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Effects of Withdrawals on Ground-Water Levels in Southern Maryland and the Adjacent Eastern Shore, 1980–2005

Scientific Investigations Report 2007–5249

U.S. Department of the Interior
U.S. Geological Survey

Cover. Photograph shows a yellowish-tan bluff of weathered Aquia Formation along the Severn River, visible from the Route 50 bridge north of Annapolis, Maryland (Photograph by Daniel J. Soeder, August 2006).

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
cubic foot (ft^3)	7.4805	gallons (gal)
	Flow rate	
gallons/minute (gal/min)	1,440	gallons/day (gal/d)
inches/year (in/yr)	2.54	centimeter/year (cm/yr)
foot squared per minute	1,440	square foot per day
foot squared per day	0.0929	square meter per day

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) by the following equation: °C = (°F – 32) / 1.8

Water Year as used in this report begins on October 1 and runs through the following September 30.

Vertical and Horizontal Datums: Vertical elevations and altitudes are referenced to the National Geodetic Vertical Datum of 1929 (NGVD29), a geodetic surface derived from a reference geoid and first-order level nets of the United States and Canada. The more recent North American Vertical Datum of 1988 (NAVD88) was not used, because all of the land surface and water-level elevations taken from the U.S. Geological Survey database for this report are referenced to NGVD29, and are internally consistent. Horizontal coordinate data for well locations presented as decimal latitude and longitude are referenced to the North American Datum of 1983 (NAD83).

ACRONYMS AND ABBREVIATIONS

AWUDS	Aggregated Water Use Data System (USGS database)
ft	feet
ft^2/day	square feet per day (transmissivity)
gal/d	gallons per day (water production)
gal/min	gallons per minute (water production)
GIS	Geographic Information System
GWSI	Ground Water Site Inventory (USGS database)
in/yr	inches per year (recharge)
K	hydraulic conductivity; in this report, horizontal hydraulic conductivity of an aquifer
K-T	Cretaceous-Tertiary (geological time boundary)
MD DNR	Maryland Department of Natural Resources
MDE	Maryland Department of the Environment
Mgal/d	million gallons per day (water production)
MGS	Maryland Geological Survey
mi	miles
NASPR	Naval Air Station, Patuxent River
NWIS	National Water Information System (USGS database)
PPRP	Power Plant Research Program
Q	flow; in this report, the rate of ground-water discharge from a pumped well
RASA	Regional Aquifer-System Analysis (USGS Program)
SWUDS	Site-Specific Water Use Data System (USGS database)
T	aquifer transmissivity, expressed in feet squared per minute or day
USGS	U.S. Geological Survey (Department of the Interior)
WSSC	Washington Suburban Sanitary Commission

Effects of Withdrawals on Ground-Water Levels in Southern Maryland and the Adjacent Eastern Shore, 1980–2005

By Daniel J. Soeder, Jeff P. Raffensperger, and Mark R. Nardi [1]

Abstract

Ground water is the primary source of water supply in most areas of Maryland's Atlantic Coastal Plain, including Southern Maryland. The counties in this area are experiencing some of the most rapid growth and development in the State, resulting in an increased demand for ground-water production.

The cooperative, basic water-data program of the U.S. Geological Survey and the Maryland Geological Survey has collected long-term observations of ground-water levels in Southern Maryland and parts of the Eastern Shore for many decades. Additional water-level observations were made by both agencies beginning in the 1970s, under the Power Plant Research Program of the Maryland Department of Natural Resources. These long-term water levels commonly show significant declines over several decades, which are attributed to ground-water withdrawals. Ground-water-level trends since 1980 in major Coastal Plain aquifers such as the Piney Point-Nanjemoy, Aquia, Magothy, upper Patapsco, lower Patapsco, and Patuxent were compared to water use and withdrawal data. Potentiometric surface maps show that most of the declines in ground-water levels can be directly related to effects from major pumping centers. There is also evidence that deep drawdowns in some pumped aquifers may be causing declines in adjacent, unpumped aquifers.

Water-level hydrographs of many wells in Southern Maryland show linear declines in levels year after year, instead of the gradual leveling-off that would be expected as the aquifers equilibrate with pumping. A continual increase in the volumes of water being withdrawn from the aquifers is one explanation for why they are not reaching equilibrium. Although reported ground-water production in Southern Maryland has increased somewhat over the past several decades, the reported increases are often not large enough to account for the observed water-level declines. Numerical modeling simulations indicate that a steady, annual increase in the number of small wells could account for the observed aquifer behavior. Such wells, being pumped at rates below the minimum legal reporting threshold of 10,000 gallons per day, might be the source of the additional withdrawals. More detailed water-use data, especially from domestic wells, central-pivot irrigation wells, and other small users not currently reporting withdrawals to the State, may help to determine the cause of the aquifer declines.

Introduction

Ground-water-level data have been collected from wells in Southern Maryland and the adjacent Eastern Shore for many years by the U.S. Geological Survey (USGS) and the Maryland Geological Survey (MGS) in cooperation with other Maryland State agencies and local governments. Over a period of several decades, many of the measured ground-water levels show large declines, which are related to the withdrawal or pumping of water from the aquifers.

Purpose and Scope

This report documents and describes drawdowns in the major aquifers of Southern Maryland and the adjacent Eastern Shore in the context of ground-water withdrawals. The intent is to provide an empirical analysis of ground-water declines over the past 25 years related to withdrawals. This report updates a similar study by Achmad and Hansen (2001), and provides a comparison of water-level declines over the past decade (1995–2005) with those from the previous decade (1985–1995). The report also suggests some future studies that may provide management tools for the Southern Maryland ground-water resource. These include investigations of the potential for leakage through confining layers, and the possible role of unreported increases in domestic pumpage as a contributing factor in water-level declines.

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Description of Study Area

The study area for this report includes Anne Arundel, Prince George's, Calvert, Charles and St. Mary's Counties in Southern Maryland, and parts of Kent, Queen Anne's, Talbot, and Dorchester Counties on Maryland's Eastern Shore. The location of the study area and its approximate boundary are shown in figure 1.

Ground water is the primary source of water supply in most of the study area. The two most populous counties in the study area, Anne Arundel County, south of Baltimore, and Prince George's County, east of Washington, D.C., used the most water (fig. 2). The majority of the water supply in Prince George's County is from surface water supplied by the Washington Suburban Sanitary Commission (WSSC). The generally flat, low-relief topography of the Atlantic Coastal Plain Physiographic Province throughout the remainder of the study area results in broad, shallow stream valleys, making surface-water reservoirs impractical in many areas for large-volume water supplies. The region is underlain by thick sand and gravel sediments, however, which provide an abundant ground-water resource. These unconsolidated sediments consist mainly of Cretaceous-to-Quaternary-age materials that overlie consolidated rock of suspected Jurassic, Triassic, Early Paleozoic and (or) Precambrian age (Hansen and Edwards, 1986).

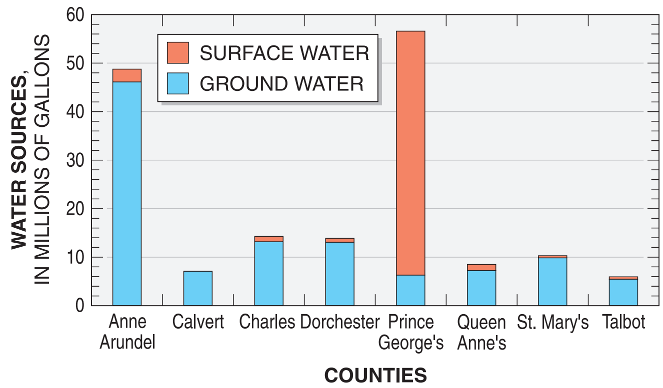


Figure 2. Sources of water supply in 2004 for the Southern Maryland counties in the study area (From U.S. Geological Survey AWUDS database).

The consolidated rocks of the Piedmont dip to the south and east from the "Fall Line" (fig. 1). This is the physiographic break between the Piedmont uplands and the lowlands of the Atlantic Coastal Plain, and is often marked by waterfalls on streams that cross it. The rocks of the Piedmont descend beneath unconsolidated materials that form the sediments of the Atlantic Coastal Plain. The sediments thicken to the south and east, forming a wedge-shaped body of material consisting of generally fluvial and deltaic sediments overlain by coastal and marine sediments. The sediment wedge thins to a featheredge at the Fall Line, and reaches a thickness of more than 7,500 ft (feet) at the Atlantic coast (Wilson and Fleck, 1990). A schematic cross section of the Atlantic Coastal Plain aquifer system aligned approximately with section A-A′ in figure 1 is shown in figure 3.

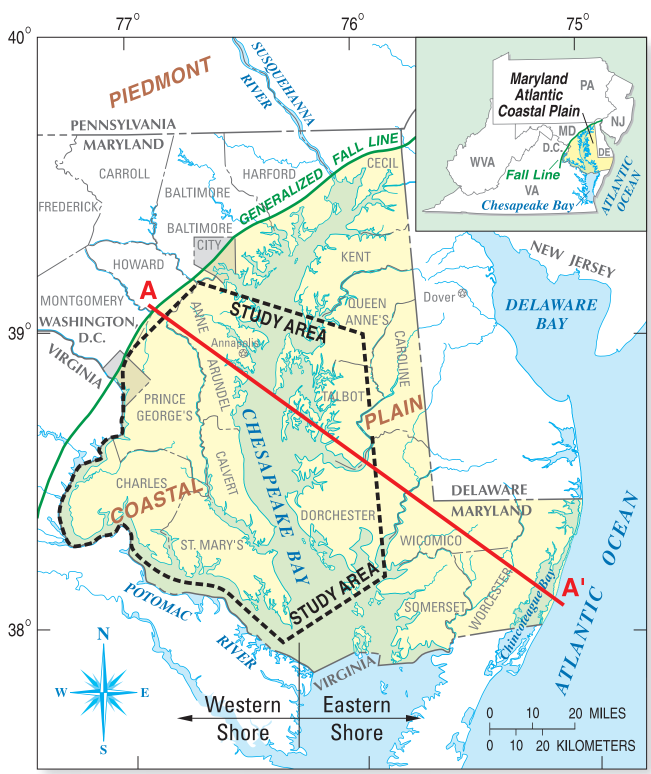


Figure 1. Location of study area in the Atlantic Coastal Plain of Maryland [Refer to figure 3 for line of section A-A′] (Modified from Shedlock and others, 2006).

The wedge of unconsolidated sediment consists of layers of sands and gravels, separated by layers of silts and clays. The coarse-grained sand and gravel beds are aquifers, which readily produce ground water. The finer-grained silt and clay layers are confining units, which act as barriers to water flow. Recharge areas for the aquifers are updip, where they outcrop or subcrop near the surface. Total dissolved solids in the ground water tend to increase in a downdip direction within the aquifers. Deeper ground water generally contains too much salt and other minerals to be drinkable.

The USGS and MGS have been measuring ground-water levels in Maryland wells on a regular basis since the 1940s (Curtin and Dine, 1995). The Maryland Department of Natural Resources (MD DNR), through the Power Plant Research Program (PPRP), supported the measurement of ground-water levels and construction of a series of potentiometric surface maps using 1975 data that were published beginning in 1978 (Achmad and Hansen, 2001). Previously published potentiometric surface difference maps show ground-water levels declining over time at many locations in the Coastal Plain. The cause of this decline is ground-water withdrawal or pumpage from the major aquifer units. Water-use data show that the withdrawal rates have been generally increasing over time, resulting in linear or sometimes accelerating decline rates of the potentiometric surfaces of the major aquifers.

Background

Water-level data have been collected from Southern Maryland wells on a regular basis since the inception of the Maryland Observation-Well Network in 1943 (Smigaj and Davis, 1987). Water-use data in Maryland have been collected since at least 1900 (Wheeler and Wilde, 1989). This section does not provide a complete review of the literature of ground-water observations in Southern Maryland, but it presents a historical overview of the data that are available, and illustrates the long-standing concerns over water resources and water use in Southern Maryland.

The history of the collection of water-level data from Southern Maryland wells has been summarized by Achmad and Hansen (2001). Potentiometric surface maps and water-level difference maps for the Aquia and Magothy aquifers have been published occasionally since 1975, and annually since 1984 (S.E. Curtin, U.S. Geological Survey, oral commun., 2007). Maps for the upper Patapsco and lower Patapsco aquifers were published annually beginning in 1990. Sporadic publication of these maps dates as far back as 1978. The most recent set of potentiometric surface and difference maps for the PPRP were published in 2004, presenting data collected in 2003 (see for example, Curtin and others, 2005). In the past, each map from each aquifer was published as a separate report. This report attempts to incorporate all of them into a single volume, updating the maps with the 2005 ground-water-level data, and including water-use data from the same areas. A bibliography of these past reports is included as appendix 1 for the years covered by this report (1980, 1985, 1990, 1995, and 2000) to facilitate comparisons.

Water-level data collected from 1946 to 1994 at 458 wells in Southern Maryland were summarized by Curtin and Dine (1995). Many of their hydrographs showed a decline in ground-water levels over time, and quite a few of these graphs showed a more rapid decline in water levels after the late 1980s. The rate of decline varies between aquifers and wells, but the general trend for confined aquifer wells is a steady decline in water levels through the mid-1980s, accelerating in the late 1980s. Some of the hydrographs showed that ground-water levels remained steady, however, and a few even show levels rising during this same time period. These data indicate that there are complex relations between ground-water levels and withdrawals in Southern Maryland.

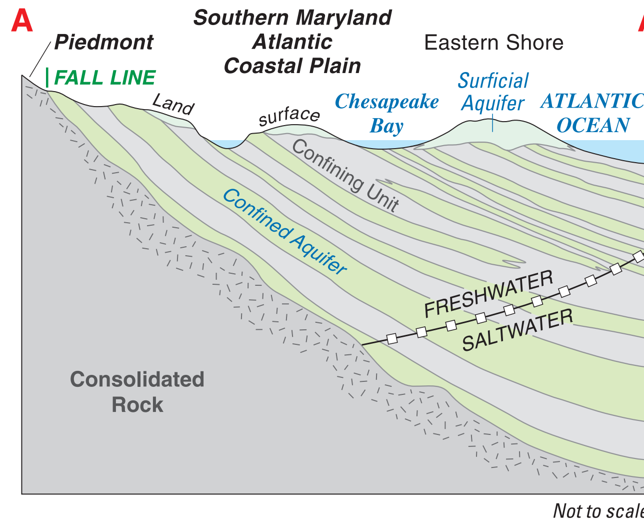


Figure 3. The Atlantic Coastal Plain aquifer system [Line of section shown in figure 1] (From Shedlock and others, 2006).

Information on water resources in Southern Maryland was assembled by Weigle and others (1970) from Prince George's County to the mouth of the Potomac River, as part of the National USGS Hydrologic Investigations Atlas, which consists of a map of ground-water flow and the potentiometric surface for the Piney Point and Aquia aquifers, a map of ground-water yields from these units, and a sheet with some information on water quality and streamflow.

A report by Williams (1979) presents the results of some early computer modeling simulations of ground-water declines in the Piney Point aquifer. Drawdowns as great as 180 ft were predicted for the Cambridge area in Dorchester County by 1990 if withdrawals at Cambridge were increased to the maximum ground-water appropriation limit. Although the Piney Point aquifer has indeed undergone drawdown since the 1970s, it is less than that modeled by Williams (1979). Well DO Db 17, located on Taylors Island and screened in the Piney Point-Nanjemoy aquifer, is in close proximity to a simulated 40-ft-drawdown contour modeled by Williams (1979) under the maximum withdrawal scenario of Cambridge pumping. The hydrograph in figure 4 shows that the actual drawdown in this well since 1979 was only about 8 ft, with some recovery in the last 3 years.

Otton (1955) was one of the first authors to describe the relation between ground-water-level declines in Southern Maryland and increases in ground-water withdrawal. A later report by Mack and others (1983) correlated withdrawals at the Chalk Point Power Plant and in the Waldorf area with a regional decline in the potentiometric surface of the Magothy aquifer, and with the formation of large cones of depression in these areas. Their report estimated that the regional potentiometric surface in the Magothy aquifer was 30 ft above sea

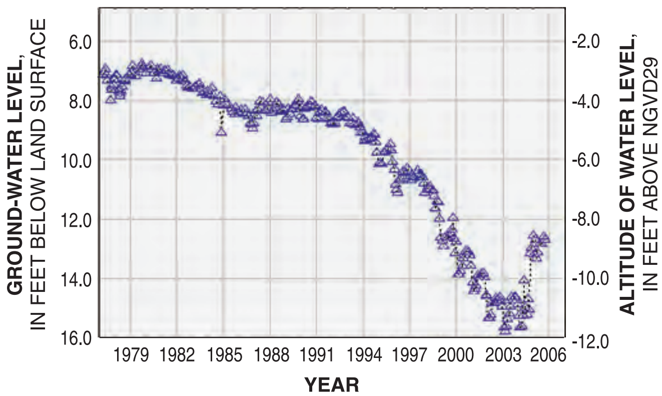


Figure 4. Water levels in the Piney Point-Nanjemoy aquifer for Well DO Db 17 located on Taylors Island, Maryland.

level at Chalk Point, and 50 ft above sea level at Waldorf prior to ground-water withdrawal. This surface had declined to more than 10 ft below sea level at Chalk Point and over 40 ft below sea level near Waldorf by 1975, and was more than 20 ft below sea level at Chalk Point and about 70 ft below sea level at Waldorf by 1981 (Mack and others, 1983).

A number of basic ground-water-resource assessments for the confined aquifers in Southern Maryland have been done on a county-by-county basis. Data from more than 1,200 wells in Anne Arundel County were compiled by Lucas (1976), and a similar compilation of 604 wells in Calvert County and 904 in St. Mary's County was assembled by Drummond (1984). Ground-water-flow models of some aquifers were developed to assess the municipal water-supply potential from the major units, and also to investigate the production of high-quality water at various simulated pumping rates. Mack and Achmad (1986) evaluated the water-supply potential of the Potomac Group aquifers in Anne Arundel County, for example. In a later report, Fleck and Andreasen (1996) assessed ground-water flow and quality by modeling the Aquia, Magothy and upper Patapsco aquifers in east-central Anne Arundel County. Anne Arundel County also had simulations and assessments performed on the Patapsco aquifer near Glen Burnie (Achmad, 1991), on the Magothy aquifer near Annapolis (Mack, 1974), and on the Aquia and Magothy aquifers in the southern part of the County (Andreasen, 2002). Similar assessments were done in Calvert and St. Mary's Counties on the Aquia and Piney Point-Nanjemoy aquifers (Achmad and Hansen, 1997), and on a number of aquifers near Waldorf in Charles County (Wilson and Fleck, 1990).

An improved understanding of the Coastal Plain geologic framework has been developed over the past few decades by various authors as part of these local ground-water assessments, or through independent geological investigations. The proceedings of a 1988 USGS workshop on the geology of Atlantic Coastal Plain sediments were assembled by Gohn (1992). The geology of the Coastal Plain sediments can be complex, especially in the Cretaceous-age fluvial deposits of the Potomac Group, where time-equivalent stratigraphy and lithology often do not match. Hydrogeologic investigations of the Potomac Group sediments have often been localized, as reported by Hiortdahl (1997) for example, in northwestern Charles County. The fluvial channel sands, overbank deposits, and lag gravels of the Potomac Group are difficult to correlate over even short distances.

Aquifer boundaries generally coincide with formation boundaries, but this is not always the case. Facies changes and changes in thickness of the units can significantly alter hydrologic properties laterally within a formation, thereby affecting ground-water productivity. A report by Hansen (1974) on the Aquia Formation describes an example of facies changes within a single geological formation deposited contemporaneously in a nearshore lagoon, an offshore sand bar, and farther offshore on a shelf. The coarse, sand bar deposits form the main productive aquifer, whereas the finer-grained lagoonal and shelf sediments form either a poor aquifer or a confining unit. Such lateral variations in lithology are not uncommon in Coastal Plain sediments, and must be taken into account when assessing regional aquifer productivity. The geologic framework of the Southern Maryland Coastal Plain is described in more detail elsewhere in the report.

The USGS, under the Regional Aquifer-System Analysis (RASA) Program, analyzed the geologic, hydrologic, and geochemical properties of aquifer systems on a regional scale to better understand, predict, and manage ground-water resources. The aquifers underlying the northern Atlantic Coastal Plain from North Carolina to New York were one of the regional systems studied (Trapp and Meisler, 1992). The Cretaceous and younger sediments throughout this broad region were subdivided into 11 regional aquifers separated by 9 confining units (Trapp, 1992). A sub-regional study of the Coastal Plain in Maryland, Delaware, and the District of Columbia included 11 aquifers and 10 confining beds (Vroblesky and Fleck, 1991). These were then correlated to the hydrogeologic units used in other sub-regional RASA studies in Virginia and New Jersey. This hydrogeologic framework was used to provide a basis for the construction of a sub-regional, digital, multilayer, ground-water-flow model of the local aquifer system in Maryland, Delaware, and the District of Columbia, which was fitted into the regional flow model developed for the entire area from North Carolina to New York (Vroblesky and Fleck, 1991; Trapp, 1992).

Concerns about the sustainability of ground-water supplies in Southern Maryland have been expressed at the local government level since the late 1990s. St. Mary's County established a Water Policy Task Force in 2000 to investigate the adequacy of future supplies from the Aquia and Piney Point-Nanjemoy aquifers. The task force concluded that the County would need to develop additional supplies from the deeper Potomac Group aquifers to make up for the projected shortfall (St. Mary's County, written commun., 2000). In response to these findings, a project was initiated with MGS by the commissioners of Calvert, Charles, and St. Mary's

Counties to assess the water-supply potential of aquifers in Southern Maryland. A report on the study prepared by MGS (Drummond, 2005) concluded that the projected water demands into 2030 could be met by developing new sources of supply in deeper aquifers, and by careful management of production from the aquifers that have already been utilized.

An advisory committee to the Governor of Maryland, formed in response to a statewide drought in 2002, produced a report on managing water resources in the State (Wolman, 2004). The committee found that the population of Maryland had increased by 35 percent from 1970 to 2000, and is expected to grow an additional 20 percent by the year 2030, which could increase the demands on water resources, especially ground water. As a result of the committee's report, a comprehensive assessment of ground water in the Atlantic Coastal Plain in Maryland was undertaken by the Maryland Department of the Environment (MDE), MGS, and the USGS (Shedlock and others, 2006). The information presented in this report will be used in that assessment.

Methods of Analysis

The data used in this report were reviewed, approved, and published ground-water-level measurements collected by either the USGS or MGS. The data were retrieved from the Ground Water Site Inventory (GWSI) database, which is part of National Water Information System (NWIS), managed by the USGS. The wells selected for data retrieval were those used by Curtin and others (2005) to construct the previously published potentiometric surface maps for the PPRP. Water-use data were retrieved from the Site-Specific Water Use Data System (SWUDS) or the Aggregated Water Use Data System (AWUDS), both of which are maintained by the USGS.

Ground-Water Levels

Ground-water-level measurements were retrieved from GWSI from 1980 through 2005 for over 400 wells and placed in a spreadsheet. Some of the wells had monthly measurements, others had twice-yearly measurements, and others had a combination of one or the other, which varied by water year. Instructions on methods for performing similar data retrievals using the USGS public water data website are included in appendix 2.

The ground-water-level data were selected to populate a second spreadsheet in 5-year increments from 1980 through 2005 for the four major Coastal Plain aquifers: Aquia, Magothy, upper Patapsco, and lower Patapsco, sorted by aquifer and year. When possible, ground-water-level measurements taken near the end of each water year (the September or October monthly measurement) were used to represent the annual, lowest ground-water level. Many wells do not have ground-water levels extending back to 1980, and some wells do not have records that extend all the way to 2005.

Ground-water-level data also were retrieved from the Piney Point-Nanjemoy and Patuxent aquifers. Fewer wells are screened in these two aquifers than those screened in the other four aquifers in the study area. As such, less ground-water-level data were available for the Piney Point-Nanjemoy and Patuxent aquifers, and data were gathered from Water Year 2005 only, so that 2005 potentiometric surface maps could be created. All of the ground-water level data evaluated for this study are included as appendix 3.

Geographic Information System (GIS) software was used to create the initial potentiometric surface maps, and also to create potentiometric difference maps to evaluate changes in water levels. Potentiometric surface maps for the years 1985, 1995, and 2005 were constructed for the Aquia, Magothy, upper Patapsco, and lower Patapsco aquifers to graphically show the areas of greatest stress (cones of depression), changes in these units over time, and directions of ground-water flow. The surfaces are drawn relative to sea level, as defined by the National Geodetic Vertical Datum of 1929, a geodetic surface derived from a reference geoid and first-order level nets of the United States and Canada. The maps include the locations of major ground-water withdrawal sites to show the relation between pumping centers and aquifer drawdowns.

Potentiometric surface difference maps were constructed for the Aquia, Magothy, upper, and lower Patapsco aquifers in Southern Maryland to show the changes in the potentiometric surface over a fixed time interval. Water-level difference maps were constructed for 1985 through 1995, and also for 1995 through 2005. Comparisons of the differences in the potentiometric surfaces of the major aquifers during these two time periods show the changes in ground-water withdrawals across two different decades.

The contours were initially generated using GIS software with a kriging algorithm, but difficulties ensued because of the inability of the algorithm to deal with drawdowns in separate pumping centers. Instead of making separate "bulls eyes," the algorithm tried to connect similar levels together throughout the map area. It was hoped that automated contouring could be combined with GIS to rapidly produce the Coastal Plain potentiometric surface maps, but it became apparent that manual oversight and technical judgment are necessary for generating reliable maps. Surfer[2] contouring software was used in a second attempt, but this too, required significant manual oversight. The advantage of Surfer over the GIS contouring software is that it was easier to make adjustments and corrections to the lines. The experience with automated contouring software to produce potentiometric surface and difference maps indicated that it can be useful, if properly reviewed and adjusted. The initial, draft maps can be produced more rapidly with the software than drawing by hand, and once the lines are corrected, the electronic maps can be uploaded into commercial drawing or drafting software and turned into a final product fairly quickly.

[2] Surfer is a product of RockWare, Inc., 2221 East Street, #101, Golden, CO 80401 (*http://www.rockware.com*).

Water-Use Data

Water-use data for Southern Maryland were analyzed to assess the volumes of water pumped from various aquifers at different well field locations. The expectation was that analysis of these data over time would provide an indication of the total volume of water removed from the aquifer, and would relate to the drawdowns observed on the potentiometric surface maps. Water-use data for Maryland are compiled annually by the USGS in cooperation with MDE.

MDE administers the water-appropriation permit program for public water supply, industrial, commercial, irrigation, and power plant water uses, but not for livestock and most domestic water use. Water users who withdraw more than 10,000 gal/d (gallons per day) are required to submit monthly withdrawal reports twice a year to MDE. The water-use data are stored in a database maintained by MDE. Domestic withdrawals from private wells are estimated by the USGS at 80 gal/d per capita (a national average), and then combined with population estimates for the number of people per household to derive a withdrawal value for individual wells.

Quality assurance of the water-use data in the USGS database involves checking data from the current year with the previous year's water-use data, and comparing it to the permitted amount. The data are entered into the USGS SWUDS database, which stores water-use data for specific wells, or well fields. Water use data are aggregated by county and aquifer in the USGS AWUDS database.

During 2000, about 245 Mgal/d (million gallons per day) of the freshwater used in Maryland was from the Coastal Plain, representing 27 percent of the state total (Wheeler, 2003). Of that amount, about 66 Mgal/d was from surface-water sources, and 179 Mgal/d (73 percent) was from ground-water sources. Ground-water withdrawals in the Coastal Plain have increased about 32 percent since 1980, with withdrawals by public-water suppliers increasing nearly 34 percent and irrigation withdrawals increasing over 100 percent. Public supply and self-supplied domestic water withdrawals make up 86 percent of the current freshwater withdrawals in Southern Maryland.

Total annual water withdrawals were estimated by taking the daily average in Mgal/d for pumping from each reporting site in any given year, and multiplying by 365 to get the yearly total in Mgal/yr (millions of gallons per year). The annual totals for all sites reporting for an aquifer were then summed to arrive at the total withdrawal from that aquifer for the given year. Different aquifers were compared during the same year to determine the contribution of each to the total ground-water supply, and year-to-year comparisons of withdrawals from a single aquifer showed trends in water use and growth.

Hydrologic Data Analyses

Hydrographs for selected wells were constructed to graphically display the trends of water levels over time, along with the rates of decline. Analyses of the Southern Maryland aquifers using hydrographs, potentiometric surface maps, difference maps, and water-use data were used to assess the effects of withdrawals on water levels.

An important factor in assessing ground-water-level trends is the evaluation of the effects of withdrawals from adjacent aquifers. Some aquifers may be hydraulically connected through leaky confining beds, so that pumping from one aquifer causes water levels to decline in adjacent aquifers. An example of such a semi-confined aquifer is the upper Patapsco in east-central Anne Arundel County, Maryland, which has a hydraulic connection to the overlying Magothy aquifer (Achmad and Hansen, 2001). Water levels were compared to pumping centers on potentiometric surface maps to correlate areas of reduced levels to areas of high water use in adjacent aquifers.

The potentiometric surface maps for each of the major aquifers include the locations of large pumping centers reported in the water-use data (10,000 gal/d or greater). These maps reveal certain large aquifer drawdowns as cones of depression in the potentiometric surface, which usually coincide with major pumping centers. An aquifer showing a noticeable degree of drawdown at a location with little or no pumpage raised the possibility that the aquifer might be responding to pumpage from underlying or overlying units. It is also possible that the aquifer was responding to unreported water use, or to local pumping effects.

Eight hydrographs were constructed to investigate the effects of withdrawals from adjacent aquifers on aquifers that were unpumped, or moderately pumped. This was done for the Patuxent and lower Patapsco aquifers in Charles County, and for the Aquia and Piney Point-Nanjemoy aquifers in St. Mary's County. Water levels in adjacent aquifers were estimated from the potentiometric surface contour maps in cases where an observation well in the pumped aquifer was not close to an observation well in the unpumped aquifer. These empirical correlations were then used to investigate the effects that high rates of pumping might have on water levels in the adjacent aquifers.

Water withdrawn from a well is obtained from elastic storage within the aquifer. Initially, water will be removed from storage in the immediate vicinity of the well, reducing the hydraulic head and inducing flow toward the well. These reductions in hydraulic head, or drawdown, will propagate outward, forming a cone of depression in the potentiometric surface of the aquifer. At an observation well within the cone of depression, the rate of drawdown will be at a maximum initially; the rate of drawdown will decrease with time, so that the drawdown will eventually be approximately logarithmic in time.

Many of the hydrographs of Southern Maryland observation wells do not follow the expected logarithmic curve mathematically defined by Theis (1935) for a pumped aquifer, but drop continually in a straight line. The most likely cause is a constant increase in the amount of water being withdrawn from the aquifer. This is not fully supported by the available water-use data, however. In some cases, trends in the volume of withdrawals reported to MDE do not appear to be large enough to account for the observed drops in aquifer water levels. This was investigated through the use of some standard hydrologic modeling in an attempt to develop possible explanations. One answer may be that increased amounts of water are being pumped from the aquifer by large numbers of domestic wells, which individually produce too little water to be within the minimum legal reporting threshold for the water-use data.

Hydrogeologic Framework

The hydrogeologic framework was assembled from existing Coastal Plain geologic data obtained from a wide variety of sources, including geologic maps and reports produced at the Regional, State, and County levels. Many of the geologic formation names and initial publications of type-section descriptions in the Coastal Plain of the Mid-Atlantic region originated from N.H. Darton, W.B. Clark, and other early geologists in the 19th Century. These efforts have been documented by Wilmarth (1957). The geologic descriptions have been updated by Nancy Stamm of the USGS in the National Geologic Map Database, available on the web at *http://ngmdb.usgs.gov/*. Information on the hydrologic properties of the various Coastal Plain units also was taken from a variety of sources. Because the properties of many of these formations change with location, and the depositional environments, formation boundaries, and ages have been re-interpreted by different authors, multiple references were cited to accurately describe the geology and hydrogeology in the study area.

Hydrogeology

In the Atlantic Coastal Plain, the primary geologic formations of interest containing the confined aquifers are Cretaceous and Tertiary in age. A generalized cross section constructed for the sediments in the Coastal Plain of Maryland is shown in figure 3, and was adapted from Shedlock and others (2006). An important aspect of the geologic framework is that the Coastal Plain sediments dip and thicken toward the east and southeast, forming a wedge-shaped body that thins to a feather edge against the consolidated rocks of the Piedmont, and thickens toward the Atlantic Ocean. Other large-scale features of the geology include (1) a number of stratigraphic units at the thicker, eastern side of the sediment wedge are not present in the thinner, western part, and (2) sediments at the surface become increasingly younger toward the east. This eastward-thickening wedge of sediment exerts major controls on the location and depth of aquifers in the Maryland Coastal Plain.

The consolidated basement rocks of suspected Jurassic, Triassic, Paleozoic, and (or) Precambrian age form the base of the Coastal Plain aquifer system (Hansen and Edwards, 1986). Overlying the basement rocks are terrestrial sediments that were eroded from the ancestral Appalachian and Piedmont highland areas and deposited during the Cretaceous Period. These deposits consist of the fluvial-deltaic sediments of the Lower Cretaceous Potomac Group (Patuxent Formation, Arundel Clay, and Patapsco Formation), and the fluvio-marine and marine sediments of the Upper Cretaceous Magothy, Matawan and Severn Formations. The remainder of the sedimentary sequence in Southern Maryland consists of Tertiary coastal and marine deposits, overlain by Quaternary fluvial and marine sediments. A generalized geologic framework for the Coastal Plain of Southern Maryland is shown in table 1.

Potomac Group

The Potomac Formation was first described by McGee in 1886, and named for exposures along the Potomac River near Washington, D.C. (Wilmarth, 1957). It was recognized as the basal sedimentary unit of the Coastal Plain in that it usually rests on gneiss or other consolidated rocks of the Piedmont. The Potomac Formation was raised to the rank of group by Clark and Bibbins (1897), who subdivided it into three formations: the basal Patuxent Formation, overlain by the Arundel Clay (also referred to as the Arundel Formation by some authors), which is overlain in turn by the Patapsco Formation. Hansen (1984) added an additional basal subsurface formation to the Potomac Group underlying the eastern Delmarva Peninsula that he named the “Waste Gate,” which was described as a brine aquifer isolated from the freshwater-flow system (Trapp, 1992). A number of authors have attempted to refine the stratigraphic boundaries and correlations within the Potomac Group, including Groot (1955), Brenner (1963), and Jordan (1968, 1983). The time-stratigraphic equivalence of various sedimentary bodies within the Potomac Group has often been determined by palynological studies of spores and pollen, due to discontinuities and facies changes within contemporaneous depositional units (Hiortdahl, 1997). As an example, Mack and Achmad (1986) reported that sand lenses 25 ft thick at certain locations in the Potomac have been found to be much thicker, thinner, or absent at lateral distances of only 25 to 100 ft.

The Potomac Group contains three major aquifers in Southern Maryland. These are the Patuxent aquifer, at the base of the group and within the Patuxent Formation, and two aquifers within the Patapsco Formation (upper and lower Patapsco aquifers). The Arundel Clay, lying between the Patuxent and Patapsco Formations, forms a confining unit. The Patapsco Formation contains clay confining units that separate the upper and lower Patapsco aquifers. These aquifers are described in greater detail in the following sections.

Patuxent Aquifer and Arundel Clay Confining Bed

The Patuxent aquifer consists of multiple sand layers in the Patuxent Formation of varying thickness and lateral extent. The Patuxent Formation was described by Clark (1897) as

Table 1. Generalized stratigraphy and hydrogeology of Southern Maryland and adjacent Eastern Shore.

[From Achmad and Hansen, 2001; Trapp, 1992; and modified after D.C. Andreasen, Maryland Geological Survey, oral commun., 2006; and H.J. Hansen, Maryland Geological Survey, written commun., 2007; RASA, Regional Aquifer-System Analysis Program (U.S. Geological Survey)]

System	Series	Group	Formation	Hydrogeology	RASA units
Quaternary	Holocene		undifferentiated	*Columbia aquifer*	*Surficial aquifer*
	Pleistocene				
Tertiary	Pliocene				
	Miocene	Chesapeake	St. Mary's	St. Mary's confining bed	confining unit
			Choptank	*Frederica aquifer*	*Upper Chesapeake*
				confining bed	
				Federalsburg aquifer	
				confining bed	*Lower Chesapeake*
			Calvert	*Cheswold aquifer*	
				Piney Point confining bed	confining unit
	Oligocene		unnamed	*Piney Point-Nanjemoy aquifer (includes basal part of Calvert Formation)*	*Castle Hayne Piney Point*
	Eocene	Pamunkey	Piney Point		
			Nanjemoy		
			Marlboro	Marlboro-lower Nanjemoy confining bed ("Marlboro clay")	confining unit
	Paleocene		Aquia	*Aquia aquifer*	*Beaufort-Aquia*
			Brightseat	Brightseat confining bed	confining unit
Cretaceous	Upper Cretaceous		Severn or Monmouth	*Monmouth aquifer*	
			Matawan	Matawan confining bed	confining unit
			Magothy	*Magothy aquifer*	
	Lower Cretaceous	Potomac	Patapsco	upper Patapsco confining bed	confining unit
				upper Patapsco aquifer	*Upper Potomac*
				lower Patapsco confining bed	
				lower Patapsco aquifer	*Middle Potomac*
			Arundel Clay	Arundel clay confining bed	confining unit
			Patuxent	*Patuxent aquifer*	*Lower Potomac*
			Waste Gate	*"Waste Gate" brine aquifer*	
Jurassic, Triassic, lower Paleozoic to Precambrian				consolidated basement rocks	basement

a cross-bedded, arkosic sand with layers of relatively pure sand, although some of the arenaceous beds contain clay lumps and sandy clays. Clark stated that the sediments show evidence of shallow-water deposition. The lithology of the Patuxent Formation was described by Glaser (1969) as a medium-grained to coarse-grained sand or pebbly sand and gravel, interbedded with relatively thin, pale-gray clays. The formation is composed of generally finer-grained sands in the upper part, where it is overlain and confined by the low-permeability Arundel Clay. The general lack of silt and clay in the lower part of the Patuxent Formation indicates that the sands were deposited in a relatively high-energy, fluvial, and deltaic environment (Glaser, 1969).

The Patuxent aquifer is capable of yielding large quantities of water to wells. Well fields in Anne Arundel and Prince George's Counties have produced yields as high as 2 Mgal/d, and yields of 0.5 to 1 Mgal/d are not uncommon (Mack and Achmad, 1986). Within the study area, the Patuxent aquifer is pumped only in Anne Arundel, Prince George's and Charles Counties. The aquifer is relatively thin to the north, and pinches out in the northwestern part of Anne Arundel County (Mack and Achmad, 1986). The recharge area for the Patuxent aquifer is a relatively narrow outcrop band located between the western limit of the overlying Arundel Clay and the pinch-out of the Patuxent against the consolidated rocks of the Piedmont a few miles farther west (Mack and Achmad, 1986). This outcrop band runs parallel to the Fall Line through the northeastern part of the Washington, D.C., western Prince George's County, the eastern edges of Montgomery and Howard Counties, and into northwestern Anne Arundel County (Achmad and Hansen, 2001).

Overlying the Patuxent aquifer is the Arundel Clay, which forms an effective confining bed in most areas, separating the Patuxent aquifer from the overlying lower Patapsco aquifer. Clark (1897) described the Arundel Clay from stream valley outcrops as a series of large and small lenses of carbonaceous, iron-bearing clay, up to 125 ft in thickness. Achmad and Hansen (2001) reported that the Arundel Clay can be 300 to 400 ft thick in Southern Maryland. Hiortdahl (1997) described the Arundel Clay in Charles County as a dark gray to maroon, tough, massive clay containing abundant lignite and siderite concretions. He noted that the clay is very dense, and was more difficult to penetrate with a drill rig than the overlying and underlying sands. The Arundel Clay was probably deposited in a low-energy river flood plain and swamp environment (Glaser, 1976). The association of massive clays, lignitic logs, rooted stumps, occasional dinosaur bones, and the complete absence of marine fossils indicate that the clay was deposited in shallow, backswamp basins maintained by ponded drainage and slow sediment influx (Glaser, 1969). The contact between the top of the Arundel Clay and the overlying Patapsco Formation was described as unconformable (Brenner, 1963).

Lower Patapsco Aquifer and Confining Bed

The lower Patapsco aquifer consists of multiple sand layers and lenses within the lower part of the Patapsco Formation. The Patapsco Formation was described by Clark (1897) as colored and variegated clays, which grade into lighter-colored sandy clays with interstratified sandy bands of coarser materials. In Charles County, Hiortdahl (1997) described the lithology of the Patapsco Formation as consisting of layers of fine- to medium-grained sand to silt, separated by thick clay layers. The descriptions indicate that the Patapsco Formation is generally finer-grained than the underlying Patuxent sands, which was confirmed by Hiortdahl (1997) on the basis of continuous drill core from Well CH Bb 22 at Indian Head. He also stated that beds of lignitic plant remains were common in some of the Patapsco Formation deposits in this core, further indicating a lower-energy depositional environment. Nevertheless, Patapsco sediments are often very similar to the Patuxent sediments, and differentiation of the two units based solely on lithologic properties can be difficult (Glaser, 1969). The outcrop and recharge area for the Patapsco Formation runs northeast from the eastern side of Washington, D.C. to the southeastern side of Baltimore City, through western Prince George's and Anne Arundel Counties (Achmad and Hansen, 2001).

