4	0	0	0	0	0	0
50a,b	AA77G048	Annapolis Landing	Kmg	AA De 127, 133	Inactive	84,88,3	0	0	0	0	0	0.003

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day															
	Year															
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
34a	0.019	0.052	0.227	0.027	0.192	0.167	0.111	0.214	0.026	0.312	0.301	0.297	0.233	0.269	0.105	0.098
34b	0.019	0.052	0.227	0.027	0.192	0.167	0.111	0.214	0.026	0.312	0.301	0.297	0.233	0.269	0.105	0.098
34c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.105	0.098
34d	0	0	0	0	0	0	0	0	0	0	0	0	0.223	0.269	0.105	0.098
34e	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.105	0.098
34f	0	0	0	0	0	0	0	0.	0	0	0	0	0	0	0.105	0.098
Total	0.038	0.104	0.454	0.054	0.384	0.334	0.222	0.428	0.052	0.624	0.602	0.594	0.689	0.807	0.630	0.588
35	2.397	2.210	2.175	2.168	2.401	2.634	2.797	2.632	2.410	2.665	2.366	1.974	1.604	1.584	1.664	1.749
36a,b	0.001	0.001	0.001	0.003	0.003	0.004	0.004	0.012	0.012	0.012	0.012	0.023	0.023	0.023	0.023	0.023
37	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0.011	0	0	0.032	0.023	0.171	0.116	0.059	0.015
38a,b,c	0	0	0.042	0.091	0.129	0.147	0.189	0.230	0.233	0.243	0.286	0.260	0.258	0.291	0.275	0.294
39	0	0.296	0.029	0.307	0.035	0.080	0.026	0.200	0.162	0.139	0.699	0.452	0.452	0.452	0.452	0.452
40a,b	0.078	0.064	0.072	0.077	0.077	0.069	0.081	0.078	0.054	0.075	0.100	0.107	0.076	0.071	0.055	0.065
41a	0.180	0.187	0.229	0.261	0.378	0.275	0.310	0.359	0.384	0.381	0.438	0.416	0.583	0.578	0.535	0.624
41b	0.180	0.187	0.229	0.261	0.378	0.275	0.310	0.359	0.384	0.381	0.438	0.416	0.583	0.578	0.535	0.624
41c	0	0	0	0	0.378	0.275	0.310	0.359	0.384	0.381	0.438	0.416	0.583	0.578	0.535	0.535
41d	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41e	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0.360	0.373	0.458	0.521	1.135	0.826	0.933	1.076	1.152	1.142	1.314	1.248	1.745	1.734	1.606	1.876
42a	0.706	0.754	0.837	0.694	0.699	0.766	0.685	0.748	0.794	0.808	1.028	0.596	0.615	0.688	0.906	0.919
42b	0.706	0.754	0.837	0.694	0.699	0.766	0.685	0.748	0.794	0.808	1.028	0.596	0.615	0.688	0.906	0.919
42c,d	1.411	1.507	1.674	1.388	1.398	1.533	1.369	1.496	1.587	1.616	2.056	1.191	1.230	1.375	1.813	1.838
Total	2.823	3.015	3.348	2.776	2.796	3.065	2.739	2.992	3.175	3.232	4.112	2.383	2.460	2.751	3.625	3.676
43a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43d	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44a	1.048	0.877	0.853	0.968	0.783	0.551	0.838	0.795	0.511	1.315	1.395	0.173	0.199	0.145	0.072	0.345
44b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.345
Total	1.048	0.877	0.853	0.968	0.783	0.551	0.838	0.795	0.511	1.315	1.395	0.173	0.199	0.145	0.072	0.690
45a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46a,b	0	0	0	0.014	0.016	0.019	0.025	0.041	0.038	0.072	0.139	0.140	0.141	0.150	0.130	0.143
47	0	0	0	0	0.014	0.015	0.015	0.015	0.015	0.015	0.001	0	0	0	0	0
48a,b,c	0	0	0	0	0	0.050	0.050	0.046	0.060	0.035	0.036	0	0	0	0	0
49a,b	0	0	0	0	0	0	0	0	0.001	0.007	0.021	0.034	0.047	0.061	0.084	0.078
50a,b	0.006	0.008	0.009	0.008	0.009	0.006	0.007	0.007	0.008	0.007	0.033	0.031	0.036	0.028	0.033	0

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day																
	Year																
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
34a	0.176	0.145	0.275	0.445	0.615	0.426	0.134	0.102	0.099	0.178	0.228	0.167	0.162	0.200	0.128	0.181	0.275
34b	0.176	0.145	0.275	0.445	0.615	0.426	0.134	0.102	0.099	0.178	0.228	0.167	0.162	0.200	0.128	0.181	0.275
34c	0.176	0.145	0.275	0.445	0.615	0.426	0.134	0.102	0.099	0.178	0.228	0.167	0.162	0.200	0.128	0.181	0.275
34d	0.176	0.145	0.275	0.445	0.616	0.426	0.134	0.102	0.099	0.178	0.228	0.167	0.162	0.200	0.128	0.181	0.275
34e	0.176	0.145	0.275	0.445	0.615	0.426	0.134	0.102	0.099	0.178	0.228	0.167	0.162	0.200	0.128	0.181	0.275
34f	0.176	0.145	0.275	0.445	0.615	0.426	0.134	0.102	0.099	0.178	0.228	0.167	0.162	0.200	0.128	0.181	0.275
Total	1.056	0.870	1.650	2.670	3.691	2.556	0.804	0.612	0.594	1.068	1.368	1.002	0.972	1.200	0.768	1.086	1.650
35	1.857	2.163	1.953	1.983	1.773	1.789	1.864	2.094	1.737	1.644	1.225	1.531	1.343	1.424	1.493	1.112	0.551
36a,b	0.023	0.023	0.023	0.023	0.023	0.036	0.025	0.029	0.026	0.030	0.025	0.030	0.018	0.028	0.032	0.027	0.029
37	0.012	0.001	0.003	0.002	0.004	0.013	0.037	0.054	0.029	0.051	0.020	0.059	0.085	0.057	0.004	0.033	0.060
38a,b,c	0.314	0.293	0.299	0.282	0.274	0.308	0.299	0.373	0.353	0.372	0.349	0.386	0.398	0.393	0.349	0.351	0.351
39	0.452	0.452	0.452	0.452	0.452	0.452	0.452	0.203	0.145	0.029	0.108	0.331	0.046	0.028	0.125	0.134	0.525
40a,b	0.074	0.073	0.076	0.064	0.072	0.083	0.148	0.082	0.073	0.086	0.063	0.074	0.084	0.090	0.071	0.084	0.116
41a	0.664	0.685	0.875	0.866	0.906	0.964	1.106	1.074	0.719	0.387	0.420	0.291	0.329	0.311	0.381	0.454	0.658
41b	0.664	0.685	0.875	0.866	0.906	0.964	1.106	1.074	0.719	0.387	0.420	0.291	0.329	0.311	0.381	0.454	0.658
41c	0.664	0.685	0.875	0.866	0.906	0.964	1.106	1.074	0.719	0.387	0.420	0.291	0.329	0.311	0.381	0.454	0.658
41d	0	0	0	0	0	0	0	0	0	0	0	0.291	0.329	0.311	0.381	0.454	0.658
41e	0	0	0	0	0	0	0	0	0	0	0	0.291	0.329	0.311	0.381	0.454	0.658
Total	1.992	2.055	2.625	2.598	2.718	2.892	3.318	3.222	2.157	1.161	1.260	1.455	1.645	1.555	1.905	2.270	3.290
42a	0.462	0.330	0.426	0.608	0.341	0.467	0.406	0.427	0.462	0.535	0.405	0.431	0.446	0.461	0.432	0.622	0.609
42b	0.462	0.330	0.426	0.608	0.341	0.467	0.406	0.427	0.462	0.535	0.405	0.431	0.446	0.461	0.432	0.622	0.609
42c,d	0.924	0.661	0.851	1.215	0.681	0.934	0.813	0.854	0.924	1.070	0.809	0.863	0.893	0.922	0.863	1.243	1.218
Total	1.848	1.321	1.703	2.431	1.363	1.868	1.625	1.708	1.848	2.140	1.619	1.725	1.785	1.844	1.727	2.487	2.436
43a	0	0	0.275	0.260	0.310	0.390	0.595	0.540	0.609	1.166	1.224	0.617	0.660	0.674	0.523	0.756	0.583
43b	0	0	0.275	0.260	0.310	0.390	0.595	0.540	0.609	1.166	1.224	0.617	0.660	0.674	0.523	0.756	0.583
43c	0	0	0	0	0	0	0	0	0	0	0	0.617	0.660	0.674	0.523	0.756	0.583
43d	0	0	0	0	0	0	0	0	0	0	0	0.617	0.660	0.674	0.523	0.756	0.583
Total	0	0	0.550	0.520	0.620	0.780	1.190	1.080	1.218	2.332	2.448	2.468	2.640	2.696	2.092	3.024	2.332
44a	1.389	1.668	1.543	0.973	1.504	1.260	1.299	1.361	1.271	1.189	1.323	1.348	1.467	1.310	1.239	0.944	1.000
44b	1.389	1.668	1.543	0.973	1.504	1.260	1.299	1.361	1.271	1.189	1.323	1.348	1.467	1.310	1.239	0.944	1.000
Total	2.778	3.336	3.086	1.946	3.008	2.520	2.598	2.722	2.542	2.378	2.646	2.696	2.934	2.620	2.478	1.888	2.000
45a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46a,b	0.128	0.121	0.115	0.110	0.104	0.113	0.115	0.119	0.116	0.112	0.106	0.106	0.117	0.113	0.111	0.110	0.094
47	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48a,b,c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49a,b	0.083	0.088	0.090	0.082	0.081	0.087	0.076	0	0	0	0	0	0	0	0	0	0
50a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Ground-water appropriation permit	Owner	Aquifer	Production wells	Average appropriation, Mgal/d	Model cell (row, column, layer)	Average withdrawals, million gallons per day					
							Year					
							1900-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969
51	AA81G025	AA DPW, Stevenson Road	LKpt	AA Bd 121	0.700	52,26,5	0	0	0	0	0	0
52	AA81G026	AA DPW, Telegraph Road	LKpt	AA Bc 215	1.000	56,23,5	0	0	0	0	0	0
53	AA81G039	Millennium Convalescent Center	Kmg	AA De 216	0.014	78,91,3	0	0	0	0	0	0
54a,b	AA82G031	AA DPW, Herald Harbor	LKpt	AA Ce 123, 124	0.110	54,58,5	0	0	0	0	0	0.093
55a,b	AA82G032	AA DPW, Crofton	Kpx	AA Cc 86, 102	Inactive	92,42,6	0	0	0	0	0	0.114
56a,b,c	AA82G033	AA DPW, Severna Park	UKpt	AA Ce 65, 66, 67	Inactive	45,59,4	0	0	0	0.042	0.142	0.551
57a	AA82G034	AA DPW, Amberly	UKpt	AA Cf 134	1.056	32,91,4	0	0	0	0	0	0
57b				AA Cf 135		31,90,4	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
58a	AA82G036	AA DPW, Arnold	UKpt	AA Cf 118	1.500	39,80,4	0	0	0	0	0	0
58b				AA Cf 119		40,80,4	0	0	0	0	0	0
58c				AA Cf 120		40,81,4	0	0	0	0	0	0
58d				AA Cf 155		41,83,4	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
59a,b	AA82G037	AA DPW, Harundale	LKpt	AA Bd 36, 37	2.200	32,32,5	0	0	0	0	0.398	0.707
59c,d				AA Bd 63, 162		33,31,5	0	0	0	0	0.398	0.707
						Total =	0	0	0	0	0.796	1.414
60a	AA82G038	AA DPW, Sawmill Creek	LKpt	AA Ad 1	Inactive	30,21,5	0	0	0.022	0.048	0.087	0.206
60b				AA Ad 23		29,21,5	0	0	0.022	0.048	0.087	0.206
60c				AA Ad 40		29,22,5	0	0	0.022	0.048	0.087	0.206
60d				AA Ad 41		30,20,5	0	0	0.022	0.048	0.087	0.206
60e				AA Ad 67		29,20,5	0	0	0	0	0.087	0.206
60f				AA Ad 68		32,19,5	0	0	0	0	0.087	0.206
						Total =	0	0	0.088	0.192	0.522	1.236
61	AA82G039	AA DPW, Elvaton	LKpt	AA Bd 107	0.900	42,32,5	0	0	0	0	0	0
62	AA82G040	AA DPW, Thelma Avenue	LKpt	AA Bd 108	Inactive	37,24,5	0	0	0	0	0	0
63a,b	AA82G041	AA DPW, Meade Village	LKpt	AA Bc 175, 176	0.100	56,15,5	0	0	0	0	0.005	0.005
64	AA82G042	AA DPW, Phillip Drive	LKpt	AA Bd 101	0.900	36,28,5	0	0	0	0	0.001	0.018
65	AA82G043	AA DPW, Glendale	LKpt	AA Bd 103	0.775	28,28,5	0	0	0	0	0	0.087
66a,b	AA82G044	AA DPW, Crain Highway	LKpt	AA Bd 174 (105 old)	0.900	44,30,5	0	0	0	0	0	0.001
67	AA82G045	AA DPW, Quarterfield Road	LKpt	AA Bd 109	0.900	45,24,5	0	0	0	0	0	0
68	AA82G069	Campbell Sand and Gravel Co.	LKpt	AA Cc 127	0.057	92,36,5	0	0	0	0	0	0
69	AA82G132	AA DPW, Crofton	LKpt	AA Cc 89	Inactive	92,42,5	0	0	0	0	0	0
70a,b	AA83G038	AA DPW, Kings Heights	Kpx	AA Cc 87, 88	Inactive	69,33,6	0	0	0	0	0.009	0.039