Hiortdahl (1997) noted a number of sequences of upward-fining sediments in a Patapsco Formation core from Charles County. These graded sequences typically began with a coarse sand or gravel/pebble zone at the base that grades upward into medium- and fine-grained sand, overlain by silt, and eventually grading into silty, hard gray clay containing lignite and carbonaceous plant remains. Glaser (1969) interpreted the lithologic character of the Patapsco Formation as typical of deposition on a low deltaic plain by sluggish, low-gradient, and perhaps meandering rivers. The graded bedding noted by Hiortdahl (1997) appears to support this interpretation: as a stream meanders across a flood plain, different flow regimes control the sedimentation at different times in any particular location, resulting in uniform, gradual changes in grain size. A series of fluvial deposits graded in this manner are known as "fluvial cyclothems" (Allen, 1970).

Despite the finer-grained nature of the sediments, Mack and Achmad (1986) reported that the lower Patapsco aquifer is capable of yielding 0.5 to 2 Mgal/d from individual wells in most locations where it has been tested in Anne Arundel County. They noted that one well owned by the City of Annapolis yielded about 1.5 Mgal/d.

The confining layer separating the lower and upper Patapsco aquifers was described by Mack and Achmad (1986) as unnamed massive beds of clay with low vertical hydraulic conductivity, although some layers within the confining bed are more permeable. They reported a thickness of over 200 ft at Annapolis. Hiortdahl (1997) did not describe the confining layer as a distinct, single unit in Charles County, but mentioned three relatively continuous sand layers, separated by clay beds or lenses, which appear to be aquifers in the Patapsco Formation at Indian Head. The confining layer separating the lower and upper Patapsco aquifers was informally named the Patapsco confining bed by Achmad and Hansen (2001), who described it as multi-colored, massive, clayey beds of low hydraulic conductivity, although they also noted that at some locations, it may be more sandy and less effective as a confining unit. The representative thickness of the confining bed was given by Achmad and Hansen (2001) as 250 ft in Anne Arundel County, 170 ft in Charles County, and 300 ft in St. Mary's County. This report refers to the confining layer as the "lower Patapsco confining bed" (table 1) to differentiate it from the confining unit overlying the upper Patapsco aquifer.

Upper Patapsco Aquifer and Confining Bed

The upper Patapsco aquifer consists of multiple sand layers and lenses within the upper part of the Patapsco Formation. The upper Patapsco aquifer was described by Mack and Achmad (1986) as "one of the best water-bearing formations in Anne Arundel County," although they noted that it is much more limited in aerial extent than the deeper lower Patapsco and Patuxent aquifers. The upper Patapsco consists of the same type of fluvial, interbedded, fine- to medium-grained sand, silt, and clay layers as the lower Patapsco.

Overlying the upper Patapsco aquifer is the fine-grained, clayey, upper Patapsco confining bed (table 1). The thickness and vertical hydraulic conductivity of this confining layer are quite variable according to Mack and Achmad (1986). They reported thicknesses ranging from 50 to 100 ft in Anne Arundel County. Achmad and Hansen (2001) described the confining unit as a gray, red, and orange clay, and noted that it thins to the northwest toward the outcrop area of the Patapsco Formation. Gaps in the upper Patapsco confining bed in east-central Anne Arundel County result in a direct hydraulic connection between the upper Patapsco aquifer and the overlying Magothy aquifer (Mack and Andreasen, 1991).

Magothy and Monmouth Aquifers and Matawan Confining Bed

The Magothy aquifer consists of sandy beds of the Magothy Formation, and in some areas may include sands of the Patapsco Formation (Mack, 1977). The Magothy Formation was first described and named by N.H. Darton in 1893 (Wilmarth, 1957). According to Hansen (1972), the lithology consists of unconsolidated light gray to white, fine to medium quartz sand and fine gravel, containing pyrite and lignite, with glauconite in the upper part. The lower parts of the Magothy Formation are characterized by massive beds of uniform, coarse-grained sands (Andreasen, 2002). The Magothy thins to the south and west, disappearing entirely before reaching the vicinity of the Potomac River (Achmad and Hansen, 2001). It is absent in southern Charles County, and in all but the most northern part of St. Mary's County. The outcrop and recharge area occurs in a narrow band through the northern end of Prince George's County and across north-central Anne Arundel County (Achmad and Hansen, 2001). On the New Jersey Coastal Plain, the Raritan Formation is present between the Magothy and the Potomac, but the Raritan is not recognized as a separate unit in Southern Maryland. The Magothy Formation has been interpreted in New Jersey as a transitional delta-front or prograding delta deposit (Sugarman, 1992), implying that a reduction in grain size occurs from the depocenter toward the fringes of the sediment body. In Maryland, it changes facies from coarse sand and gravel at the southwestern end of the outcrop belt to interbedded silt, clay, and sand to the northeast (Trapp, 1992), leading to the interpretation that it is a coarse fluvial deposit in updip locations, grading into a finer, estuarine-lagoonal-tidal-shoreface deposit downdip (Glaser, 1969). The Magothy Formation is part of a transgressive sequence from Lower Cretaceous fluvial-dominated deposits to Tertiary marine-dominated strata (Hansen, 1972).

The Magothy aquifer has been described by Andreasen (2002) in central and southern Anne Arundel County as consisting of lower and upper sand units separated by 20 to 50 ft of clay. Mack (1974) also depicted an upper and lower unit separated by 10 to 20 ft of clay, and noted that the coarse sand layers interbedded with clay result in hydraulic conductivites that are much higher in the horizontal direction than the vertical. Achmad and Hansen (2001) identified the Magothy aquifer as a single unit throughout Southern Maryland.

The confining beds overlying the Magothy aquifer are made up of several geologic units that may, in places, also function as aquifers (Achmad and Hansen, 2001). These beds consist of the predominantly marine sediments of the Matawan and Monmouth (or equivalent Severn) Formations. In Anne Arundel County, the Matawan Formation consists of dark gray and black silty clay, and acts as a confining unit on top of the Magothy aquifer (Andreasen, 2002). Achmad and Hansen (2001) described the Matawan and Monmouth Formations in Southern Maryland as fine-grained, dark gray, micaceous, silty or clayey sand and clay, and treated them collectively, along with the overlying Brightseat Formation, as a confining unit.

The Severn Formation is stratigraphically equivalent to the upper part of the Monmouth Group in New Jersey (Hansen and Drummond, 1994). The Severn Formation was initially named by N.H. Darton in 1891 as a unit distinctly separable from the New Jersey Cretaceous "green sand" series, but the name was discarded by the USGS in 1938 (Wilmarth, 1957). It has since been reinstated, and the Severn Formation is located above the Matawan Formation at the type locality in Anne Arundel County (Andreasen, 2002). The Severn Formation on the upper Eastern Shore of Maryland, the underlying Mount Laurel Sand in Delaware and New Jersey, and the Wenonah Formation in New Jersey form a regional coastal Atlantic aquifer named the "Peedee-Severn" in the RASA reports (Trapp, 1992). The geologic relations in this part of the stratigraphic section are somewhat confusing, because different names were used at different times to describe the same units.

For simplicity, the Monmouth aquifer is shown in table 1 as the water-bearing sand within the stratigraphically equivalent Severn and Monmouth Formations. It should be noted that the Monmouth is a minor aquifer in Southern Maryland, and is often combined with the Aquia aquifer in Anne Arundel County. It becomes thinner and more clayey to the south, where it functions as a confining bed (D.C. Andreasen, Maryland Geological Survey, written commun., 2007).

Pamunkey Group

The Tertiary-age Pamunkey Formation was initially named by N.H. Darton in 1891, who described it as a homogenous sheet of fine-grained materials (Wilmarth, 1957). Clark and Martin (1901) elevated the Pamunkey from a formation to a group, and divided it into the Aquia Formation in the lower part, and the Nanjemoy Formation in the upper. Like other Coastal Plain sedimentary units, the stratigraphy has evolved through re-interpretation over the years. The currently accepted formations that make up the Pamunkey Group include (from bottom to top) the Brightseat, Aquia, Marlboro Clay, Nanjemoy, and Piney Point in Maryland, with the Chickahominy overlying the Piney Point in Virginia (Rader and Evans, 1993). The group is dated from early Paleocene to late Eocene in age. Individual units are discussed in detail below.

Brightseat Confining Bed

The Brightseat is the basal formation of the Pamunkey Group, and was named by Bennett and Collins (1952) to describe a dark gray, micaceous sandy clay unit with a thickness of 4 to 8 ft, exposed in a creek in Prince George's County, Maryland. In the subsurface of eastern Maryland, the Brightseat Formation ranges from 50 to 75 ft thick. The Cretaceous-Tertiary (K-T) boundary occurs between the top of the Severn Formation and the base of the overlying Brightseat Formation; however, in Southern Maryland, the contact between these two formations is described as unconformable (Bennett and Collins, 1952), so the iridium-rich clay layer identified by Alvarez and others (1980) at the actual K-T boundary is absent. There has been some debate about whether the Brightseat should be considered a member of the overlying Aquia Formation, or left to stand as a formation on its own. Although the Brightseat is thin, it is relatively widespread, and may be important as a confining unit (Achmad and Hansen, 2001). It is considered a "poorly confined" confining unit in Anne Arundel County by Andreasen (2002), allowing a hydraulic connection between the Aquia and Severn Formations. He includes both the Brightseat and Severn, along with the Aquia Formation, as component parts of the "Aquia aquifer."

Aquia Aquifer, Marlboro Clay, and Lower Nanjemoy Confining Beds

The Aquia Formation was named by Clark and Martin (1901) during a revision of Eocene stratigraphy in Maryland, upgrading it from a "stage" in the Pamunkey Group described by Clark a few years earlier. The lithology consists of fine- to medium-grained, glauconitic quartz sand (Nogan, 1964). It is frequently referred to as a "greensand" because of the abundant glauconite content. The color can vary from dark greenish gray in unweathered zones to bright yellowish-tan where weathered. The lower boundary of the Aquia Formation with the underlying Brightseat is often marked by a bed of mollusc shells, and the Brightseat is composed of a finer glauconitic quartz sand, with grains approximately half the diameter of the Aquia sands (Nogan, 1964). This basal part of the Pamunkey Group represents a regressive depositional sequence into a shoaling sea. The finer-grained Brightseat was deposited in fairly deep continental shelf waters, the coarser Aquia in higher-energy, shallow water near shore, and the Marlboro Clay above the Aquia was deposited in a shallow, brackish, low-energy environment, possibly a lagoon (Nogan, 1964).

The outcrop and recharge area for the Aquia Formation extends in an irregular band from the Potomac River in western Charles County, through Prince George's County and into eastern Anne Arundel County, where it forms prominent, yellowish-tan bluffs along some of the tributary streams into Chesapeake Bay (Hansen, 1974). Bluffs composed of weathered Aquia sand are visible along the Severn River north of Annapolis from the bridge on highway U.S. 50 (a photograph of one of these bluffs is shown on the cover of this report). Outcrops continue on the Eastern Shore along the Chester River and northward to the Sassafras River (Hansen, 1974).

The Aquia Formation has been eroded away under the Chesapeake Bay from just south of the Bay Bridge northward to the outcrop boundary (Chapelle and Drummond, 1983). A paleochannel of the ancestral Susquehanna River downcut several hundred feet below current sea level during a Pleistocene glacial lowstand, and eroded completely through the Aquia Formation in this area.

An investigation of sedimentary facies in the Aquia Formation by Hansen (1974) provides some insight into how depositional environments can affect the performance of a single geological unit as an aquifer. The Aquia has three distinct facies identified in the Coastal Plain of Maryland. The first is a coarse, sandy-textured facies running parallel to the outcrop belt, which is interpreted to have been an offshore sand bank or barrier island. The second is a fine, glauconitic, sand-silt-clay facies that occurs in the southern parts of the Western Shore, and is interpreted to have been deposited in a lower energy, inner-shelf or lagoonal environment landward of the sand bank. The third is a thin, very muddy facies underlying the Eastern Shore and known only from drill cores (it does not outcrop); this is interpreted to be outer shelf sediments deposited in deeper water, seaward of the sand bank. The coarse, sand-bank facies form an excellent aquifer, but the finer, inner-shelf facies is generally a poor aquifer. The thin, muddy, outer-shelf facies of the Aquia Formation under the Eastern Shore is not considered to be an aquifer (Hansen, 1974).

The Aquia is an important aquifer in Southern Maryland. The greatest reported well yields in the Aquia aquifer are as high as 500 gal/min (gallons per minute) in eastern St. Mary's and southern Calvert counties (Weigle and others, 1970). Water from the Aquia aquifer is often described as being "hard" because of the relatively high calcium bicarbonate content (Andreasen, 2002). The source of the dissolved minerals appears to be layers of weathered marine invertebrate shell material that are common throughout the formation.

The confining unit overlying the Aquia Formation consists of the Marlboro Clay and the lower part of the Nanjemoy Formation (Achmad and Hansen, 2001). The Marlboro Clay was named by Clark and Martin (1901) for exposures of a red clay bed at the base of the Nanjemoy Formation in Prince George's County. It was originally considered to be part of the Nanjemoy, but was discovered to be uniform and widespread, extending into Virginia, and it was raised to the rank of formation by Glaser (1971). It was described by Achmad and Hansen (2001) as a red, plastic clay interbedded with gray silt, up to 30 ft thick. The basal contact of the clay with the top of the underlying Aquia Formation is thought to be an unconformity (Glaser, 1971).

The lower part of the overlying Nanjemoy Formation, which forms some of the confining unit above the Aquia, was described by Achmad and Hansen (2001) as a glauconitic, very fine muddy sand to sandy clay, ranging in thickness from 45 ft to 170 ft.

Piney Point-Nanjemoy Aquifer

The Nanjemoy Formation was named by Clark and Martin (1901) as the upper formation in the Pamunkey Group. The Nanjemoy was described by McCartan (1989) as a dark green to olive, glauconitic quartz sand and dark silty clay, up to 230 ft thick, and early Eocene in age. It crops out in valleys in the western part of Charles County. It was deposited in a shallow shelf environment, and the upper and lower contacts are highly burrowed (McCartan, 1989).

The overlying Piney Point Formation consists of a wedge-shaped body of sand and interspersed shell beds in conformable contact with the Nanjemoy Formation below and the Calvert Formation above. The lithology is described as an olive gray and green, poorly sorted, medium to coarse glauconitic quartz sand, with scattered pebbles and moldic limestone layers (Rader and Evans, 1993). The Piney Point is truncated and buried by the overlying beds of the Calvert Formation (Achmad and Hansen, 2001), and it was originally thought that this unit was not exposed anywhere at the surface, but was only known through drill cores (Otton, 1955). In fact, the "type section" is located in a well drilled in 1950 at the tip of the Piney Point Peninsula, in St. Mary's County, Maryland.

Ward (1985) later discovered that a Piney Point lithologic section more than 28 ft thick could be pieced together from a number of small exposures along the Pamunkey River in Virginia, where he established a reference section and informally subdivided the unit into three beds. According to Otton (1955), the Piney Point attains a maximum thickness of about 60 ft in southern Calvert County, and Achmad and Hansen (2001) reported a thickness of up to 130 ft at Point Lookout in the southern tip of St. Mary's County. It is considered to be middle Eocene in age based on fossil contents, including the presence of a large oyster, *Cubitostrea sellaformis*, a middle Eocene marker (Rader and Evans, 1993). Like the Aquia Formation, the Piney Point Formation has been eroded away under the Chesapeake Bay north of Calvert Cliffs by a paleochannel of the ancestral Susquehanna River (Achmad and Hansen, 1997).

From oldest to youngest, the Piney Point-Nanjemoy aquifer consists of the following stratigraphic units: (1) the upper part of the lower Eocene Nanjemoy Formation, (2) the middle Eocene Piney Point Formation, (3) unnamed beds that are possibly early Oligocene in age and may correlate with the Old Church Formation described by Ward (1985), and (4) the basal strata of the lower to middle Miocene Calvert Formation (Hansen, 1995). As the Piney Point-Nanjemoy aquifer has very limited surface outcrops, most of the recharge is thought to occur through poorly confined layers. Well yields as high as 500 gal/min have been reported for the Piney Point-Nanjemoy in Calvert and St. Mary's Counties (Weigle and others, 1970).

Chesapeake Group

The confining unit overlying the Piney Point-Nanjemoy aquifer is the basal part of the Chesapeake Group. The Chesapeake Formation was named by Darton (1891) for Miocene-age marine deposits which outcrop near the Chesapeake Bay in both Maryland and Virginia. It was raised to the status of a group in 1894 by Dall, and applied to all Miocene strata from Florida to Delaware, although the component formations differ from place to place (Wilmarth, 1957). Current usage does not generally extend the Chesapeake Group any farther south than the North Carolina Coastal Plain, and there has been considerable debate on how to divide the group into formations and correlate it elsewhere. In Southern Maryland, the Chesapeake Group consists of the Calvert Formation at the base, overlain by the Choptank and St. Mary's Formations (Achmad and Hansen, 2001). The Yorktown Formation is a fourth member that occurs above the St. Mary's Formation in eastern Virginia (Stephenson and MacNeil, 1954).

The Chesapeake Group consists of fine to coarse quartz sand, shelly and diatomaceous, with intervals of silt and clay, deposited mainly in shallow middle and inner continental shelf waters (Rader and Evans, 1993). In Southern Maryland, it ranges in thickness from 50 ft in Charles County to 215 ft in central Calvert County (Achmad and Hansen, 2001). Aquifers in the Chesapeake Group, principally the Cheswold, Federalsburg, and Frederica, are important water sources for Maryland and Delaware on the central and eastern Delmarva Peninsula.

In Southern Maryland, the Chesapeake Group consists mostly of confining units (D.C. Andreasen, Maryland Geological Survey, written commun., 2007).

Water Use and Water Levels in Confined Aquifers

Total ground-water use in Southern Maryland and the counties on the adjacent Eastern Shore has increased from about 42 Mgal/d in the early 1980s to nearly 65 Mgal/d in 2005. The contribution of water supplied from the various major aquifers has also shifted over time, as shown in figure 5. This figure shows all reported withdrawals by users with permits for 10,000 gal/d or more, and domestic use estimated by population density.

The Patuxent, Magothy, and Piney Point-Nanjemoy aquifers are currently used less than they were in the 1980s, but withdrawals have increased from the Aquia, upper Patapsco, and lower Patapsco aquifers. The upper Patapsco and Piney Point-Nanjemoy aquifers are relatively minor contributors in terms of the overall water supply.

Population growth in Maryland has been steady from the 1960s onward (Wheeler, 2003). Census data for the counties in the study area show details of these trends in figures 6 and 7 from 1990 through 2005 (U.S. Census Bureau, 2006). Population increased in Southern Maryland and the Eastern Shore counties of Dorchester, Talbot, and Queen Anne's over the past 15 years, although at disproportionate rates (fig. 6).

Calvert County experienced the highest rate of growth, with more than a 50-percent increase in population between 1990 and 2005 (fig. 7). The number of people in Charles County increased by about 30 percent over the same period, while St. Mary's County had about 25 percent growth. The high growth rates in these semi-rural counties east of Washington, D.C., which depend on ground water for domestic and municipal supplies, have probably affected aquifer drawdown in these locations. The reported municipal pumpages in these counties do not always appear to be increasing at the same rate as the populations. Much of the water may be withdrawn by domestic wells, which are not accurately captured in the SWUDS water-use database because domestic withdrawals are estimated, not reported.

The number of people in the large, urban counties (population over 250,000) in the study area increased by 18 percent in Anne Arundel County, and by 15 percent in Prince George's County. These two counties were already quite populous, however, and reporting a percentage masks growth in total numbers from 1990 to 2005 that were higher than any of the other counties in the study area: 123,418 people in Prince George's County, and 83,639 in Anne Arundel County (U.S. Census Bureau, 2006).

The other counties experienced population increases of less than 40,000 people, and Queen Anne's, Talbot, and Dorchester Counties increased less than 20,000. Dorchester County, with the smallest population in the study area, also had the smallest population increase in both percentage (4 percent between 1990 and 2005) and in absolute numbers, adding less than 1,200 people. Population increases in the

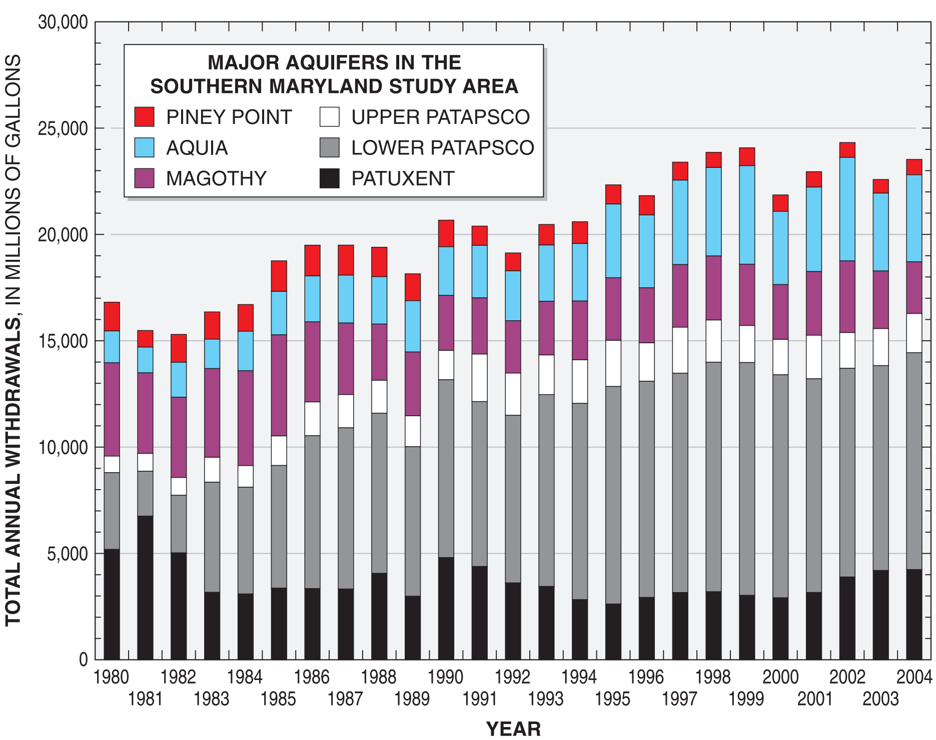


Figure 5. Total annual ground-water withdrawals reported in the U.S. Geological Survey AWUDS database for the six major aquifers in the Southern Maryland study area from 1980 to 2004.

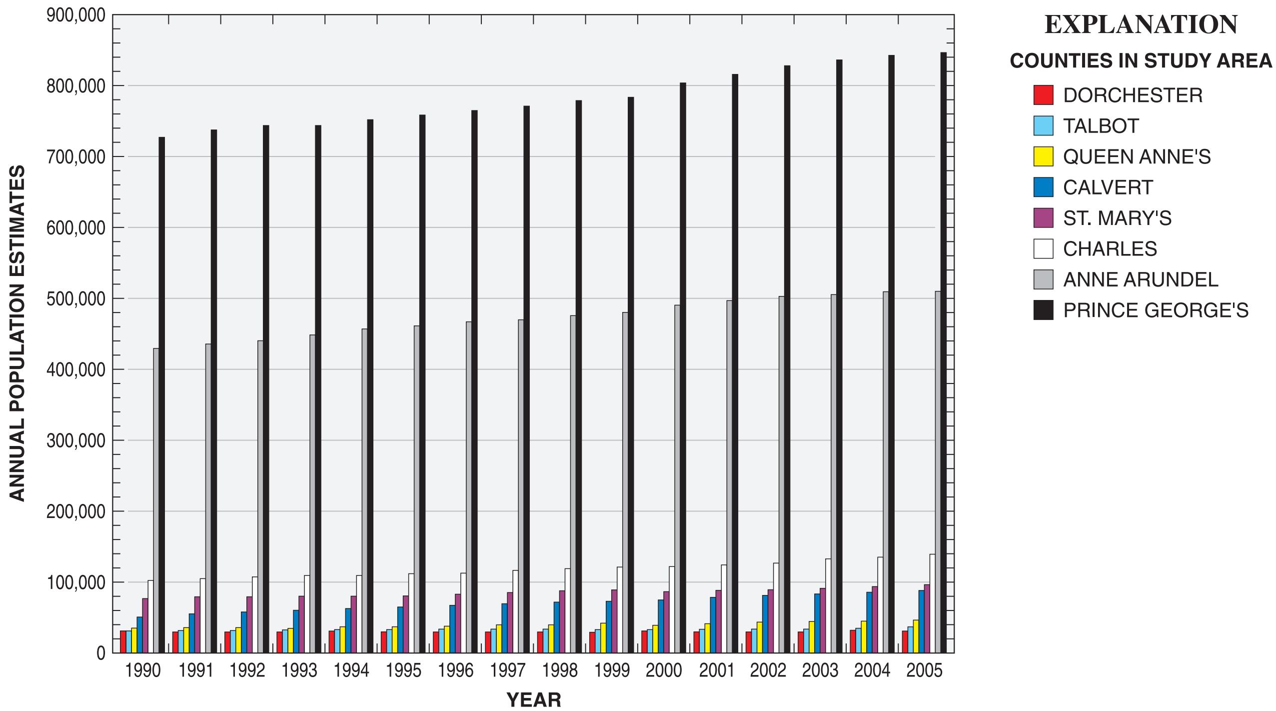


Figure 6. Southern Maryland population estimates by county from 1990 to 2005 (Source: U.S. Census Bureau, 2006).

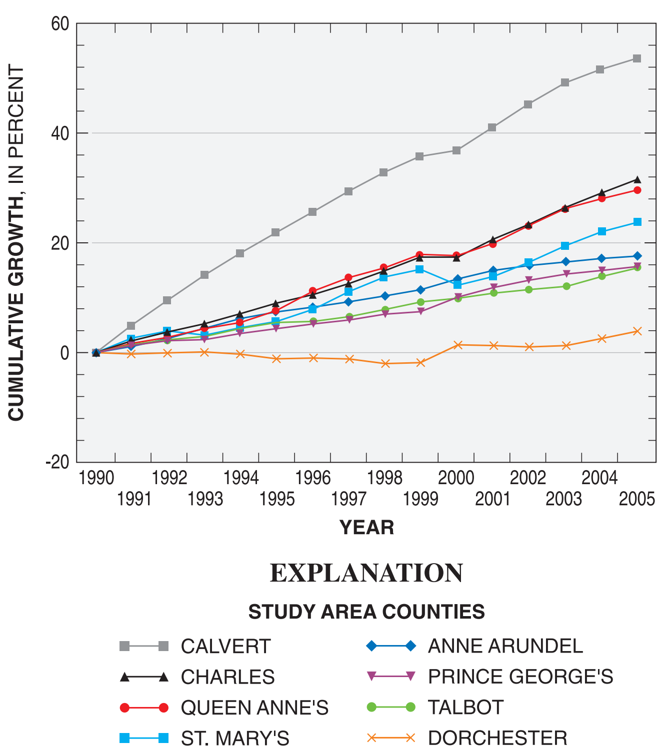


Figure 7. Population growth rates for counties in the study area from 1990 to 2005 (Source: U.S. Census Bureau, 2006).

smaller counties of the study area (less than 250,000 people) from 1990 to 2005 are shown in figure 8.

The distribution of ground-water use on a county-by-county basis for the study area is shown in figure 9, broken down by major category. Rural counties like Dorchester use a much larger percentage of ground water for farming activities, specifically irrigating crops and watering livestock. More densely populated, urban counties like Anne Arundel tend to use more water for public supply, and counties dominated by scattered rural populations with generally non-farming occupations, such as Calvert, use ground water primarily for domestic supply. Prince George's County has an even larger urban population than Anne Arundel, but uses more surface water for public supply (fig. 2). The use of ground water in thermoelectric power plants is a fairly small percentage of the total ground water withdrawn (shown in fig. 9 for Calvert and Charles Counties). Ground-water withdrawals and potentiometric surface declines in Southern Maryland are discussed in each of the following sections for the major aquifers, starting with the oldest units in the geologic column and working upward.

Patuxent Aquifer

Ground-water withdrawals from the Patuxent aquifer are most common just to the east of the outcrop in Prince George's and Anne Arundel Counties (Mack and Achmad, 1986). Major pumping centers in Anne Arundel County are near Dorsey Road in the northern part of the county, and at Crofton Meadows, and Fort Meade. In Prince George's County, the major pumpage occurs at the Town of Bowie. The history of withdrawals from the major pumping centers are shown for the period 1980 through 2004 in figure 10, and the sites are shown in figure 11.

Pumpage from the Patuxent aquifer in northern Anne Arundel County reached rates as high as 4.5 Mgal/d in 1983, but this was reduced to around 3 Mgal/d in successive years, and remained constant at approximately that level. Withdrawals from the two main Patuxent aquifer pumpage centers at Fort Meade are shown as a combined value in figure 10. Withdrawal rates have ranged from about 0.5 Mgal/d in the early 1980s to more than 4 Mgal/d in 1990, before dropping back to less than 1.5 Mgal/d throughout the remainder of the 1990s (after falling below 1 Mgal/d in the early 1990s). Rates increased again from 2003–04 to above 2 Mgal/d. The higher-use periods appear to coincide with periods of greater military activity at Fort Meade, such as the Persian Gulf War in 1990–91, and the Iraq War in 2003–04.

The Patuxent water supply for the Town of Bowie was initially established in the 1960s, and withdrawal rates typically ranged from about 1 to 1.4 Mgal/d (D.C. Andreasen, Maryland Geological Survey, written commun., 2007). After 1992, Patuxent withdrawals at Bowie gradually declined below 1 Mgal/d, presumably as additional water supplies came

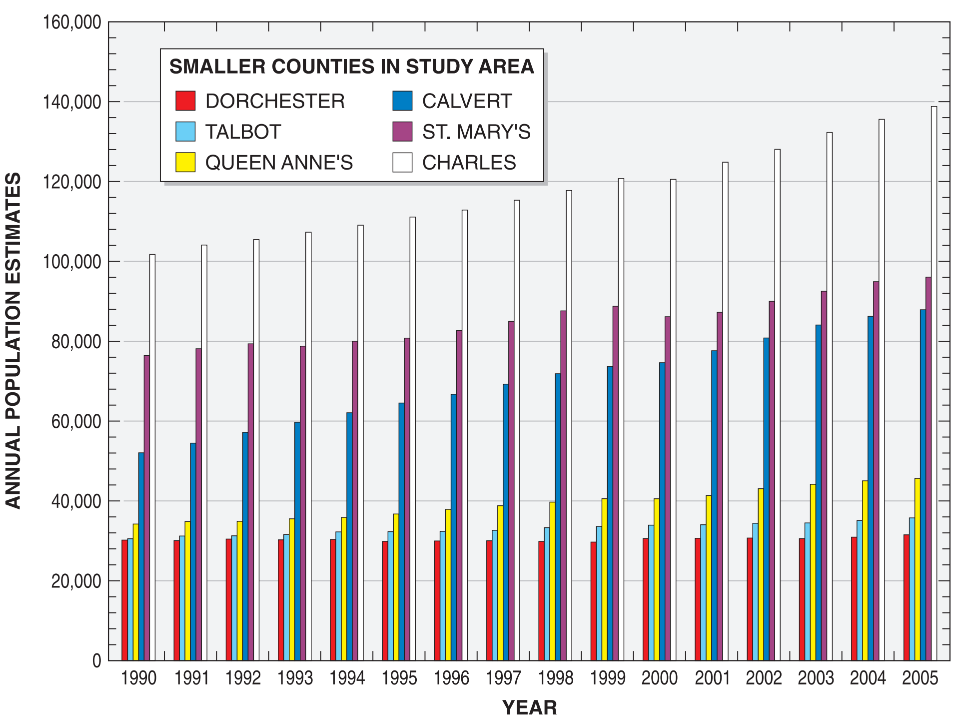


Figure 8. Population growth in smaller counties in the study area from 1990 to 2005 (Source: U.S. Census Bureau, 2006).

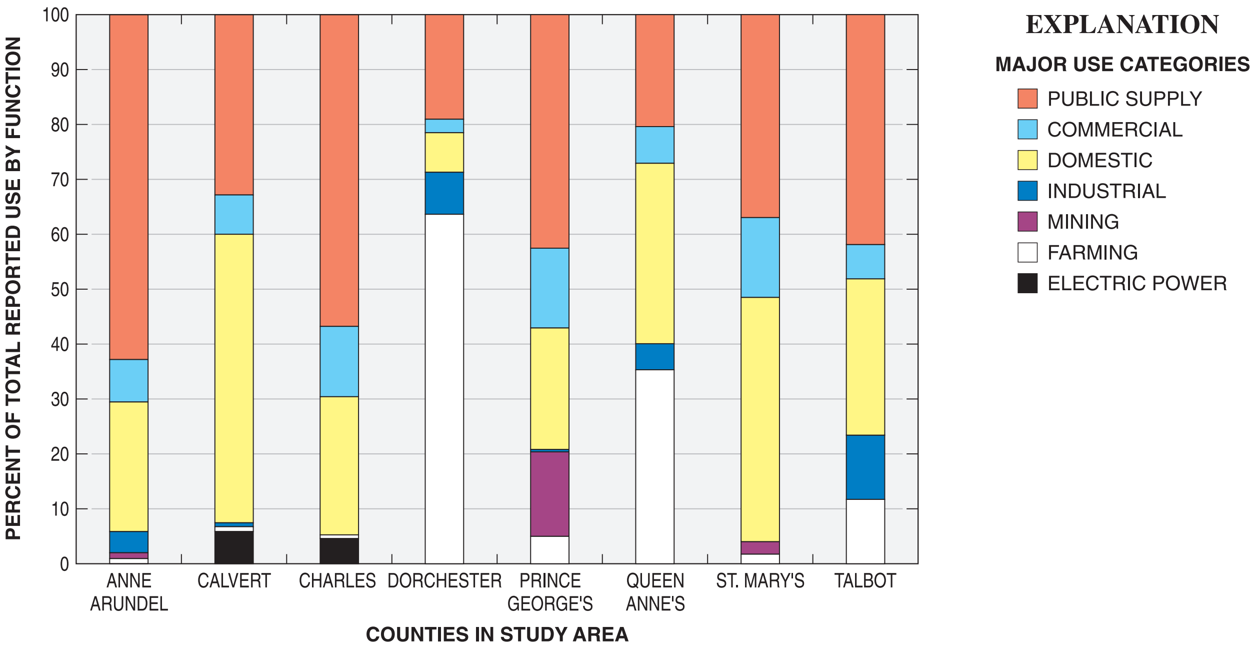


Figure 9. Ground-water use by county in the study area, shown as a function of major use category for 2004 (From U.S. Geological Survey AWUDS database).

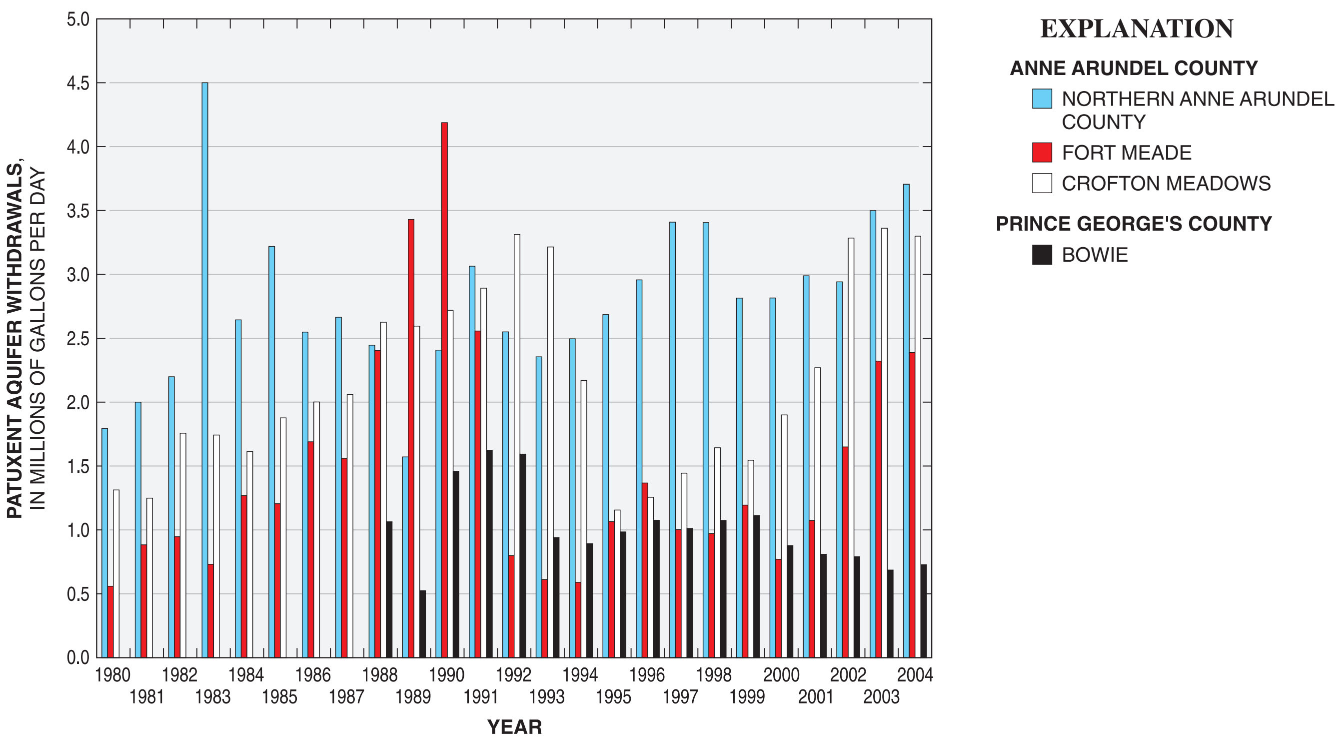


Figure 10. Trends in ground-water withdrawals from the Patuxent aquifer at four major pumping centers in Anne Arundel and Prince George's Counties from 1980 to 2004.

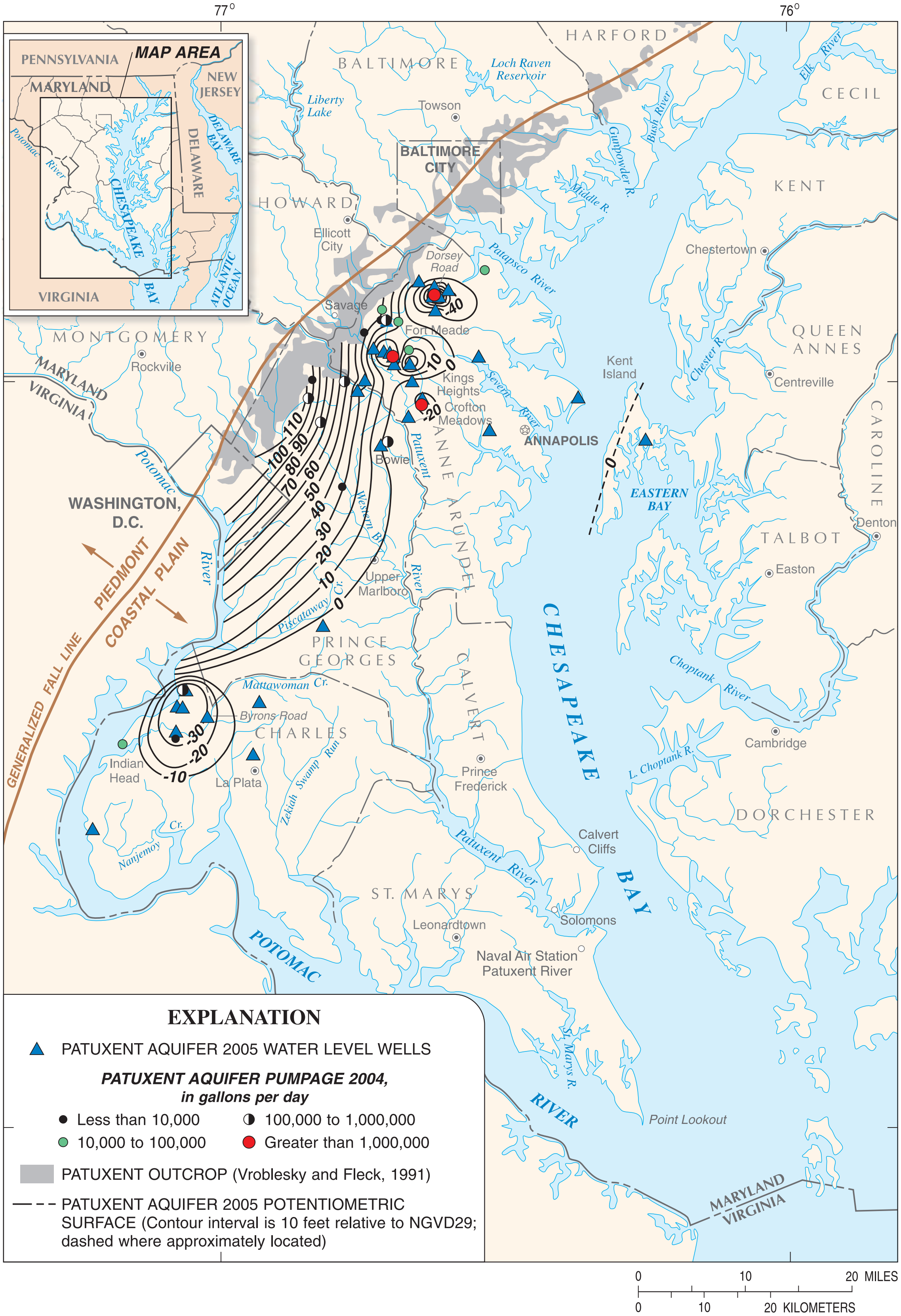


Figure 11. Potentiometric surface and water use, Patuxent aquifer, 2005.

online. Withdrawals from the Patuxent aquifer at Crofton Meadows, however, have peaked twice, once in the early 1990s at more than 3 Mgal/d, and then declining to below 1 Mgal/d before exceeding 3 Mgal/d levels again about 10 years later. Water-supply pumpage at Crofton Meadows is distributed between the Patuxent aquifer and the lower Patapsco aquifer. The year-to-year changes in withdrawal rates from the Patuxent that are visible in figure 10 are probably related more to operational issues than to water-supply issues (D.C. Andreasen, Maryland Geological Survey, written commun., 2007). It should also be noted that in addition to the well field at Crofton Meadows, Anne Arundel County also had a municipal supply field in the Patuxent aquifer at Crofton, which was abandoned in 1992.