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day															
	Year															
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.033	0.166
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.751
53	0	0	0	0	0	0	0	0	0	0	0	0	0.004	0.010	0.014	0.013
54a,b	0.123	0.187	0.229	0.260	0.310	0.032	0.027	0.011	0.021	0.075	0.062	0.073	0.098	0.106	0.086	0.086
55a,b	0.360	0.373	0.458	0.521	1.135	0.551	0.622	0.717	0.768	0.762	0	0	0	0.024	0.019	0.040
56a,b,c	0.758	1.189	1.291	1.557	1.997	2.136	2.355	2.011	2.724	3.167	0	0	0	0.031	0.014	0.036
57a	0	0	0	0	0	0	0	0	0	0	0	0	0	0.026	0.021	0.050
57b	0	0	0	0	0	0	0	0	0	0	0	0	0	0.026	0.021	0.050
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0.052	0.042	0.100
58a	0	0	0	0	0	0	0	0	0	0	0	0	0	0.551	0.496	0.619
58b	0	0	0	0	0	0	0	0	0	0	0	0	0	0.551	0.496	0.619
58c	0	0	0	0	0	0	0	0	0	0	0	0	0	0.551	0.496	0.619
58d	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	1.653	1.488	1.857
59a,b	0.738	0.677	0.648	0.656	0.629	0.614	0.592	0.429	0.356	0.613	0.893	0.770	0.845	0.927	0.649	0.589
59c,d	0.738	0.677	0.648	0.656	0.629	0.614	0.592	0.429	0.356	0.613	0.893	0.770	0.845	0.927	0.649	0.589
Total	1.476	1.354	1.296	1.312	1.258	1.228	1.184	0.858	0.712	1.226	1.786	1.540	1.690	1.854	1.298	1.178
60a	0.235	0.252	0.247	0.232	0.169	0.142	0.225	0.188	0.137	0.280	0.287	0.294	0.300	0.307	0.277	0.235
60b	0.235	0.252	0.247	0.232	0.169	0.142	0.225	0.188	0.137	0.280	0.307	0.294	0.300	0.307	0.277	0.235
60c	0.235	0.252	0.247	0.232	0.169	0.142	0.225	0.188	0.137	0.280	0. 307	0.294	0.300	0.307	0.277	0.235
60d	0.235	0.252	0.247	0.232	0.169	0.142	0.225	0.188	0.137	0.280	0.307	0.294	0.300	0.307	0.277	0.235
60e	0.235	0.252	0.247	0.232	0.169	0.142	0.225	0.188	0.137	0.280	0.307	0.294	0.300	0.307	0.277	0.235
60f	0.235	0.252	0.247	0.232	0.169	0.142	0.225	0.188	0.137	0.280	0.307	0.294	0.300	0.307	0.277	0.235
Total	1.410	1.512	1.482	1.392	1.014	0.852	1.350	1.128	0.822	1.680	1.515	1.764	1.800	1.842	1.662	1.410
61	0.138	0.496	0.449	0.525	0.368	0.442	0.533	0.541	0.612	0.672	0.700	0.728	0.757	0.785	0.625	0.553
62	0	0.045	0.293	0.273	0.256	0.303	0.341	0.314	0.339	0.283	0.207	0.209	0.171	0.134	0.097	0.001
63a,b	0.005	0.018	0.051	0.066	0.110	0.099	0.098	0.085	0.107	0.117	0.112	0.120	0.122	0.123	0.079	0.052
64	0.429	0.503	0.482	0.464	0.519	0.465	0.369	0.364	0.467	0.425	0.656	0.530	0.580	0.636	0.784	0.456
65	0.411	0.630	0.596	0.398	0.360	0.344	0.383	0.529	0	0.561	0.462	0.692	0.757	0.822	0.807	0.755
66a,b	0.030	0.010	0.046	0.086	0.175	0.356	0.696	0.549	0.595	0.594	0.410	0.706	0.762	0.819	0.817	0.912
67	0	0.331	0.408	0.464	0.234	0.093	0.022	0.003	0.262	0.338	0.732	0.564	0.677	0.790	0.808	0.729
68	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.033	0.056
69	0	0	0	0	0	0.275	0.311	0.359	0.384	0.381	0	0	0	0.008	0.006	0.013
70a,b	0.064	0.050	0.096	0.103	0.108	0.111	0.123	0.120	0.150	0.162	0.164	0.164	0.164	0.429	0.846	0.687

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day																
	Year																
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
51	0.668	0.717	0.576	0.528	0.586	0.549	0.615	0.605	0.637	0.521	0.445	0.501	0.544	0.716	0.903	0.810	0.740
52	0.964	0.886	0.803	0.852	0.797	0.851	0.874	0.838	0.913	0.869	0.875	0.781	0.894	0.884	0.899	0.591	0.643
53	0.014	0.014	0.013	0.013	0.014	0.014	0.014	0.014	0.014	0.012	0.018	0.023	0.024	0.032	0.024	0.021	0.008
54a,b	0.098	0.107	0.116	0.096	0.109	0.108	0.104	0.118	0.114	0.125	0.119	0.127	0.135	0.137	0.125	0.136	0.158
55a,b	0.006	0.035	0.024	0	0.003	0.037	0	0	0	0	0	0	0	0	0	0	0
56a,b,c	0.074	0.044	0	0	0	0.023	0	0	0	0	0	0	0	0	0	0	0
57a	0.054	0.068	0.076	0.048	0.069	0.192	0.028	0.024	0.004	0.033	0.002	0.034	0.097	0.015	0.006	0.036	0
57b	0.054	0.068	0.076	0.048	0.069	0.192	0.028	0.024	0.004	0.033	0.002	0.034	0.097	0.015	0.006	0.036	0
Total	0.108	0.136	0.152	0.096	0.138	0.384	0.056	0.048	0.008	0.066	0.004	0.068	0.194	0.030	0.012	0.072	0
58a	0.710	0.698	0.699	0.637	0.575	0.632	0.413	0.127	0.186	0.196	0.120	0.142	0.302	0.247	0.285	0.419	0.351
58b	0.710	0.698	0.699	0.637	0.575	0.632	0.413	0.127	0.186	0.196	0.120	0.142	0.302	0.247	0.285	0.419	0.351
58c	0.710	0.698	0.699	0.637	0.575	0.632	0.413	0.127	0.186	0.196	0.120	0.142	0.302	0.247	0.285	0.419	0.351
58d	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.351
Total	2.130	2.094	2.097	1.911	1.725	1.896	1.239	0.381	0.558	0.588	0.360	0.426	0.906	0.741	0.855	1.257	1.404
59a,b	0.854	0.956	0.621	0.623	0.634	0.429	0.615	0.791	0.660	1.093	0.999	0.888	1.065	1.063	1.079	1.066	1.064
59c,d	0.854	0.956	0.621	0.623	0.634	0.429	0.615	0.791	0.660	1.093	0.999	0.888	1.065	1.063	1.079	1.066	1.064
Total	1.708	1.912	1.242	1.246	1.268	0.858	1.230	1.582	1.320	2.186	1.998	1.776	2.130	2.126	2.158	2.132	2.128
60a	0.231	0.222	0.228	0.081	0	0	0	0	0	0	0	0	0	0	0	0	0
60b	0.231	0.222	0.228	0.081	0	0	0	0	0	0	0	0	0	0	0	0	0
60c	0.231	0.222	0.228	0.081	0	0	0	0	0	0	0	0	0	0	0	0	0
60d	0.231	0.222	0.228	0.081	0	0	0	0	0	0	0	0	0	0	0	0	0
60e	0.231	0.222	0.228	0.081	0	0	0	0	0	0	0	0	0	0	0	0	0
60f	0.231	0.222	0.228	0.081	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1.386	1.332	1.368	0.486	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0.576	0.651	0.601	0.665	0.698	0.600	0.476	0.832	0.775	0.707	0.589	0.650	0.621	0.644	0.605	0.567	0.526
62	0.004	0.086	0.338	0.054	0	0	0	0	0	0	0	0	0	0	0	0	0
63a,b	0.065	0.067	0.066	0.060	0.056	0.055	0.056	0.057	0.060	0.066	0.069	0.063	0.011	0	0	0	0
64	0.576	0.746	0.656	0.736	0.839	0.830	0.567	0.604	0.557	0.623	0.604	0.571	0.201	0	0	0	0
65	0.733	0.623	0.725	0.706	0.593	0.748	0.473	0	0	0	0	0	0.027	0	0	0	0
66a,b	0.723	0.850	0.740	0.781	0.888	0.745	0.665	0.649	0.611	0.691	0.622	0.675	0.513	0	0	0	0
67	0.594	0.848	0.829	0.760	0.719	0.694	0.588	0.438	0.775	0.581	0.681	0.800	0.245	0	0	0	0
68	0.058	0.058	0.056	0.042	0.042	0.033	0.030	0.044	0.033	0.034	0.026	0.032	0.040	0.039	0.030	0.015	0.018
69	0.002	0.012	0.008	0	0.001	0.012	0	0	0	0	0	0	0	0	0	0	0
70a,b	0.980	0.721	0.082	0.004	0.030	0.252	0.019	0.699	0.127	0.188	0.014	0.156	0.024	0.058	0	0	0

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Ground-water appropriation permit	Owner	Aquifer	Production wells	Average appropriation, Mgal/d	Model cell (row, column, layer)	Average withdrawals, million gallons per day					
							Year					
							1900-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969
71a	AA83G052	AA DPW, Dorsey Road	LKpt	AA Ad 74	Inactive	35,17,5	0	0	0	0	0.128	0.193
71b,c				AA Bd 55, 56		36,18,5	0	0	0	0	0.256	0.385
71d				AA Bd 64		37,16,5	0	0	0	0	0.128	0.193
71e				AA Bd 92		40,15,5	0	0	0	0	0	0.193
71f				AA Bd 95		42,18,5	0	0	0	0	0	0.193
						Total =	0	0	0	0	0.512	1.157
72a,b	AA83G060	Ridgeview Plaza	Kpx	AA Bc 237, 251	0.018	60,11,6	0	0	0	0	0	0
73	AA84G051	Praxair, Inc.	Kpx	AA Ae 44	Inactive	19,29,6	0	0	0	0	0	0
74a	AA86G070	AA DPW, Broad Creek	LKpt	AA De 177	1.000	63,80,5	0	0	0	0	0	0
74b				AA De 208		65,84,5	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
75a	AA87G069	AA DPW, Arnold	LKpt	AA Cf 142	2.200	40,80,5	0	0	0	0	0	0
75b				AA Cf 150		41,83,5	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
76a	AA87G070	Eisenhower Golf Course	UKpt/ LKpt	AA Ce 136 (UKpt)	0.030	59,67,4	0	0	0	0	0	0
76b				AA Ce 137 (LKpt)		59,67,5	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
77	AA88G044	Central Sod Farm	Kmg	AA Fe 54	0.126	97,99,3	0	0	0	0	0	0
78	AA88G058	Shady Oaks Sod Farm	Kmg	AA Fe 55	0.200	96,98,3	0	0	0	0	0	0
79a,b	AA89G041	Old South County Golf Course	UKpt	AA Fd 50, 51	0.040	101,95,4	0	0	0	0	0	0
80a,b	AA89G059	James Schillinger	LKpt	AA Bd 175, 176	0.043	52,32,5	0	0	0	0	0	0
81	AA90G045	South River Colony Golf Course	Kmg	AA De 217	0.061	90,92,3	0	0	0	0	0	0
82	AA90G054	Walden Golf Club	Kmg	AA Cd 130	0.059	81,47,3	0	0	0	0	0	0
83a,b	AA91G018	John Schillinger	UKpt	AA Cd 131, 132	0.017	58,40,4	0	0	0	0	0	0
84	AA92G022	Lyons Creek Mobile Home Park	Kmg	AA Fc 23	0.038	102,97,3	0	0	0	0	0	0
85a,b	AA97G030	Crofton Athletic Complex	Kmg	AA Dc 22, 23	0.016	91,56,3	0	0	0	0	0	0
86	AA99G041	Maryland Manor Mobile Estates	UKpt	AA Ec 12	0.016	100,89,4	0	0	0	0	0	0
87a	BA46G003	Bethlehem Steel Corp.	Kpx	BA Gf 3	4.500	11,33,6	0.120	0.210	0.447	0.691	0.570	0.561
87b,c,d				BA Gf 5, 8, 9		11,34,6	0.361	0.630	1.342	2.072	1.709	1.682
87e,h				BA Gf 32, 210		11,36,6	0.241	0.420	0.895	1.381	1.139	1.122
87f				BA Gf 35		10,35,6	0.120	0.210	0.447	0.691	0.570	0.561
87g				BA Gf 139		12,35,6	0.120	0.210	0.447	0.691	0.570	0.561
87i,j				BA Gf 211, 212		12,36,6	0.241	0.420	0.895	1.381	1.139	1.122
						Total =	1.203	2.100	4.473	6.907	5.697	5.609