Patuxent aquifer withdrawals in Charles County are significantly less than those in Anne Arundel or Prince George's Counties. The maximum withdrawal in the water-use records was 0.16 Mgal/d from a well at South Hampton in 2001.

The potentiometric surface map of the Patuxent aquifer in the study area is shown in figure 11. The outcrop (and recharge) area shown on this and all subsequent maps in this report follow the boundaries defined by Vroblesky and Fleck (1991) in their Coastal Plain RASA report.

A large cone of depression is visible in northern Anne Arundel County, corresponding to the pumping center on Dorsey Road. Cones of depression are also centered on ground-water withdrawal locations at Fort Meade and Crofton Meadows. A mound-like feature is shown on the potentiometric surface of the Patuxent aquifer east of Fort Meade at Kings Heights. This is a real feature in the data, and may be caused by an isolated sand unit within the Patuxent aquifer system (D.C. Andreasen, Maryland Geological Survey, written commun., 2007).

Another broad cone of depression in Charles County centered on Bryons Road between the towns of Indian Head and LaPlata resulted from increased utilization of the Patuxent aquifer in northwestern Charles County, as water demands increased with population growth.

All of the 2005 potentiometric surface maps constructed for this report show ground-water withdrawals for 2004, the most recent year for which reviewed and approved data were available. It is not unreasonable to expect that ground-water drawdowns observed in 2005 were caused by 2004 pumpages. The 2004 water-use data have been checked as closely as possible against the 2005 water-use data that were available when this report was being prepared, and no significant differences were noted.

Patapsco Aquifer

Ground-water withdrawals from the Patapsco Formation are reported separately for the lower Patapsco and upper Patapsco aquifers. These are described in separate sections below.

Lower Patapsco Aquifer

As shown in figure 12, the largest volume of water pumped from the lower Patapsco aquifer at a single location occurred in the Anne Arundel County well field at Severndale. Withdrawal rates were approximately 2 to 3.5 Mgal/d during the 1980s, increasing to more than 6 Mgal/d in the mid-1990s. Pumping at the Town of Arnold, near the City of Annapolis on the Broadneck Peninsula, began in the early 1990s, and has been maintained at a rate of about 2 Mgal/d through the present. The annual water report to consumers from Anne Arundel County (2006) indicates that the populous Broadneck Peninsula is mainly supplied with water from the Severndale and Arnold pumping centers.

Other areas of drawdown in the lower Patapsco aquifer in Southern Maryland are in Charles County, at Waldorf, LaPlata, Indian Head, and at the Morgantown Powerplant. Pumping-induced drawdowns increased over time, and are shown in the series of lower Patapsco potentiometric surface maps for 1985, 1995, and 2005 (figs. 13–15). A cone of depression approximately 35 ft below sea level had developed in the vicinity of Severndale by 1985, which increased to about 62 ft below sea level in 1995, and developed to a depth of over 90 ft below sea level by 2005. Drawdowns to a depth of about 55 ft below sea level are also shown on the 1995 potentiometric surface at Arnold after pumping began in 1992. In 2005, the largest cone of depression in the lower Patapsco aquifer in Southern Maryland was located in an area of northern and western Charles County, with drawdowns nearly 200 ft below sea level at Waldorf and LaPlata (fig. 15). A number of production wells withdrawing between 0.1 and 1 Mgal/d are located in the Waldorf area, at LaPlata, and in the Indian Head-Bryons Road area to the west. Ground water in the lower Patapsco near Indian Head has been pumped at a rate of about 1 Mgal/d since 1980 (fig. 12). Ground-water withdrawals in Charles County and in Southern Prince George's County have resulted in declines in ground-water levels in the lower Patapsco aquifer.

A number of observation wells screened in the underlying Patuxent aquifer, which is lightly pumped, also showed declines (Andreasen, 1999). The possibility of pumpage from one aquifer affecting water levels in adjacent aquifers is discussed in more detail in a later section of this report.

A map of the difference in the potentiometric surface of the lower Patapsco aquifer is shown in figure 16 for the period 1985 to 1995, and a similar map is shown in figure 17 for the period 1995 to 2005. The differences in the potentiometric surface from 1985 to 1995 are most pronounced in central Anne Arundel County and Charles County, and were presumably caused by ground-water withdrawals at Severndale and in the vicinity of Waldorf. The 1995–2005 difference map shows some recovery of the potentiometric surface at Arnold, but continued declines at Severndale and in Charles County.

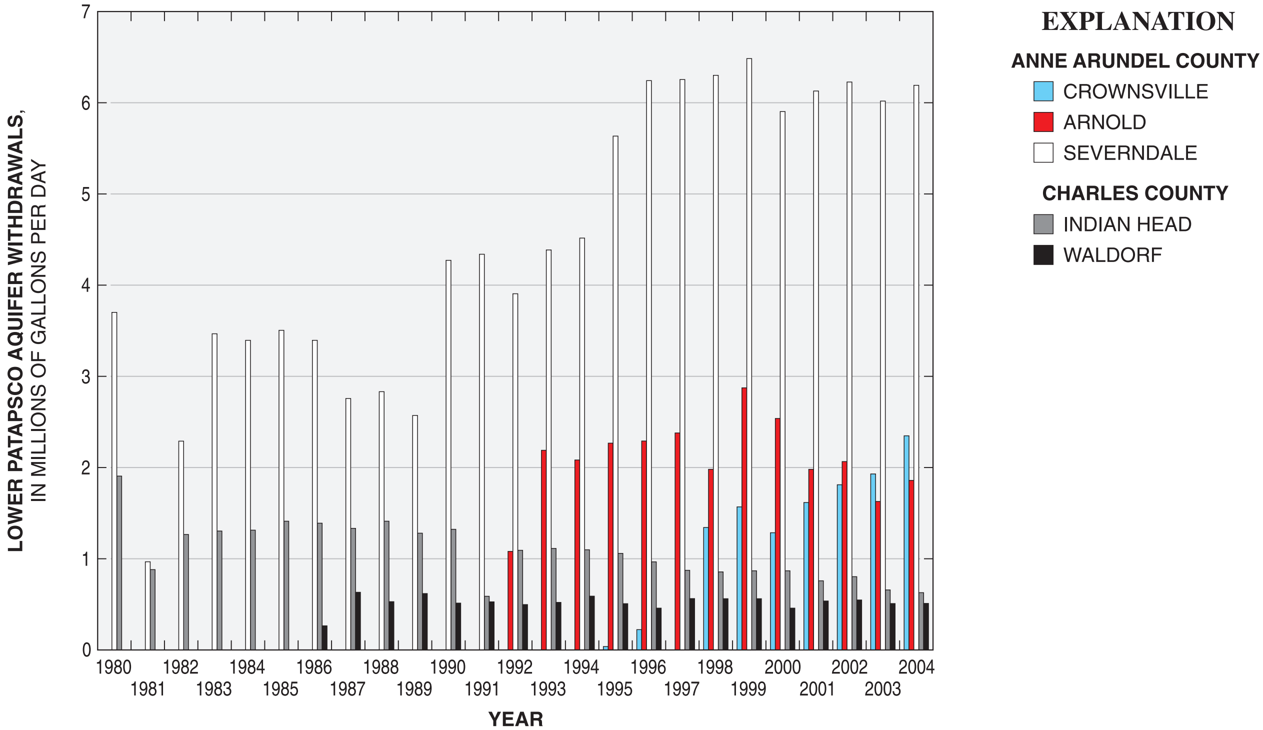


Figure 12. Ground-water withdrawals from the lower Patapsco aquifer at five major pumping centers in Anne Arundel and Charles Counties from 1980 to 2004 (From U.S. Geological Survey AWUDS database).

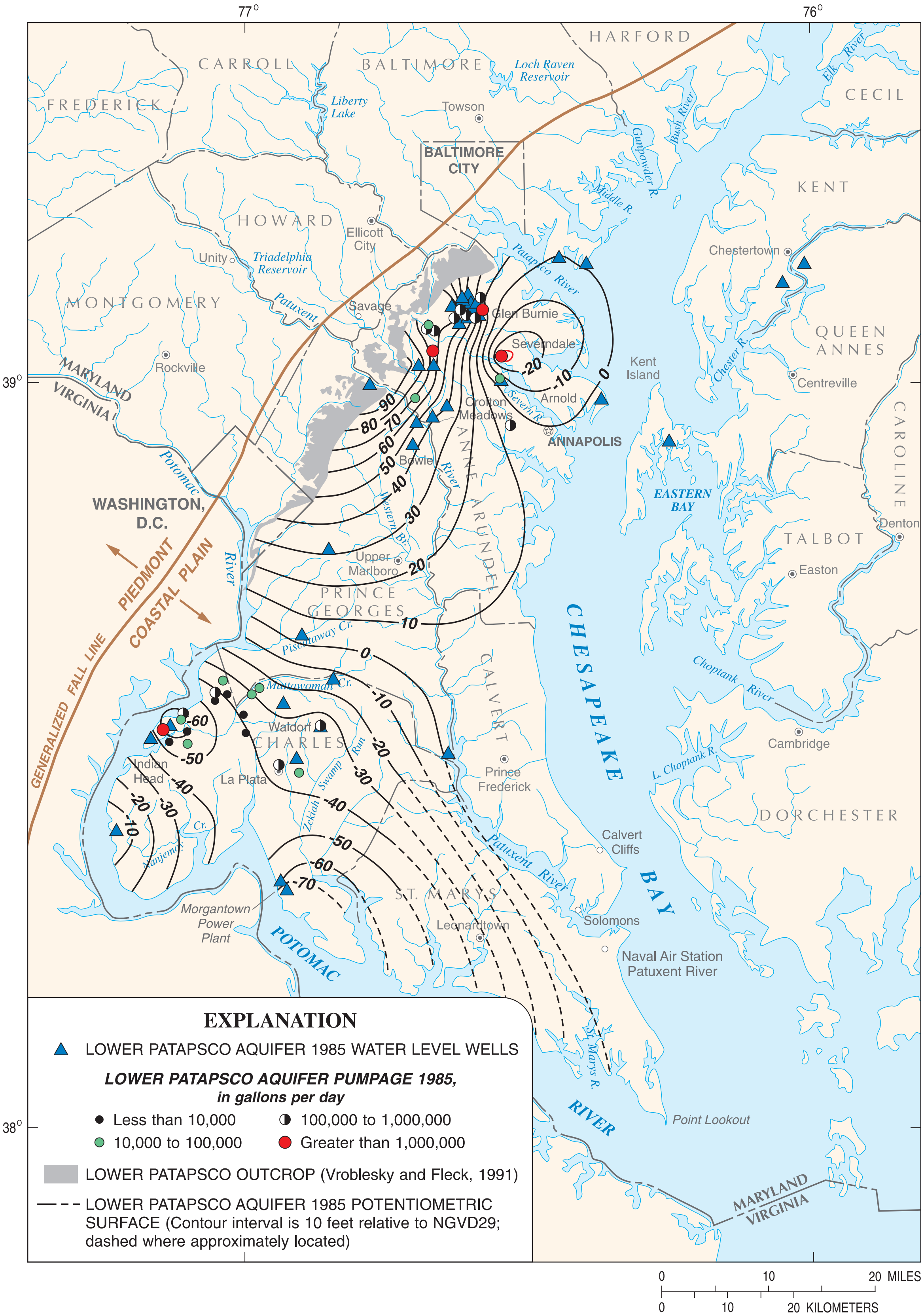


Figure 13. Potentiometric surface and water use, lower Patapsco aquifer, 1985.

Figure 14. Potentiometric surface and water use, lower Patapsco aquifer, 1995.

Figure 15. Potentiometric surface and water use, lower Patapsco aquifer, 2005.

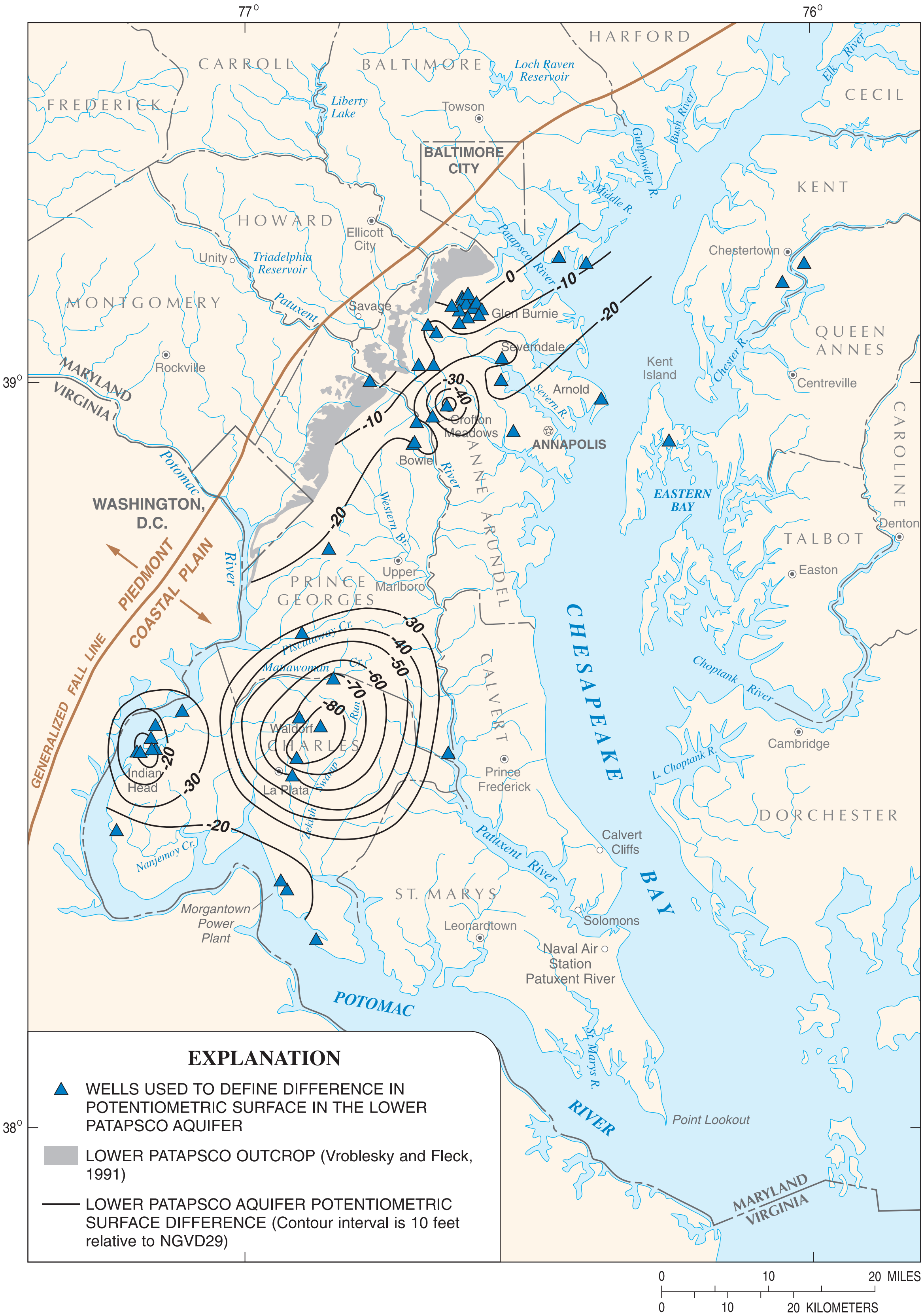


Figure 16. Potentiometric difference, lower Patapsco aquifer, 1985 to 1995.

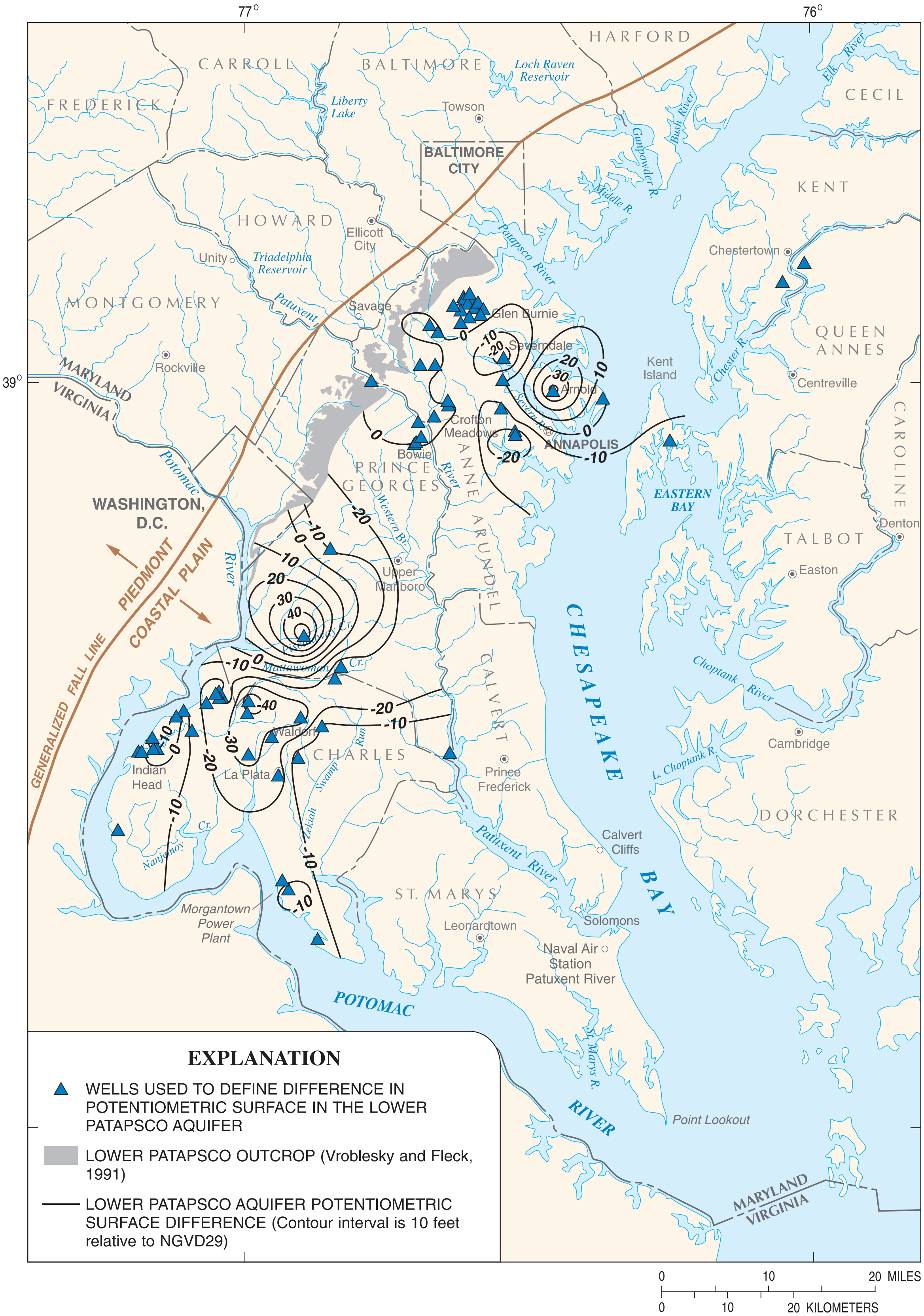


Figure 17. Potentiometric difference, lower Patapsco aquifer, 1995 to 2005.

Upper Patapsco Aquifer

Ground-water withdrawals from the upper Patapsco aquifer tend to be lower in total volume than those from the lower Patapsco aquifer. The main user of ground water from the upper Patapsco aquifer is the City of Annapolis, as shown in figure 18. Water from the upper Patapsco aquifer is supplied by a well field within the City of Annapolis (AA1932G101), and a second nearby at Broad Creek (AA1968G006) on the west side of town. The combined withdrawals from these two well fields are shown as “Annapolis” in figure 18. The municipal area also is supplied by a well field located northeast of the city near the Town of Arnold. As shown in figure 18, these pumping localities have withdrawn the largest amounts of ground water from the upper Patapsco aquifer over the past 25 years.

A number of ground-water withdrawals from the upper Patapsco aquifer did not begin until the early 1990s, for example, near the Eastern Shore towns of Easton and Cambridge (fig. 18). Water supplies at Severndale from the lower Patapsco aquifer were supplemented by ground-water withdrawals from the upper Patapsco aquifer beginning in the 1990s. The trend appears to be toward greater use of this aquifer.

The only major ground-water withdrawals from the upper Patapsco aquifer in Southern Maryland are reported for the Chalk Point Power Plant in southern Prince George’s County. The water-use data since 1980 show Chalk Point steadily withdrawing less than 0.5 Mgal/d from the upper Patapsco aquifer.

Potentiometric surface maps of the upper Patapsco aquifer for 1985, 1995, and 2005 are shown in figures 19, 20, and 21. An unexpected feature of these maps is the cone of depression centered on the Waldorf-LaPlata area in Charles County. None of the individual wells or well fields in this part of Charles County are reported as withdrawing water at rates higher than 100,000 gal/d, and there are many smaller users (S.E. Curtin, U.S. Geological Survey, oral commun., 2007). The potentiometric surface map (fig. 21) shows local declines as great as -120 ft in the upper Patapsco aquifer by 2005. Wilson and Fleck (1990) reported that transmissivities of the upper Patapsco aquifer and its equivalents in Charles County are higher to the north and east of the Waldorf area. The reduced transmissivity of the upper Patapsco aquifer in southwestern Charles County may be responsible for the large cones of depression under relatively low pumping rates as shown in the potentiometric surface maps of this area.

It is also possible that drawdowns in the upper Patapsco aquifer in the Waldorf-LaPlata area might be a response to the significant withdrawals of ground water from the lower Patapsco aquifer at this location. As noted earlier, Achmad and Hansen (2001) reported that the confining bed between the lower and upper Patapsco aquifers was sandy and less effective at some locations. The upper Patapsco at Waldorf-LaPlata might be affected by pumpage from the lower Patapsco.

The upper Patapsco aquifer is not pumped in Calvert County and is used only to a limited extent in St. Mary’s County. An assessment of the projected water demands to the year 2030 in these counties led Drummond (2005) to conclude that new sources of supply would have to be developed, and drilling into deeper aquifers like the upper Patapsco was a solution suggested for obtaining additional ground water. Total reported withdrawals from the upper Patapsco aquifer in St. Mary’s County were less than 0.1 Mgal/d until the late 1990s, but had increased to 0.47 Mgal/d by 2004.

A map of the difference in the potentiometric surface of the lower Patapsco aquifer is shown in figure 22 for the period 1985 to 1995, and a similar map is shown in figure 23 for the period 1995 to 2005. The 1985–95 map shows the effects of drawdown in the vicinity of Annapolis, and near the Chalk Point Power Plant, which is a relatively minor user, at about 0.3 to 0.4 Mgal/d. The 1995–2005 map shows some recovery at Annapolis and Chalk Point, but continued declines in western Charles County, and new declines in St. Mary’s County.

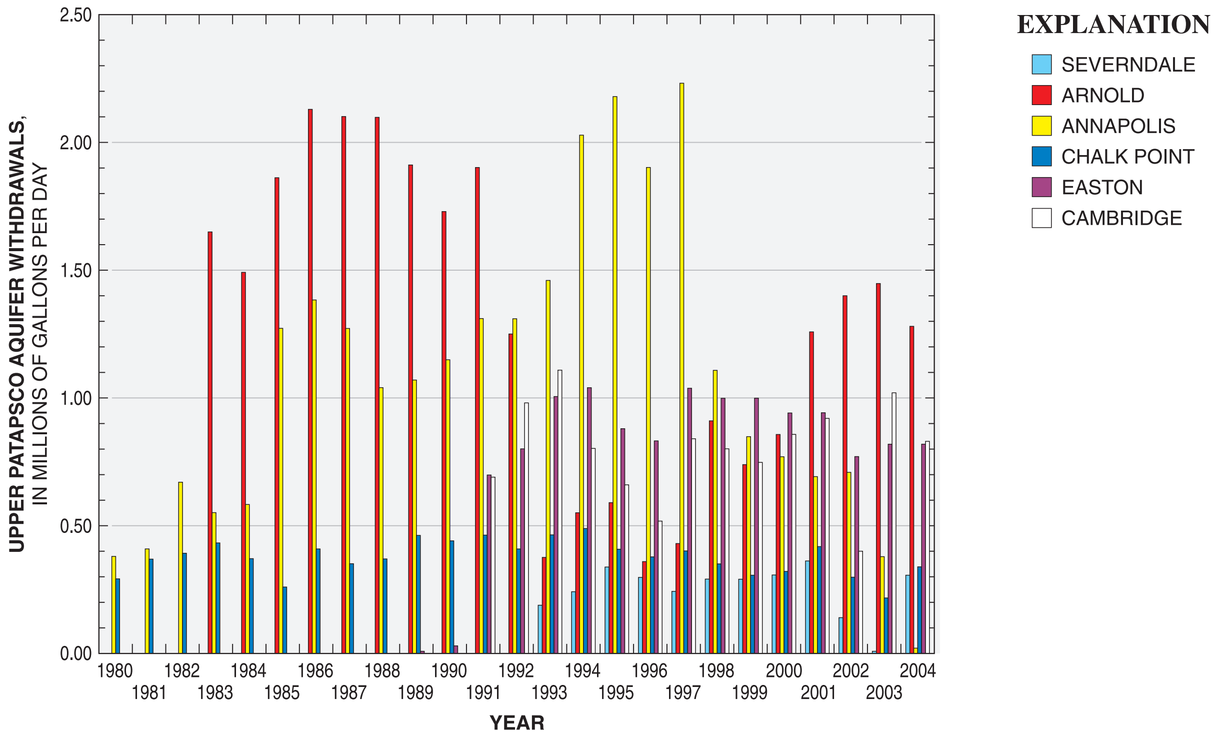


Figure 18. Trends in ground-water withdrawals from the upper Patapsco aquifer at six major pumping centers in Southern Maryland from 1980 to 2004. (Annapolis and Arnold are both in the Annapolis metropolitan area.)

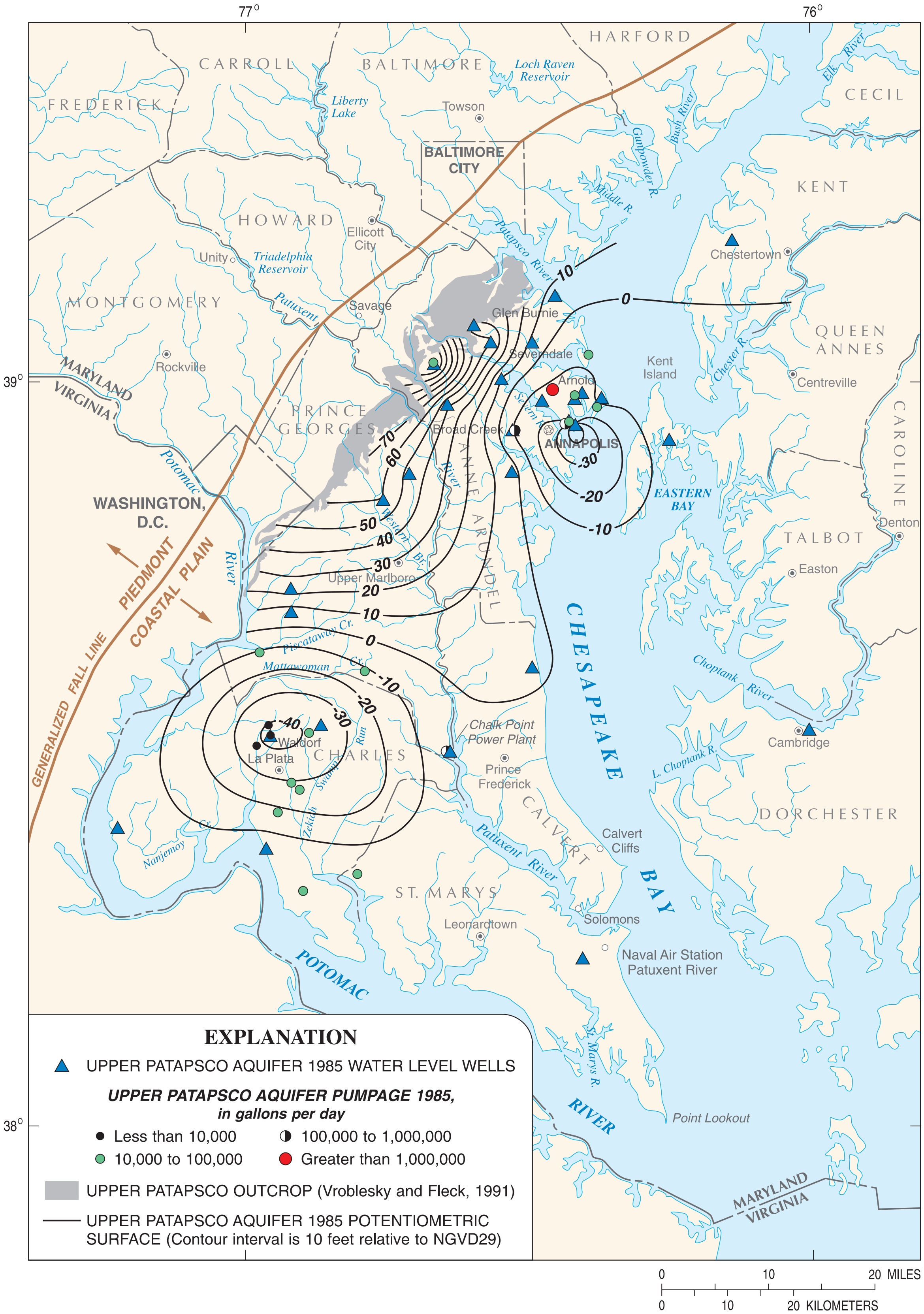


Figure 19. Potentiometric surface and water use, upper Patapsco aquifer, 1985.

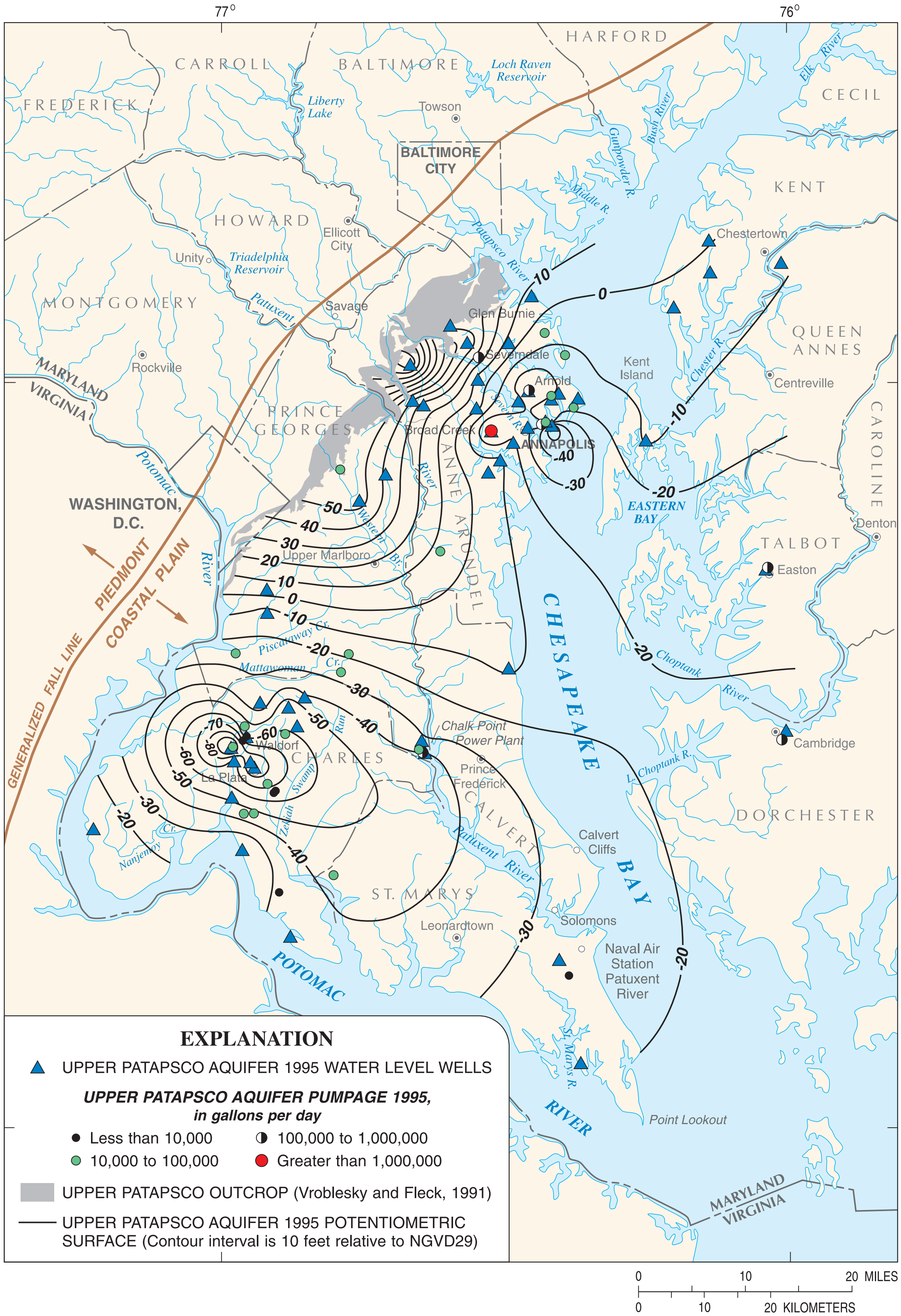


Figure 20. Potentiometric surface and water use, upper Patapsco aquifer, 1995.

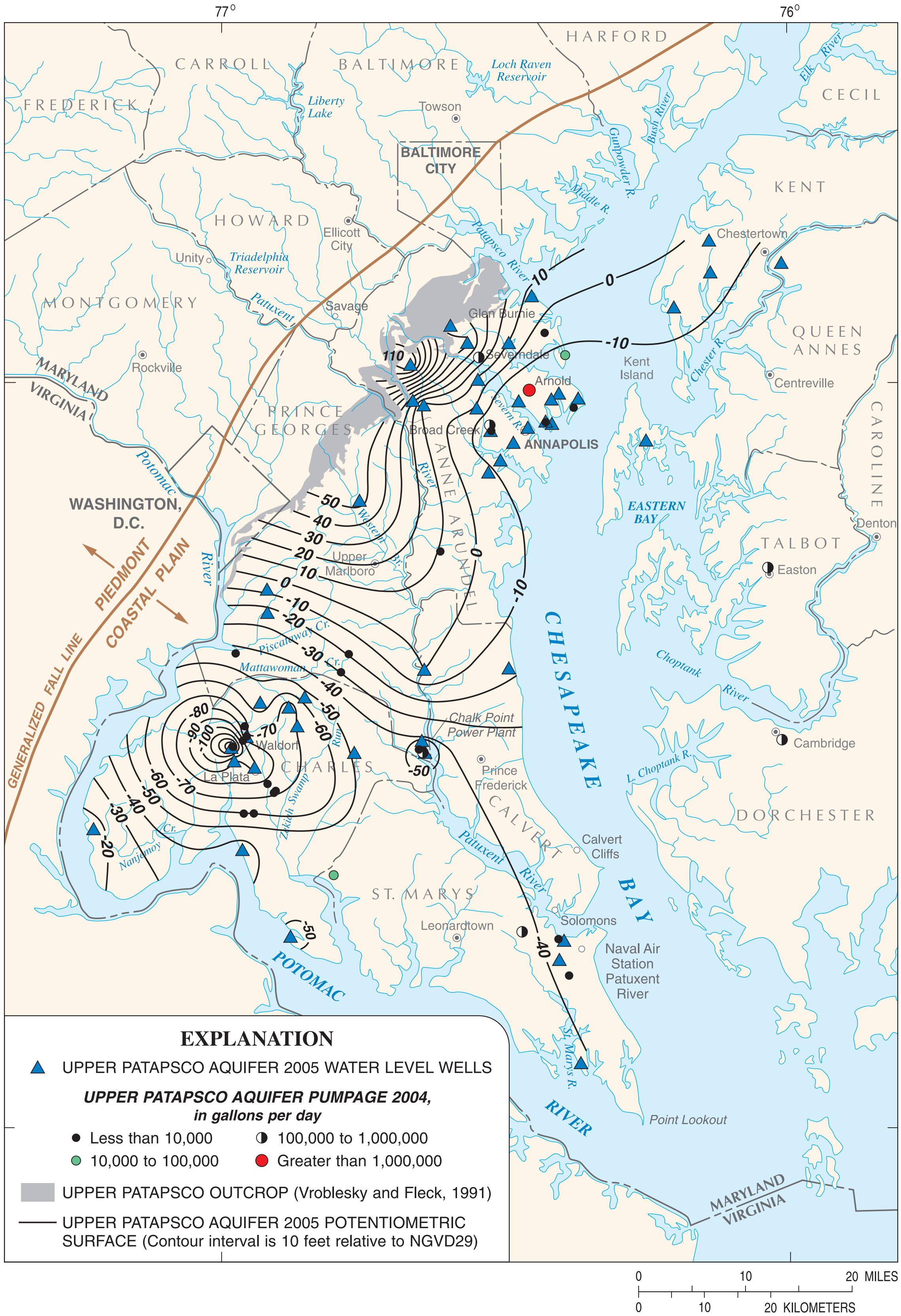


Figure 21. Potentiometric surface and water use, upper Patapsco aquifer, 2005.