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day															
	Year															
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
71a	0.248	0.243	0.252	0.249	0.234	0.186	0.343	0.422	0.104	0.729	0.510	0.675	0.648	0.401	0.620	0.605
71b,c	0.494	0.485	0.503	0.496	0.467	0.371	0.684	0.842	0.207	1.450	1.020	1.341	1.288	0.802	1.233	1.201
71d	0.248	0.243	0.252	0.249	0.234	0.186	0.343	0.422	0.104	0.729	0.510	0.675	0.648	0.401	0.620	0.605
71e	0.248	0.243	0.252	0.249	0.234	0.186	0.343	0.422	0.104	0.729	0.510	0.675	0.648	0.401	0.620	0.605
71f	0.248	0.243	0.252	0.249	0.234	0.186	0.343	0.422	0.104	0.729	0.510	0.675	0.648	0.401	0.620	0.605
Total	1.486	1.457	1.511	1.492	1.403	1.115	2.056	2.530	0.623	4.366	3.060	4.041	3.880	2.406	3.713	3.621
72a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.002
73	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.001
74a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76a	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
80a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
83a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
85a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87a	0.778	0.659	0.503	0.558	0.541	0.498	0.556	0.515	0.542	0.493	0.354	0.215	0.189	0.196	0.236	0.223
87b,c,d	2.333	1.977	1.508	1.673	1.624	1.493	1.667	1.545	1.627	1.479	1.062	0.644	0.568	0.589	0.707	0.668
87e,h	1.556	1.318	1.005	1.116	1.083	0.995	1.111	1.030	1.085	0.986	0.708	0.429	0.379	0.392	0.471	0.446
87f	0.778	0.659	0.503	0.558	0.541	0.498	0.556	0.515	0.542	0.493	0.354	0.215	0.189	0.196	0.236	0.223
87g	0.778	0.659	0.503	0.558	0.541	0.498	0.556	0.515	0.542	0.493	0.354	0.215	0.189	0.196	0.236	0.223
87i,j	1.556	1.318	1.005	1.116	1.083	0.995	1.111	1.030	1.085	0.986	0.708	0.429	0.379	0.392	0.471	0.446
Total	7.779	6.590	5.027	5.579	5.413	4.977	5.557	5.150	5.423	4.930	3.540	2.147	1.893	1.961	2.357	2.229

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day																
	Year																
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
71a	0.460	0.352	0.313	0.190	0.118	0.203	0.261	0.249	0.276	0.099	0	0	0	0	0	0	0
71b,c	0.917	0.702	0.623	0.379	0.235	0.404	0.521	0.497	0.551	0.197	0	0	0	0	0	0	0
71d	0.460	0.352	0.313	0.190	0.118	0.203	0.261	0.249	0.276	0.099	0	0	0	0	0	0	0
71e	0.460	0.352	0.313	0.190	0.118	0.203	0.261	0.249	0.276	0.099	0	0	0	0	0	0	0
71f	0.460	0.352	0.313	0.190	0.118	0.203	0.261	0.249	0.276	0.099	0	0	0	0	0	0	0
Total	2.757	2.110	1.875	1.139	0.707	1.216	1.565	1.493	1.655	0.593	0	0	0	0	0	0	0
72a,b	0.011	0.017	0.021	0.015	0.017	0.016	0.015	0.014	0.015	0.015	0.013	0.012	0.015	0.016	0.015	0.014	0.014
73	0.001	0.004	0.015	0.082	0.107	0.109	0.111	0	0	0	0	0	0	0	0	0	0
74a	0	0	0	0	0	0	0	0	0	0.014	0.105	0.002	0.672	0.779	0.639	0.805	0.900
74b	0	0	0	0	0	0	0	0	0	0.014	0.105	0.002	0.672	0.779	0.639	0.805	0.900
Total	0	0	0	0	0	0	0	0	0	0.028	0.210	0.004	1.344	1.558	1.278	1.610	1.800
75a	0	0	0	0	0	0	2.170	2.178	2.064	2.260	2.276	2.366	0.984	1.437	1.265	0.992	1.032
75b	0	0	0	0	0	0	0	0	0	0	0	0	0.984	1.437	1.265	0.992	1.032
Total	0	0	0	0	0	0	2.170	2.178	2.064	2.260	2.276	2.366	1.968	2.874	2.530	1.984	2.064
76a	0	0	0	0	0.007	0.005	0.007	0.004	0.002	0.002	0.001	0.002	0	0	0	0	0
76b	0	0	0	0	0.007	0.005	0.007	0.004	0.002	0.002	0.001	0.002	0	0	0	0	0
Total	0	0	0	0	0.014	0.010	0.014	0.008	0.004	0.004	0.002	0.004	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0.015	0.005	0.023	0.044	0.027	0.009	0	0
78	0	0	0	0	0	0	0	0	0	0.015	0	0.025	0	0.019	0.019	0	0
79a,b	0	0	0	0	0.018	0.029	0.016	0.022	0.019	0.024	0.009	0.016	0.020	0.020	0	0.021	0.021
80a,b	0	0	0	0	0	0	0	0	0	0	0.002	0.113	0.007	0	0.068	0.071	0.123
81	0	0	0	0	0	0	0	0	0	0.028	0.058	0.094	0.144	0.128	0.091	0.091	0.084
82	0	0	0	0	0	0.026	0	0.064	0.059	0.069	0.025	0.070	0.098	0.075	0.022	0.036	0.042
83a,b	0	0	0	0	0	0	0	0	0	0	0	0.069	0.013	0	0.007	0.060	0.057
84	0	0	0	0	0	0	0.050	0.080	0.087	0.083	0.076	0.066	0.066	0.060	0.056	0	0
85a,b	0	0	0	0	0	0	0	0	0	0	0	0	0.014	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.004	0	0
87a	0.278	0.251	0.276	0.221	0.199	0.098	0.058	0.067	0.251	0.297	0.345	0.342	0.329	0.278	0.143	0.287	0.284
87b,c,d	0.834	0.753	0.827	0.662	0.597	0.294	0.175	0.201	0.753	0.892	1.035	1.025	0.986	0.835	0.430	0.862	0.852
87e,h	0.556	0.502	0.551	0.441	0.398	0.196	0.116	0.134	0.502	0.595	0.690	0.683	0.657	0.557	0.287	0.574	0.568
87f	0.278	0.251	0.276	0.221	0.199	0.098	0.058	0.067	0.251	0.297	0.345	0.342	0.329	0.278	0.143	0.287	0.284
87g	0.278	0.251	0.276	0.221	0.199	0.098	0.058	0.067	0.251	0.297	0.345	0.342	0.329	0.278	0.143	0.287	0.284
87i,j	0.556	0.502	0.551	0.441	0.398	0.196	0.116	0.134	0.502	0.595	0.690	0.683	0.657	0.557	0.287	0.574	0.568
Total	2.780	2.510	2.757	2.207	1.990	0.980	0.581	0.670	2.510	2.973	3.450	3.417	3.287	2.783	1.433	2.871	2.840

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Ground-water appropriation permit	Owner	Aquifer	Production wells	Average appropriation, Mgal/d	Model cell (row, column, layer)	Average withdrawals, million gallons per day					
							Year					
							1900-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969
88a,b	BA56G006	Avesta Sheffield East, Inc.	Kpx	BA Fe 59, 64	1.200	8,11,6	0	0.167	0.562	0.928	0.572	0.534
88c				BA Fe 66		8,12,6	0	0.167	0.562	0.928	0.572	0.534
						Total =	0	0.334	1.124	1.856	1.144	1.068
89	BA59G009	Joseph Merritt, Inc.	LKpt	BA Fe 68	Inactive	10,24,5	0.003	0.003	0.003	0.005	0.010	0.013
90a,b,c	BA69G020	American Yeast Corp.	Kpx	BA Ff 85, 90, 91	3.200	8,30,6	0	0	0	0	0	0.700
91	BA70G006	Rocky Point Golf Course	Kpx	BA Fg 176	0.0.65	6,37,6	0	0	0	0	0	0
92	BA75G012	Marshy Point Nursery	LKpt	BA Eg 260	0.0.65	2,31,5	0	0	0	0	0	0
93a,b	BC56G001	Hood Vinegar Co.	Kpx	IN3E-9, 11	Inactive	10,7,6	0	0	0	0	0	0.065
94a,b,c	BC58G001	Schluderberg-Kurdle, Inc.	Kpx	1S3E-45, 46, 47	Inactive	11,8,6	0	0	0.685	0.870	0.714	0.256
95a,b,c,d,e	BC60G001	SAF Corp.-Lesaffre Yeast Corp.	Kpx	3S5E-39, 40, 41, 42, 43	1.400	11,13,6	0	0	0	1.000	0.840	1.052
96	BC60G002	FMC Corp.	Kpx	5S2E-20	Inactive	16,13,6	0	0	0	1.619	1.730	1.929
97	BC01G002	Millennium Inorganic Chemicals, Inc.	Kpx	7S4E-5	Inactive	15,30,6	0	0	0	0	0	0
98a,b	CA70G004	CA. Co., Cavalier Country	Kmg	CA Bb 23, 24	0.050	102,99,3	0	0	0	0	0	0
99a,b	CA72G002	CA. Co., Shores of Calvert	Kmg	CA Bc 7, 8	0.035	103,98,3	0	0	0	0	0	0
100a,b,c,d	KE71G004	Town of Rock Hall	Kmg	KE Db 35, 55, 56, 57	0.230	5,95,3	0	0.075	0.081	0.110	0.110	0.125
101	KE78G102	Eastern Neck Island Wildlife Refuge	Kmg	KE Eb 14	0.023	11,100,3	0	0	0	0	0	0
102a,b,c	PG56G007	Boy's Village of Maryland	Kmg	PG Fd 5, 55, 67	0.065	107,89,3	0.008	0.011	0.017	0.027	0.069	0.149
103a	PG58G003	Patuxent Wildlife Research Center	Kpx	PG Be 8	0.300	95,12,6	0	0	0	0	0	0
103b				PG Be 23		94,25,6	0	0	0	0	0	0
103c				PG Be 24		95,26,6	0	0	0	0	0	0
103d				PG Be 28		95,20,6	0	0	0	0	0	0
103e				PG Be 29		94,15,6	0	0	0	0	0	0
103f				PG Be 30		95,28,6	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
104	PG58G103	Patuxent Wildlife Research Center	LKpt	PG Be 22	0.200	95,15,5	0	0	0	0	0	0.070
105	PG61G005	Bowie Quality Inn	Kmg	PG Cf 54	Inactive	96,57,3	0	0	0	0	0	0.012
106a	PG61G008	City of Bowie	Kmg	PG Cf 33	0.200	96,47,3	0	0	0	0	0	0.092
106b				PG Cf 34		96,40,3	0	0	0	0	0	0.092
						Total =	0	0	0	0	0	0.184
107a,c	PG61G108	City of Bowie	LKpt	PG Cf 32, 76	1.500	96,47,5	0	0	0	0	0	0.355
107b,d				PG Cf 35, 77		96,45,5	0	0	0	0	0	0.355
107e				PG Cf 80		97,43,5	0	0	0	0	0	0
						Total =	0	0	0	0	0	0.710

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day															
	Year															
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
88a,b	0.548	0.548	0.534	0.521	0.510	0.517	0.473	0.438	0.403	0.411	0.482	0.557	0.479	0.430	0.589	0.328
88c	0.548	0.548	0.534	0.521	0.510	0.517	0.473	0.438	0.403	0.411	0.482	0.557	0.479	0.430	0.589	0.328
Total	1.096	1.096	1.068	1.042	1.020	1.034	0.946	0.876	0.806	0.822	0.964	1.114	0.958	0.860	1.178	0.656
89	0.015	0.019	0.015	0.016	0.014	0.015	0.021	0.013	0.017	0.018	0.017	0.011	0.011	0.012	0.002	0
90a,b,c	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.700	0.586	0.744
91	0.015	0.028	0.029	0.022	0.026	0.025	0.025	0.056	0.035	0.015	0.038	0.019	0.021	0.024	0.011	0.030
92	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
93a,b	0.068	0.078	0.087	0.050	0.065	0.087	0.043	0.029	0.047	0.065	0.079	0.086	0.079	0.079	0.079	0.039
94a,b,c	0.164	0.151	0.210	0.174	0.305	0.219	0.137	0.186	0.213	0.261	0.154	0.199	0.236	0.224	0.086	0.065
95a,b,c,d,e	1.375	1.496	1.739	1.617	1.632	1.725	2.052	2.262	2.590	2.705	2.585	2.638	2.550	2.770	3.395	3.671
96	2.002	2.003	2.074	1.811	1.484	0.865	0.723	0.533	0.374	0.593	0.418	0.003	0	0	0	0
97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98a,b	0	0.038	0.041	0.044	0.047	0.047	0.049	0.053	0.038	0.042	0.050	0.046	0.050	0.051	0.047	0.053
99a,b	0	0	0.004	0.004	0.004	0.030	0.030	0.025	0.028	0.032	0.036	0.030	0.033	0.036	0.035	0.039
100a,b,c,d	0.140	0.164	0.133	0.133	0.129	0.127	0.136	0.141	0.163	0.175	0.153	0.140	0.153	0.158	0.164	0.158
101	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
102a,b,c	0.110	0.096	0.082	0.082	0.082	0.082	0.082	0.101	0.090	0.116	0.112	0.096	0.071	0.058	0.052	0.049
103a	0	0	0	0	0	0	0	0.013	0.024	0.023	0.029	0.035	0.029	0.027	0.029	0.034
103b	0	0	0	0	0	0	0	0.013	0.024	0.023	0.029	0.035	0.029	0.027	0.029	0.034
103c	0	0	0	0	0	0	0	0.013	0.024	0.023	0.029	0.035	0.029	0.027	0.029	0.034
103d	0	0	0	0	0	0	0	0.013	0.024	0.023	0.029	0.035	0.029	0.027	0.029	0.034
103e	0	0	0	0	0	0	0	0.013	0.024	0.023	0.029	0.035	0.029	0.027	0.029	0.034
103f	0	0	0	0	0	0	0	0.013	0.024	0.023	0.029	0.035	0.029	0.027	0.029	0.034
Total	0	0	0	0	0	0	0	0.078	0.144	0.138	0.174	0.210	0.174	0.162	0.174	0.204
104	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.070	0.027	0.014	0	0	0	0	0	0
105	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.012	0.011	0.015	0.014	0.014	0.014	0.014	0.001	0.014
106a	0.134	0.239	0.177	0.098	0.086	0.127	0.115	0.076	0.087	0.061	0.221	0.238	0.180	0.190	0.174	0.150
106b	0.134	0.239	0.177	0.098	0.086	0.127	0.115	0.076	0.087	0.061	0.221	0.238	0.180	0.190	0.174	0.150
Total	0.268	0.478	0.354	0.196	0.172	0.254	0.230	0.152	0.174	0.122	0.442	0.476	0.360	0.380	0.348	0.300
107a,c	0.497	0.704	0.436	0.552	0.579	0.566	0.640	0.620	0.614	0.406	0.082	0.460	0.460	0.460	0.460	0.460
107b,d	0.497	0.704	0.436	0.552	0.579	0.566	0.640	0.620	0.641	0.406	0.082	0.460	0.460	0.460	0.460	0.460
107e	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0.994	1.408	0.872	1.104	1.158	1.132	1.280	1.240	1.255	0.812	0.164	0.920	0.920	0.920	0.920	0.920

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day																
	Year																
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
88a,b	0.138	0.162	0.138	0.203	0.177	0.187	0.144	0.094	0.064	0.020	0.027	0.049	0.052	0.023	0.022	0.023	0.018
88c	0.138	0.162	0.138	0.203	0.177	0.187	0.144	0.094	0.064	0.020	0.027	0.049	0.052	0.023	0.022	0.023	0.018
Total	0.276	0.324	0.276	0.406	0.354	0.374	0.288	0.188	0.128	0.040	0.054	0.098	0.104	0.046	0.044	0.046	0.036
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
90a,b,c	1.069	1.294	0.984	1.009	1.052	1.135	1.433	1.524	1.714	0	3.079	3.141	3.112	3.054	3.098	3.082	3.091
91	0.049	0.024	0.075	0.005	0.020	0.036	0.015	0.027	0.040	0.040	0.013	0.040	0.063	0.042	0.024	0.053	0.050
92	0	0	0	0	0	0	0	0	0	0.014	0.028	0.028	0.048	0.040	0.040	0.047	0
93a,b	0.039	0.047	0.014	0.001	0.018	0.036	0.001	0	0	0	0	0	0	0	0	0	0
94a,b,c	0.051	0.002	0.002	0.123	0.140	0.277	0.246	0.097	0	0	0	0	0	0	0	0	0
95a,b,c,d,e	4.139	4.274	4.049	4.005	4.353	4.333	3.906	4.998	4.384	4.755	4.708	3.700	0.253	0.089	0.113	0.093	0.493
96	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
97	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
98a,b	0.061	0.052	0.053	0.043	0.045	0.050	0.041	0.050	0.046	0.048	0.045	0.055	0.067	0.071	0.056	0.044	0.050
99a,b	0.047	0.047	0.048	0.037	0.035	0.041	0.032	0.041	0.039	0.039	0.040	0.037	0.036	0.034	0.028	0.032	0.034
100a,b,c,d	0.178	0.206	0.212	0.214	0.206	0.200	0.203	0.205	0.174	0.165	0.162	0.170	0.172	0.166	0.170	0.168	0.183
101	0	0	0	0	0	0	0.005	0	0	0.030	0.021	0.018	0.004	0.023	0.017	0	0.010
102a,b,c	0.061	0.062	0.059	0.063	0.069	0.075	0.046	0.057	0.053	0.073	0.056	0.052	0.059	0.063	0.044	0.041	0.036
103a	0.066	0.067	0.059	0.056	0.050	0.031	0.030	0.028	0.030	0.030	0.030	0.030	0.031	0.031	0.033	0.024	0.020
103b	0.066	0.067	0.059	0.056	0.050	0.031	0.030	0.028	0.030	0.030	0.030	0.030	0.031	0.031	0.033	0.024	0.020
103c	0.066	0.067	0.059	0.056	0.050	0.031	0.030	0.028	0.030	0.030	0.030	0.030	0.031	0.031	0.033	0.024	0.020
103d	0.066	0.067	0.059	0.056	0.050	0.031	0.030	0.028	0.030	0.030	0.030	0.030	0.031	0.031	0.033	0.024	0.020
103e	0.066	0.067	0.059	0.056	0.050	0.031	0.030	0.028	0.030	0.030	0.030	0.030	0.031	0.031	0.033	0.024	0.020
103f	0.066	0.067	0.059	0.056	0.050	0.031	0.030	0.028	0.030	0.030	0.030	0.030	0.031	0.031	0.033	0.024	0.020
Total	0.396	0.402	0.354	0.336	0.300	0.186	0.180	0.168	0.180	0.180	0.180	0.180	0.186	0.186	0.198	0.144	0.120
104	0	0	0	0.190	0.186	0.178	0.158	0.131	0.134	0.148	0.148	0.148	0.165	0.191	0	0.085	0.079
105	0.014	0.011	0.010	0.012	0.009	0.008	0.006	0.001	0	0	0	0	0	0	0	0	0
106a	0.239	0.190	0.106	0.185	0.073	0.130	0.021	0.094	0.051	0.074	0.024	0.106	0.041	0.023	0.037	0.093	0.134
106b	0.239	0.490	0.106	0.185	0.073	0.130	0.021	0.094	0.051	0.074	0.024	0.106	0.041	0.023	0.037	0.093	0.134
Total	0.478	0.680	0.212	0.370	0.146	0.260	0.042	0.188	0.102	0.148	0.048	0.212	0.082	0.046	0.074	0.186	0.268
107a,c	0.460	0.460	0.468	0.560	0.254	0.255	0.194	0.428	0.332	0.426	0.382	0.426	0.338	0.378	0.381	0.397	0.416
107b,d	0.460	0.460	0.468	0.560	0.254	0.255	0.194	0.428	0.332	0.406	0.372	0.426	0.338	0.378	0.381	0.397	0.416
107e	0	0	0.234	0.280	0.127	0.133	0.097	0.214	0.166	0.213	0.186	0.213	0.206	0.189	0.190	0.199	0.208
Total	0.920	0.920	1.170	1.400	0.635	0.643	0.485	1.070	0.830	1.045	0.940	1.065	0.882	0.945	0.952	0.993	1.040