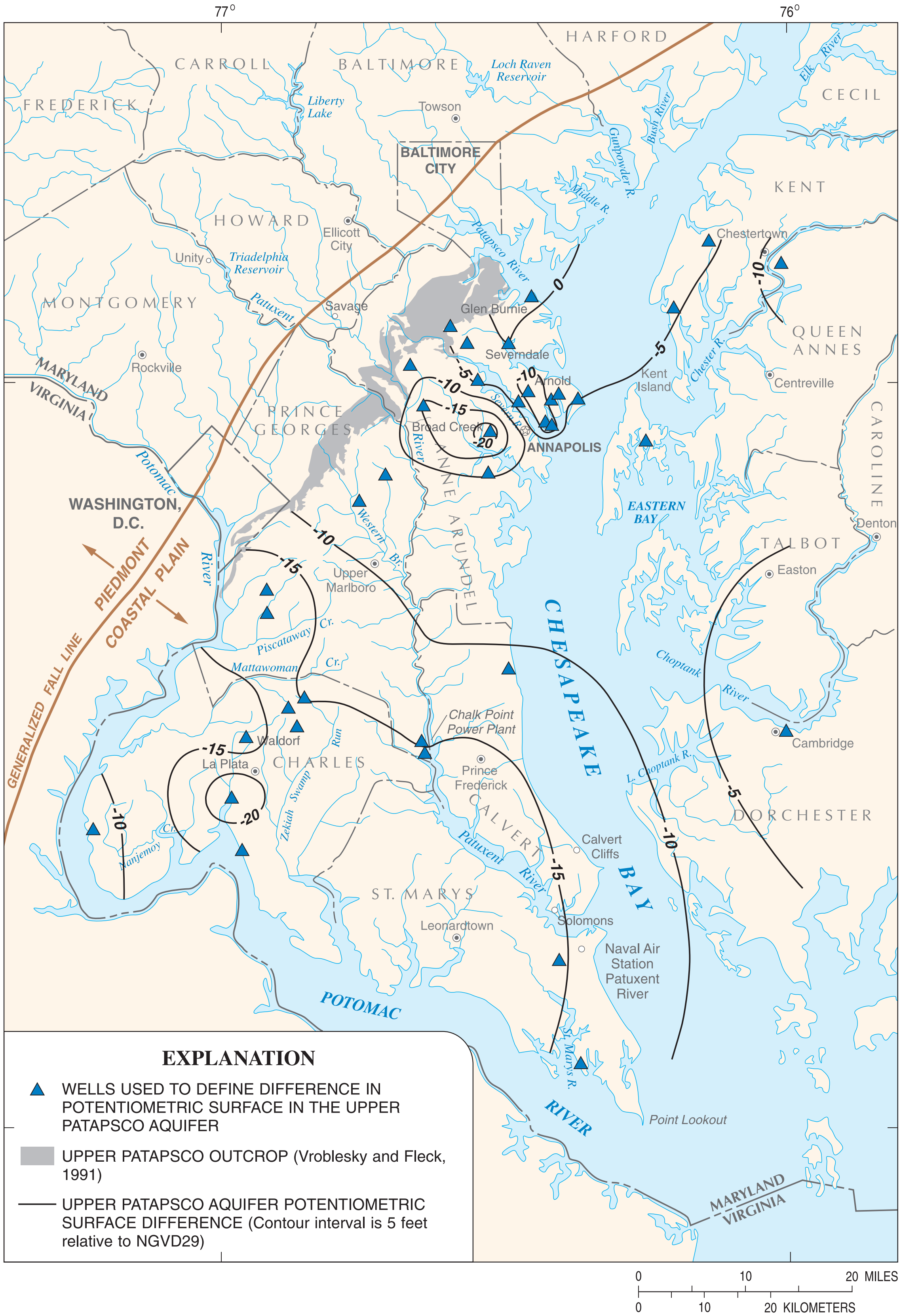


Figure 22. Potentiometric difference, upper Patapsco aquifer, 1985 to 1995.

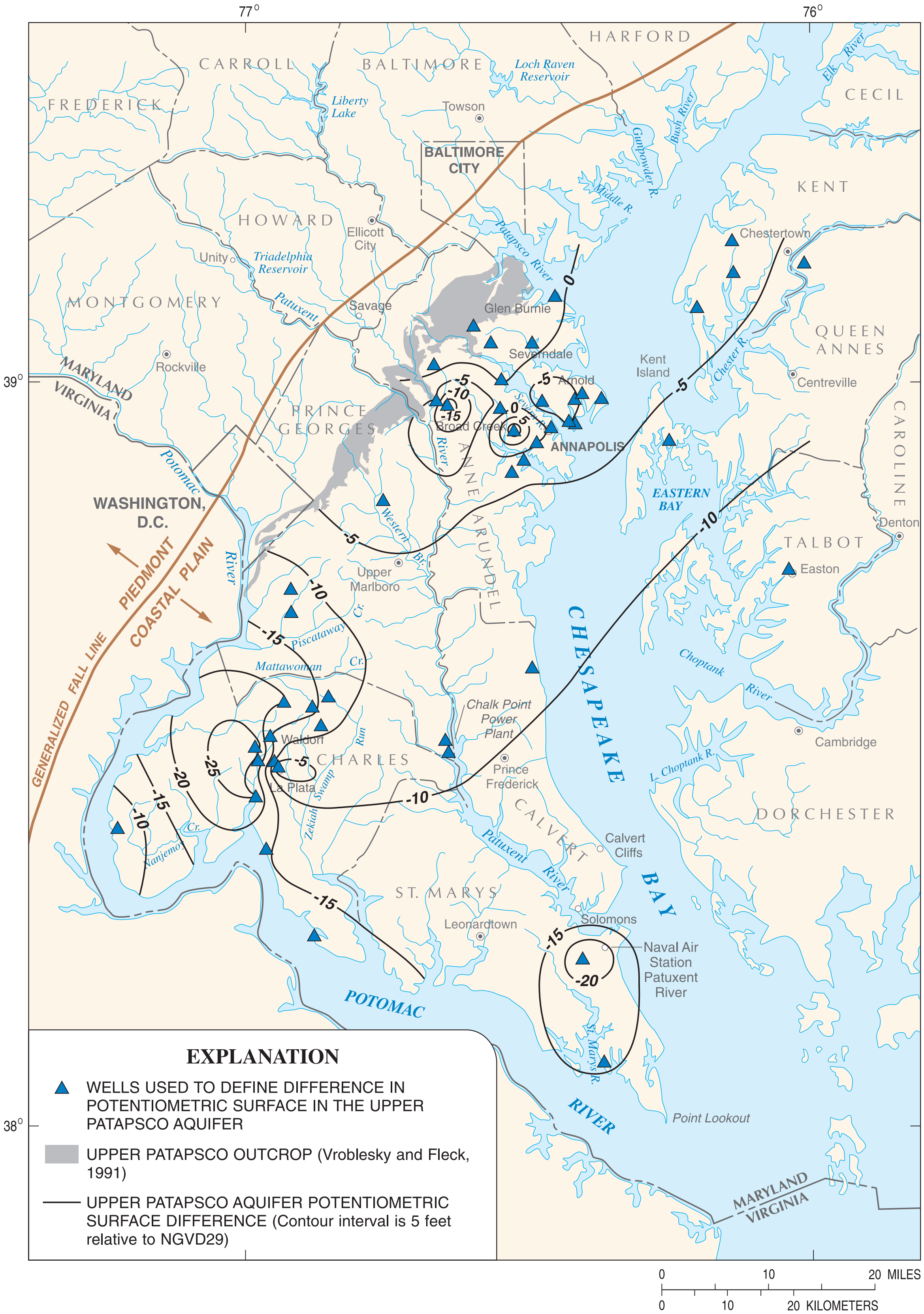


Figure 23. Potentiometric difference, upper Patapsco aquifer, 1995 to 2005.

Magothy Aquifer

As shown in figure 24, rates of ground-water withdrawal from the Magothy aquifer were relatively high at the City of Annapolis in the early 1980s, exceeding 4 Mgal/d in some years. During this time, the Town of Bowie and production wells in the Waldorf area also were withdrawing 2 to 3 Mgal/d from the aquifer. The Town of Bowie severely reduced and maintained withdrawals from the Magothy aquifer at less than 0.3 Mgal/d since 1988. Production at the City of Annapolis and near Waldorf has continued to steadily withdraw 1.5 to nearly 3 Mgal/d. The values shown in figure 24 for these two locations represent the sum totals of multiple production wells reported for each area. The Chalk Point Power Plant has withdrawn slightly more to slightly less than 0.5 Mgal/d since 1980. Production at Easton from the Magothy aquifer has dropped by about half since 1990, compared to withdrawal rates in the 1980s.

Potentiometric surface maps and ground-water withdrawal centers for the Magothy aquifer are shown for 1985, 1995, and 2005 in figures 25–27. Sustained, high rates of pumpage at the City of Annapolis in Anne Arundel County, in the range of 1–2 Mgal/d for the last decade, resulted in the development of a relatively shallow cone of depression in the potentiometric surface of the Magothy aquifer. A group of wells in the Waldorf area pumping less than 0.1 Mgal/d have created a broad and deep cone of depression in the potentiometric surface, however. A similar cone of depression in the potentiometric surface of the Magothy aquifer at the Chalk Point Power Plant resulted from pumpage of about 0.5 Mgal/d from 1980 to 2004.

Yields from the Magothy aquifer vary at different locations, probably because of variations in hydraulic conductivity due to facies changes within the formation. This also occurs in the upper Patapsco aquifer as described previously. The Magothy Formation was noted in the hydrogeologic framework section of this report as thinning to the south and west in Southern Maryland, with the subsurface boundary located only about 8 mi (miles) southwest of Chalk Point. The finer-grained sands in this area (Hansen, 1972) may be responsible for the reduced hydraulic conductivity of the aquifer and result in a greater drawdown.

A map of the difference in the potentiometric surface of the Magothy aquifer is shown in figure 28 for the period 1985 to 1995, and a similar map is shown in figure 29 for the period 1995 to 2005. The earlier map shows a broad area of decline to the southwest, toward the Town of Bowie and the Waldorf area. Waldorf has continued to withdraw ground water from the Magothy aquifer at 2 to 3 Mgal/d since 1980, pumping from a number of small production wells. This steady withdrawal has maintained a broad and deep cone of depression in northern Charles County that continues to develop.

Reductions in ground-water withdrawals from the Magothy aquifer by the Town of Bowie, shown in figure 24 as decreasing from about 2.5 Mgal/d in the early 1980s to less than 0.2 Mgal/d beginning in 1988, have resulted in the recovery of water levels. This can be seen on the potentiometric surface difference maps (figs. 28 and 29) as a positive recovery of the potentiometric surface in central and northern Prince George's County.

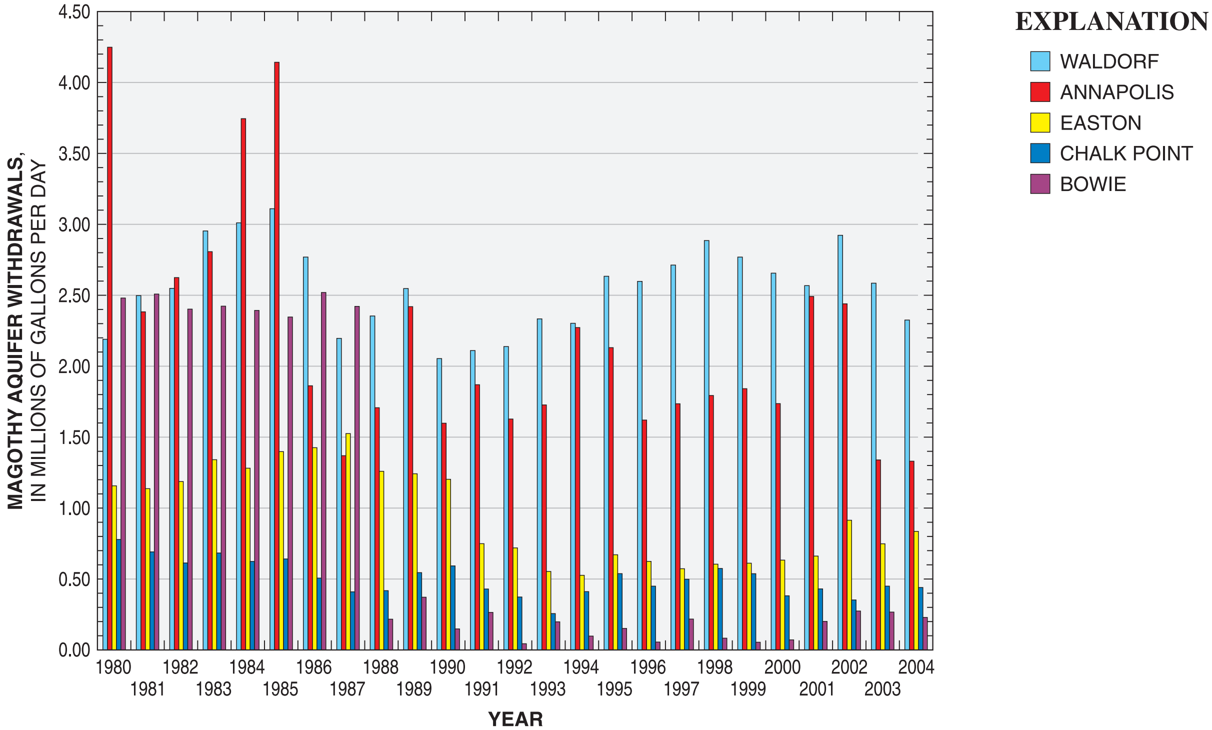


Figure 24. Trends in ground-water withdrawals from the Magothy aquifer at five major pumping centers in Southern Maryland from 1980 to 2004 (Withdrawal data for Annapolis and Waldorf are aggregated from multiple wells) (Source: U.S. Geological Survey AWUDS database).

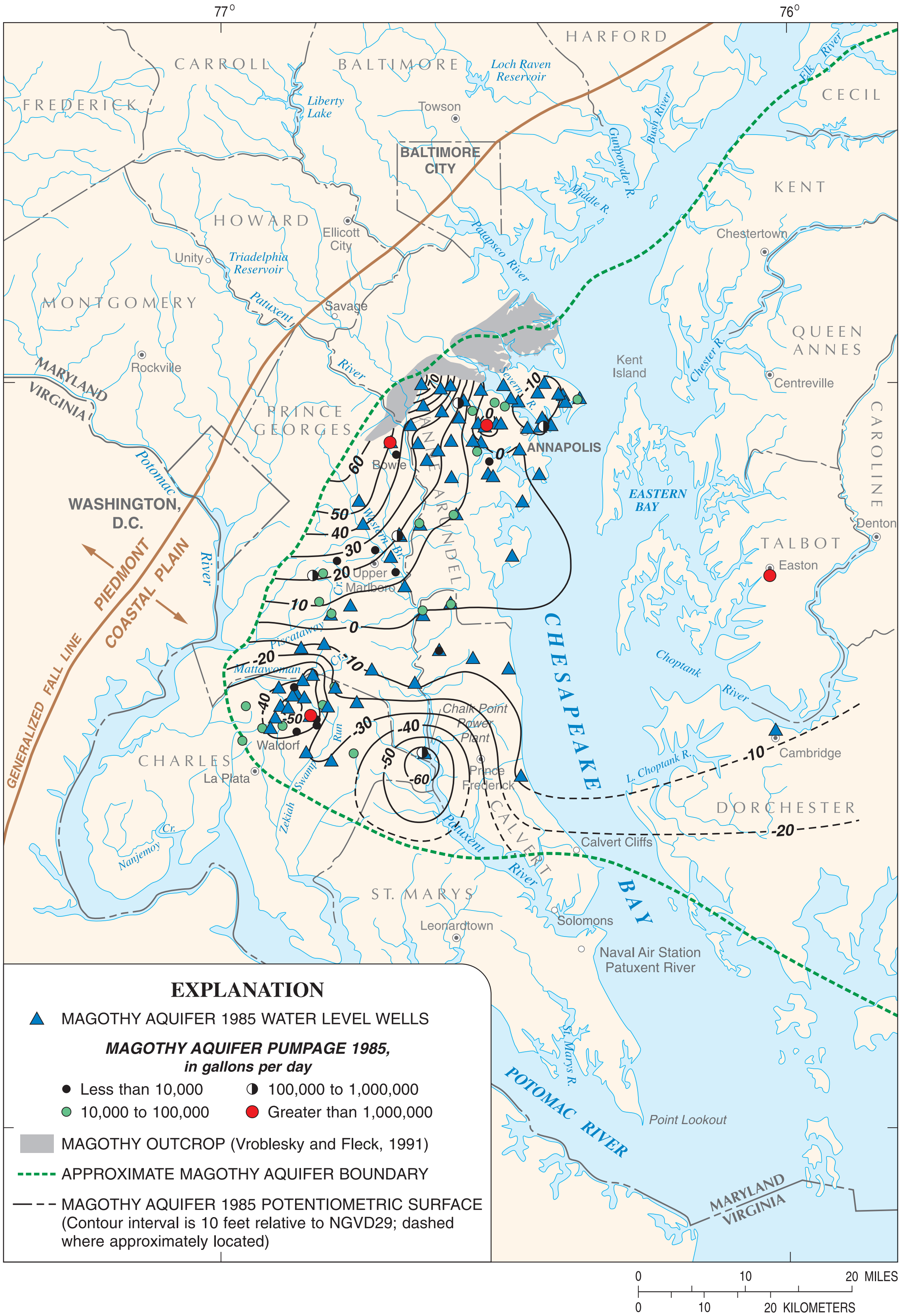


Figure 25. Potentiometric surface and water use, Magothy aquifer, 1985.

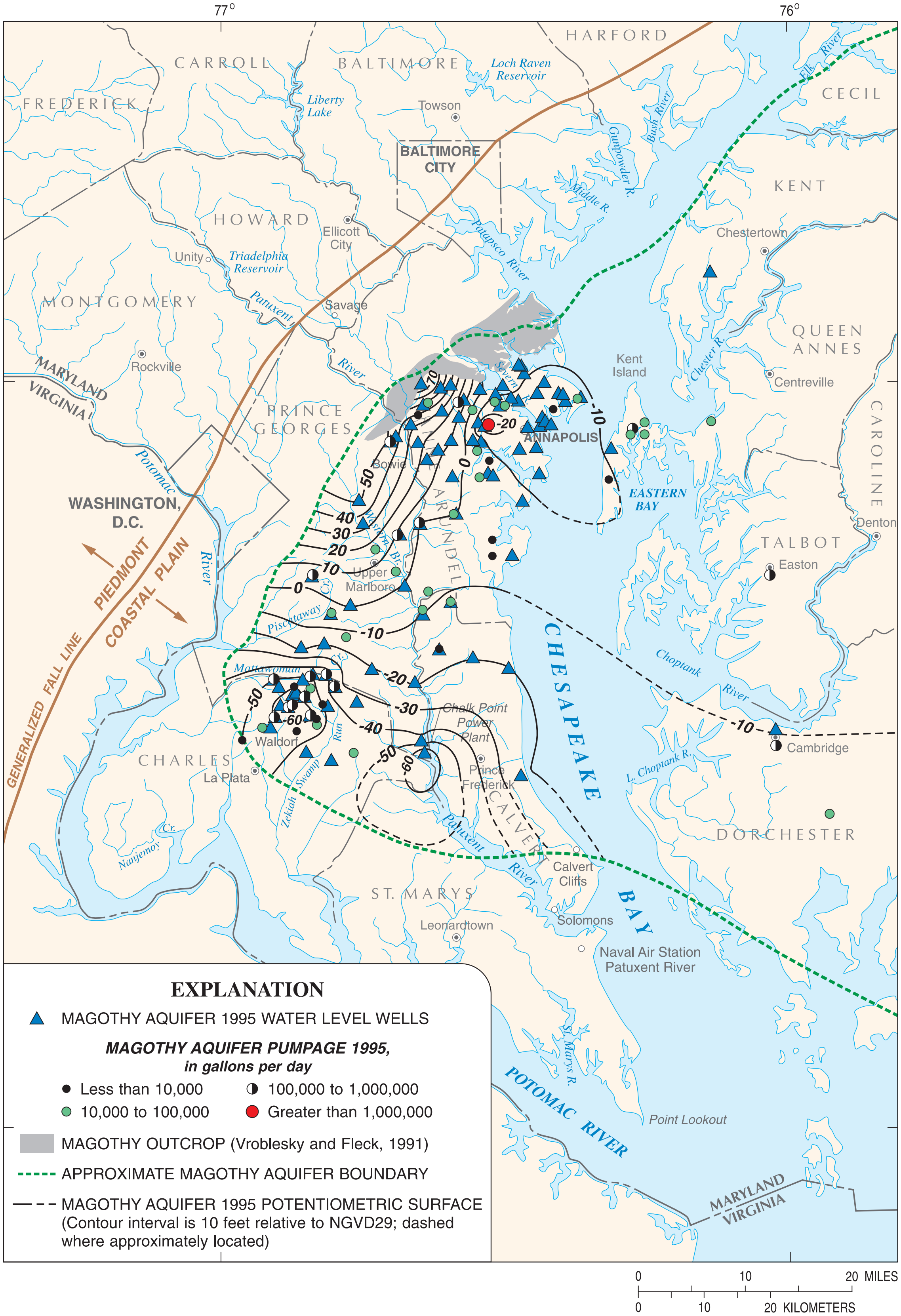


Figure 26. Potentiometric surface and water use, Magothy aquifer, 1995.

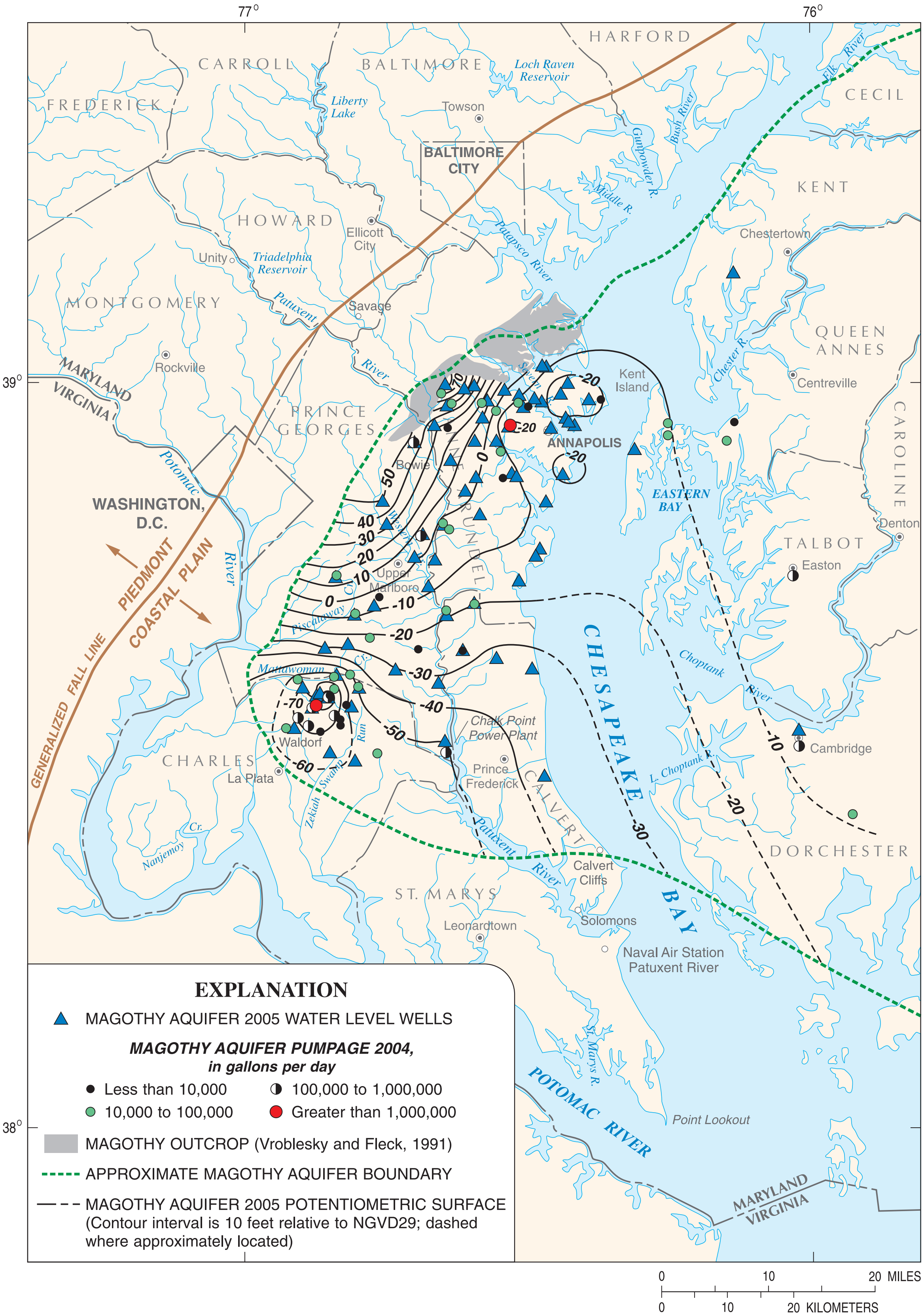


Figure 27. Potentiometric surface and water use, Magothy aquifer, 2005.

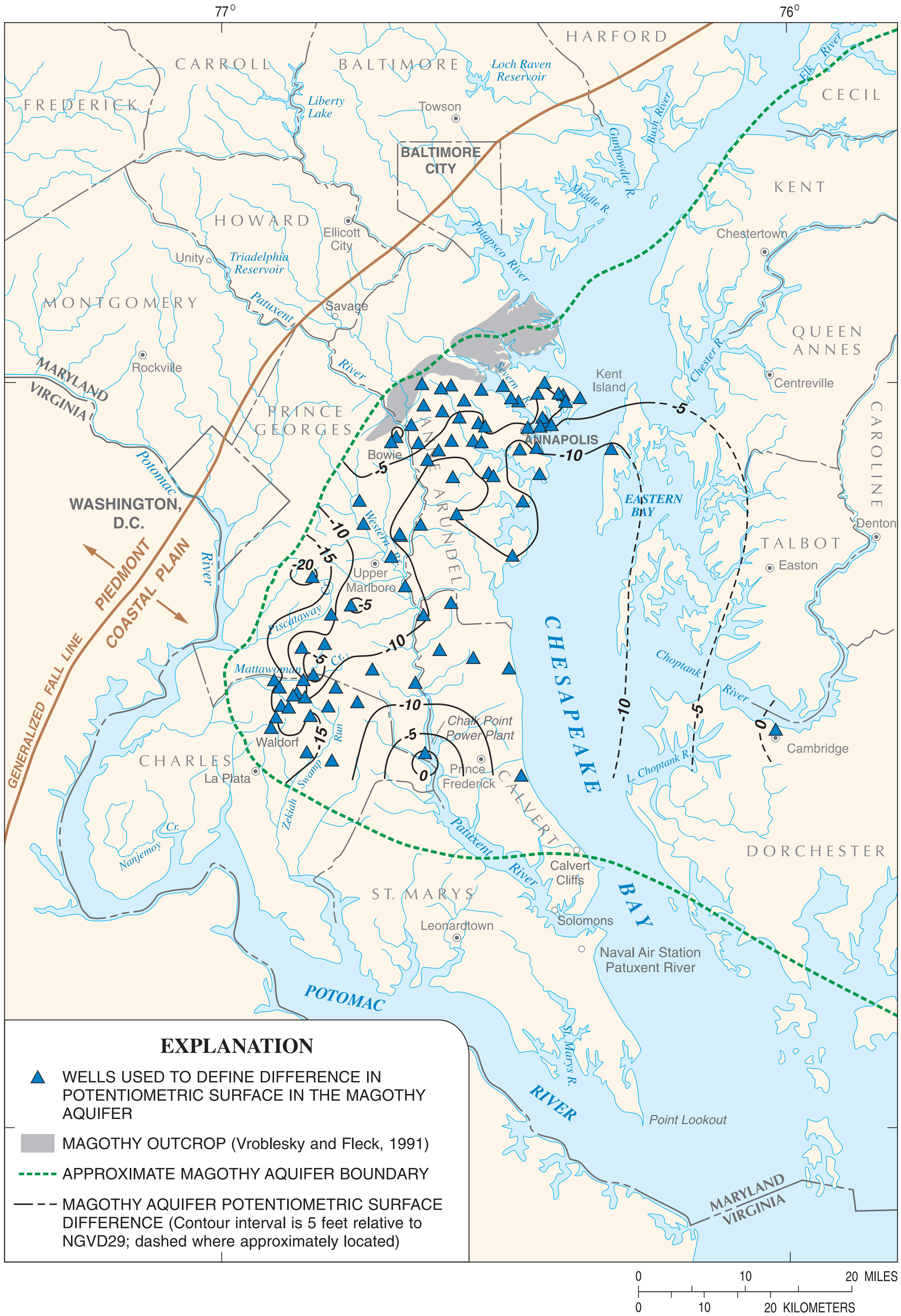


Figure 28. Potentiometric difference, Magothy aquifer, 1985 to 1995.

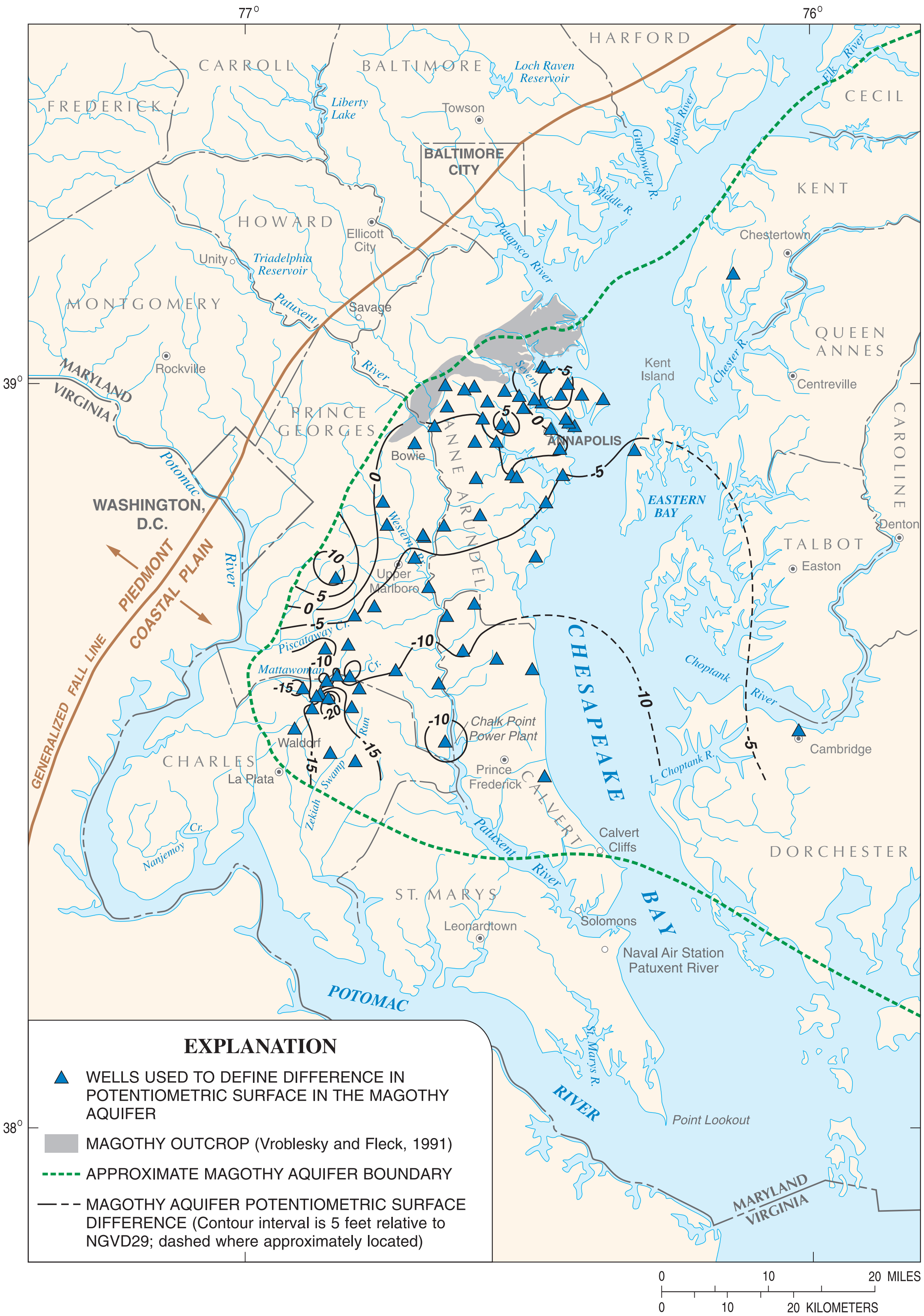


Figure 29. Potentiometric difference, Magothy aquifer, 1995 to 2005.

Aquia Aquifer

Significant rates of ground-water withdrawal from the Aquia aquifer in Southern Maryland began in 1942, when the U.S. Navy constructed Naval Air Station, Patuxent River (NASPR) and Webster Outlying Field on the Point Lookout Peninsula in the southernmost part of St. Mary's County (Klohe and Feehley, 2001). The Naval Air Station and the Town of Lexington Park outside its front gate have withdrawn water from the Aquia aquifer at a steady rate of about 2 Mgal/d since 1980, as shown in figure 30. No other Aquia well field in the study area has withdrawn water from this aquifer at this magnitude or duration. The second largest well field, at Solomons Island, has steadily climbed to a rate of 1 Mgal/d, and is only a few miles from NASPR, just across the Patuxent River to the north. Potentiometric surface maps and ground-water withdrawal centers for the Aquia aquifer are shown for 1985, 1995, and 2005 in figures 31–33. Ground-water withdrawals from the Aquia aquifer at NASPR and Solomons Island have resulted in regional drawdown of the potentiometric surface.

Ground-water withdrawals at NASPR and the Town of Lexington Park have created a large cone of depression in the potentiometric surface of the Aquia aquifer, which reached a depth of more than 150 ft below sea level in 2005. Ground-water withdrawal from the Aquia aquifer at the Calvert Cliffs Power Plant, which increased slightly in the mid-1990s to near 0.5 Mgal/d, is visible on the potentiometric surface maps as a slight "indentation" in the northern curve of the contour lines around NASPR and Solomons Island. The effect of pumpage wells near the Town of Chesapeake Beach, located in northern Calvert County, is also visible on some of the maps, most noticeably in 2005 (fig. 33). Many other small users of the Aquia aquifer in northern Calvert County, southern Anne Arundel County, and at multiple locations on the Eastern Shore have produced little individual disturbance in the potentiometric surface compared to the cone of depression in the Solomons Island/NASPR area. The collective volume of ground-water withdrawn from this aquifer by these smaller users has probably been significant, however (D.C. Andreasen, Maryland Geological Survey, written commun., 2007).

Different sedimentary facies of the Aquia Formation affect yields from the Aquia aquifer. The Aquia Formation contains coarse, sandy-textured, high-transmissivity, beach-face or offshore bar sands extending along and parallel to the outcrop belt (Hansen, 1974), which make an excellent aquifer. Toward the southern parts of the study area, the coarse sand grades into a finer-grained lagoonal facies, which is often considered a marginal to poor aquifer. On the Eastern Shore, the Aquia Formation is composed of a thin, muddy, offshore shelf facies, which is not a productive aquifer (Hansen, 1974). This transition between the sandy offshore bar and muddy shelf facies is shown in figures 31–33 as a dashed boundary running northeastward through Dorchester and Talbot Counties.

The large withdrawals at Solomons Island, NASPR, and the Town of Lexington Park are responsible for the deep cones of depression in southern Calvert and St. Mary's Counties; however, the drawdowns may also be partly due to the lower transmissivity of the finer-grained Aquia Formation lagoonal facies in this area. The more transmissive parts of the Aquia aquifer, in northern Calvert and southern Anne Arundel Counties, show less drawdown.

Maps of the difference in the potentiometric surface of the Aquia aquifer for the period 1985 to 1995, and 1995 to 2005, respectively, are shown in figures 34 and 35. Declines of more than 60 ft occurred near NASPR from 1985 to 1995, decreasing to about 20 ft by 2005.

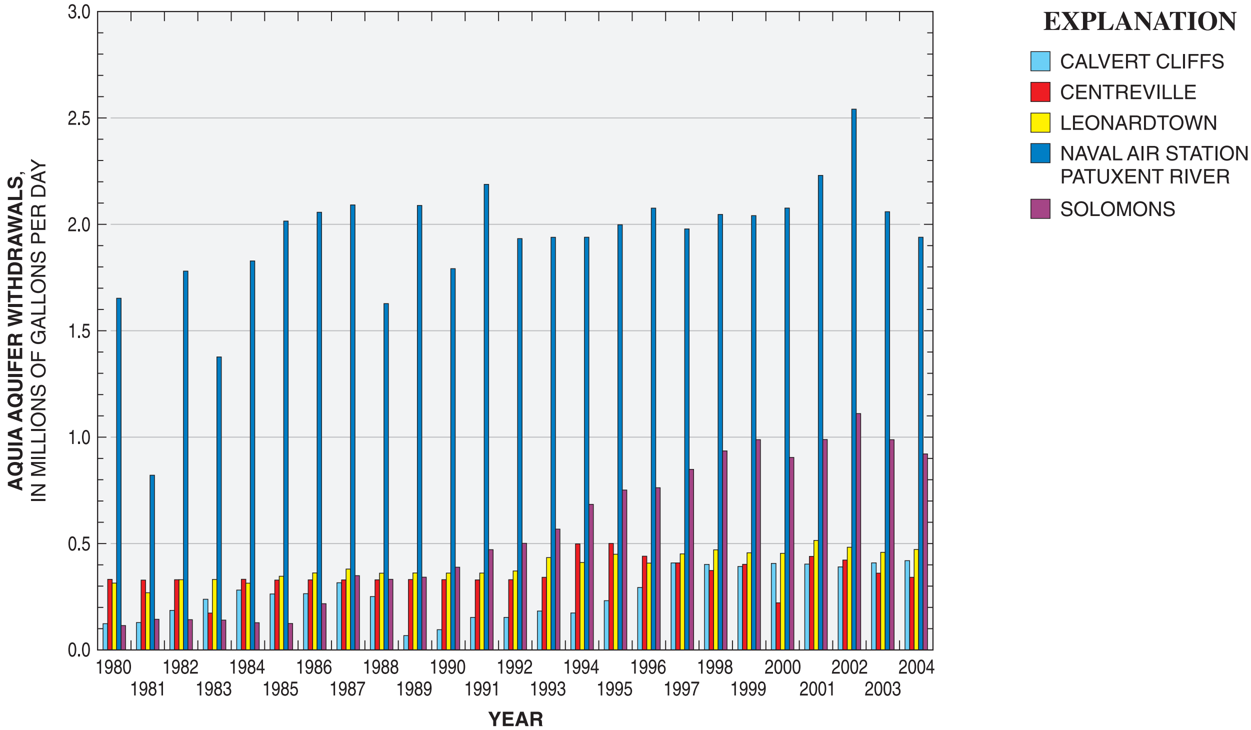


Figure 30. Trends in ground-water withdrawals from the Aquia aquifer at five major pumping centers in Southern Maryland from 1980 to 2004.

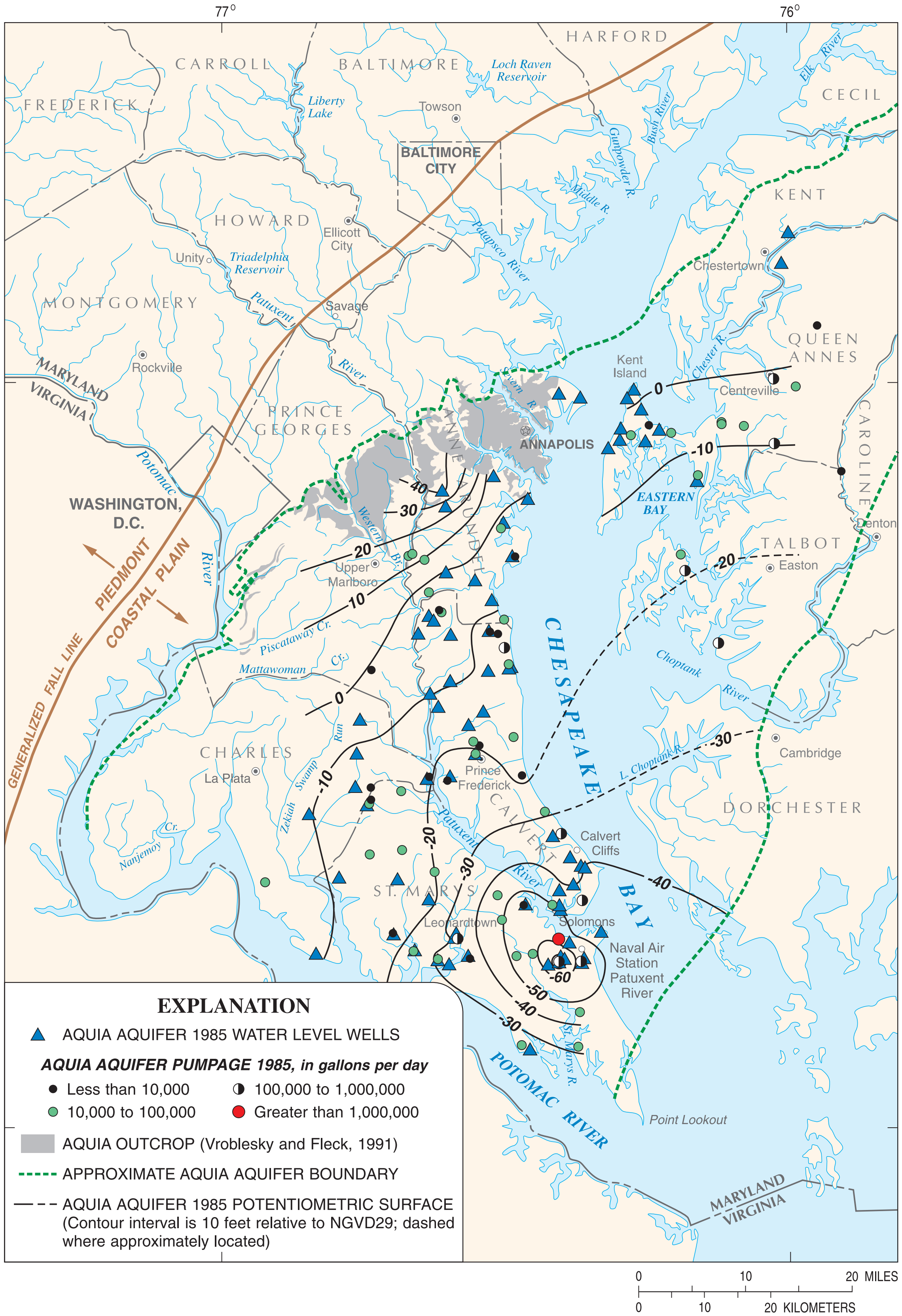


Figure 31. Potentiometric surface and water use, Aquia aquifer, 1985.

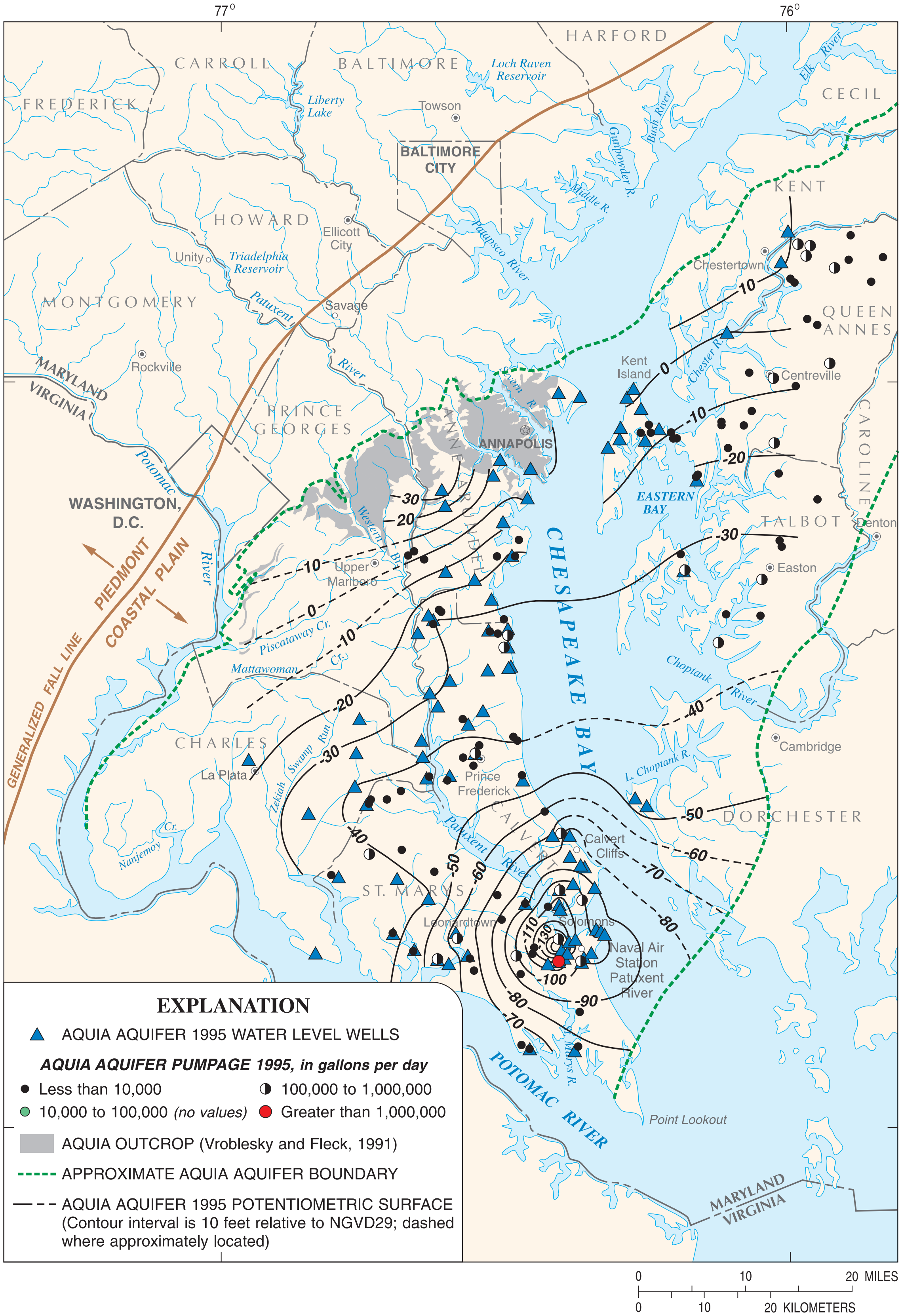


Figure 32. Potentiometric surface and water use, Aquia aquifer, 1995.

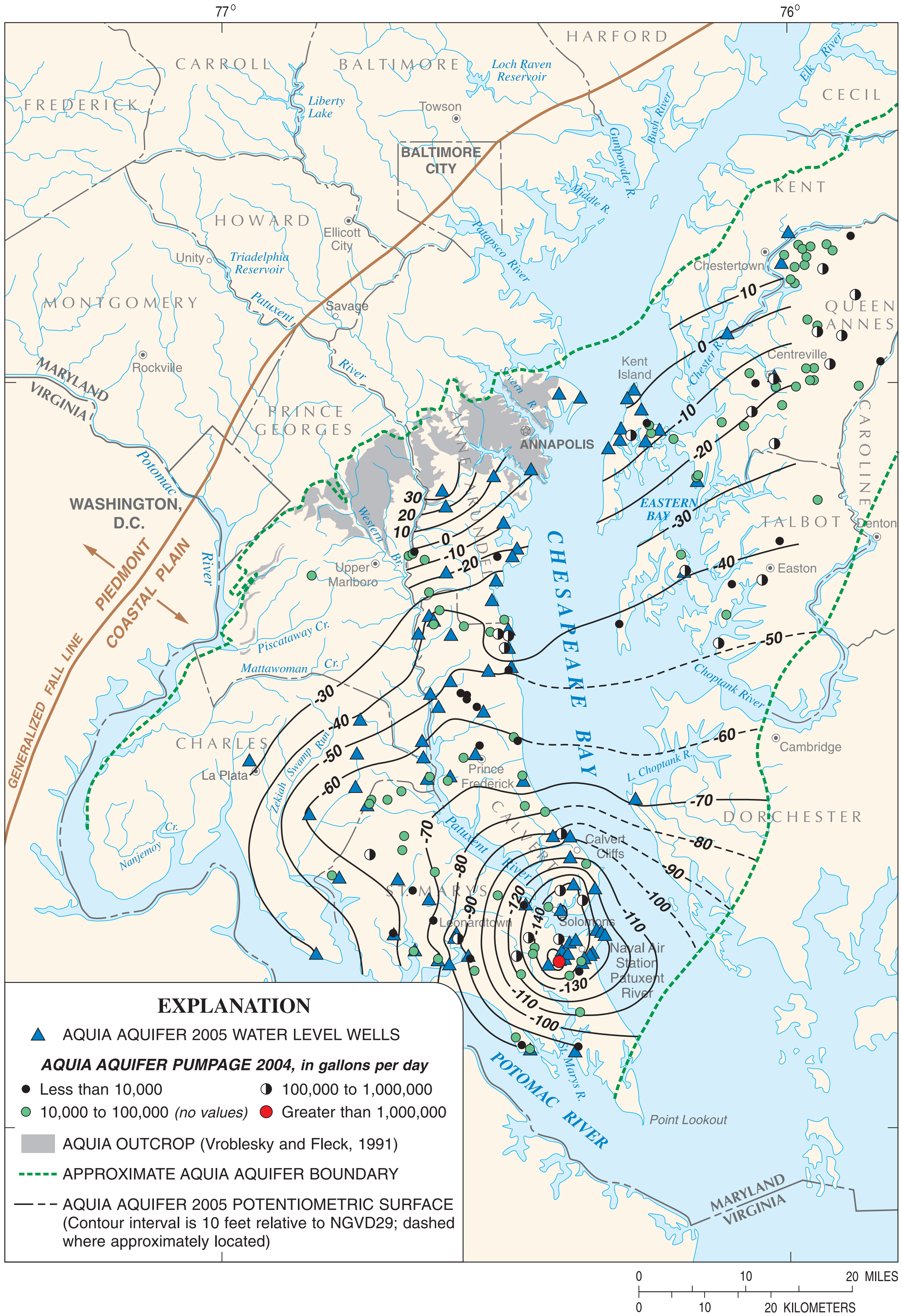


Figure 33. Potentiometric surface and water use, Aquia aquifer, 2005.

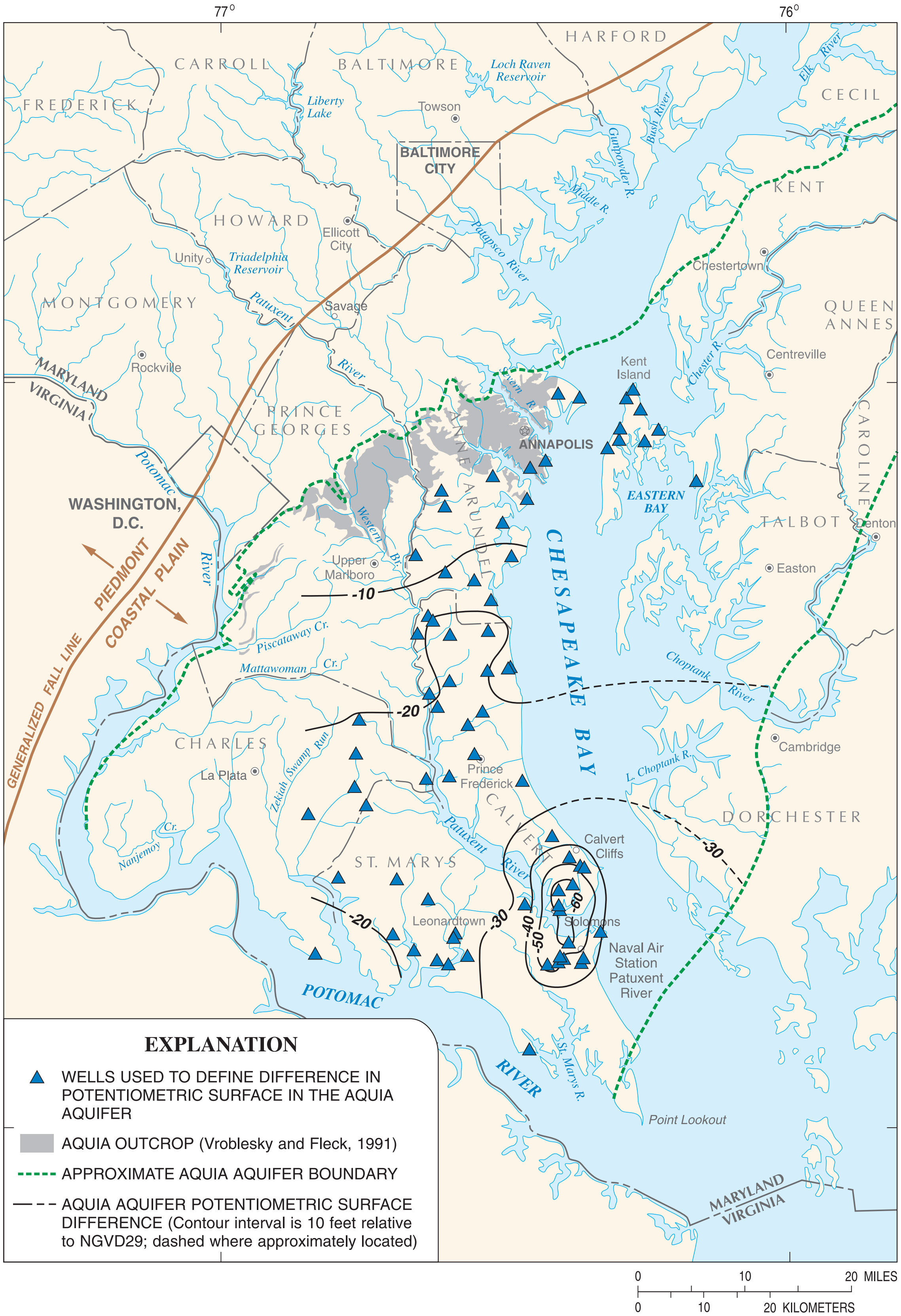


Figure 34. Potentiometric difference, Aquia aquifer, 1985 to 1995.

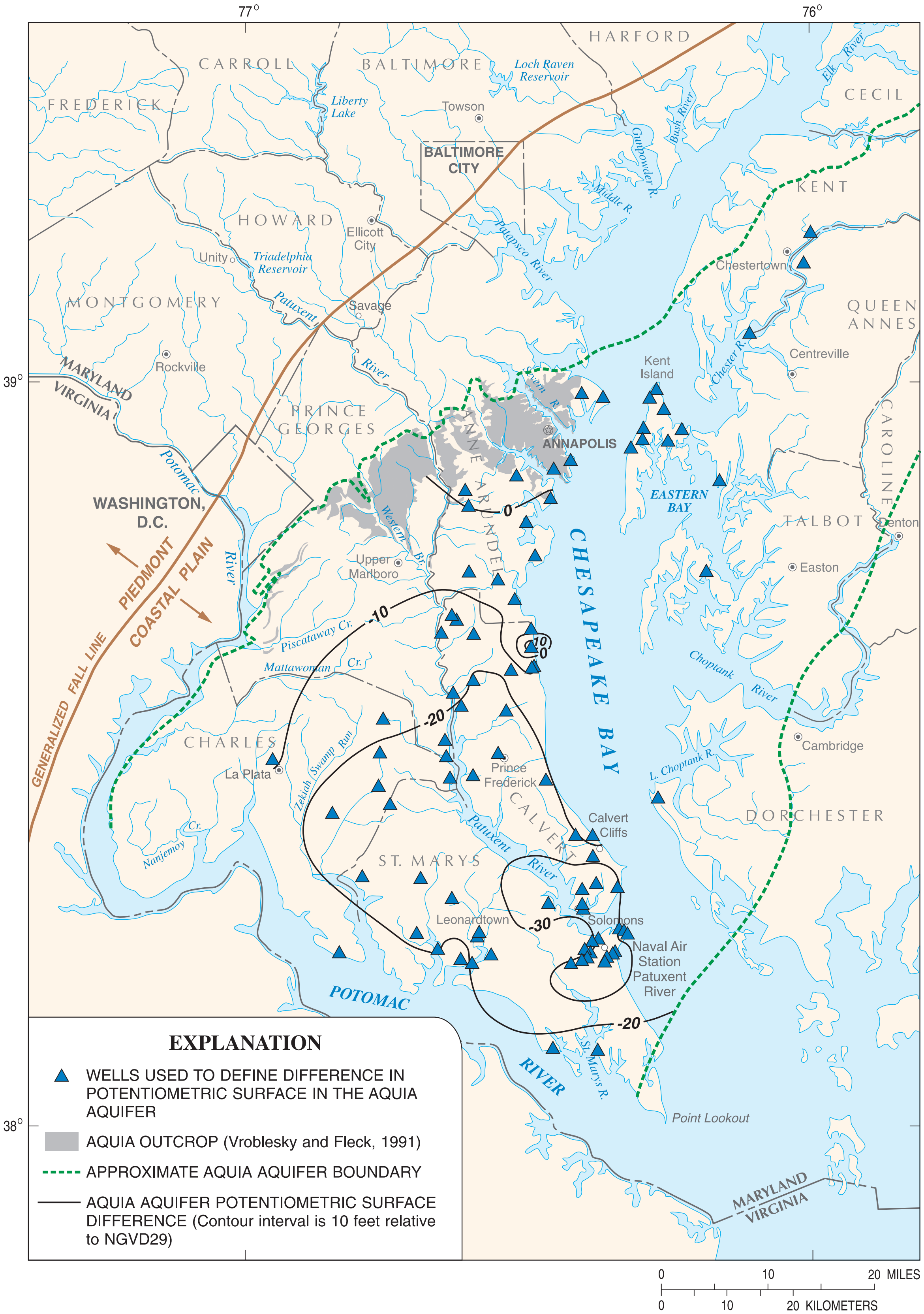


Figure 35. Potentiometric difference, Aquia aquifer, 1995 to 2005.

Piney Point-Nanjemoy Aquifer

The largest user of water from the Piney Point-Nanjemoy aquifer is the City of Cambridge on the Eastern Shore. With the exception of the year 1981, when withdrawals averaged 1.3 Mgal/d, the City of Cambridge consistently pumped 2.5 to 3 Mgal/d from the Piney Point-Nanjemoy between 1980 and 1990 (fig. 36). Withdrawals after 1990 were cut back to less than 1.5 Mgal/d, and from the late 1990s through 2004, pumpage was about 1 Mgal/d. This was probably the result of some shifting of withdrawals to the deeper upper Patapsco aquifer in 1992 (fig. 18). Several other small towns in western Dorchester and Talbot Counties obtain municipal water supplies from the Piney Point-Nanjemoy aquifer, although these withdrawals are generally 0.1 Mgal/d or less. The Piney Point-Nanjemoy aquifer also is an important municipal water source for the Town of Dover, Delaware (Leahy, 1976).

Withdrawals from the Piney Point-Nanjemoy aquifer on the Western Shore of Chesapeake Bay are relatively minor, even for the highest levels of production at Solomons Island and NASPR. The Naval Air Station and adjacent Town of Lexington Park, which have steadily withdrawn 2.5 to 3 Mgal/d from the Aquia aquifer since 1980, pumped only a few hundred thousand gallons per day from the overlying Piney Point-Nanjemoy aquifer over the same period. Pumpage at Solomons Island also has been modest, peaking at less than 0.5 Mgal/d in the mid-1990s. Because this aquifer is at relatively shallow depths on the Western Shore, there are a significant number of small domestic users (Achmad and Hansen, 1997; table 3), as well as commercial users in Calvert and St. Mary's Counties (Curtin and Dine, 1995).

A map of the potentiometric surface of the Piney Point-Nanjemoy aquifer in 2005 is shown in figure 37. A 1994 potentiometric surface map of the aquifer (Achmad and Hansen, 1997) showed a major drawdown centered at Cambridge. Due to the lack of more recent water-level data east of Taylors Island, it is unclear if the same cone of depression was present in 2005. The City of Cambridge reduced pumpage from the Piney Point-Nanjemoy aquifer beginning in 1991, however, so drawdowns in 2005 were probably less than those shown by Achmad and Hansen (1997) a decade earlier. The hydrograph for Well DO Db 17 on Taylors Island (fig. 4) shows a steep decline from 1993 to 2003, followed by a recovery between 2003 and 2005.

The Piney Point-Nanjemoy aquifer is shallow enough that a ground-water divide is formed by the Chesapeake Bay and underlying paleochannels created during a lowstand of sea level by the ancestral Susquehanna River. The paleochannels were back-filled with silt as sea levels rose, which prevents pressure changes in the aquifer from transmitting across Chesapeake Bay (Achmad and Hansen, 1997; fig. 5). South of Calvert Cliffs, where the Piney Point Formation is deeper, it is separated from the paleochannels by clay confining beds. It is unlikely that drawdown from pumpage of the Piney Point-Nanjemoy aquifer at Cambridge is responsible for the cones of depression at St. Leonard in Calvert County, or near NASPR in St. Mary's County.

The cone of depression in the Piney Point-Nanjemoy aquifer near NASPR is consistent with the large head decline in the underlying Aquia aquifer. This may indicate downward leakage, which is discussed in more detail in the section on "Effects of Withdrawal on Multiple Aquifers" elsewhere in this report.

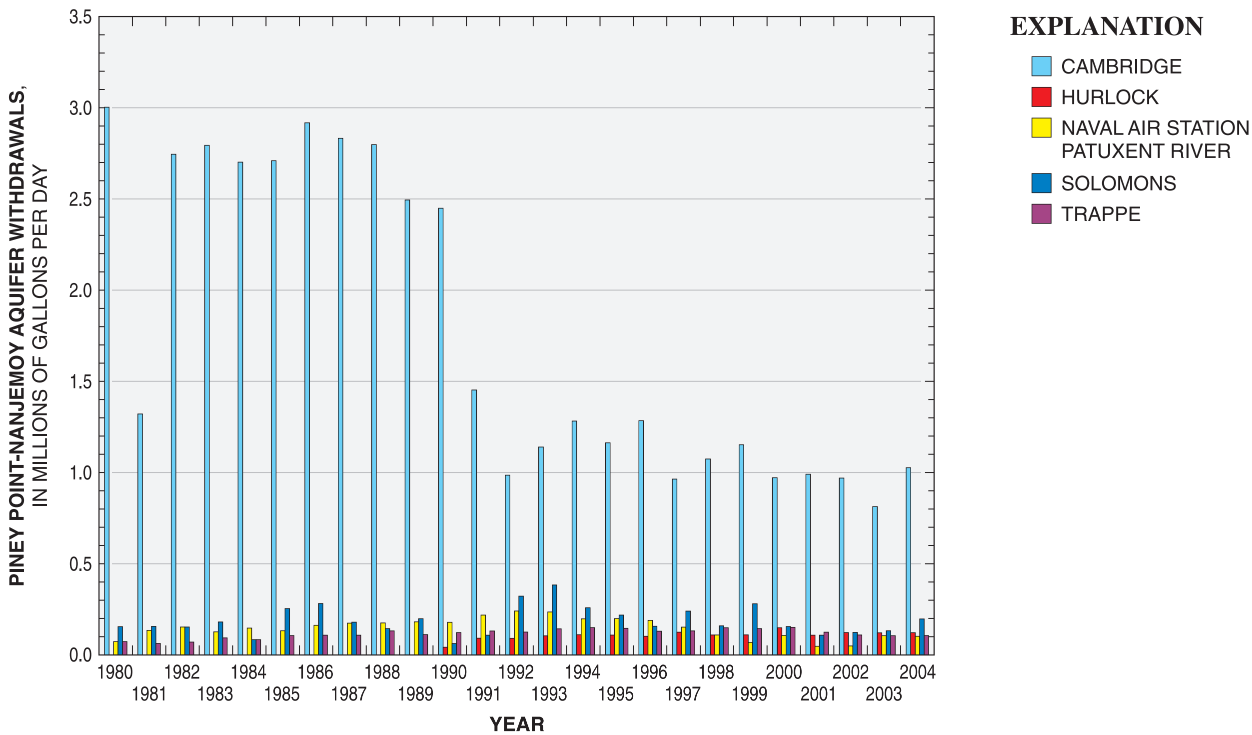


Figure 36. Trends in ground-water withdrawals from the Piney Point-Nanjemoy aquifer at five major pumping centers in Southern Maryland from 1980 to 2004 (Source: U.S. Geological Survey AWUDS database).

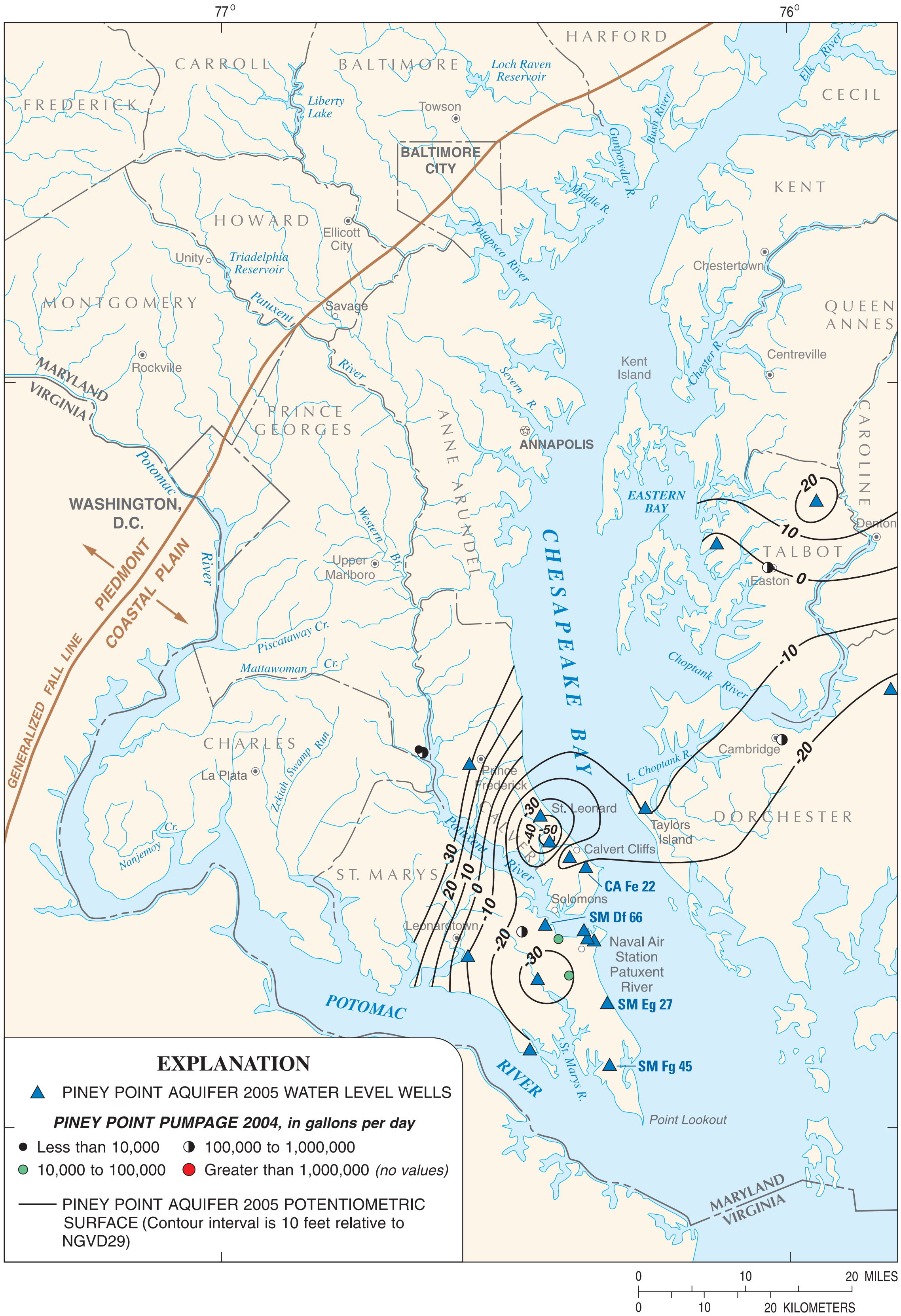


Figure 37. Potentiometric surface and water use, Piney Point-Nanjemoy aquifer, 2005.

Relations Between Withdrawals and Water-Level Drawdowns

A direct cause-and-effect relation often occurs between withdrawals from confined aquifers, and observed drawdowns of water levels. Although this relation can often be verified by correlating withdrawals with water-level changes, the task becomes more problematic in complex hydrogeologic settings, and with greater amounts of withdrawal.

The Coastal Plain sediments in Southern Maryland form a stacked stratigraphic sequence. The major aquifers are generally separated by continuous, low-permeability confining units; in some places, however, the confining beds may be more permeable ("leaky"), thinner, or absent altogether. As previously described in the hydrogeologic framework section, the sedimentary units tend to vary laterally, changing in thickness, grain size, clay content, and physical properties as a function of the ancient depositional or erosional environments. Mack and Achmad (1986) illustrated the discontinuous nature of confining units in their investigation of Potomac Group aquifers (Patuxent, lower Patapsco, and upper Patapsco), reporting poorly confined aquifers or confining beds that thin laterally over short distances. Confining units commonly form less than perfect seals on the aquifers, and leakage between adjacent aquifers may occur as water is withdrawn.

Effects of Withdrawal on Multiple Aquifers

One of the issues in water use and aquifer resource assessment concerns the degree of hydraulic connection between aquifers, and whether major drawdowns caused by pumping in one aquifer can affect pressure heads in "unpumped" aquifers above or below the pumped unit. There appears to be some evidence supporting this possibility at two locations—the Patuxent aquifer in Charles County, and the Piney Point-Nanjemoy aquifer in St. Mary's County.

Withdrawals from the lower Patapsco aquifer in Charles County and southern Prince George's County increased in the mid-1980s, rising to just over 5 Mgal/d by 1988, and reaching 6 Mgal/d in 1990 (Andreasen, 1999; fig. 18). The total annual rates of all the lower Patapsco ground-water withdrawals reported for Charles County since 1980 are shown in figure 38. A steady increase in withdrawals occurred through the 1980s, leveling to a sustained higher rate in the 1990s.

Ground-water withdrawals from the lower Patapsco aquifer in Charles County and southern Prince George's County of about 3 Mgal/d took place during the early to mid-1980s, resulting in a water-level drop of about 20 ft in the lower Patapsco aquifer at Well CH Ce 37 near La Plata, and a lesser drop of 2 to 3 ft in the lower Patapsco aquifer at Well CH Da 20 at Douglas Point on the south bend of the

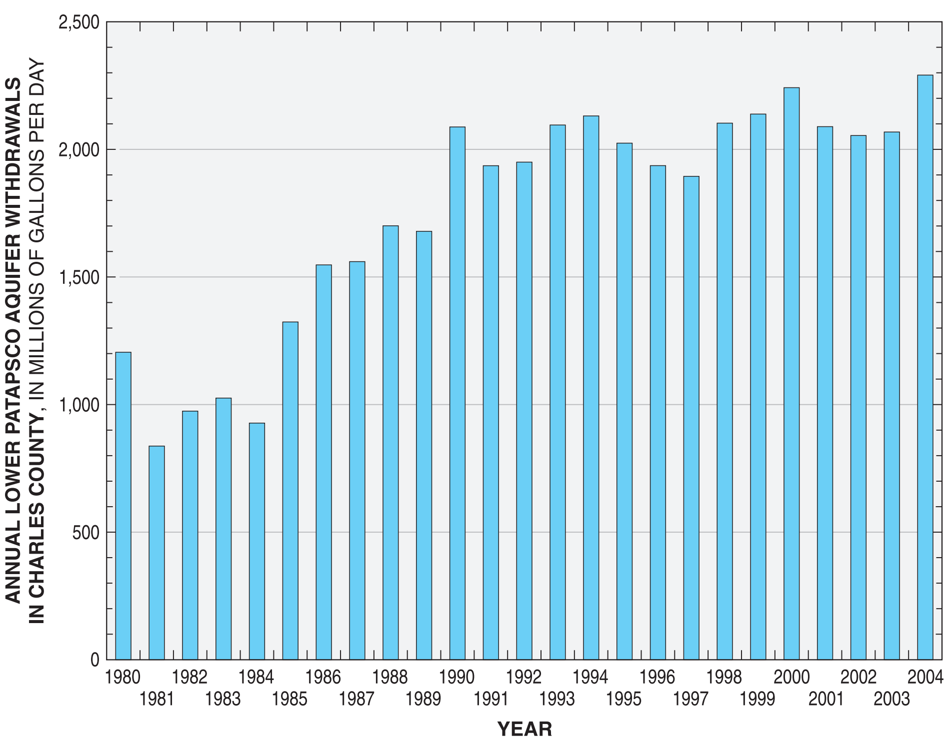


Figure 38. Annual total ground-water withdrawals from the lower Patapsco aquifer in Charles County, Maryland, since 1980 (Source: U.S. Geological Survey AWUDS database).

Potomac River, some 20 mi from La Plata (Andreasen, 1999). The Patuxent aquifer at Douglas Point, monitored in Well CH Da 18, showed a response identical to the lower Patapsco above it during this period, but to a somewhat lesser degree. Andreasen (1999) also reported that ground-water levels in the Patuxent aquifer may be affected locally by withdrawals from the overlying lower Patapsco aquifer near the Indian Head area of Charles County.

Ground-water levels in the lower Patapsco aquifer in LaPlata Observation Well CH Ce 37 responded to this withdrawal by dropping from about -20 ft in 1981 to -40 ft in 1987, and then falling further with the increase in pumpage rates to a level of -120 ft by 1995, as shown on the hydrograph in figure 39. Ground-water levels in lower Patapsco Observation Well CH Da 20, near Douglas Point, also responded to this pumpage to a lesser degree. Ground-water levels in the underlying Patuxent aquifer in Well CH Be 57 near Waldorf declined by about 11 ft between 1986 and 1995, even though there is no reported Patuxent pumpage in the area. Ground-water levels in Well CH Da 18 in the Patuxent aquifer at Douglas Point also showed a response to this increased lower Patapsco pumpage, with the decline curve of the hydrograph becoming steeper after crossing an inflection point at about 1986. Well CH Be 57, which is closer to the pumping center, shows a slightly steeper rate of decline than Well CH Da 18, some distance south near the Potomac River. Andreasen (1999) concluded that pumpage from the lower Patapsco aquifer may affect water levels in the underlying Patuxent aquifer in localized areas within Charles County, where the intervening Arundel Clay confining bed is relatively thin or contains sandy sections. This interconnection is probably limited, however, given the general continuity, thickness (100–300 ft), and low permeability of the Arundel Clay throughout most of Charles County. It was also noted earlier that declines in the upper Patapsco aquifer in the vicinity of Waldorf-LaPlata (figs. 19–21) might also be partially caused by withdrawals from the lower Patapsco.

The potentiometric surface map of the Piney Point-Nanjemoy aquifer in 2005 shows a moderate cone of depression near NASPR (fig. 37). The total, annual ground-water withdrawals from the Piney Point-Nanjemoy and Aquia aquifers reported for St. Mary's County from 1980–2004 are shown in figure 40. Withdrawals from the Aquia aquifer in this county increased from 1.5 Mgal/d in 1981, to over 4.5 Mgal/d in 2002. Ground-water withdrawals from the Piney Point-

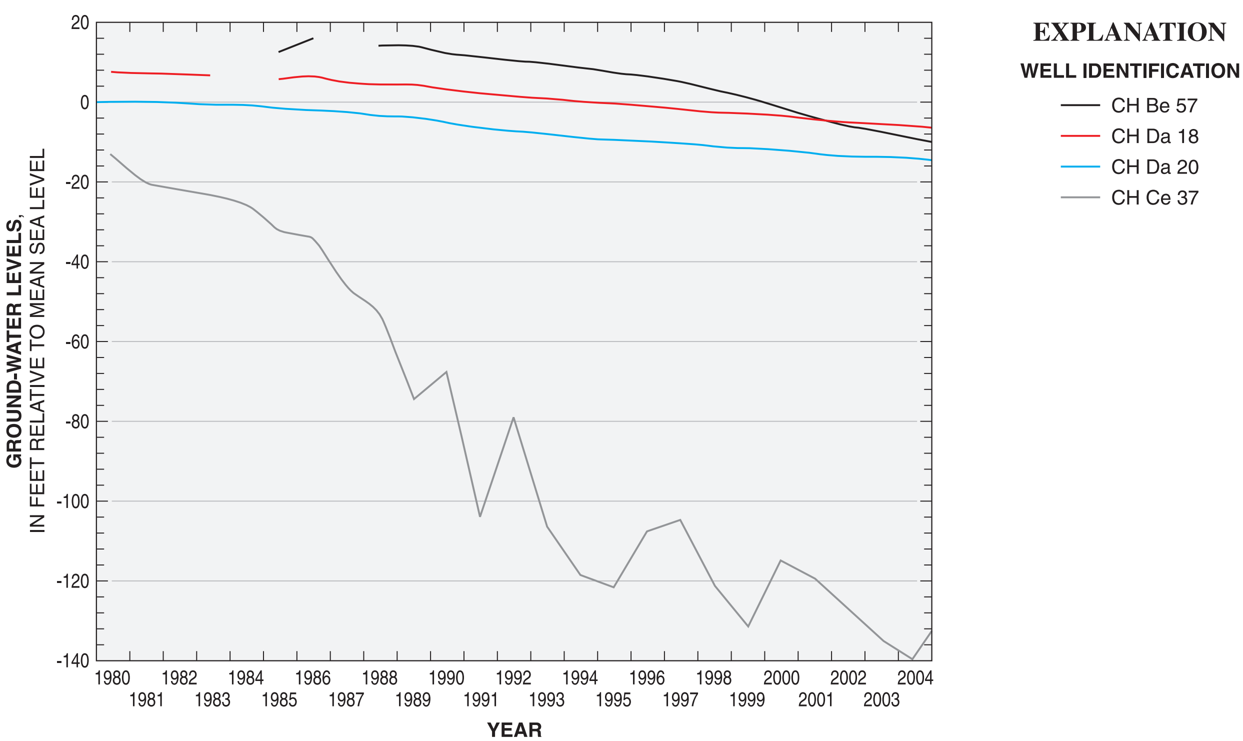


Figure 39. Patuxent and lower Patapsco aquifer observation wells in Charles County, Maryland, responding to ground-water withdrawals from the lower Patapsco aquifer (Source: U.S. Geological Survey GWSI database).

Nanjemoy aquifer, in comparison, remained below 1 Mgal/d during this same period, and were mostly below 0.5 Mgal/d. Yields from Piney Point-Nanjemoy aquifer wells of over 500 gal/min were recorded in the vicinity of NASPR (Weigle and others, 1970), indicating that for the entire county, the aquifer should be capable of a sustained withdrawal on the order of 0.5 Mgal/d without suffering significant drawdown.

The Aquia aquifer, on the other hand, has been pumped at relatively high rates for many years in St. Mary's County, as shown in figure 40. The aquifer response to this ground-water withdrawal has been a steep decline in ground-water levels in observation wells near NASPR, in some cases nearly 100 ft over the past 30 years. Even Aquia aquifer observation wells located a moderate distance from the pumping centers at the NASPR and Lexington Park show fairly steep, steady declines of tens of feet in ground-water levels. It is possible that these deep drawdowns in the Aquia aquifer might be responsible for water-level declines in the overlying Piney Point-Nanjemoy aquifer.

In order to investigate this possibility, hydrographs were constructed from water-level data in the USGS GWSI database for four Piney Point-Nanjemoy observation wells located in southern Calvert County and St. Mary's County within the Aquia aquifer cone of depression at NASPR and Lexington Park. Although these Piney Point-Nanjemoy observation wells do not penetrate to the depth of the Aquia aquifer and no direct ground-water-level data are available, elevations of the ground-water surface in the Aquia aquifer were estimated from the Aquia potentiometric surface maps in this report (figs. 31–33). The hydrographs for the observation wells are shown in figures 41–44, and the well locations are shown on the Piney Point-Nanjemoy potentiometric surface map in figure 37.

The Well CA Fe 22 hydrograph (fig. 41) shows a definite drop in the water level in the Piney Point-Nanjemoy aquifer, which could be related to the decline in the potentiometric surface of the underlying Aquia aquifer. There is no reported pumpage from the Piney Point-Nanjemoy aquifer in the southernmost part of Calvert County near this well, and aquifer levels may be responding to pumpage from the underlying Aquia aquifer. The SM Eg 27 (fig. 42) and SM Fg 45 (fig. 43) wells show drawdown effects similar to the CA Fe 22 well. The SM Df 66 well (fig. 44) shows a drawdown response until about 1987, when it began recovering for unknown reasons.

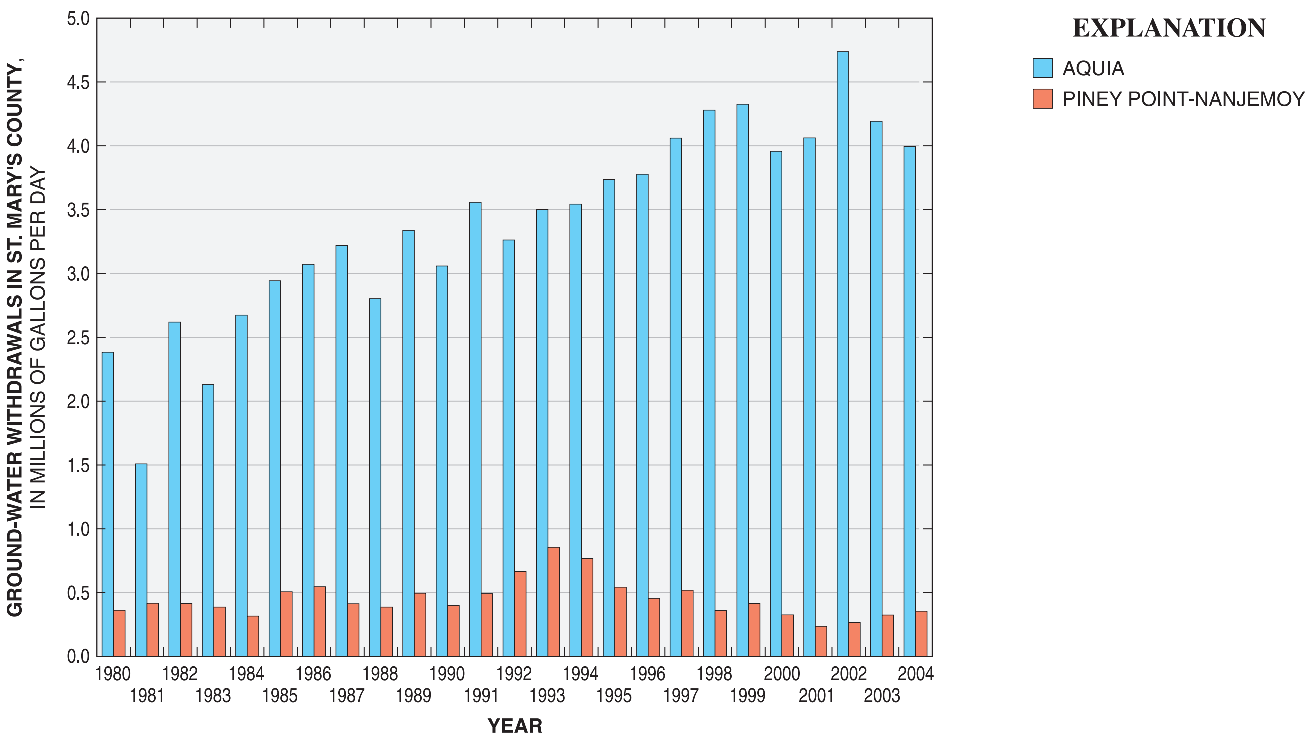


Figure 40. Total ground-water withdrawals reported for St. Mary's County from the Aquia and Piney Point-Nanjemoy aquifers from 1980 to 2004 (Source: U.S. Geological Survey AWUDS database).