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Ground-water appropriation permit	Owner	Aquifer	Production wells	Average appropriation, Mgal/d	Model cell (row, column, layer)	Average withdrawals, million gallons per day					
							Year					
							1900-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969
108a	PG61G208	City of Bowie	Kpx	PG Cf 64	1.300	96,46,6	0	0	0	0	0	0.525
108b				PG Cf 66		97,43,6	0	0	0	0	0	0.525
						Total =	0	0	0	0	0	1.050
109a	PG63G003	Marlboro Meadows	Kmg	PG Df 34	0.600	101,86,3	0	0	0	0	0	0.017
109b				PG Df 36		101,87,3	0	0	0	0	0	0.017
109c				PG Df 39		101,90,3	0	0	0	0	0	0
						Total =	0	0	0	0	0	0.034
110	PG70G002	Western Branch Waste Water Plant	Kmg	PG Ef 37	0.030	103,93,3	0	0	0	0.125	0.089	0.051
111	PG75G006	Marlboro Country Club	Kmg	PG Ef 19	0.045	102,92,3	0	0	0	0	0	0
112a,b	PG77G008	Bowie Golf and Country Club	LKpt	PG Ce 44, 45	0.011	96,36,5	0	0	0	0	0	0
113	PG77G012	Gardner Sand and Gravel	Kmg	PG Fe 35	0.079	107,95,3	0	0	0	0	0	0
114	PG79G002	Andrews Air Force Base	Kmg	PG Ed 50	0.070	106,67,3	0	0	0	0	0	0
115	PG87G003	Enterprise Golf Course	UKpt	PG Ce 46	0.030	101,40,4	0	0	0	0	0	0
116a	PG90G012	Beltsville Agriculture Research Center	Kpx	PG Bd 17	0.510	99,9,6	0	0	0	0	0	0
116b				PG Bd 162		99,8,6	0	0	0	0	0	0
116c				PG Bd 62		98,10,6	0	0	0	0	0	0
						Total =	0	0	0	0	0	0
117	PG95G019	Marlton Golf Course	Kmg	PG Ee 57	0.040	105,90,3	0	0	0	0	0	0
118	PG98G006	Beechtree Golf Course	LKpt	PG Df 42	0.095	101,79,5	0	0	0.	0	0	0
			Kpx	PG Df 42		101,79,6	0	0	0	0	0	0
119	PG98G023	NASA, Goddard	Kpx	PG Cd 25	0.257	100,21,6	0	0	0	0	0	0
120	QA70G102	QA. Co., Thompson Creek	UKpt	QA Eb 173	0.092	21,101,4	0	0	0	0	0	0
121a,b	QA84G016	QA. Co., Bridgepointe	UKpt	QA Eb 169, 170	0.046	19,102,4	0	0	0	0	0	0
122	QA85G009	QA. Co., Blue Heron Golf Course	Kmg	QA Fa 77	0.045	46,102,3	0	0	0	0	0	0
123a,b	QA85G024	QA. Co., Bayside Marina	UKpt	QA Eb 162, 171	0.144	17,101,4	0	0	0	0	0	0
124a,b	QA89G024	QA. Co., Stevensville	UKpt	QA Eb 166, 167	0.007	20,100,4	0	0	0	0	0	0
125a,b	QA94G007	QA. Co., Grasonville	UKpt	QA Ec 91, 92	0.342	13,106,4	0	0	0	0	0	0
126	QA97G050	QA. Co., Stevensville	LKpt	QA Eb 184	0.750	20,100,5	0	0	0	0	0	0
						Total	2.139	3.537	7.827	17.365	18.856	27.658

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day															
	Year															
	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985
108a	0.710	0.426	0.723	0.698	0.634	0.562	0.536	0.586	0.527	0.738	0.560	0.560	0.560	0.560	0.560	0.560
108b	0.710	0.426	0.723	0.698	0.634	0.562	0.536	0.586	0.527	0.738	0.560	0.560	0.560	0.560	0.560	0.560
Total	1.420	0.852	1.446	1.396	1.268	1.124	1.072	1.172	1.054	1.476	1.120	1.120	1.120	1.120	1.120	1.120
109a	0.030	0.048	0.059	0.063	0.072	0.088	0.094	0.057	0.097	0.094	0.092	0.117	0.098	0.159	0.174	0.205
109b	0.030	0.048	0.059	0.063	0.072	0.088	0.094	0.057	0.097	0.094	0.092	0.117	0.098	0.159	0.174	0.205
109c	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0.060	0.096	0.118	0.126	0.144	0.176	0.188	0.114	0.194	0.188	0.184	0.234	0.196	0.318	0.348	0.410
110	0.050	0.048	0.046	0.054	0.102	0.073	0.057	0.041	0.015	0.017	0.021	0.024	0.015	0.008	0.014	0.011
111	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.011	0.009
112a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
113	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
114	0	0	0	0	0	0	0	0	0	0	0	0	0.072	0.054	0.016	0.118
115	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
116a	0	0	0	0	0	0	0	0	0	0	0.139	0.143	0.148	0.136	0.154	0.121
116b	0	0	0	0	0	0	0	0	0	0	0.139	0.143	0.148	0.136	0.154	0.121
116c	0	0	0	0	0	0	0	0	0	0	0.139	0.143	0.148	0.136	0.154	0.121
Total	0	0	0	0	0	0	0	0	0	0	0.417	0.429	0.444	0.408	0.462	0.363
117	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
118	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
120	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
121a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
122	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
123a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
124a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
125a,b	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
126	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	34.877	35.960	36.593	36.170	37.128	35.687	38.696	38.463	37.501	44.352	43.812	38.645	39.646	44.451	44.841	47.223

Appendix B. Continued.