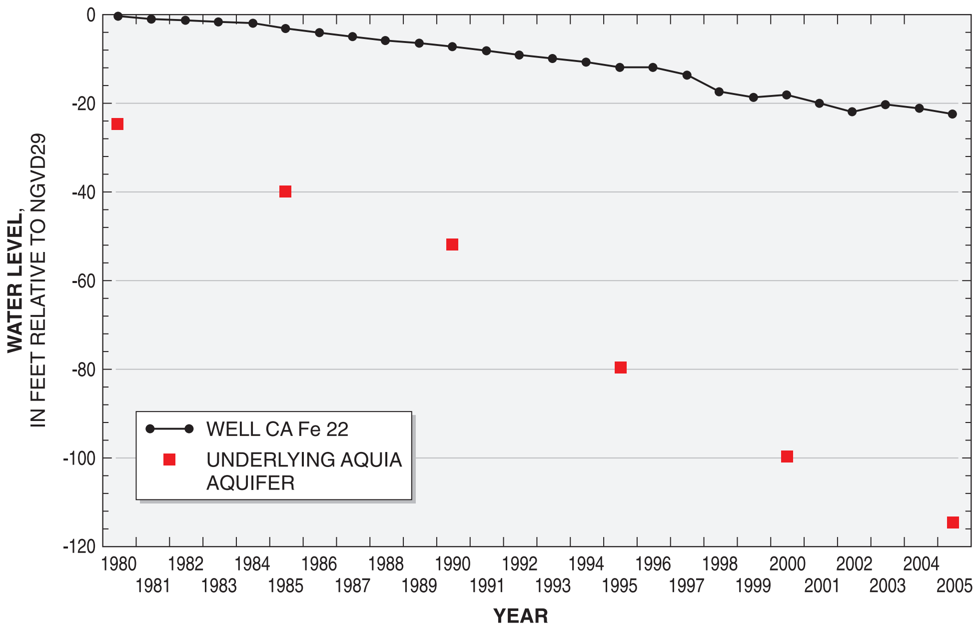


Figure 41. Ground-water-level responses in the Piney Point-Nanjemoy aquifer in Well CA Fe 22, and the drop in the potentiometric surface of the underlying Aquia aquifer in southern Calvert County, Maryland.

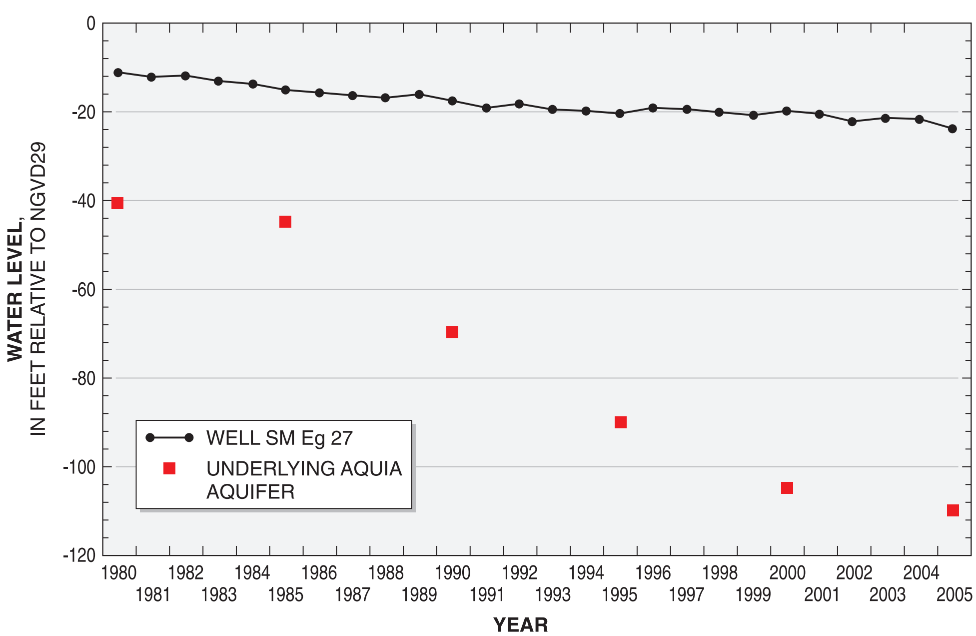


Figure 42. Ground-water-level responses in the Piney Point-Nanjemoy aquifer in Well SM Eg 27, and the drop in the potentiometric surface of the underlying Aquia aquifer in southern St. Mary's County, Maryland.

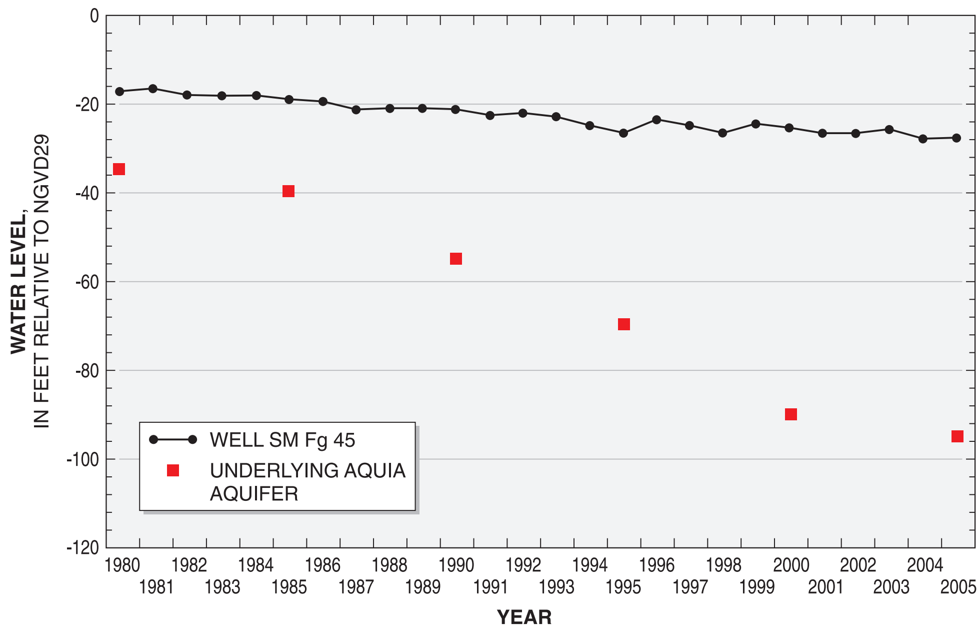


Figure 43. Ground-water-level responses in the Piney Point-Nanjemoy aquifer in Well SM Fg 45, and the drop in the potentiometric surface of the underlying Aquia aquifer in southern St. Mary's County, Maryland.

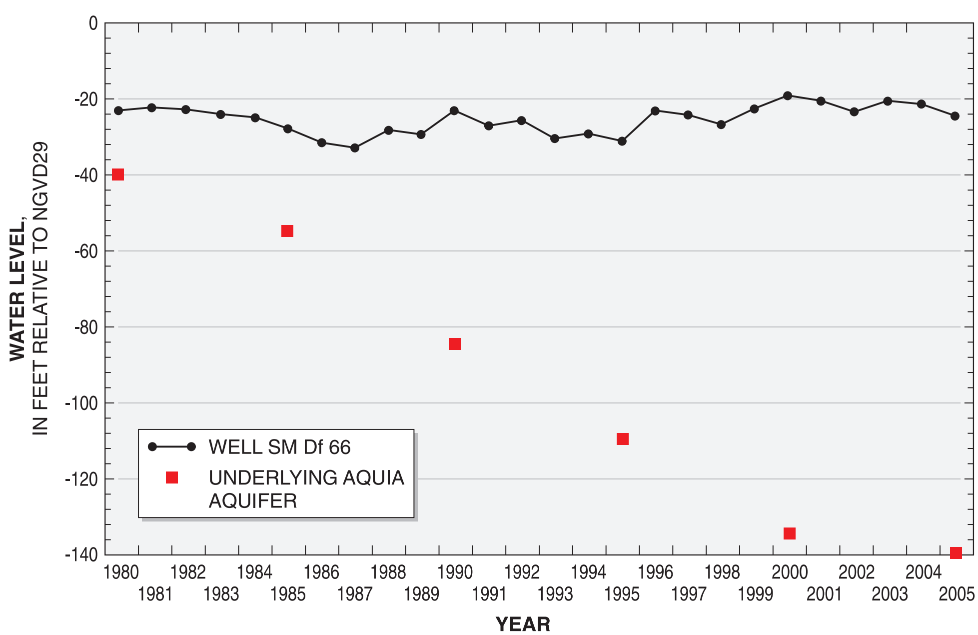


Figure 44. Ground-water-level responses in the Piney Point-Nanjemoy aquifer in Well SM Df 66, and the drop in the potentiometric surface of the underlying Aquia aquifer in southern St. Mary's County, Maryland.

These hydrographs indicate a possible connection between the two aquifers, which could be an important consideration for future assessments of ground-water withdrawals in Southern Maryland. Current water resource planning often assumes that untapped aquifers are available as a reserve water supply for the future (Drummond, 2005). Drawdowns in adjacent aquifers could mean that these other ground-water resources might not be as readily available as expected, however. More definitive information on hydraulic connections between these aquifers is needed to better understand this issue.

Linear Decline of Potentiometric Surfaces

The effect of withdrawal rate on drawdown in a hypothetical aquifer was analyzed to determine possible withdrawal rate scenarios that would lead to linear declines in hydraulic head over time, such as those commonly observed in wells in southern Maryland. Time-drawdown response in a perfectly confined aquifer under a constant pumping rate usually follows a nearly logarithmic curve mathematically defined by Theis (1935), with the rate of change of drawdown decreasing through time.

Water withdrawn from a well is obtained from elastic storage within the aquifer. Initially, water will be removed from storage in the immediate vicinity of the well, reducing the hydraulic head and inducing flow toward the well. These reductions in hydraulic head, or drawdown, will propagate outward, forming a cone of depression in the potentiometric surface of the aquifer. At an observation well within the cone of depression, the rate of drawdown will be at a maximum initially; the rate of drawdown will decrease with time, so that the drawdown will eventually be approximately logarithmic in time.

Some examples of linear declines are shown in figure 45 for a number of ground-water-level measurements in Southern Maryland wells taken from the USGS GWSI database. Well SM Dd 50 appears to follow the pattern predicted by Theis (1935), with the rate of decline decreasing significantly, and flattening out beginning in 1998. By comparison, the rate of ground-water decline in Well CA Gd 6 has actually increased since the mid-1980s, with the decline curve steepening. Linear declines are visible in the other two wells, where the hydrographs show little sign of flattening out. Well SM Ff 36 has been nearly straight-edge linear since the late 1980s.

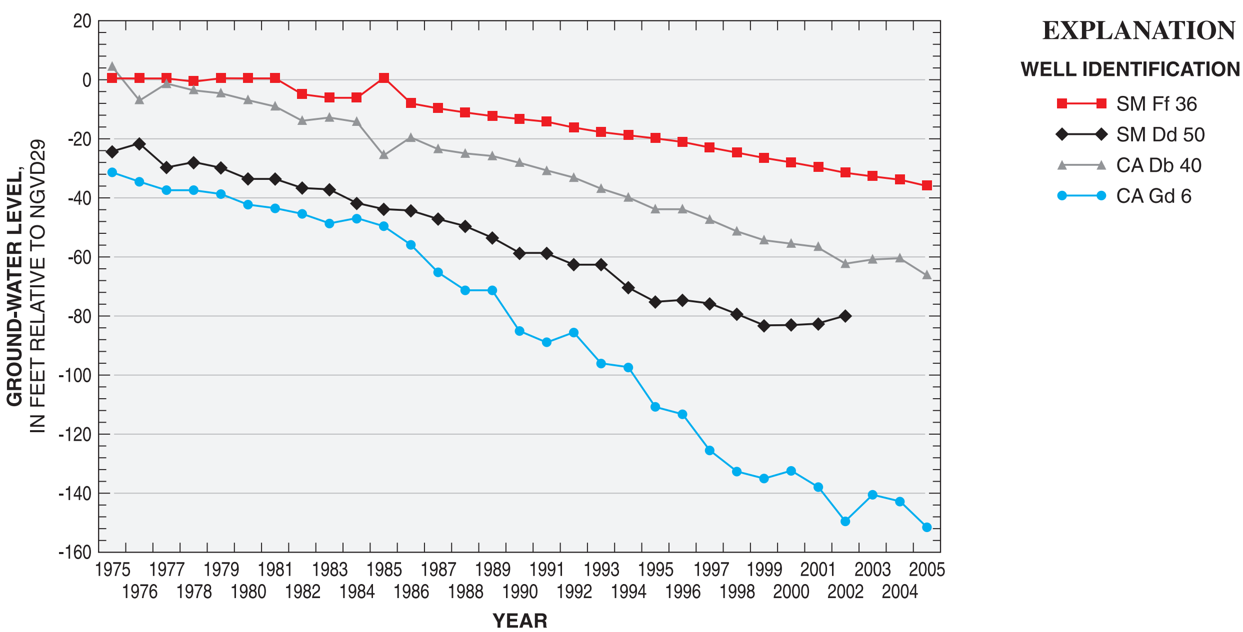


Figure 45. Nearly linear declines in the potentiometric surfaces over 30 years in four representative wells from Calvert and St. Mary's Counties, Maryland.

Only a few physical phenomena can cause an aquifer to behave in this manner. One possibility is a steady increase in withdrawal from production wells to supply ever greater amounts of water to growing populations. Constant increases in pumping prevent the cone of depression in the aquifer from reaching stability, and water levels fall steadily. This scenario is partly supported by the reported water-use data in the study area, which generally show a gradual but continuous increase in ground-water withdrawals over the past 30 years to service growing populations (fig. 5). In Charles, Calvert and St. Mary's Counties, however, there are not many big municipal suppliers, and production has changed very little for years in some cases, as shown in figure 38.

Another possible explanation for the linear drawdowns in Southern Maryland is an increase in the number of domestic supply wells completed in the confined aquifers. Domestic withdrawal data are not reported directly to the State for water-use compilation, unless the permit holder exceeds a threshold of 10,000 gal/d, which is much more water than most homeowners use. Domestic water use is estimated instead on the basis of rural population, and assumes a per capita withdrawal of 80 gal/d. An ongoing proliferation of domestic wells in rapidly developing areas could have a significant impact on aquifer drawdowns, while at the same time being undercounted due to the lag time inherent in population estimates (U.S. Census Bureau, 2006).

Simple numerical modeling runs provide some constraints for these scenarios. The modeling was done to see if the scenarios were plausible, and to investigate possible effects on ground-water levels from an annual increase in the number of small domestic wells pumping from a specific aquifer. A simulated aquifer of representative thickness, lateral dimensions, hydraulic properties, and boundaries was modeled under a variety of withdrawal patterns, ranging from constant, steady pumpage to withdrawals exponentially increasing through time. The calculated reactions of the simulated aquifer under these various conditions were compared to the actual ground-water-level data to see which pattern of withdrawal showed the closest match to the real aquifer.

Modeling Experiment

A series of mathematical solutions to the equations for unsteady flow to a well were constructed to examine the effect of different patterns of withdrawal on the rate and shape of a ground-water decline curve in an observation well in a hypothetical aquifer. The goal of this exercise was to determine possible withdrawal rate scenarios that might lead to linear declines in hydraulic heads through time, similar to those observed in actual wells in the study area. The experiment also attempted to assess the sensitivity of time-drawdown response to natural factors such as aquifer leakage and boundaries.

The aquifer was assumed to be homogeneous and isotropic, with all wells fully penetrating, allowing for the use of analytical solutions to the governing equation for a perfectly confined aquifer:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} = \frac{S}{T}\frac{\partial h}{\partial t}, \tag{1}$$

where

- h is the hydraulic head in feet,
- r is radial distance in feet from the pumping well,
- S is the dimensionless aquifer storativity,
- T is the aquifer transmissivity in square feet per minute,

and

- t is time in minutes.

An analytical solution to this equation was provided by Theis (1935). For the case of a simple leaky aquifer, with no storage in the overlying aquitard, the governing equation may be written:

$$\frac{\partial^2 h}{\partial r^2} + \frac{1}{r}\frac{\partial h}{\partial r} - \frac{h}{B^2} = \frac{S}{T}\frac{\partial h}{\partial t}, \tag{2}$$

where

- B is a function of the transmissivity of the aquifer and the hydraulic conductivity and thickness of the aquitard ($B^2 = Tb_a/K_a$, where b_a is the aquitard thickness, and K_a is the aquitard hydraulic conductivity).

Analytical solutions to this form of the equation were provided by Hantush (1956) and Hantush and Jacob (1955).

The analytical solutions to these governing equations were coded in MATLAB modeling software, based on the work of Fleming and others (2002). Multiple wells, variable withdrawal rates, and for some cases, an imposed constant-head or no-flow boundary condition were handled through the principle of superposition of solutions and the use of image wells (Freeze and Cherry, 1979).

The hypothetical aquifer modeled for this exercise was of constant thickness (100 ft) and transmissivity was set at 1,000 ft^2/day (square feet per day). The values used for these properties are based on reported ranges for the confined aquifers of southern Maryland (Fleck and Vroblesky, 1996). For the scenarios involving a leaky aquifer, the aquitard thickness and transmissivity also were constant (100 ft and 0.001 ft^2/day, respectively). Hydraulic heads were calculated on a 20-mi by 20-mi gridded area equivalent to 400 mi^2 (square miles). Additionally, hydraulic heads were calculated as a function of time for approximately 22.8 years (12,000,000 minutes) at an observation well in the center of the hypothetical aquifer at coordinate position 0,0 as shown for the conceptual design in figure 46. Additional scenarios invoked a constant-head or no-flow boundary on the eastern side of the aquifer.

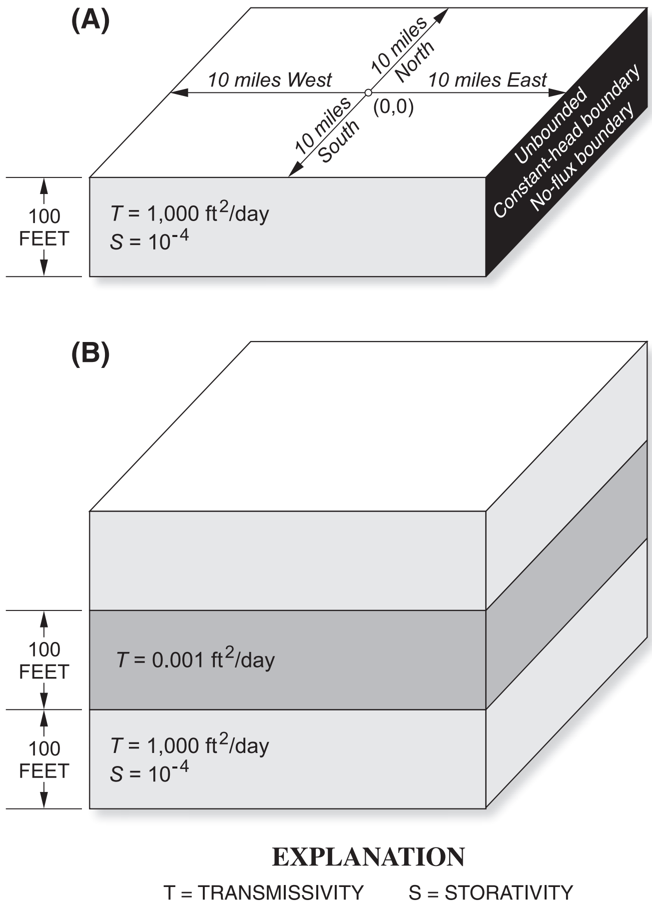


Figure 46. The modified hypothetical *(A)* aquifer, and *(B)* aquifer-aquitard.

For the case of a single pumping well in a perfectly confined aquifer without boundaries, drawdown at the observation well depends strongly on the pattern of withdrawal, as shown graphically in figure 48. For the cases of non-constant withdrawal rates, drawdown is not asymptotic, but resembles the inverse of the withdrawal rates shown in figure 47.

Time-drawdown response in the case of linearly increasing withdrawal rates is very nearly linear, and in the case of an exponentially increasing withdrawal rate, the rate of decline in hydraulic head increases with time. This finding has important implications for ground-water resource management, as well as for understanding historical well hydrographs. Although it is not unexpected that a transient stress (such as a variable withdrawal rate) would result in a transient response, it is worth emphasizing that ground-water levels in confined aquifers will continue to decline unless withdrawal rates are either reduced or held constant. This leads to the supposition that the nearly linear time-drawdown pattern observed for many wells in Southern Maryland (fig. 45) could be the result of a nearly linear increase in the rate of ground-water withdrawn (fig. 5) to supply growing populations (fig. 7). More precise data on human populations and water-supply options, as well as a more rigorous handling of the statistics, may be helpful in the future to clarify the relations and processes involved.

The case described above relies on numerous simplifying assumptions—a single pumping well in a homogeneous, isotropic, perfectly confined aquifer of infinite extent. Additional scenarios were calculated under somewhat more realistic assumptions, such as using multiple wells with variable pumping times, incorporating a leaky aquitard, and imposing boundary conditions on one side of the aquifer (fig. 46).

In addition to the natural factors of boundaries and aquifer leakage, scenarios were constructed under a variety of withdrawal rate patterns:

1. Constant withdrawal rate through time,
2. Linearly increasing withdrawal rate through time, and
3. An exponentially increasing withdrawal rate through time.

The withdrawal rates were determined in such a manner that the total volume of water withdrawn was the same in all cases. Finally, scenarios were constructed for the case of a single pumping well 5 mi west of the observation well, and for the case of 1,000 wells randomly distributed throughout the modeled region. The withdrawal rate patterns used in the modeling are shown in figure 47, and equate to an average pumping rate for each of the 1,000 wells of approximately 215 gal/d.

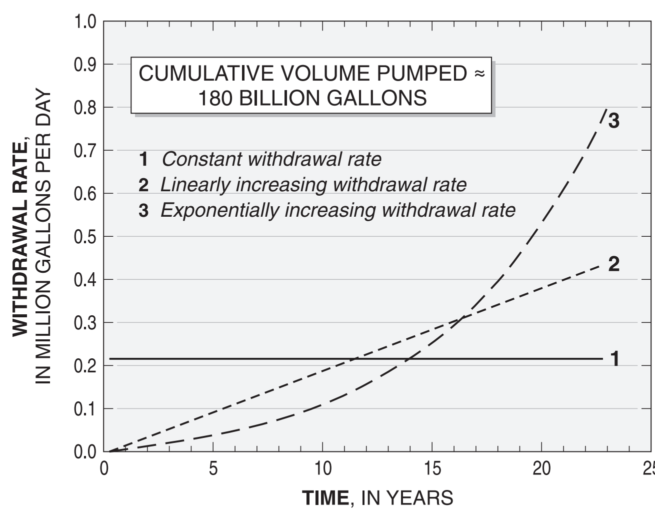


Figure 47. Withdrawal rates used for generation of drawdown scenarios.

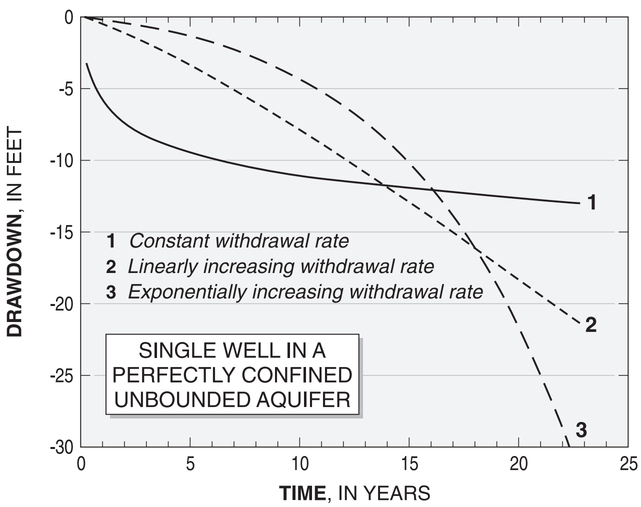


Figure 48. Time-drawdown patterns calculated for a single pumping well in a perfectly confined, unbounded aquifer under three different withdrawal rate patterns.

The multiple-well scenarios were run several different ways. In all scenarios, 1,000 wells were distributed randomly throughout the modeled region. For the case of a constant withdrawal rate, all "pumps" were activated at time zero, and withdrawal proceeded at a constant rate for the duration of the run (22.8 years). In cases where the ground-water withdrawal rate has gradually increased, new wells were added to the aquifer sequentially through time until the total of 1,000 was reached. To provide a linearly increasing total withdrawal rate, each well was pumped at a constant rate from its "completion" date to the end of the model run. For an exponentially increasing total withdrawal rate, the pumping rates were increased slightly for each successive well added to the scenario.

Modeling Results

Adding multiple wells creates a general decline in the potentiometric surface (fig. 49), with the largest drawdown near the center, due to overlapping (superposition) of each well's individual cone of depression. The calculated time-drawdown response at the "observation well" shown in figure 50 is similar to the case of a single pumping well. In the constant withdrawal scenario, multiple pumping wells, all "completed" at time zero and with the same pumping rate, produce a time-drawdown response that resembles a Theis curve. For the case of a linearly increasing withdrawal rate, the time-drawdown pattern is nearly linear. Lastly, an exponentially increasing withdrawal rate produces a pattern of increasing rate of decline in hydraulic head with time at the observation well.

As a well is pumped, water is removed from storage and the hydraulic head (and, therefore, fluid pressure) are reduced; the decrease in hydraulic head expands laterally to create a cone of depression in the potentiometric surface. Also, vertical hydraulic gradients are created within the area of the cone of depression between the aquifer and the overlying (and underlying) aquitard(s), creating the possibility of leakage across the confining unit(s). This leakage can be substantial, and obviously depends in part on the transmissivity of the aquitard. Leakage has been shown to be important in the confined aquifers in southern Maryland (Fleck and Vroblesky, 1996). Time-drawdown response near pumping wells in leaky aquifers resembles the Theis curve; however, because leakage provides an additional source of water, the drawdown will reach equilibrium more quickly as the leakage balances the rate of pumping. Drawdown of leaky aquifers will generally be less than if the aquifer was perfectly confined.

For the case of multiple wells in a leaky aquifer, the time-drawdown response calculated for the observation well under the three different withdrawal rate patterns is shown in figure 51. As expected, the drawdown is less than for the perfectly confined case under all three withdrawal rate scenarios. A constant withdrawal rate produces a time-drawdown response very typical of leaky aquifers, equilibrating at approximately 3 ft of drawdown after 10–15 years of pumping. Linearly and exponentially increasing withdrawal rates produce linear and increasing-with-time time-drawdown responses, respectively.

Aquifers are never truly unbounded, and it is very likely that an aquifer experiencing withdrawals on the spatial and temporal scale used for this exercise would display time-drawdown response indicating the presence of one or more boundaries. A no-flow boundary may be present where the aquifer pinches out or is truncated by a less permeable unit. A constant-head boundary may be present where an aquifer is in direct contact with a surface-water body. More complex boundary conditions are also likely, and the relative distance between the region of interest and the boundary should be considered in any analysis.

For this exercise, both no-flow and constant-head boundaries were imposed at the eastern end of the model domain, to determine their possible effects on time-drawdown response in the aquifer. Conceptually, a no-flow boundary reduces the part of the aquifer available to supply water to the well; as a result, more water must be withdrawn from the aquifer between the pumping well and the boundary, and drawdown will generally be greater. Conversely, a constant-head boundary may be thought of as an unlimited source of water; drawdown will generally be less (and in fact, will be zero at the boundary itself). In either case, the cone of depression around a pumped well will not be radially symmetric. Characteristics for the two different boundary conditions are shown in figure 52.

The calculated time-drawdown response at the observation well under the three withdrawal rate patterns is shown in figure 53. The general observations made in regard to the scenarios discussed earlier apply to these cases as well.

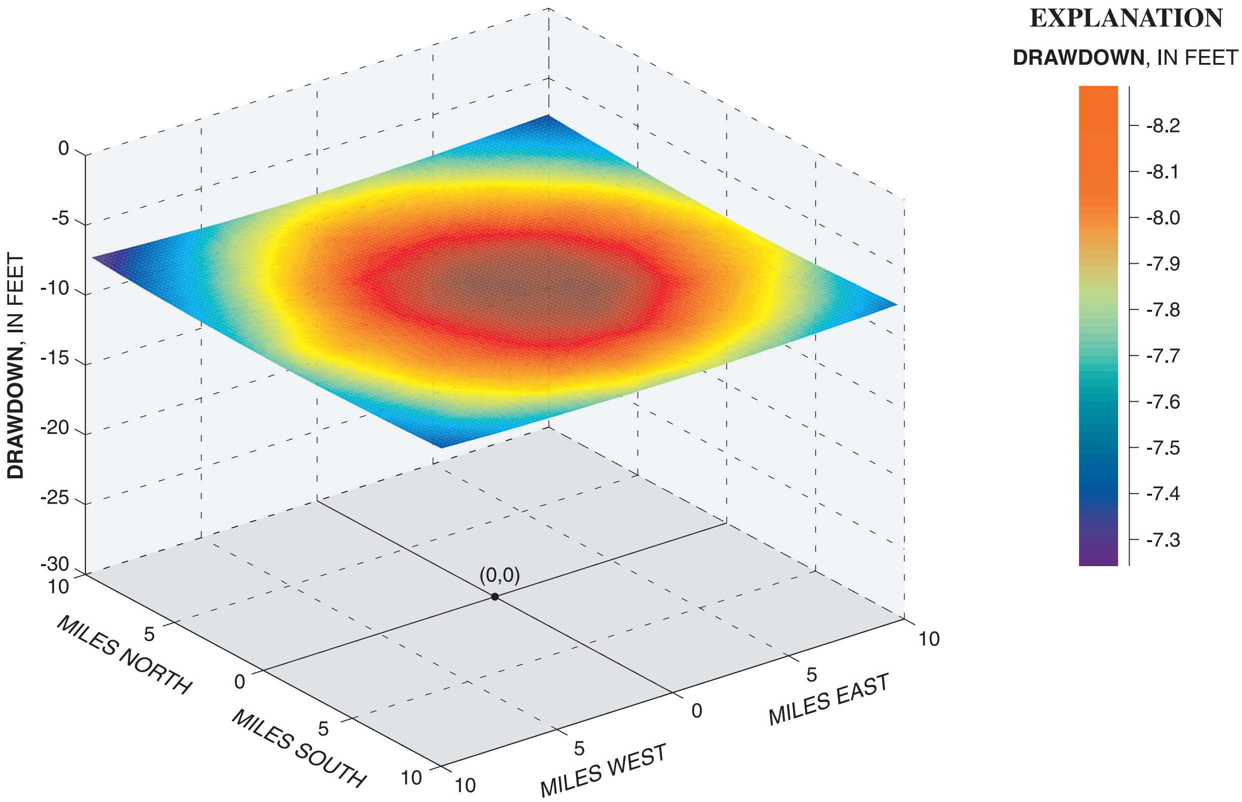


Figure 49. Drawdown in the potentiometric surface for the scenario with multiple wells under a constant withdrawal rate at time t = 22.8 years.

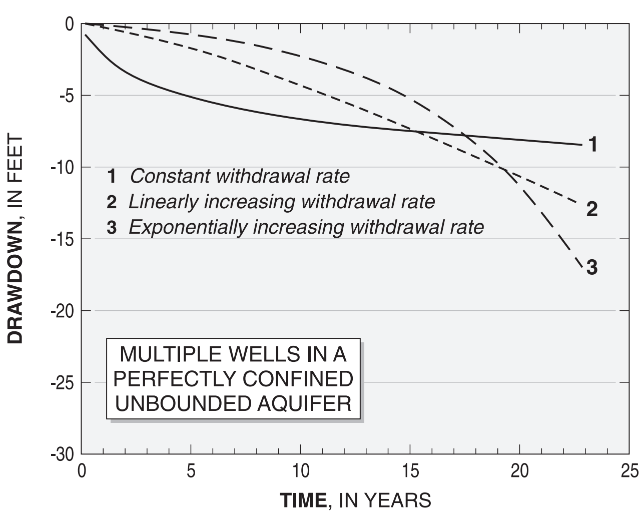


Figure 50. Time-drawdown patterns calculated for multiple pumping wells in a perfectly confined, unbounded aquifer under three different withdrawal rate patterns.

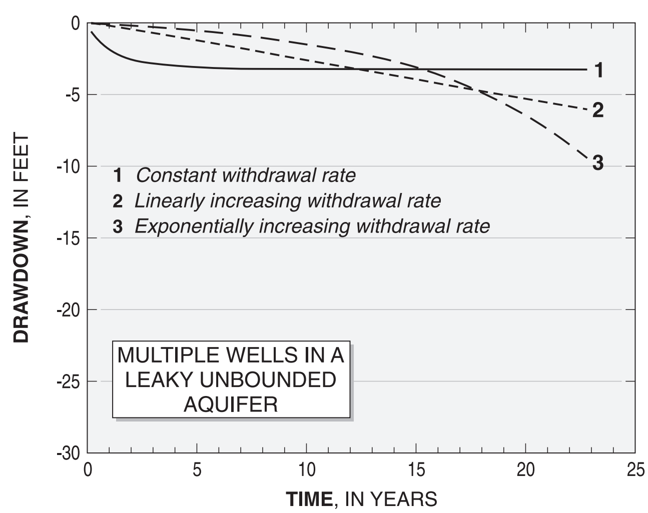
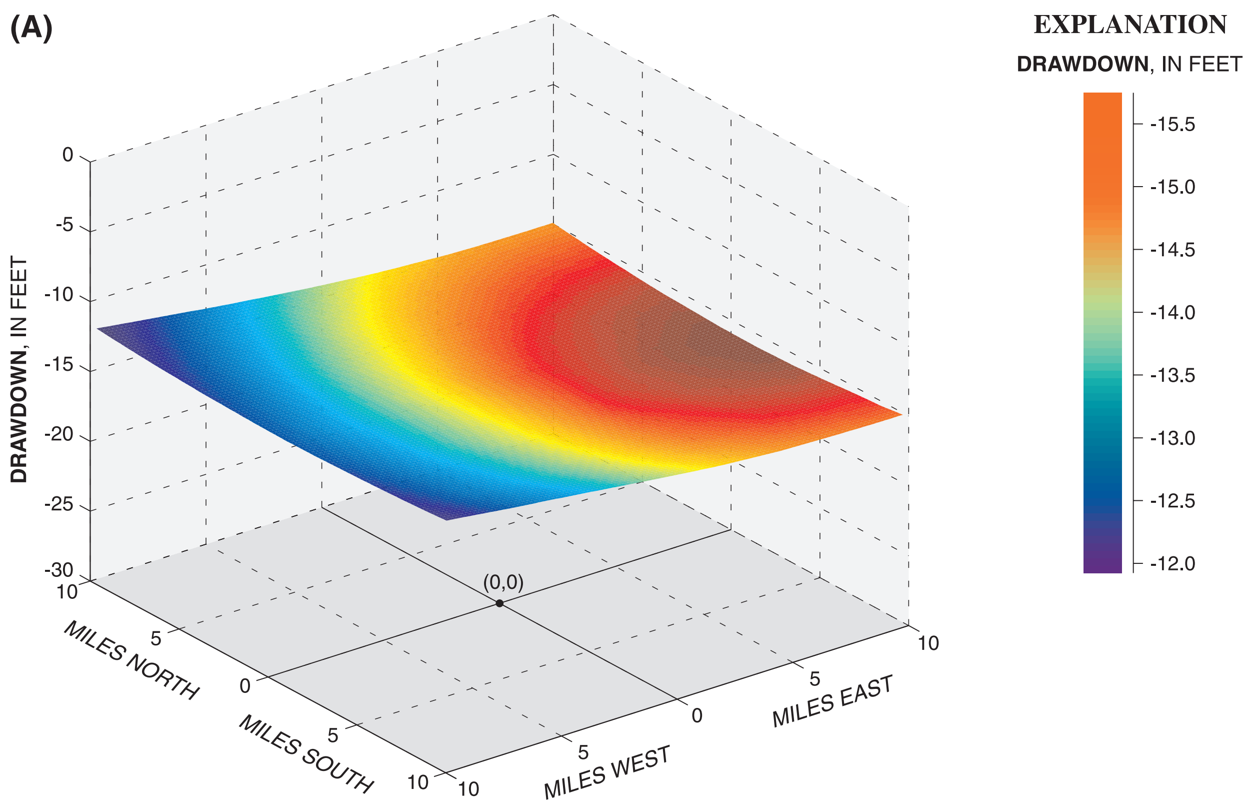


Figure 51. Time-drawdown patterns calculated for multiple pumping wells in a leaky, unbounded aquifer under three different withdrawal rate patterns.



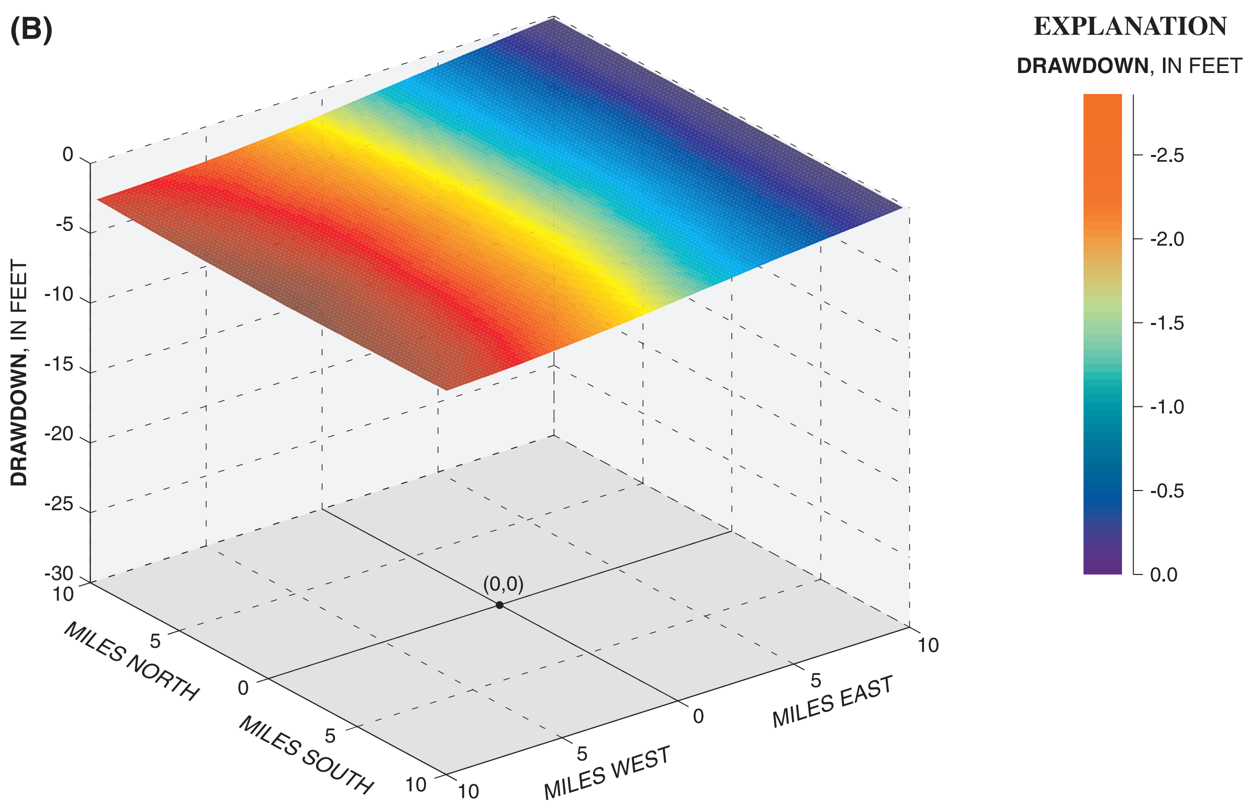


Figure 52. Drawdown in the potentiometric surfaces for the scenarios with multiple wells under a constant withdrawal rate at time t = 22.8 years and with *(A)* no-flow, and *(B)* constant-head boundaries imposed at one edge of the modeled region (eastern side).

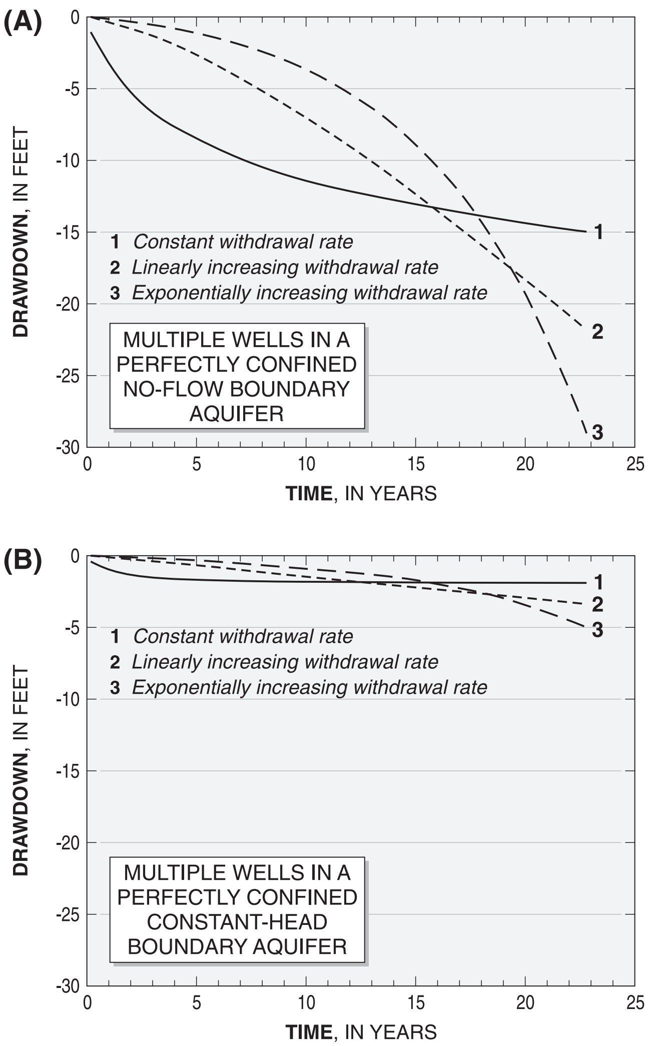


Figure 53. Time-drawdown patterns calculated for multiple pumping wells in an aquifer under three different withdrawal rate patterns and with *(A)* no-flow, and *(B)* constant-head boundaries imposed at the eastern end of the modeled region.

A constant withdrawal rate produces Theis-curve response in the case of a no-flow boundary, and an asymptotic time-drawdown response in the case of a constant-head boundary. Under either boundary condition scenario, linearly increasing withdrawal leads to a nearly linear time-drawdown response, and an exponential increase in withdrawal leads to a time-drawdown response in which the rate of change of drawdown increases with time. This analysis also provides a possible explanation for some nonlinear well hydrographs.

In summary, linear declines in the hydraulic head of a well, as observed in many of the regularly measured aquifer observation wells in the confined aquifers of Southern Maryland, are probably the result of linearly increasing rates of withdrawal. This conclusion holds for single or multiple wells, under leaky or perfectly confined aquifer conditions, and regardless of the presence or absence of no-flow or constant-head boundaries.

The exact mechanism of this withdrawal is unclear, but is probably due to increased pumpage from large supply wells, which is supported at least in part by the water-use data, and (or) by increased numbers of domestic wells, which are mostly estimated and not actually counted. Most likely, it is a combination of both factors. Obtaining more precise numbers on the rates of withdrawal from confined aquifers by both public and domestic wells is critically important for better management of the aquifer resource. Large numbers of domestic wells withdrawing from the same aquifer may be responsible for greater aquifer drawdowns than expected in areas of Southern Maryland with significant suburban residential development, such as Charles, Calvert and St. Mary's Counties.

Summary and Conclusions

The major findings of this report and conclusions from the investigation are summarized as follows:

Ground water has been and will continue to be an important source of supply in Southern Maryland and throughout the Atlantic Coastal Plain. Reported withdrawals in the Southern Maryland and Eastern Shore study area have increased from about 42 to nearly 65 million gallons per day from the early 1980s through 2005. This represents an increase of more than 50 percent, which can be projected to continue as populations grow. Additional sources of water will be needed to meet future demands.

The hydrogeologic framework of the Coastal Plain sediments is complex. Interpretations of the geology have evolved over time through different authors, and have often been made only sporadically for specific, small study areas. The Cretaceous-age, stratigraphically lower aquifers in the study area, consisting of the Patuxent, lower Patapsco, and upper Patapsco aquifers within the Potomac Group, are composed of complex sequences of fluvial and deltaic sands, silts, and clays, with hydrologic properties that may differ greatly across short expanses. These units are generally difficult to correlate over any distance, and prediction of the aquifer properties at any particular location is problematic. The stratigraphically higher aquifers, including the Magothy, Tertiary-age Aquia, and Piney Point-Nanjemoy aquifers, are coastal marine, continental shelf, and estuarine deposits with aquifer properties that tend to change in a more uniform, predictable manner.

The sensitivity of an aquifer to drawdown is related both to withdrawal rates and to the aquifer's hydraulic and hydrologic properties. Many, if not most, of the confined aquifers in the Coastal Plain have hydrologic properties that vary with lithologic facies, depth, or other geological factors. Hydraulic conductivity, in particular, appears to be a function of lithologic facies. Withdrawal of water from an aquifer with relatively high transmissivity results in less drawdown near the pumping well than does a similar withdrawal from an aquifer with relatively low transmissivity. An improved understanding of the relation between aquifer properties and geological factors may lead to better predictability and management of ground-water resources in Southern Maryland and the adjacent Eastern Shore.

Although there are exceptions, as a general rule, water levels in the confined aquifers of the Southern Maryland study area have been decreasing since about 1980. The rates of decline vary by location, but result in cones of depression in the potentiometric surfaces for some aquifers in some locations. These cones of depression are usually centered on large pumping centers within an aquifer; however, evidence indicates that deep declines caused by ground-water withdrawals can affect adjacent aquifers.

Water withdrawals by domestic well users appear to be a significant factor in overall aquifer water-level drawdowns in Southern Maryland. The linear drop in some observation well hydrographs is best explained by annual increases in the total amount of water withdrawn from the aquifer. Modeling experiments indicated that linear declines in the hydraulic head of a well, such as those observed in many observation wells in the confined aquifers of Southern Maryland, are probably the result of linearly increasing rates of withdrawal. This conclusion holds for single or multiple wells, under leaky or perfectly confined aquifer conditions, and regardless of the presence or absence of no-flow or constant-head boundaries. Reported withdrawals, however, generally have not increased at a rate sufficient to explain the declines. The most plausible explanation for the behavior of the aquifer is that additional withdrawals are from unreported, domestic-use wells. Obtaining more accurate data on the numbers and rates of pumping from domestic wells could provide a better understanding of aquifer response.

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References Cited

Achmad, G., 1991, Simulated hydrologic effects of the development of the Patapsco aquifer system in Glen Burnie, Anne Arundel County, Maryland: Maryland Geological Survey Report of Investigations No. 54, 90 p.

Achmad, G., and Hansen, H.J., 1997, Hydrogeology, model simulation, and water-supply potential of the Aquia and Piney Point-Nanjemoy aquifers in Calvert and St. Mary's Counties, Maryland: Maryland Geological Survey Report of Investigations No. 64, 197 p.

Achmad, G., and Hansen, H.J., 2001, Ground-water levels and pumpage trends in the major Coastal Plain aquifers of Southern Maryland between 1970 and 1996: Maryland Geological Survey Open-File Report No. 2000–02–12, 149 p.

Allen, J.R.L., 1970, Studies in fluviatile sedimentation—A comparison of fining-upward cyclothems, with special reference to coarse-member composition and interpretation: Journal of Sedimentary Petrology, v. 40, p. 298–323.

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V., 1980, Extraterrestrial cause for the Cretaceous-Tertiary extinction: Experimental results and theoretical interpretation: Science, v. 208, no. 4448, p. 1,095–1,108.

Andreasen, D.C., 1999, The geohydrology and water-supply potential of the lower Patapsco and Patuxent aquifers in the Indian Head-Bryans Road area, Charles County, Maryland: Maryland Geological Survey Report of Investigations No. 69, 119 p.

Andreasen, D.C., 2002, Hydrogeology, water quality, and water-supply potential of the Aquia and Magothy aquifers in southern Anne Arundel County, Maryland: Maryland Geological Survey Report of Investigations No. 74, 110 p.

Anne Arundel County (MD), 2006, Annual drinking water report (consumer confidence report), available at *http://www.aacounty.org/DPW/Utilities/waterQuality.cfm*

Bennett, R.R., and Collins, G.G., 1952, Brightseat Formation, a new name for sediments of Paleocene age in Maryland: Washington Academy of Sciences Journal, v. 42, no. 4, p. 114–116.

Brenner, G.J., 1963, The spores and pollen of the Potomac Group of Maryland: Maryland Department of Geology, Mines, and Water Resources Bulletin 27, 215 p.

Chapelle, F.H., and Drummond, D.D., 1983, Hydrogeology, digital simulation, and geochemistry of the Aquia and Piney Point-Nanjemoy aquifer system in Southern Maryland: Maryland Geological Survey Report of Investigations No. 38, 100 p.

Clark, W.B., 1897, Outline of present knowledge of the physical features of Maryland, embracing an account of the physiography, geology and natural resources, in Maryland Geological Survey, v. 1: Baltimore, Maryland, Johns Hopkins Press, p. 139–228.

Clark, W.B., and Bibbins, A.B., 1897, The stratigraphy of the Potomac Group in Maryland: Journal of Geology, v. 5, no. 5, p. 479–506.

Clark, W.B., and Martin, G.C., 1901, The Eocene deposits of Maryland, *in* Clark, W.B., and others, Eocene: Maryland Geological Survey Systematic Report, 331 p.

Curtin, S.E., Andreasen, D.C., and Wheeler, J.C., 2005, Potentiometric surface of the Aquia aquifer in Southern Maryland, September 2003: U.S. Geological Survey Open-File Report OF–2005–1004, 1 p.

Curtin, S.E., and Dine, J.D., 1995, Ground-water level data in Southern Maryland, 1946–1994: Maryland Geological Survey Basic Data Report No. 21, 365 p.

Darton, N.H., 1891, Mesozoic and Cenozoic formations of eastern Virginia and Maryland: Geological Society of America Bulletin, v. 2, p. 431–450.

Drummond, D.D., 1984, Records of selected wells, Calvert and St. Mary's Counties, Maryland: Maryland Geological Survey Water Resources Basic Data Report No. 14, 117 p.

Drummond, D.D., 2005, Water-supply potential of the Coastal Plain aquifers in Calvert, Charles, and St. Mary's Counties, Maryland, with emphasis on the upper Patapsco and lower Patapsco aquifers: Maryland Geological Survey Administrative Report, 70 p.

Fleck, W.B., and Andreasen, D.C., 1996, Geohydrologic framework, ground-water quality and flow, and brackish-water intrusion in east-central Anne Arundel County, Maryland: Maryland Geological Survey Report of Investigations No. 62, 136 p.

Fleck, W.B., and Vroblesky, D.A., 1996, Simulation of ground-water flow of the Coastal Plain aquifers in parts of Maryland, Delaware, and the District of Columbia: U.S. Geological Survey Professional Paper 1404–J, 41 p., 9 pls.

Fleming, S.W., Ruskauff, G.J., and Adams, A., 2002, HJW-FTAC: Software for Hantush-Jacob analysis of variable-rate, multiple extraction well pumping tests: Computers & Geosciences, v. 28, no. 5, p. 669–677.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: New York, Prentice Hall, 604 p.

Glaser, J.D., 1969, Petrology and origin of Potomac and Magothy (Cretaceous) sediments, Mid-Atlantic Coastal Plain: Maryland Geological Survey Report of Investigations No. 11, 102 p.

Glaser, J.D., 1971, Geology and mineral resources of Southern Maryland: Maryland Geological Survey Report of Investigations No. 15, 85 p.

Glaser, J.D., 1976, Geologic map of Anne Arundel County: Maryland Geological Survey, Atlas Map No. 1: Washington, D.C., Williams & Heinz Map Corporation, 1 sheet, scale 1:62,500.

Gohn, G.S., ed., 1992, Proceedings of the 1988 U.S. Geological Survey workshop on the geology and geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, 158 p.

Groot, J.J., 1955, Sedimentary petrography of Cretaceous sediments in northern Delaware in relation to paleogeographic problems: Delaware Geological Survey Bulletin 5, 157 p.

Hansen, H.J., 1972, A users guide to the artesian aquifers of the Maryland Coastal Plain, Part Two: Aquifer characteristics: Maryland Geological Survey Open-File Report No. 72–02–1, 123 p.

Hansen, H.J., 1974, Sedimentary facies of the Aquia Formation in the subsurface of the Maryland Coastal Plain: Maryland Geological Survey Report of Investigations No. 21, 47 p.

Hansen, H.J., 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new unit of the Potomac Group underlying the eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.

Hansen, H.J., 1995, Hydrostratigraphic framework of the Piney Point-Nanjemoy aquifer and Aquia aquifer in Calvert and St. Mary's Counties, Maryland: Maryland Geological Survey Open-File Report No. 96–02–8, 45 p.

Hansen, H.J., and Drummond, D.D., 1994, Upper Cretaceous and Tertiary stratigraphy of core-hole KE Bf 180 clarifies aquifer nomenclature in Kent County, Maryland, *in* Schultz, A.P., and Rader, E.K., eds., Studies in eastern energy and the environment: Virginia Division of Mineral Resources Publication No. 132, p. 50–56.

Hansen, H.J., and Edwards, J., 1986, The lithology and distribution of pre-Cretaceous basement rocks beneath the Maryland Coastal Plain: Maryland Geological Survey Report of Investigations No. 44, 27 p.

Hantush, M.S., 1956, Analysis of data from pumping tests in leaky aquifers: Eos, Transactions of the American Geophysical Union, v. 37, no. 6, p. 702–714.

Hantush, M.S., and Jacob, C.E., 1955, Nonsteady radial flow in an infinite leaky aquifer: Eos, Transactions of the American Geophysical Union, v. 36, no. 1, p. 95–100.

Hiortdahl, S.N., 1997, Geologic framework, hydrogeology, and ground-water quality of the Potomac Group aquifer system, northwestern Charles County, Maryland: U.S. Geological Survey Water-Resources Investigations Report 91–4059, 111 p.

Jordan, R.R., 1968, Observations on the distribution of sands within the Potomac Formation of northern Delaware: Southeastern Geology, v. 9, no. 2, p. 77–85.

Jordan, R.R., 1983, Stratigraphic nomenclature of nonmarine Cretaceous rocks of inner margin of Coastal Plain in Delaware and adjacent states: Delaware Geological Survey Report of Investigations No. 37, 43 p.

Klohe, C.A., and Feehley, C.E., 2001, Hydrogeology and ground-water quality of the Piney Point-Nanjemoy and Aquia aquifers, Naval Air Station Patuxent River and Webster Outlying Field, St. Mary's County, Maryland: U.S. Geological Survey Water-Resources Investigations Report 01–4029, 51 p.

Leahy, P.P., 1976, Hydraulic characteristics of the Piney Point aquifer and overlying confining bed near Dover, Delaware: Delaware Geological Survey Report of Investigations No. 26, 24 p.

Lucas, R.C., 1976, Anne Arundel County ground-water information: Selected well records, chemical-quality data, pumpage, appropriation data and selected well logs: Maryland Geological Survey Water Resources Basic Data Report No. 8, 149 p.

Mack, F.K., 1974, An evaluation of the Magothy aquifer in the Annapolis area, Maryland: Maryland Geological Survey Report of Investigations No. 22, 75 p.

Mack, F.K., 1977, Digital simulation and prediction of water level in the Magothy aquifer in Southern Maryland: Maryland Geological Survey Report of Investigations No. 28, 42 p.

Mack, F.K., and Achmad, G., 1986, Evaluation of the water-supply potential of aquifers in the Potomac Group of Anne Arundel County, Maryland: Maryland Geological Survey Report of Investigations No. 46, 111 p.

Mack, F.K., and Andreasen, D.C., 1991, Geohydrologic data for the Coastal Plain sediments underlying Broadneck Peninsula, Anne Arundel County, Maryland: Maryland Geological Survey Open-File Report No. 92–02–6, 70 p.

Mack, F.K., Wheeler, J.C., and Curtin, S.E., 1983, Water-level declines in the Magothy aquifer in Southern Maryland related to increases in pumpage: U.S. Geological Survey Open-File Report 82–919, 29 p.

McCartan, L., 1989, Geologic map of Charles County: Maryland Geological Survey, 1 sheet, scale 1:62,500.

Nogan, D.S., 1964, Foraminifera, stratigraphy, and paleoecology of the Aquia Formation of Maryland and Virginia: Washington, D.C., Cushman Foundation for Foraminiferal Research, Smithsonian Institution, Special Publication No. 7, 50 p.

Otton, E.G., 1955, Ground-water resources of the Southern Maryland Coastal Plain: Maryland Geological Survey Bulletin No. 15, 347 p.

Rader, E.K., and Evans, N.H., 1993, Geologic map of Virginia; expanded explanation: Richmond, Va., Virginia Division of Mineral Resources, 80 p.

Shedlock, R.J., Bolton, D.W., and Pajerowski, M.G., 2006, Sustainability of the ground-water resources in the Atlantic Coastal Plain of Maryland: U.S. Geological Survey Fact Sheet 2006–3009, 2 p.

Smigaj, M.J., and Davis, R.G., 1987, Ground-water levels from the Maryland Observation-Well Network, 1943–86: Maryland Geological Survey Basic Data Report No. 17, 234 p.

Stephenson, L.W., and MacNeil, F.S., 1954, Extension of Yorktown Formation (Miocene) of Virginia into Maryland: Geological Society of America Bulletin, v. 65, no. 8, p. 733–738.

Sugarman, P.J., 1992, Geologic controls on aquifer distribution in the Coastal Plain of northern New Jersey, *in* Gohn, G.S., ed., Proceedings of the 1988 U.S. Geological Survey workshop on the geology and geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 35–38.

Theis, C.V., 1935, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using groundwater storage: American Geophysical Union, Transactions, 16th Annual Meeting, v. 16, pt. 2, p. 519–524.

Trapp, H.J., Jr., 1992, Hydrogeologic framework of the Northern Atlantic Coastal Plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York: U.S. Geological Survey Professional Paper 1404–G, 72 p.

Trapp, H.J., Jr., and Meisler, H., 1992, The regional aquifer system underlying the northern Atlantic Coastal Plain in parts of North Carolina, Virginia, Maryland, Delaware, New Jersey, and New York; Summary: U.S. Geological Survey Professional Paper 1404–A, 42 p.

U.S. Census Bureau, 2006, Annual estimates of housing units for counties in Maryland: April 1, 2000 to July 1, 2005 (HU-EST2005-04-24), Release date: August 21, 2006, available at *http://www.census.gov/*

Vroblesky, D.A., and Fleck, W.B., 1991, Hydrogeologic framework of the Coastal Plain of Maryland, Delaware, and the District of Columbia: U.S. Geological Survey Professional Paper 1404–E, 45 p.

Ward, L.W., 1985, Stratigraphy and characteristic molluscs of the Pamunkey Group (lower Tertiary) and the Old Church Formation of the Chesapeake Group, Virginia Coastal Plain: U.S. Geological Survey Professional Paper 1346, 78 p.

Weigle, J.M., Webb, W.E., and Gardner, R.A., 1970, Water resources of Southern Maryland: U.S. Geological Survey Hydrologic Investigations Atlas HA–465, 3 pls.

Wheeler, J.C., 2003, Freshwater use trends in Maryland, 1985–2000: U.S. Geological Survey Fact Sheet 112–03, 4 p.

Wheeler, J.C., and Wilde, F.D., 1989, Ground-water use in the Coastal Plain of Maryland, 1900–1980: U.S. Geological Survey Open-File Report 87–540, 173 p.

Williams, J.F., 1979, Simulated changes in water level in the Piney Point aquifer in Maryland: Maryland Geological Survey Report of Investigations No. 31, 49 p.

Wilmarth, M.G., 1957, Lexicon of geologic names of the United States (including Alaska): U.S. Geological Survey Bulletin 896, 2,396 p.

Wilson, J.M., and Fleck, W.B., 1990, Geology and hydrogeologic assessment of Coastal Plain aquifers in the Waldorf area, Charles County, Maryland: Maryland Geological Survey Report of Investigations No. 53, 138 p.

Wolman, M.G., 2004, Report of the Advisory Committee on the management and protection of the water resources of the State of Maryland: Baltimore, Md., Maryland Department of the Environment, Special Report to the Governor, 96 p.

Appendixes 1–3

Appendix 1. Bibliography of U.S. Geological Survey Southern Maryland Potentiometric Surface Maps: 1980, 1985, 1990, 1995, and 2000

Information on historical maps is provided for comparison with the maps included in this report. Citation format is that of the USGS Library, and includes library call number and accessibility options.

1980

Aquia

U.S. Geological Survey Open-File Report 81–416 (1981): Map showing the potentiometric surface of the Aquia aquifer, May 19–23, 1980.
Authors: Chapelle, Frank; Drummond, Dave; Curley, Tracey
USGS Library Call Number: M(200) R29o no.81-416
Access: Library (paper copy) only.

Magothy

U.S. Geological Survey Open-File Report 81–633 (1981): Map showing the potentiometric surface of the Magothy aquifer in Southern Maryland, August 1980.
Authors: Mack, F.K.; Wheeler, J.C.; Curtin, S.E.
USGS Library Call Number: (200) R29o no.81-633
Access: Library (paper copy) only.
(Note: Patapsco maps not published before 1990; Aquia and Magothy maps only.)

1985

Aquia

U.S. Geological Survey Water-Resources Investigations Report 87–4029 (1987): The potentiometric surface of the Aquia aquifer in Southern Maryland, September 1985.
Authors: Mack, F.K.; Wheeler, J.C.; Curtin, S.E.; Andreasen, D.C.
USGS Library Call Number: (200) WRi no.87-4029
Access: Library (paper copy) only.

Magothy

U.S. Geological Survey Water-Resources Investigations Report 87–4025 (1987): The potentiometric surface of the Magothy aquifer in Southern Maryland, September 1985.
Authors: Mack, F.K.; Wheeler, J.C.; Curtin, S.E.; Andreasen, D.C.
USGS Library Call Number: (200) WRi no.87-4025
Access: Electronic image available.
(Note: Patapsco maps not published before 1990; Aquia and Magothy maps only.)

1990

Aquia

U.S. Geological Survey Open-File Report 92–459 (1992): Potentiometric surface of the Aquia aquifer in Southern Maryland, September 1990.
Authors: Mack, F.K.; Curtin, S.E.; Andreasen, D.C.; Wheeler, J.C.
USGS Library Call Number: M(200) R29o no.92-459
Access: Electronic image available.

Magothy

U.S. Geological Survey Open-File Report 92–460 (1992): Potentiometric surface of the Magothy aquifer in Southern Maryland, September 1990.
Authors: Mack, F.K.; Curtin, S.E.; Andreasen, D.C.; Wheeler, J.C.
USGS Library Call Number: M(200) R29o no.92-460
Access: Electronic image available.

Upper Patapsco

U.S. Geological Survey Open-File Report 92–461 (1992): Potentiometric surface of the upper Patapsco aquifer in Southern Maryland, September 1990.
Authors: Mack, F.K.; Curtin, S.E.; Andreasen, D.C.; Wheeler, J.C.
USGS Library Call Number: M(200) R29o no.92-461
Access: Electronic image available.

Lower Patapsco

U.S. Geological Survey Open-File Report 92–462 (1992): Potentiometric surface of the lower Patapsco aquifer in Southern Maryland, September 1990.
Authors: Mack, F.K.; Curtin, S.E.; Andreasen, D.C.; Wheeler, J.C.
USGS Library Call Number: M(200) R29o no.92-462
Access: Electronic image available.

1995

Aquia

U.S. Geological Survey Open-File Report 96–620 (1997): Potentiometric surface of the Aquia aquifer in Southern Maryland, September 1995.
Authors: Curtin, S.E.; Andreasen, D.C.; Mack, F.K.
USGS Library Call Number: (200) R29o no.96-620
Access: Electronic image available.

Magothy

U.S. Geological Survey Open-File Report 96–621 (1996): Potentiometric surface of the Magothy aquifer in Southern Maryland, September 1995.
Authors: Curtin, S.E.; Andreasen, D.C.; Mack, F.K.
USGS Library Call Number: (200) R29o no.96-621
Access: Electronic image available.

Upper Patapsco

U.S. Geological Survey Open-File Report 96–622 (1996): Potentiometric surface of the upper Patapsco aquifer in Southern Maryland, September 1995.
Authors: Curtin, S.E.; Andreasen, D.C.; Mack, F.K.
USGS Library Call Number: (200) R29o no.96-622
Access: Electronic image available.

Lower Patapsco

U.S. Geological Survey Open-File Report 96–623 (1996): Potentiometric surface of the lower Patapsco aquifer in Southern Maryland, September 1995.
Authors: Curtin, S.E.; Andreasen, D.C.; Mack, F.K.
USGS Library Call Number: (200) R29o no.96-623
Access: Electronic image available.

2000

Aquia

U.S. Geological Survey Open-File Report 02–244 (2002): Potentiometric surface of the Aquia aquifer in Southern Maryland, September 2000.
Authors: Curtin, S.E.; Andreasen, D.C.; Wheeler, J.C.
USGS Library Call Number: M(200) R29o no.2002-244
Access: Electronic image available.

Magothy

U.S. Geological Survey Open-File Report 02–245 (2002): Potentiometric surface of the Magothy aquifer in Southern Maryland, September 2000.
Authors: Curtin, S.E.; Andreasen, D.C.; Wheeler, J.C.
USGS Library Call Number: M(200) R29o no.2002-245
Access: Electronic image available.

Upper Patapsco

U.S. Geological Survey Open-File Report 02–246 (2002): Potentiometric surface of the upper Patapsco aquifer in Southern Maryland, September 2000.
Authors: Curtin, S.E.; Andreasen, D.C.; Wheeler, J.C.
USGS Library Call Number: M(200) R29o no.2002-246
Access: Electronic image available.

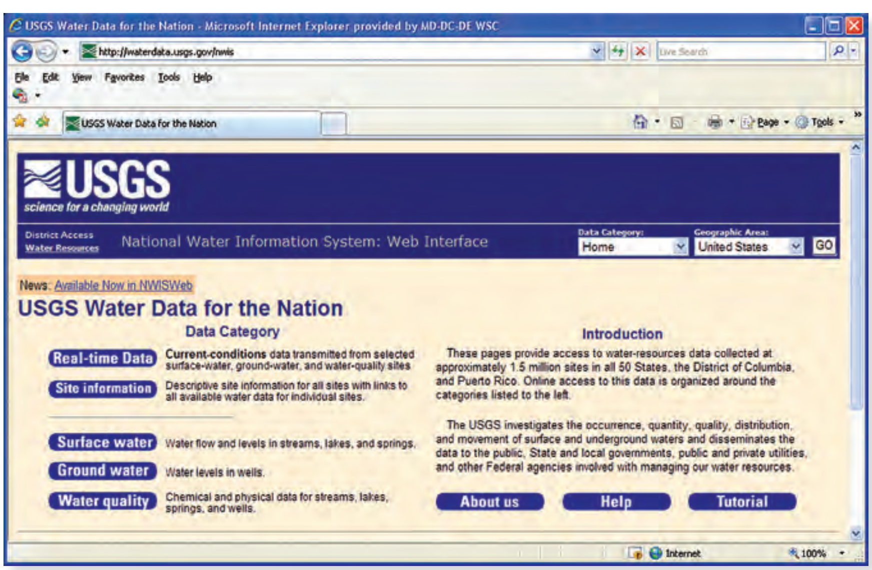
Lower Patapsco

U.S. Geological Survey Open-File Report 02–247 (2002): Potentiometric surface of the lower Patapsco aquifer in Southern Maryland, September 2000.
Authors: Curtin, S.E.; Andreasen, D.C.; Wheeler, J.C.
USGS Library Call Number: M(200) R29o no.2002-247
Access: Electronic image available.

Appendix 2. Access to U.S. Geological Survey Water Data

Water data from the U.S. Geological Survey can be accessed online via the National Water Information System (NWIS), by following the step-by-step instructions below.

1. Start by visiting the USGS water data page at *http://waterdata.usgs.gov/nwis*.
2. In the box at the upper right, select the data category of interest (for example, ground water).
3. In the adjacent box, select the geographic area of interest (for example, Maryland). This will bring up the local data and site-selection page.
4. To access real-time ground-water data, select the "real time data" button. Please be aware that locations providing real-time ground-water data are limited. Select "field water-level measurements" to access the standard, manual, periodic ground-water-level measurements for individual wells.
5. This will bring up a site-selection criteria menu page. Multiple sites can be selected by number, name, aquifer, or other attributes on this menu. Select the search criteria, click the submit button, and enter the values for the selection criteria on the next menu. Selecting by latitude/longitude box, county, or aquifer code will likely return a large number of sites, many of which may be project wells with only one measurement. Select the "number of measurements" box and increase the value to 10 or 12 to eliminate single-measurement wells.
6. If the USGS site ID number is known, check only the box marked "site number" on the site-selection criteria menu page and click submit. Enter the FULL number of the site ID in the box on the next menu page—including all the zeros, and click the submit button.
7. Click the desired sites on the site list. The individual web page will come up, showing the data graphically in a hydrograph. If tabular data (numbers) are desired instead, select "Table of Data" under the box marked "output format" on the data page. The time span of the retrieval can also be changed by using the "reselect period" button and specifying different starting and ending dates. Ground-water-level data can be retrieved up to and including the most recent measurement entered into the database. All data for the current water year are considered provisional, however, and may be subjected to review and changes until published in the annual data report. These instructions were successfully executed in 2007 by D. Soeder.



Appendix 3. Southern Maryland ground-water-level data used in this report.

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Aquia aquifer										
AA Cf 122	390149076261702	39.03038890	-76.43773750	20.0	1.40	2.60	2.10	3.10	2.40	2.90
AA Cg 25	390127076240301	39.02427797	-76.40051418	17.3	0.94	1.59	1.33	1.05	0.40	--
AA De 102	385512076331602	38.92011310	-76.55412800	49.6	9.66	9.17	7.93	9.81	8.99	10.59
AA De 137	385930076342102	38.99177795	-76.57218569	133.6	--	--	33.79	32.94	36.18	--
AA De 173	385628076323101	38.94122380	-76.54162799	34.0	--	2.04	1.17	--	--	--
AA Df 98	385550076292101	38.93066879	-76.48884808	11.3	1.90	1.92	1.32	1.72	--	--
AA Df 103	385623076274401	38.93983528	-76.46190312	26.5	--	24.09	21.64	23.03	--	--
AA Ed 45	385406076383901	38.90177960	-76.64385339	110.0	40.35	39.90	39.40	41.89	43.05	45.12
AA Ed 49	385249076382101	38.88039125	-76.63885290	60.0	20.86	21.74	20.61	24.35	25.25	29.83
AA Ee 67	385124076322001	38.85678145	-76.53857026	11.2	-8.55	-6.29	-7.56	-3.46	-2.81	0.08
AA Ef 17	385318076294501	38.88844763	-76.49551374	20.2	--	4.10	1.17	1.90	-0.40	2.79
AA Fd 43	384646076352401	38.77956066	-76.58968223	150.0	--	-19.38	-18.71	-9.19	-2.73	3.36
AA Fd 46	384727076382501	38.79094883	-76.63996286	140.3	-17.81	-11.46	-11.19	-4.14	-0.60	9.20
AA Fe 46	384840076312801	38.81122714	-76.52412398	8.5	-23.17	-18.67	-20.89	-12.27	-7.72	-3.97
AA Fe 48	384508076334101	38.75233936	-76.56106899	85.0	-33.26	-27.10	-24.56	-14.40	-7.12	2.22
AA Fe 60	384917076305802	38.82150473	-76.51579051	8.5	-19.08	-14.68	--	--	--	--
AA Fe 92	384644076331201	38.77900546	-76.55301359	9.0	-33.92	-26.53	--	--	--	--
CA Ba 11	384357076401601	38.73261660	-76.67079721	115.3	-40.40	-27.47	-26.49	-14.93	-8.15	-4.61
CA Ba 13	384231076412501	38.70872819	-76.68996469	56.0	-37.41	-27.63	-23.60	-13.25	-4.80	8.59
CA Bb 27	384333076394701	38.72595018	-76.66274113	137.9	-44.30	-32.28	-30.48	-18.03	-9.59	0.94
CA Bb 33	384222076380101	38.70622871	-76.63329482	110.6	-47.64	-35.45	--	-19.47	-7.45	3.68
CA Bc 25	384114076320301	38.68734102	-76.53384467	17.8	-17.85	-26.74	-37.28	--	--	--
CA Bc 32	384238076340301	38.71067358	-76.56718005	129.3	--	--	-35.71	-21.58	-12.68	-2.68
CA Bc 44	384243076320201	38.71206271	-76.53356707	7.6	-45.32	-40.20	-36.07	--	--	--
CA Ca 12	383737076401601	38.62706385	-76.67079606	53.9	-43.36	-34.23	-27.00	-17.54	-9.21	3.27
CA Cb 26	383837076381001	38.64373027	-76.63579433	115.3	-51.34	-38.97	-30.69	-18.46	-8.96	4.33
CA Cb 32	383632076392701	38.60900883	-76.65718402	95.2	-57.35	-45.30	-36.01	-23.60	-14.52	-0.38
CA Cb 37	383501076362001	38.58373188	-76.60523653	23.8	--	--	-36.54	-24.52	-14.48	-2.88
CA Cc 18	383940076314801	38.66123049	-76.52967756	111.3	-48.61	-39.48	-31.95	-21.67	-14.39	-6.39
CA Cc 39	383934076320202	38.65956383	-76.53356665	93.7	--	-39.86	-32.64	-22.23	-14.77	-6.29
CA Cc 57	383605076344601	38.60150933	-76.57912418	138.6	-55.83	-45.20	-34.52	-22.72	-13.69	-4.97
CA Cc 58	383924076341201	38.65678589	-76.56967972	122.5	-49.35	-38.75	-30.80	-19.40	-10.65	2.10
CA Db 40	383053076382101	38.51484463	-76.63884873	23.4	-66.88	-56.12	-44.26	-28.45	-25.91	-7.42
CA Db 47	383239076354201	38.54428840	-76.59468004	140.4	-68.07	-56.48	-44.20	-31.20	-20.97	-12.40
CA Dc 29	383025076304701	38.50706708	-76.51273101	123.1	-63.93	-56.98	-43.33	-27.49	-18.81	-8.59

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Aquia aquifer—Continued										
CA Ed 42	382528076280701	38.43123443	-76.46300729	121.7	-90.69	-82.19	-69.77	-39.10	-34.84	--
CA Ed 52	382549076260101	38.43040093	-76.43328409	10.0	-99.59	-98.26	-86.27	--	--	--
CA Fd 54	382407076260301	38.40206788	-76.43383978	129.4	-106.72	-95.86	-80.51	-47.45	-35.45	-24.33
CA Fd 68	382128076271301	38.35790179	-76.45328509	90.4	--	--	-106.94	-71.13	-41.39	--
CA Fd 69	382015076271501	38.33762422	-76.45384076	21.0	--	-141.11	-113.06	-84.16	-48.30	--
CA Fd 70	382155076254502	38.36540155	-76.42883974	108.5	-142.42	-122.90	-101.05	-68.82	-39.50	--
CA Fe 19	382316076243201	38.38790120	-76.40856118	113.4	--	-100.05	-83.51	-53.88	-41.68	-25.38
CA Fe 20	382325076245601	38.39040122	-76.41522807	114.5	--	-102.61	-84.09	-50.92	-34.99	-25.33
CA Fe 30	382134076233301	38.35956803	-76.39217179	118.8	-120.17	--	-89.75	-61.67	--	--
CA Gd 6	381952076270901	38.33123539	-76.45217406	12.7	-151.91	-132.37	-111.62	-85.44	-49.91	-42.93
CH Bg 11	383536076473601	38.59345318	-76.79302354	196.8	-40.86	-33.11	-23.49	-10.92	-3.03	21.63
CH Ce 41	382225076591002	38.54039844	-76.98580733	194.2	-25.12	-20.88	-16.75	--	--	--
CH Cg 20	383251076480001	38.54762118	-76.79968993	181.6	-54.75	-43.49	-33.37	-20.50	-12.50	-2.28
CH Cg 21	383009076481201	38.50262250	-76.80302290	184.2	-64.50	-50.16	-40.00	-17.28	-13.76	5.72
CH Ch 15	383043076404501	38.51206691	-76.67885078	9.8	-63.70	-53.90	-42.69	-28.29	-17.75	-3.68
CH Df 17	382800076530301	38.46678988	-76.88385908	161.0	-61.80	-45.63	-36.67	-21.07	-9.73	10.65
CH Ff 59	381639076523201	38.27762869	-76.87524772	8.0	-39.99	-31.88	-23.36	-15.86	-8.75	-1.39
DO Db18	382807076175801	38.46873317	-76.29911305	1.5	--	-55.54	-44.12	-29.23	--	--
DO Db19	382847076190901	38.47984429	-76.31883590	1.5	-66.26	-57.01	-45.64	-31.43	--	--
KE Cd 44	391432076015501	39.24233150	-76.03161140	50.0	13.82	8.75	10.41	7.25	2.79	3.94
KE Dc 91	390626076083302	39.10733302	-76.14217115	4.6	0.98	0.65	-0.02	--	--	--
PG Hf 35	383228076410601	38.54123278	-76.68468474	11.2	-61.84	-50.46	-39.28	-25.04	--	--
PG Hf 42	383348076411303	38.56345439	-76.68662954	27.8	-59.21	-47.65	-36.89	-23.42	--	--
QA Bc 17	391203076024303	39.20094315	-76.04494493	25.0	11.60	14.95	13.00	14.90	14.82	--
QA Db32	390201076182703	39.03372248	-76.30717813	18.0	1.17	1.77	1.13	0.92	1.08	--
QA Db35	390119076191001	39.02205595	-76.31912290	7.5	1.55	2.09	1.10	0.88	1.51	--
QA Db37	390023076174302	39.00650065	-76.29495549	7.1	-1.25	-0.27	-1.32	-1.88	-1.19	--
QA De27	390251076034401	39.04761175	-76.06188876	10.2	-18.24	-8.85	--	--	--	--
QA Ea78	385718076211502	38.95511290	-76.35384487	11.8	-1.54	-0.76	-1.23	-1.79	-0.41	--
QA Ea80	385757076200102	38.96594599	-76.33328901	8.5	-3.03	-1.82	-2.56	-2.77	-1.95	--
QA Eb 113	385748076172001	38.96344615	-76.28856540	11.3	-8.83	-7.46	-8.03	-6.66	-5.76	--
QA Eb 155	385843076155302	38.97872357	-76.26439846	3.9	-7.64	-6.07	-7.08	-5.80	-4.37	--
QA Eb 156	385852076195201	38.98122338	-76.33078935	12.0	-2.74	-1.48	-2.08	-2.14	-1.20	--
QA Fc 7	385429076120201	38.90816973	-76.20022712	10.0	-25.84	-19.61	-23.18	-17.79	-14.84	-10.54
SM Bb 15	382838076470101	38.4773455	-76.78330006	165.40	-69.66	-54.69	-42.79	-27.33	-13.46	1.96