Identification number (see figures 8, 9, 10, and 11)	Average withdrawals, million gallons per day																
	Year																
	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002
108a	0.560	0.560	0.532	0.262	0.735	0.809	0.791	0.470	0.446	0.488	0.536	0.507	0.540	0.560	0.442	0.407	0.395
108b	0.560	0.560	0.532	0.262	0.735	0.809	0.791	0.470	0.446	0.488	0.536	0.507	0.540	0.560	0.442	0.407	0.395
Total	1.120	1.120	1.064	0.524	1.470	1.618	1.582	0.940	0.892	0.976	1.072	1.014	1.080	1.120	0.884	0.814	0.790
109a	0.154	0.159	0.204	0.191	0.202	0.215	0.171	0.173	0.120	0.119	0.123	0.112	0.120	0.115	0.125	0.123	0.129
109b	0.154	0.159	0.204	0.191	0.202	0.215	0.171	0.173	0.120	0.119	0.123	0.112	0.120	0.115	0.125	0.123	0.129
109c	0	0	0	0	0	0	0.171	0.173	0.120	0.119	0.123	0.112	0.120	0.115	0.125	0.123	0.129
Total	0.308	0.318	0.408	0.382	0.404	0.430	0.513	0.519	0.360	0.357	0.369	0.336	0.360	0.345	0.375	0.369	0.387
110	0.008	0.005	0.007	0.011	0.011	0.010	0.013	0.013	0.026	0.028	0.029	0.032	0.026	0.015	0.003	0.001	0.001
111	0.006	0.018	0.016	0.024	0.006	0.006	0.006	0.006	0.001	0.020	0.010	0.023	0.027	0.019	0	0.035	0.026
112a,b	0.005	0.007	0.008	0.004	0.006	0.034	0.030	0.032	0.032	0.033	0.014	0.023	0.042	0.033	0.013	0.028	0.027
113	0.035	0.033	0.033	0.026	0.009	0.018	0.020	0.008	0.028	0.032	0.031	0.029	0.041	0.038	0.044	0.066	0.075
114	0.043	0.078	0.078	0.078	0.078	0.113	0.039	0.061	0.070	0.117	0.011	0.073	0.093	0.078	0.067	0.141	0.141
115	0	0.008	0.010	0.002	0.002	0.015	0.011	0.015	0.012	0.047	0.003	0	0.021	0.045	0.007	0.031	0.043
116a	0.135	0.145	0.145	0.133	0.134	0.081	0.134	0.126	0.115	0.083	0.068	0.082	0.142	0.127	0.103	0.067	0.088
116b	0.135	0.145	0.145	0.133	0.134	0.081	0.134	0.126	0.115	0.083	0.068	0.082	0.142	0.127	0.103	0.067	0.088
116c	0.135	0.145	0.145	0.133	0.134	0.081	0.134	0.126	0.115	0.083	0.068	0.082	0.142	0.127	0.103	0.067	0.088
Total	0.405	0.435	0.435	0.399	0.402	0.243	0.402	0.378	0.345	0.249	0.204	0.246	0.426	0.381	0.309	0.201	0.264
117	0	0	0	0	0	0	0	0	0	0	0.009	0.032	0.035	0.036	0.006	0.021	0.027
118	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
119	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.084	0.178
120	0	0	0.034	0.036	0.049	0.062	0.058	0.048	0.054	0.050	0.095	0.193	0.149	0.076	0	0	0
121a,b	0	0	0	0	0	0.003	0.006	0.009	0.014	0.016	0.017	0.015	0.015	0.018	0.021	0.013	0.044
122	0.006	0.007	0.008	0.005	0.006	0.008	0.007	0.011	0.006	0.012	0.003	0.008	0.013	0.007	0.003	0.002	0.024
123a,b	0	0	0	0	0.008	0.009	0.017	0.030	0.034	0.036	0.024	0.037	0.025	0.044	0.054	0.067	0.040
124a,b	0	0	0	0	0	0.002	0.009	0.009	0.049	0.136	0.249	0.259	0.204	0.229	0	0	0
125a,b	0	0	0	0	0	0	0	0	0	0.003	0.007	0.009	0.011	0.011	0.017	0.026	0.038
126	0	0	0	0	0	0	0	0	0	0	0	0	0	0.065	0.437	0.442	0.460
Total	49.669	49.502	48.709	45.011	47.708	47.156	44.809	46.477	45.766	47.452	49.073	50.526	46.777	45.231	41.016	44.324	45.728

Appendix C. Projected average-day withdrawals used in optimization from wells other than those operated by the Anne Arundel County Department of Public Works

Ground-water appropriation permit	Owner	Aquifer	Production wells	2005-09	2010-14	2015-19	2020-24	2025-29	2030-34	2035-39	2040-44
				Stress period							
				1	2	3	4	5	6	7	8
				Withdrawals, million gallons per day							
AA32G003	U.S. Naval Academy	UKpt	AA Df 12, 13	0.317	0.367	0.417	0.467	0.517	0.567	0.617	0.667
			AA Df 80, 83, 160	0.480	0.555	0.629	0.703	0.777	0.852	0.926	1.000
			AA Df 101	0.160	0.185	0.210	0.235	0.259	0.284	0.309	0.333
AA47G003	Laurel Racing Association	Kpx	AA Bb 22	0.012	0.016	0.021	0.025	0.030	0.034	0.039	0.043
AA49G004	Sandy Point State Park	Kmg	AA Cg 6, 8	0.018	0.020	0.021	0.023	0.024	0.026	0.027	0.029
AA54G001	Crownsville State Hospital	Kmg	AA Cd 11	0.062	0.061	0.059	0.058	0.057	0.056	0.055	0.054
			AA Cd 43, 72	0.123	0.121	0.119	0.117	0.114	0.112	0.110	0.108
			AA Cd 50	0.062	0.061	0.059	0.058	0.057	0.056	0.055	0.054
AA54G019	Parkway Inn	LKpt	AA Bb 37, 71	0.007	0.008	0.009	0.010	0.012	0.013	0.014	0.015
AA56G002	Sylvan Shores	Kmg	AA De 69, 122	0.073	0.071	0.068	0.066	0.063	0.060	0.058	0.055
AA60G021	Landsman Mobile Home Park	Kmg	AA Cd 93	0.013	0.015	0.016	0.018	0.020	0.022	0.023	0.025
AA60G024	U.S. Department of Defense	Kpx	AA Bb 50, 54, 70	0.003	0.004	0.005	0.006	0.006	0.007	0.008	0.009
			AA Bb 75	0.003	0.004	0.005	0.006	0.006	0.007	0.008	0.009
AA62G003	Atlas Container Corp.	UKpt	AA Bc 182	0.009	0.012	0.015	0.018	0.021	0.024	0.027	0.030
AA62G030	Chemetals Corporation	Kpx	AA Ae 35, 36	0.016	0.050	0.083	0.117	0.150	0.183	0.217	0.250
AA63G008	Holiday Mobile Home Park	Kpx	AA Bc 177, 178	0.106	0.109	0.111	0.114	0.117	0.120	0.122	0.125
AA63G029	Sherwood Forest Water Co.	Kmg	AA Ce 98, 125	0.090	0.091	0.093	0.094	0.096	0.097	0.099	0.100
AA65G032	Maryland Manor Mobile Estates	Kmg	AA Ec 6, 7, 8	0.074	0.075	0.076	0.077	0.077	0.078	0.079	0.080
AA66G027	Northrop Grumman Corp.	UKpt	AA Cg 18, 19	0.026	0.031	0.036	0.041	0.045	0.050	0.055	0.060
AA66G028	Epping Forest	Kmg	AA Ce 99, 119	0.035	0.036	0.037	0.038	0.039	0.040	0.041	0.042
AA66G048	Crofton Country Club	Kmg	AA Cc 62	0.009	0.016	0.024	0.031	0.038	0.045	0.053	0.060
AA68G011	Southern High School	Kmg	AA Ed 39, 41	0.018	0.019	0.020	0.021	0.022	0.023	0.024	0.025
AA69G016	Pioneer City	LKpt	AA Bc 169, 195	0.474	0.486	0.499	0.511	0.523	0.535	0.548	0.560
AA70G013	Chesapeake School Complex	UKpt	AA Bf 50, 51	0.029	0.029	0.029	0.030	0.030	0.030	0.030	0.030
AA70G041	U.S. Naval Academy Golf Course	UKpt	AA Df 89	0.060	0.064	0.067	0.071	0.074	0.078	0.081	0.085
AA70G046	Provinces Water Co.	Kpx	AA Bc 192, 193, 241	0.351	0.360	0.369	0.378	0.388	0.397	0.406	0.415
AA72G009	City of Annapolis	Kmg	AA De 2	0.650	0.590	0.530	0.470	0.390	0.310	0.230	0.140
			AA De 45	0.650	0.590	0.530	0.470	0.390	0.310	0.230	0.140
			AA De 46, 88	1.310	1.340	1.380	1.430	1.440	1.450	1.450	1.460
AA72G209		LKpt	AA De 94	1.090	1.120	1.150	1.190	1.200	1.210	1.210	1.220
			AA De 139	1.090	1.120	1.150	1.190	1.200	1.210	1.210	1.220
AA72G309		UKpt	AA De 219	0.130	0.210	0.290	0.390	0.470	0.560	0.640	0.730
			AA De 220	0.130	0.210	0.290	0.390	0.470	0.560	0.640	0.730

Appendix C. Continued.