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Aquia aquifer—Continued										
SM Ca 6	382248076500101	38.38012583	-76.83330201	143.85	-55.77	-44.10	-33.98	-22.28	-10.87	3.10
SM Cc 8	382235076435801	38.37651487	-76.73246535	128.85	-63.00	-50.25	-39.03	-23.96	-12.88	--
SM Cc 22	382055076404601	38.34873729	-76.67912944	133	-64.29	-51.87	-38.68	-26.49	-15.89	-4.40
SM Ce 38	382222076304602	38.3395691	-76.51245419	15.92	-127.25	-111.00	-85.78	-81.17	-56.12	-28.18
SM Dc 42	381648076421801	38.28012808	-76.70468677	13.5	-67.40	-55.33	-45.97	-34.00	-23.95	--
SM Dc 59	381807076442801	38.30207246	-76.74079961	40.89	-58.03	-46.37	-36.81	-25.95	-16.21	-13.41
SM Dd 01	381745076381201	38.29596013	-76.63634979	93.28	-91.50	-71.22	-63.34	-47.47	-30.01	-21.72
SM Dd 44	381557076395701	38.26596116	-76.66551817	31	-64.45	-67.42	-55.18	-45.90	-31.73	-16.40
SM Dd 47	381537076384601	38.26040542	-76.64579495	10	-79.83	-65.38	-56.18	-44.49	-33.49	-20.27
SM Dd 49	381616076364702	38.27123805	-76.6127376	118.94	-90.71	-71.95	-62.59	-46.52	-34.98	-27.70
SM Dd 50	381807076380001	38.30207108	-76.63301624	99.4	-82.91	-75.91	-62.86	-47.49	-37.06	-30.06
SM Df 01	381552076265001	38.26484714	-76.44689638	93.35	-140.69	-144.75	-113.04	-106.94	-71.65	--
SM Df 10	381715076261601	38.28679129	-76.438007	46	-146.02	-137.75	-115.4	--	-51.15	--
SM Df 42	381537076272401	38.26040281	-76.45634121	86.5	-165.14	-149.14	-125.87	-106.81	-71.56	-43.50
SM Df 61	381604076271701	38.26818049	-76.4532855	108.86	-153.99	-181.19	-124.41	-95.10	-70.93	--
SM Df 71	381527076283101	38.25762522	-76.47495307	69.15	-147.70	-134.08	-114.73	-94.29	-62.31	-59.15
SM Df 80	381532076250101	38.25901362	-76.41661743	42	-137.90	-122.35	-99.67	-81.87	-54.30	-53.10
SM Df 86	381548076272103	38.26345833	-76.45550783	112.09	-164.40	-149.35	-125.71	-106.25	-81.62	-67.43
SM Df 95	381617076263201	38.27151369	-76.44134058	80	-149.8	-137.46	-118	--	--	--
SM Df 96	381724076253901	38.29012451	-76.42717329	9	-146	-135.17	-109.53	--	--	--
SM Df 98	381634076270501	38.27623594	-76.4510632	80.46	-145.15	-147.95	-183.19	--	--	--
SM Dg 5	381805076225701	38.30067962	-76.38244934	21.4	-73.15	-117.75	-84.59	-67.67	-44.80	-42.05
SM Dg 10	381555076244801	38.26540242	-76.41300616	22	-142.25	-127.32	-104.09	-77.12	-57.54	-44.21
SM Dg 14	381813076232501	38.30317966	-76.39050519	19	-135.65	-121.75	-95.46	--	--	--
SM Dg 16	381624076235601	38.27234668	-76.39856113	11.15	-138.82	-125.3	-106.85	--	--	--
SM Dg 18	381607076241401	38.26956896	-76.402728	18	-134.35	-119.56	-103.5	--	--	--
SM Dg 19	381747076223901	38.29623517	-76.376338	10	-129.55	-116.35	-100.39	--	--	--
SM Fe 31	380834076303402	38.14290512	-76.50912114	8	-79.14	-73.05	-62.02	-44.79	-29.74	-26.46
SM Ff 64	380821076255501	38.13929316	-76.43161793	10	-87.2	-86.02	-76.64	--	--	--
TA Cc 50	384707076133202	38.78567286	-76.22661425	8	-39.2	-31.82	-33.05	--	--	--
Magothy aquifer										
AA Cc 95	390247076403501	39.04649876	-76.67607829	131.09	88.99	84.23	85.48	87.91	86.71	92.32
AA Cc 117	390103076402603	39.01761031	-76.67357794	134.14	50.48	48.67	48.88	51.78	53.24	56.34
AA Cd 12	390124076361202	39.02344392	-76.60302027	98.82	14.07	15.72	13.01	14.09	14.77	13.08
AA Cd 48	390001076364301	39.00038866	-76.61163149	102.8	10.69	12.82	10.66	15.96	16.70	22.66
AA Cd 78	390238076373301	39.04399906	-76.62552112	128.82	43.66	39.55	40.05	43.04	44.75	50.02

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Magothy aquifer—Continued										
AA Cd 85	390032076383001	39.00899949	-76.64135466	46.55	--	30.85	29.62	32.70	33.29	35.90
AA Cd 87	390224076383501	39.04011014	-76.64274385	75.27	58.35	53.90	53.87	57.17	57.66	63.78
AA Ce 69	390115076303003	39.02094444	-76.50801734	18.9	-17.36	-4.87	-12.37	-5.40	-10.00	-2.55
AA Ce 103	390214076342201	39.03733276	-76.57246385	59.2	2.10	2.69	1.54	1.20	2.33	--
AA Ce 105	390310076340701	39.05288811	-76.56829713	41	--	-1.33	-2.54	-1.53	-1.57	-0.10
AA Ce 110	390231076320601	39.04205510	-76.53468490	75.58	--	--	-1.04	0.25	-1.42	0.93
AA Ce 114	390130076311501	39.02511098	-76.52051774	84.23	-15.45	-7.13	-11.99	-6.44	-9.07	-2.81
AA Ce 128	390404076300703	39.06788823	-76.50162836	7.13	-6.90	-1.09	-3.23	-0.41	--	--
AA Ce 130	390148076325202	39.03011077	-76.54746303	2.68	-8.22	-5.73	-8.65	-4.32	--	--
AA Ce 133	390410076302401	39.06955484	-76.50635074	15.14	-3.26	-0.02	-1.66	0.06	--	--
AA Ce 138	390049076322702	39.01372216	-76.54051831	69	-14.07	-9.29	-14.69	--	--	--
AA Cf 39	390142076254901	39.02844452	-76.42995950	23.34	--	--	-13.45	-10.66	-9.31	-0.50
AA Cf 99	390150076283002	39.03066661	-76.47468304	93.7	-28.19	-9.16	-17.19	-11.03	-11.65	-6.59
AA Cf 104	390242076274501	39.04511088	-76.46218270	26.77	-23.70	-9.92	-16.68	-9.68	-12.10	-5.49
AA Cf 129	390149076261704	39.03038892	-76.43773751	18	--	-11.12	-15.92	-10.36	-11.28	--
AA Cf 130	390108076253501	39.01900022	-76.42607048	20.69	--	-9.96	-13.38	-8.46	-8.43	--
AA Cf 141	390326076295003	39.05733284	-76.49690597	61.5	--	--	-7.29	-3.34	--	--
AA Cf 152	390121076253301	39.02250000	-76.42583333	22	-22.80	-14.18	--	--	--	--
AA Cg 8	390125076240502	39.02372242	-76.40106975	17.8	--	-8.92	--	-6.38	-4.14	-1.36
AA Dc 13	385800076410301	38.96677791	-76.68385556	123.45	--	--	23.07	27.01	25.23	38.32
AA Dc 15	385928076414601	38.99122176	-76.69580059	109.99	32.79	33.09	32.85	34.06	34.57	35.98
AA Dc 16	385637076400801	38.94372296	-76.66857704	92.19	--	--	16.61	22.66	25.81	28.15
AA Dc 20	385637076400802	38.94372296	-76.66857704	92.19	15.16	19.01	--	--	--	--
AA Dd 24	385722076385701	38.95622280	-76.64885427	162.46	--	--	13.02	19.35	20.94	25.31
AA Dd 37	385807076351901	38.96872286	-76.58829686	132.93	-6.04	-2.46	-5.73	3.42	3.30	8.33
AA Dd 40	385511076373101	38.91983489	-76.62496401	135.79	0.9	5.51	2.59	10.71	16.75	21.97
AA Dd 42	385808076373502	38.96900041	-76.62607589	105.48	6.67	10.37	10.30	14.92	16.15	20.16
AA De 1	385915076340401	38.98761141	-76.56718545	13.72	-21.81	-13.37	-30.35	-16.92	-27.84	-25.48
AA De 75	385758076342702	38.96622300	-76.57385189	67.17	--	-1.83	-6.42	0.93	0.87	4.14
AA De 101	385512076331601	38.92011312	-76.55412796	49.42	--	-4.68	-5.85	1.73	2.73	8.96
AA De 103	385512076331603	38.92011312	-76.55412796	49.67	-9.87	-4.90	-6.09	1.47	2.42	8.56
AA De 107	385720076302804	38.95566809	-76.50746049	41.17	--	-8.83	-12.58	-4.16	1.22	1.70
AA De 113	385929076324901	38.99150031	-76.54662935	89.89	--	--	--	--	-7.85	-4.61
AA De 124	385528076334601	38.92455741	-76.56246171	27.84	-7.73	--	--	5.52	3.89	10.05
AA De 125	385526076334801	38.92400186	-76.56301727	31.74	--	-4.73	-6.35	1.63	2.44	8.52

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Magothy aquifer—Continued										
AA De 135	385932076344401	38.99233346	-76.57857479	48.8	--	--	-10.99	-1.38	-2.54	--
AA Df 20	385916076270702	38.98788963	-76.45162640	21.87	-17.12	-11.43	-13.71	-8.25	-9.40	-3.27
AA Df 64	385909076281704	38.98594520	-76.47107136	30.93	--	-12.46	-19.46	-10.81	-14.05	-6.54
AA Df 79	385905076293601	38.98483408	-76.49301641	5.17	-16.77	-10.62	-16.14	-7.29	-11.06	-4.30
AA Df 82	385953076280201	38.99816712	-76.46690492	87.77	-20.42	-10.54	-17.97	-9.46	-12.60	-5.11
AA Df 84	385518076282701	38.92178016	-76.47384740	7.32	-22.51	-15.84	-17.33	--	-1.94	4.96
AA Df 87	385934076274301	38.99288949	-76.46162684	19.86	-18.17	-9.81	-15.93	-7.86	-10.16	-0.42
AA Df 102	385726076284201	38.95733480	-76.47801519	22.12	--	-10.57	-12.80	-5.26	--	--
AA Ec 6	385122076405801	38.85622480	-76.68246566	55.07	-3.46	1.84	-0.32	6.76	12.32	15.76
AA Ed 39	385210076371002	38.86955831	-76.61912966	176.47	-3.33	0.86	0.42	7.74	10.06	--
AA Ed 65	385406076383902	38.90177962	-76.64385339	110	3.03	6.70	--	--	--	--
AA Ee 65	385306076301501	38.88511434	-76.50384727	27.19	-11.20	-7.66	-6.30	0.21	2.06	8.24
AA Fc 34	384833076415601	38.80928124	-76.69857717	51	-2.34	1.99	--	--	--	--
AA Fe 47	384843076312601	38.81206046	-76.52356842	6.36	-11.02	-7.83	-5.21	1.00	4.61	9.72
AA Fe 51	384917076305801	38.82150473	-76.51579051	8.5	-12.96	-9.28	--	--	--	--
AA Fe 56	384731076325501	38.79206074	-76.54829142	9	--	-10.88	--	--	--	--
AA Fe 93	384644076331202	38.77900546	-76.55301359	9	-14.65	-10.19	--	--	--	--
CA Ba 8	384401076404902	38.73372759	-76.67996440	59.16	-19.51	-12.37	-10.01	-2.93	-0.83	-8.75
CA Bb 10	384028076354201	38.67456310	-76.59468126	186.9	-32.57	-25.65	-19.60	-11.34	-7.56	-1.80
CA Bb 23	384458076375501	38.74956097	-76.63162850	146.86	-19.69	-13.08	-12.01	-4.63	0.91	6.74
CA Bb 25	384109076391101	38.68595130	-76.65274014	119.78	-26.02	-20.76	-16.80	-11.87	-3.52	5.98
CA Cc 56	383934076320001	38.65956383	-76.53301106	96.11	-33.83	-27.31	-20.02	-12.19	-5.02	2.53
CA Dc 35	383050076305501	38.51401138	-76.51495340	91.6	-35.50	-28.33	-20.67	-12.59	-6.24	0.47
CH Be 17	383502076565101	38.58400842	-76.94719515	204.23	-66.88	-60.86	-57.32	--	-41.92	--
CH Be 40	383553076562001	38.59817470	-76.93858384	209	--	-66.21	-60.69	-43.67	-45.05	--
CH Be 43	383819076555501	38.63872909	-76.93163942	216.79	-70.42	-60.09	-52.81	-46.85	-40.03	-32.34
CH Be 48	383649076554701	38.61372983	-76.92941698	207	--	-66.90	-62.63	-46.24	-49.78	--
CH Be 61	383855076562703	38.64872876	-76.94052864	220	--	--	-49.34	--	--	--
CH Bf 98	383739076543001	38.62761839	-76.90830529	216.39	-65.19	-56.83	-63.42	-44.86	-47.06	-29.06
CH Bf 101	383853076532601	38.64817341	-76.89024933	216.45	--	-50.47	-50.27	-33.52	-39.69	-25.57
CH Bf 124	383750076540801	38.63067388	-76.90191623	207.78	-76.11	--	-62.86	-45.96	-45.76	-31.37
CH Bf 132	383643076505201	38.61206353	-76.84746992	200	-54.92	-45.83	-46.04	-26.66	-33.36	-16.20
CH Bf 133	383640076545901	38.61122996	-76.91608320	223.5	-80.28	-68.91	-62.76	-46.44	-54.62	-31.98
CH Bf 134	383728076531701	38.62456301	-76.88774907	202.09	-88.95	-63.61	-57.70	-35.39	-48.52	-46.76
CH Bf 135	383814076500301	38.63734061	-76.83385862	207.82	-47.65	-36.94	-30.99	-9.60	-13.01	-15.86

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
				Magothy aquifer—Continued						
CH Bf 143	383918076522201	38.65511772	-76.87247107	206.59	-59.73	-51.06	-45.51	-26.64	-47.60	-18.43
CH Bf 145	383558076524501	38.59956378	-76.87885971	203	--	-58.70	-62.61	-38.25	-46.60	--
CH Bf 160	383913076510202	38.65372896	-76.85024816	202.2	--	-49.83	-45.91	--	--	--
CH Bg 10	383702076475001	38.61734135	-76.79691282	196.18	--	-37.07	-32.91	-23.02	-21.60	-4.26
CH Cf 29	383219076503502	38.53873238	-76.84274687	178.02	-59.09	-49.46	-41.66	-29.83	-27.64	-12.42
CH Cf 31	383301076531101	38.55039854	-76.88608178	165	-63.12	-50.76	-45.61	-30.54	-30.10	--
DO Ce 15	383408076042402	38.56900759	-76.07299564	6	-8.71	-5.76	-6.55	-9.86	-7.77	-7.94
KE Cb 97	391124076101001	39.19010967	-76.16911738	65.84	6.28	7.66	7.63	--	--	--
PG Cf 33	385806076435303	38.96844427	-76.73107937	115.4	46.62	50.45	48.84	52.38	51.31	--
PG Cf 79	385831076432102	38.97538862	-76.72219021	145	--	42.88	42.07	--	--	--
PG De 21	385130076465501	38.85844637	-76.78163628	95.76	33.64	35.83	35.34	40.69	42.03	47.94
PG De 32	385323076471801	38.88983461	-76.78802541	131.85	50.82	52.77	51.97	55.78	57.10	61.34
PG Df 34	385037076430901	38.84372478	-76.71885614	84.78	5.65	8.83	8.45	16.67	20.11	--
PG Df 36	385029076430201	38.84150262	-76.71691159	64.98	--	8.53	7.29	15.58	18.88	--
PG Ed 50	384715076522001	38.78761419	-76.87191639	240.88	16.49	21.82	2.75	25.87	--	--
PG Ef 34	384623076424001	38.77317080	-76.71079980	39.18	-7.11	-2.76	-0.15	6.77	9.08	16.84
PG Ef 40	384847076440401	38.81316975	-76.73413453	79.85	1.55	5.53	--	14.07	16.50	23.40
PG Fd 32	384148076510901	38.69678323	-76.85219305	230.94	-25.52	-21.56	-17.57	-6.34	-7.89	7.51
PG Fd 39	384410076502501	38.73622655	-76.83997085	233.42	-8.58	-5.11	-4.24	2.67	7.26	17.91
PG Fd 41	384131076533301	38.69206100	-76.89219417	196.92	-28.95	-22.36	-15.96	-8.88	-10.32	3.78
PG Fe 30	384453076482101	38.74817077	-76.80552559	237.59	-7.74	-1.87	1.25	7.28	4.79	19.64
PG Ge 15	383940076461301	38.66122904	-76.76996804	210.51	-29.89	-25.06	-20.06	-10.44	-9.14	5.03
PG Gf 35	383832076414701	38.64234108	-76.69607538	34.96	-31.06	-25.01	-18.65	-10.73	-5.43	5.56
PG Hf 33	383250076405302	38.54734373	-76.68107351	10.36	--	--	-64.77	-54.27	-63.46	-189.43
PG Hf 36	383248076405302	38.54678819	-76.68107350	11.69	--	-69.92	-69.77	-58.72	-73.53	-74.46
PG Hf 41	383348076411302	38.56345439	-76.68662954	28.3	-49.90	-43.74	-41.88	-32.80	--	--
QA Ea 27	385718076205501	38.95400183	-76.34801133	18.27	-14.43	-11.00	-8.89	-3.48	--	3.77
				Upper Patapsco aquifer						
AA Ad 108	391032076385906	39.17566368	-76.64941189	78.31	71.39	71.75	70.13	71.70	69.63	--
AA Bd 99	390604076354501	39.10122060	-76.59552052	137	53.39	46.68	49.49	53.15	52.30	58.73
AA Bd 159	390737076374402	39.12705338	-76.62857740	75.48	38.15	36.50	33.10	36.55	37.82	--
AA Be 102	390559076312602	39.09983209	-76.52357362	36.36	9.96	8.21	7.74	9.62	7.61	10.87
AA Bf 3	390945076285601	39.16260912	-76.48190574	20.38	6.07	6.77	5.76	7.00	4.98	4.91
AA Cc 43	390422076414501	39.07288717	-76.69552364	180	121.55	118.25	119.04	120.52	126.88	126.45
AA Cc 116	390103076402602	39.01761031	-76.67357794	134.35	7.61	15.92	26.41	25.85	42.39	45.35
AA Cc 127	390122076434601	39.02288773	-76.72913525	135	--	56.11	59.92	--	--	--
AA Cc 131	390126076413404	39.02399901	-76.69246747	102	34.74	38.55	39.93	--	--	--
AA Ce 70	390115076303002	39.02094444	-76.50801734	18.2	-25.09	-6.85	-15.51	-8.03	-13.88	-2.80

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Upper Patapsco aquifer—Continued										
AA Ce 120	390303076344301	39.05094364	-76.57829744	161.8	7.70	7.69	6.58	9.52	9.62	11.87
AA Ce 137	390043076345402	39.01205531	-76.58135287	57.5	0.17	1.67	4.85	--	--	--
AA Cf 119	390203076292801	39.03427764	-76.49079463	131.03	--	-19.40	-36.18	-26.43	--	--
AA Cf 120	390203076292301	39.03427764	-76.48940570	125.98	--	--	--	-36.38	--	-21.02
AA Cf 121	390149076261701	39.03038892	-76.43773751	20	-23.48	-13.77	-19.83	-15.20	-17.11	-6.23
AA Cf 128	390149076261703	39.03038892	-76.43773751	14	--	--	-18.10	-11.90	-13.79	-6.03
AA Cf 134	390121076270501	39.02261122	-76.45107122	24	-24.43	-12.13	-18.74	-13.54	-13.95	--
AA Cg 24	390123076241603	39.02316687	-76.40412540	12.68	-15.35	-9.59	-11.08	-6.36	-6.32	-0.97
AA De 95	385853076333001	38.98150050	-76.55801837	73.2	-20.65	-23.77	-35.22	-14.46	-11.04	-8.30
AA De 128	385530076334701	38.92511295	-76.56273951	28.31	-9.02	-4.11	-5.45	2.32	4.54	11.45
AA De 199	385753076310801	38.96483446	-76.51857223	35	-17.79	-12.61	-18.05	-9.00	--	--
AA De 205	385628076323102	38.94122380	-76.54162799	33.46	-11.87	-6.57	-8.61	-2.54	--	--
AA Df 19	385921076270701	38.98955626	-76.45079309	15.84	-20.10	-11.79	-17.30	-8.50	-10.99	-3.22
AA Df 65	385913076281401	38.98705629	-76.45079309	15.84	--	-49.71	-63.01	--	-50.80	--
AA Df 89	385934076274302	38.99288949	-76.46162684	20.58	-19.39	-11.77	-12.85	-8.69	-14.72	-2.93
AA Df 99	385905076293604	38.98483408	-76.49301641	5.17	-23.17	-25.46	-27.28	-21.26	--	--
AA Df 100	385905076293603	38.98483408	-76.49301641	5.17	-16.61	-10.04	-16.12	-7.35	--	--
AA Ec 12	385125076404801	38.65956383	-76.68000000	55	0.22	4.00	--	--	--	--
CA Cc 55	383934076320201	38.65956383	-76.53356665	95.98	-17.80	-13.25	-8.62	-2.67	2.14	8.64
CH Be 60	383706076575604	38.61845178	-76.96525147	212.8	-51.61	-40.34	-31.30	-22.13	--	--
CH Bf 151	383508076540703	38.58567521	-76.90163812	192.8	-69.62	-56.57	-57.13	-39.23	-38.50	--
CH Bf 157	383637076545803	38.61122996	-76.91608320	225	-76.01	-61.11	-59.40	-44.70	--	--
CH Bf 158	383732076531902	38.62484077	-76.88830465	193	-52.76	-47.15	-40.51	-29.98	--	--
CH Cd 31	383222077004401	38.53956505	-77.01191924	130	-88.31	-70.02	-64.71	--	--	--
CH Cd 43	383328077010201	38.55789784	-77.01691945	68	-142.07	-127.83	-113.28	--	--	--
CH Ce 16	383217076590201	38.53817629	-76.98358503	188	--	-95.75	-86.16	--	--	--
CH Ce 30	383149076583801	38.53039876	-76.97691810	190	-92.00	-88.58	-91.42	--	--	--
CH Ce 50	383420076592501	38.57234193	-76.98997428	205	-69.55	-58.44	-54.45	-50.85	-43.85	-18.85
CH Cg 24	383254076481401	38.54845447	-76.80357896	171.04	-52.77	--	--	--	--	--
CH Da 21	382659077152401	38.44984513	-77.25636926	88	-15.20	-12.24	-9.86	-5.71	-2.24	-0.75
CH Dd 33	382607077002601	38.41929093	-76.99969605	99.8	-33.79	-26.20	-18.42	-9.68	-3.70	0.89
CH Dd 38	382925077010101	38.49039984	-77.01664135	60	--	-61.45	-52.32	--	--	--
CH Fe 5	381803076550801	38.30096131	-76.91858214	12	-55.09	-36.79	-36.90	--	--	--
DO Ce 88	383401076032001	38.56706296	-76.05521730	4.42	--	-8.99	-11.25	-12.17	-11.25	--
KE Cb 36	391400076101401	39.23344244	-76.17022876	40	-2.41	-0.45	0.56	2.57	4.16	--

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Upper Patapsco aquifer—Continued										
KE Cb 103	391124076101005	39.19010967	-76.16911738	65.6	-5.61	-3.34	-2.22	--	--	--
KE Db 40	390837076140401	39.14372123	-76.23412034	15	-5.68	-4.70	-2.53	0.79	--	3.39
PG Cf 25	385529076443101	38.92483401	-76.74163517	106.29	--	--	37.48	--	46.39	50.47
PG De 33	385323076471802	38.88983461	-76.78802541	103.68	54.24	56.02	55.12	58.80	59.92	63.90
PG Ec 31	384616076570401	38.77122535	-76.95080738	256.04	-6.15	3.22	6.02	--	25.37	27.10
PG Fb 36	384423077004501	38.73983694	-76.95080738	78	-24.4	-16.83	-13.3	-4.15	5.81	7.6
PG Hf 38	383248076405303	38.54678819	-76.68107350	11.6	-41.18	-34.57	-45.04	-36.98	-10.73	-9.9
PG Hf 40	383348076411301	38.56345439	-76.68662954	27.98	-41.26	-36.40	-31.49	-23.55	--	--
PG Hf 44	383250076405304	38.54734373	-76.68107351	10.48	-53.49	-35.41	-32.01	-23.54	-2.22	-3.83
QA Be 16	391203076024302	39.20094315	-76.04494493	25	-15.26	-8.94	-8.93	3.75	--	--
QA Eb 111	385751076171601	38.96427946	-76.28745430	14.03	-14.85	-11.47	-8.82	-2.57	-2.26	4.91
SM Df 84	381548076272102	38.26345833	-76.45550783	108.39	-47.79	-37.22	-26.48	-18.02	-10.22	--
SM Df 100	381721076264801	38.28916667	-76.44666667	21	-46.29	-36.79	--	--	--	--
SM Ff 36	380724076251901	38.12318216	-76.42189528	5.5	-36.14	-28.58	-20.47	-14.10	--	--
TA Cd 57	384709076050301	38.78594908	-76.08383090	12	--	-47.73	-34.25	--	--	--
Lower Patapsco aquifer										
AA Ad 102	391032076385904	39.17566368	-76.08383090	12	4.15	3.08	5.51	2.22	-2.36	--
AA Ad 109	391006076380101	39.16844164	-76.63330012	35.78	39.44	39.61	38.00	38.01	27.38	--
AA Bc 176	390736076421602	39.12677523	-76.7041356	188.5	48.91	54.45	50.31	56.19	60.5	69.68
AA Bc 215	390700076412601	39.11677544	-76.69024614	124	37.53	43.25	38.48	44.02	--	--
AA Bd 37	390848076363601	39.14677541	-76.60968798	38.2	11.40	10.21	6.84	16.22	13.98	-21.38
AA Bd 56	390950076384001	39.16399721	-76.64413382	61.6	54.16	53.66	51.10	49.46	40.64	-59.44
AA Bd 101	390855076373402	39.14871975	-76.62579969	55	33.31	31.07	25.05	26.66	23.93	-24.53
AA Bd 105	390810076380702	39.13621988	-76.63496659	90	--	51.94	46.83	--	49.45	11.20
AA Bd 108	390917076381401	39.15483071	-76.63691125	70	--	--	36.09	36.71	32.53	-76.19
AA Bd 109	390845076385801	39.14594189	-76.64913385	190	--	63.07	61.20	59.10	59.07	-11.59
AA Bd 152	390821076365401	39.13927550	-76.61468811	53.29	26.55	24.04	20.65	23.85	23.01	--
AA Bd 155	390938076383701	39.16066393	-76.64330042	57.5	48.92	48.38	46.06	39.83	33.73	--
AA Bd 156	390922076371001	39.15621967	-76.61913284	68.99	23.02	25.19	19.06	20.53	17.04	--
AA Bd 157	390922076371001	39.15621967	-76.62857740	75.75	38.75	36.62	33.36	36.39	36.05	--
AA Bd 158	390744076390001	39.12899769	-76.64968928	108.25	60.41	56.96	53.50	56.13	55.08	--
AA Bd 160	390908076394402	39.15233062	-76.66191214	88	76.33	74.50	71.28	73.14	70.50	--
AA Bf 99	390654076283601	39.11510983	-76.47634993	40	-10.05	--	--	--	--	--
AA Cc 40	390423076432001	39.07316481	-76.72191340	136.92	88.35	87.11	86.39	88.17	88.01	89.59
AA Cc 82	390422076414505	39.07288717	-76.69552364	178.39	56.78	57.79	54.22	59.47	63.76	48.48
AA Cc 89	390010076415703	39.00288817	-76.69885633	52.77	13.15	14.54	11.87	24.00	41.55	42.38

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Lower Patapsco aquifer—Continued										
AA Cc 115	390103076402601	39.01761031	-76.67357794	134.38	-12.18	-11.17	-17.67	9.55	41.27	44.09
AA Cc 137	390126076402901	39.02399910	-76.67441136	115.34	14.21	21.03	22.66	--	--	--
Aa Cd 128	390327076363701	39.05761005	-76.60996516	110	18.12	--	--	--	--	--
AA Ce 94	390450076343503	39.08066544	-76.57607530	90	-91.46	-76.77	-62.20	-42.15	-35.32	-104.34
AA Ce 124	390303076344303	39.05094364	-76.57829744	160	-13.29	-11.81	-13.07	0.87	-5.00	9.06
Aa Ce 136	390043076345401	39.01205531	-76.58135287	60	-15.52	-12.07	-2.38	--	--	--
AA Cf 137	390205076292702	39.03483319	-76.49051685	124.3	-11.78	-50.60	-56.10	--	--	--
AA Cg 23	390123076241602	39.02316687	-76.40412540	12.57	-13.02	-20.34	-14.24	-2.30	3.04	7.06
AA De 177	385852076333201	38.98122272	-76.55857393	93.85	--	--	-20.73	-4.03	--	--
AA De 206	385833076332801	38.97594508	-76.55746267	81.74	-49.61	-18.51	-18.50	--	--	--
BA Gf 168	391257076282501	39.21594170	-76.47329448	10	--	--	-1.70	-0.55	-0.19	-0.89
BA Gf 178	391226076253401	39.20733088	-76.42579307	6	--	--	-0.22	1.28	1.98	1.43
Ca Fd 85	382236076255401	38.37679040	-76.43133979	105.98	-18.91	--	--	--	--	--
CH Bb 17	383524077111802	38.59011884	-77.18803553	52	--	-57.49	-64.32	-62.45	--	--
CH Bc 5	383524077094401	38.59011888	-77.16192368	38.2	--	--	--	-81.73	-69.77	--
CH Bc 24	383633077083001	38.60928501	-77.14136773	72	-121.70	-108.65	-112.75	-88.04	--	--
CH Bc 67	383606077092101	38.60178521	-77.15553473	30	-73.81	-79.32	-83.10	--	--	--
CH Bc 76	383754077051201	38.63178443	-77.08636630	171	-138.17	-116.28	-112.25	--	--	--
CH Bc 81	383709077061002	38.61928477	-77.10247779	156.46	-130.95	-111.55	--	-81.54	--	--
CH Bd 22	383740077043501	38.62789568	-77.07608819	175	-118.95	-108.44	-118.52	--	--	--
CH Bd 29	383805077045201	38.63483991	-77.08081060	170	-138.58	-115.95	-111.30	--	--	--
Ch Bd 35	383825077042601	38.64789509	-77.07358825	170	--	-112.32	-104.17	--	--	--
CH Bd 49	383617077015702	38.60484088	-77.03219788	183	-142.20	-114.52	-103.55	--	--	--
CH Bd 50	383734077044901	38.62622905	-77.07997718	180	-133.35	-110.18	-107.90	--	--	--
CH Bd 51	383715077014901	38.62095152	-77.02997567	185	--	-122.91	-98.25	--	--	--
CH Be 58	383706076575602	38.61845178	-78.96525150	212.5	-182.15	-152.91	-150.17	--	-24.10	--
CH Be 64	383553076562002	38.59817470	-76.93858384	209	-198.01	-147.21	-160.65	--	--	--
CH Bf 146	383508076540701	38.58567521	-76.90163812	192.8	-135.24	-130.87	-126.39	-94.53	-36.50	--
CH Bf 150	383901076524301	38.65039561	-76.87830454	215	--	-89.63	-86.21	--	-13.00	--
CH Cb 7	383422077114601	38.57289712	-77.19581333	36	-30.24	-36.31	-45.86	-49.42	-44.32	-37.62
CH Cb 11	383313077125401	38.55428654	-77.21470251	10	-49.18	-50.34	-46.80	-39.30	--	--
CH Cb 28	383315077131401	38.55484207	-77.22025822	5	-44.99	-43.99	-44.82	-43.10	--	--
CH Cb 38	383328077114201	38.55789757	-77.19470201	4	-60.26	--	-73.18	-73.25	--	--
CH Cb 42	383328077111702	38.55789758	-77.18775738	5	-81.08	-90.37	-91.56	--	--	--
CH Cc 31	383455077074401	38.58206362	-77.12858934	35	-99.65	-93.36	--	--	--	--

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29					
		Latitude	Longitude		2005	2000	1995	1990	1985	1980
Lower Patapsco aquifer—Continued										
CH Cd 42	383256077015301	38.54900919	-77.03108645	185	-110.56	-87.36	-76.75	--	--	--
CH Ce 35	383111076584801	38.51984351	-76.97969592	165	-123.31	-106.86	-98.82	--	--	--
CH Ce 37	383236076563901	38.54345407	-76.94386147	184.95	-126.25	-114.59	-121.42	-67.64	-32.36	-12.83
CH Ce 51	383111076570701	38.51984362	-76.95163939	150	--	-97.44	-94.68	--	--	--
CH Ce 53	383420076592504	38.57234193	-76.98997428	205	-100.55	-85.05	-73.70	--	--	--
CH Ce 56	383251076583901	38.54762048	-76.97719596	196.48	-180.41	-120.51	--	--	--	--
CH Da 20	382654077152701	38.44845629	-77.25720260	90	-14.80	-11.45	-9.22	-4.89	-1.26	0.31
CH Ee 70	382154076574801	38.36568153	-76.96386135	22.83	-104.62	-90.68	-95.96	-88.58	-82.15	-87.39
CH Ee 78	382240076582801	38.37790336	-76.97413948	75	-82.19	-79.90	-70.61	-66.83	-55.18	--
CH Ff 60	381806076545401	38.30179462	-76.91469316	12	-53.30	-38.40	-41.00	--	--	--
PG Be 14	390226076481001	39.04066508	-76.80247095	155	111.55	110.40	--	111.83	111.64	113.91
PG Be 15	390253076482801	39.04816496	-76.80747117	145	--	103.27	111.55	104.66	102.85	105.45
PG Cf 32	385806076435302	38.96844427	-76.73107937	115.4	15.17	16.72	12.64	37.71	--	47.64
PG Cf 44	385944076433801	38.99566594	-76.72691267	44.34	--	37.01	31.47	43.52	50.43	58.37
PG Cf 76	385757076440402	38.96594431	-76.73413502	127.61	12.86	14.72	13.10	39.89	43.11	48.80
PG Cf 78	385831076432101	38.97538862	-76.72219021	145	--	21.56	17.56	--	--	--
PG Ed 34	384933076530001	38.82594675	-76.88302793	270	-1.74	4.16	10.92	20.19	32.13	35.04
PG Fc 17	384230076555501	38.70844926	-76.93163985	58.6	--	-35.12	-25.74	-7.80	4.60	8.76
PG Gd 5	383957076520601	38.66595075	-76.86802658	216.43	--	-76.33	-68.92	--	--	--
PG Hf 32	383250076405303	38.54734373	-76.68107351	10.48	-39.61	-32.22	-24.10	-12.14	1.78	7.55
QA Be 15	391203076024301	39.20094315	-76.04494493	25	-2.56	0.42	2.18	5.35	7.07	--
QA Eb 112	385751076171602	38.96427946	-76.28745430	13.92	-18.21	-16.97	-5.08	0.74	4.71	7.60
SM Bc 39	382605076430201	38.43484663	-76.71690860	161.54	-34.17	--	--	--	--	--
SM Dd 72	381626076393401	38.27391667	-76.65966667	109.99	-25.81	--	--	--	--	--

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29		
		Latitude	Longitude		2005	2004	2003
Piney Point-Nanjemoy aquifer							
CA Db 86	383152076361701	38.53123315	-76.60440265	162.00	31.03	--	--
CA Ed 32	382527076280801	38.42429009	-76.46856306	100.00	-58.46	--	--
CA Ed 49	382733076290101	38.45928980	-76.48328557	100.00	-39.18	--	--
CA Fd 51	382408076260401	38.40234566	-76.43411756	129.40	-2.29	--	--
CA Fe 22	382318076242401	38.38845673	-76.40633888	113.90	-22.33	--	--
DO Bg 59	383708075503801	38.61900455	-75.84354571	25.00	-23.01	--	--
DO Cd 1	383151076080801	38.53095325	-76.13521954	4.00	--	-44	--
DO Ce 5	383340076041601	38.56122989	-76.07077331	18.00	--	-54.9	--
DO Db 17	382800076180701	38.46678876	-76.30161313	12.70	-8.7	--	--
QA Df 62	390039075560201	39.01094609	-75.93354928	16.23	--	--	23.77
SM Bb 22	382838076470102	38.47734550	-76.78330006	165.20	143.12	--	--
SM Dd 46	381616076364701	38.27123805	-76.61273761	118.84	-9.77	--	--
SM Dd 62	381616076364703	38.27123805	-76.61273761	115.00	-14.37	--	--
SM Dd 63	381615076364701	38.27096027	-76.61273761	119.72	-10.66	--	--
SM Df 14	381719076264801	38.28901355	-76.44634070	17.71	--	-17.02	--
SM Df 66	381841076284401	38.31151356	-76.47856402	15.00	-24.45	--	--
SM Dg 20	381718076234001	38.28901316	-76.39467205	12.00	-23.02	--	--
SM Dg 21	381810076244601	38.30290205	-76.41189489	3.00	-21.21	--	--
SM Dg 22	381731076242401	38.29206877	-76.40633916	12.00	-27.59	--	--
SM Dg 24	381728076234601	38.29111111	-76.39611111	20.00	--	-13.94	--
SM Ef 89	381418076293601	38.23833333	-76.49333333	45.00	-36.33	--	--
SM Eg 27	381213076222801	38.20373615	-76.37411566	10.00	-23.53	--	--
SM Fe 30	380834076303401	38.14290512	-76.50912114	9.00	-18.01	--	--
SM Fg 45	380711076222201	38.11984827	-76.37244872	65.00	-27.87	--	--
TA Bf 73	385242075593101	38.87761384	-75.99299482	42.00	22.26	--	--
TA Cc 35	384923076100601	38.82317143	-76.16800162	5.00	-3.01	--	--
TA Cc 36	384514076103701	38.75400634	-76.17661163	7.00	--	-5.94	--
Patuxent aquifer							
AA Ac 11	391101076404001	39.18371898	-76.67746857	132.28	4.62	--	--
AA Ad 29	391015076373501	39.17094164	-76.62607765	75.1	-38.1	--	--
AA Ad 90	391032076385902	39.17566368	-76.64941189	127.78	-49.93	--	--
AA Bb 67	390538076453001	39.09399768	-76.75802591	121.79	11.21	--	--
AA Bc 163	390524076442501	39.09010891	-76.73996976	164.85	-29.74	--	--

Appendix 3. Southern Maryland ground-water-level data used in this report.—Continued

[All depth and elevation measurements are in feet. Land and water elevations are measured from the National Geodetic Vertical Datum of 1929 (NGVD29). Digital latitude and longitude measured with respect to North American Datum 1983 (NAD83); --, no data]

Well name	USGS ID	Location NAD83		Land elevation	Water levels in feet relative to NGVD29		
		Latitude	Longitude		2005	2004	2003
Patuxent aquifer—Continued							
AA Bc 235	390513076434401	39.08705346	-76.72858045	131.28	-1.28	--	--
AA Bc 240	390752076441001	39.13121945	-76.73580346	233.75	26.25	--	--
AA Bd 57	390952076384102	39.16455276	-76.64441161	235.23	-165.23	--	--
AA Bd 179	390946076391601	39.16277778	-76.65444444	205.13	-118.13	--	--
AA Bd 182	390839076385703	39.14433333	-76.64933333	198.35	-18.35	--	--
AA Cb 1	390303076463201	39.05094274	-76.77524807	92.35	36.75	--	--
AA Cc 80	390422076414503	39.07288717	-76.69552364	133.26	45.11	--	--
AA Cc 81	390422076414504	39.07288717	-76.69552364	130.23	48.15	--	--
AA Cc 102	390004076420001	39.00122153	-76.69968967	64.72	-10.76	--	--
AA Cc 113	390256076413101	39.04899865	-76.69163437	156.03	-4.14	--	--
AA Cc 119	390437076432302	39.07705364	-76.72274680	135.92	3.08	--	--
AA Cc 121	390456076432501	39.08233134	-76.72330244	139.57	-20.57	--	--
AA Cc 124	390419076432301	39.07205371	-76.72274674	128.9	1.1	--	--
AA Cc 135	390126076403001	39.02399910	-76.67468914	141.17	-26.36	--	--
AA Ce 117	390450076343402	39.08066544	-76.57579752	90.05	-4.05	--	--
AA Cg 22	390123076241601	39.02316687	-76.40412540	20.29	-7.68	--	--
AA De 203	385854076333202	38.98177826	-76.55857394	100.96	-6.57	--	--
CH Bc 75	383645077062401	38.61261830	-77.10636674	156.13	-31.54	--	--
CH Bc 77	383644077055501	38.61234054	-77.09831095	128.52	-31.88	--	--
CH Bc 78	383809077053401	38.63595096	-77.09247762	50.96	-30.83	--	--
CH Bc 80	383645077062402	38.61261830	-77.10636674	145.20	--	-22.07	--
CH Bd 52	383553077032401	38.59817437	-77.05636520	78.30	-30.8	--	--
CH Be 57	383706076575601	38.61845178	-76.96525147	222.78	-10.52	--	--
CH Cc 34	383441077063901	38.57817487	-77.11053325	76.12	-34.3	--	--
CH Ce 57	383250076584001	38.54734271	-76.97747375	203.22	-9.75	--	--
CH Da 18	382654077152501	38.44845629	-77.25664704	96.40	-6.5	--	--
PG Bc 16	390151076561501	39.03094285	-76.93719695	22.83	167.17	--	--
PG Be 23	390213076471301	39.03705404	-76.78663712	88.23	31.77	--	--
PG Cf 66	385745076445201	38.96261097	-76.74746879	151.22	-1.15	--	--
PG Cf 81	385745076445202	38.96261097	-76.74746879	138	-20.65	--	--
PG Fd 62	384309076511401	38.71928256	-76.85358218	230.3	-1.7	--	--
QA Eb 110	385751076171603	38.96427946	-76.28745430	11.17	2.81	--	--

Note: The Patuxent and Piney Point-Nanjemoy potentiometric surface maps were generated for 2005 only. Water-level data from 2005 were used when available; some data from 2004 and occasionally from 2003 were used when necessary.

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