Ground-water appropriation permit	Owner	Aquifer	Production wells	2005-09	2010-14	2015-19	2020-24	2025-29	2030-34	2035-39	2040-44
				Stress period							
				1	2	3	4	5	6	7	8
				Withdrawals, million gallons per day							
AA73G025	Lake Village Apartments	Kpx	AA Bc 201, 202	0.094	0.104	0.113	0.122	0.132	0.141	0.151	0.160
AA81G039	Millennium Convalescent Center	Kmg	AA De 216	0.008	0.009	0.010	0.011	0.011	0.012	0.013	0.014
AA82G069	Cambell Sand and Gravel Co.	LKpt	AA Cc 127	0.018	0.023	0.029	0.035	0.040	0.046	0.051	0.057
AA83G060	Ridgeview Plaza	Kpx	AA Bc 237, 251	0.014	0.014	0.015	0.015	0.016	0.017	0.017	0.018
AA87G070	Eisenhower Golf Course	LKpt	AA Ce 136	0.000	0.002	0.004	0.006	0.009	0.011	0.013	0.015
			AA Ce 137	0.000	0.002	0.004	0.006	0.009	0.011	0.013	0.015
AA88G058	Shady Oaks Sod Farm	Kmg	AA Fe 54	0.000	0.029	0.057	0.086	0.114	0.143	0.171	0.200
AA89G041	Old South County Golf Course	UKpt	AA Fd 50, 51	0.021	0.024	0.026	0.029	0.032	0.035	0.037	0.040
AA89G059	James Schillinger	LKpt	AA Bd 175, 176	0.123	0.111	0.100	0.088	0.077	0.066	0.054	0.043
AA90G045	South River Colony Golf Course	Kmg	AA De 217	0.085	0.081	0.078	0.074	0.071	0.068	0.064	0.061
AA90G054	Walden Golf Club	Kmg	AA Cd 130	0.042	0.044	0.047	0.049	0.052	0.054	0.057	0.059
AA91G018	James Schillinger	UKpt	AA Cd 131, 132	0.057	0.052	0.046	0.040	0.034	0.029	0.023	0.017
AA92G022	Lyons Creek Mobile Home Park	Kmg	AA Fc 23	0.000	0.005	0.011	0.016	0.022	0.027	0.033	0.038
AA97G030	Crofton Athletic Complex	Kmg	AA Dc 22, 23	0.000	0.002	0.005	0.007	0.009	0.012	0.014	0.016
AA99G041	Maryland Manor Mobile Estates	UKpt	AA Ec 12	0.000	0.002	0.005	0.007	0.009	0.011	0.014	0.016
BA46G003	Bethlehem Steel Corp.	Kpx	BA Gf 3	0.284	0.308	0.331	0.355	0.379	0.403	0.426	0.450
			BA Gf 5, 8, 9	0.852	0.923	0.994	1.066	1.137	1.208	1.279	1.350
			BA Gf 32, 210	0.568	0.616	0.663	0.710	0.758	0.805	0.853	0.900
			BA Gf 35	0.284	0.308	0.331	0.355	0.379	0.403	0.426	0.450
			BA Gf 139	0.284	0.308	0.331	0.355	0.379	0.403	0.426	0.450
			BA Gf 211, 212	0.568	0.616	0.663	0.710	0.758	0.805	0.853	0.900
BA56G006	Avesta Sheffield East, Inc.	Kpx	BA Fe 59, 64	0.018	0.101	0.184	0.267	0.350	0.433	0.516	0.600
			BA Fe 66	0.018	0.101	0.184	0.267	0.350	0.433	0.156	0.600
BA69G020	American Yeast Corporation	Kpx	BA Ff 86, 90,91	3.091	3.106	3.122	3.137	3.153	3.169	3.184	3.200
BA70G006	Rocky Point Golf Course	Kpx	BA Fg 176	0.050	0.052	0.054	0.056	0.058	0.060	0.062	0.065
BA75G012	Marshy Point Golf Course	LKpt	BA Eg 260	0.047	0.050	0.052	0.055	0.057	0.060	0.062	0.065
BC60G001	SAF Corp-Lesaffre Yeast Corp.	Kpx	BC 3S5E-39, 40, 41, 42, 43	0.493	0.622	0.752	0.882	1.011	1.141	1.270	1.400
CA70G004	CA. Co., Cavalier Country	Kmg	CA Bb 23, 24	0.050	0.050	0.050	0.050	0.050	0.050	0.050	0.050
CA72G002	CA. Co., Shores of Calvert	Kmg	CA Bc 7, 8	0.034	0.034	0.034	0.034	0.034	0.035	0.035	0.035
KE71G001	Town of Rock Hall	Kmg	KE Db 35, 55, 56, 57	0.183	0.189	0.196	0.203	0.210	0.216	0.223	0.230
KE78G102	Eastern Neck Island Wildlife Refuge	Kmg	KE Eb 14	0.010	0.012	0.014	0.016	0.018	0.019	0.021	0.023
PG56G007	Boy's Village of Maryland	Kmg	PG Fd 5, 55, 67	0.036	0.040	0.044	0.048	0.053	0.057	0.061	0.065

Appendix C. Continued.

Ground-water appropriation permit	Owner		Production wells	2005-09	2010-14	2015-19	2020-24	2025-29	2030-34	2035-39	2040-44
				Stress period							
				1	2	3	4	5	6	7	8
				Withdrawals, million gallons per day							
PG58G003	Patuxent Wildlife Research Center	Kpx	PG Be 8	0.020	0.060	0.100	0.140	0.180	0.220	0.260	0.300
			PG Be 23	0.020	0.060	0.100	0.140	0.180	0.220	0.260	0.300
			PG Be 24	0.020	0.060	0.100	0.140	0.180	0.220	0.260	0.300
			PG Be 28	0.020	0.060	0.100	0.140	0.180	0.220	0.260	0.300
			PG Be 29	0.020	0.060	0.100	0.140	0.180	0.220	0.260	0.300
			PG Be 30	0.020	0.060	0.100	0.140	0.180	0.220	0.260	0.300
PG58G103	Patuxent Wildlife Research Center	LKpt	PG Be 22	0.079	0.096	0.114	0.131	0.148	0.165	0.183	0.200
PG61G008	City of Bowie	Kmg	PG Cf 33	0.134	0.129	0.124	0.119	0.115	0.110	0.105	0.100
			PG Cf 34	0.134	0.129	0.124	0.119	0.115	0.110	0.105	0.100
PG61G108		LKpt	PG Cf 32, 76	0.333	0.371	0.409	0.447	0.485	0.524	0.562	0.600
			PG Cf 35, 77	0.333	0.371	0.409	0.447	0.485	0.524	0.562	0.600
			PG Cf 80	0.166	0.185	0.204	0.224	0.243	0.262	0.281	0.300
PG61G208	City of Bowie	Kpx	PG Cf 64	0.395	0.432	0.468	0.505	0.514	0.577	0.614	0.650
			PG Cf 66	0.395	0.432	0.468	0.505	0.514	0.577	0.614	0.650
PG63G003	Marlboro Meadows	Kmg	PG Df 34	0.129	0.139	0.150	0.160	0.170	0.180	0.190	0.200
			PG Df 36	0.129	0.139	0.150	0.160	0.170	0.180	0.190	0.200
			PG Df 39	0.129	0.139	0.150	0.160	0.170	0.180	0.190	0.200
PG70G002	Western Branch Waste Water Plant	Kmg	PG Ef 37	0.001	0.005	0.009	0.013	0.017	0.022	0.026	0.030
PG75G006	Marlboro Country Club	Kmg	PG Ef 19	0.026	0.029	0.032	0.034	0.037	0.040	0.042	0.045
PG77G008	Bowie Golf and Country Club	LKpt	PG Ce 44, 45	0.027	0.025	0.022	0.020	0.018	0.016	0.013	0.011
PG77G012	Gardner Sand and Gravel	Kmg	PG Fe 35	0.075	0.076	0.076	0.077	0.077	0.078	0.078	0.079
PG79G002	Andrews Air Force Base	Kmg	PG Ed 50	0.141	0.131	0.121	0.111	0.100	0.090	0.080	0.070
PG87G003	Enterprise Golf Course	UKpt	PG Ce 46	0.043	0.041	0.039	0.038	0.036	0.034	0.032	0.030
PG90G012	Beltsville Agricultural Research Center	Kpx	PG Bd 17	0.088	0.100	0.111	0.123	0.135	0.147	0.158	0.170
			PG Bd 162	0.088	0.100	0.111	0.123	0.135	0.147	0.158	0.170
			PG Bd 62	0.088	0.100	0.111	0.123	0.135	0.147	0.158	0.170
PG95G019	Marlton Golf Course	Kmg	PG Ee 57	0.027	0.029	0.030	0.032	0.034	0.036	0.038	0.040
PG98G006	Beechtree Golf Course	LKpt	PG Df 42	0.000	0.007	0.014	0.020	0.027	0.034	0.041	0.047
			PG Df 42	0.000	0.007	0.014	0.020	0.027	0.034	0.041	0.047
PG98G023	NASA, Goddard	Kpx	PG Cd 25	0.178	0.189	0.201	0.212	0.223	0.234	0.246	0.257
QA70G102	QA Co., Thompson Creek	UKpt	QA Eb 173	0.000	0.013	0.026	0.040	0.053	0.066	0.079	0.092
QA84G016	QA Co., Bridgepointe	UKpt	QA Eb 169, 170	0.044	0.044	0.045	0.045	0.045	0.046	0.046	0.046
QA85G009	QA Co., Blue Heron Golf Course	Kmg	QA Fa 77	0.024	0.027	0.030	0.033	0.036	0.039	0.042	0.045
QA85G014	QA Co., Bayside Marina	UKpt	QA Eb 162, 171	0.040	0.054	0.069	0.084	0.099	0.114	0.129	0.144
QA89G024	QA Co., Stevensville	UKpt	QA Eb 166, 167	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007
QA94G007	QA Co., Grasonville	UKpt	QA Ec 91, 92	0.038	0.081	0.125	0.168	0.212	0.255	0.299	0.342
QA97G050	QA Co., Stevensville	LKpt	QA Eb 184	0.460	0.501	0.543	0.584	0.626	0.667	0.709	0.750
			Total	19	20	22	24	25	27	28	30

Martin O'Malley
Governor

Anthony G. Brown
Lieutenant Governor

John R. Griffin
Secretary

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A message to Maryland's citizens

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

Martin O'Malley
Governor

MARYLAND DEPARTMENT OF NATURAL RESOURCES
Resource Assessment Service
Tawes State Office Building
580 Taylor Avenue
Annapolis, Maryland 21401
Toll free number: 1-(877) 620-8DNR
Out of State call: (410) 260-8367
TTY via Maryland Replay: 711 (within MD) 800-735-2258 (out of state)
www.dnr.state.md.us

MARYLAND GEOLOGICAL SURVEY
2300 St. Paul Street
Baltimore, Maryland 21218
(410) 554-5500
www.mgs.md.gov

MARYLAND
DEPARTMENT OF
NATURAL RESOURCES