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

REPORT OF INVESTIGATIONS NO. 76

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

by

David D. Drummond

Prepared in cooperation with the
Boards of County Commissioners of
Calvert, Charles, and St. Mary's Counties
and the
United States Department of the Interior
Geological Survey

2007

State of Maryland

Martin O'Malley
Governor

Anthony G. Brown
Lieutenant Governor

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

Maryland Department of
Natural Resources

John R. Griffin
Secretary

REPORT OF INVESTIGATIONS NO. 76

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

by

David D. Drummond

Prepared by Maryland Geological Survey
Jeffrey P. Halka, Acting Director
in cooperation with the
Boards of County Commissioners of Calvert, Charles, and St. Mary's Counties
and the
United States Department of the Interior, Geological Survey
Publication Number DNR-12-882007-236

August 2007

CONTENTS

CONTENTS—CONTINUED

ILLUSTRATIONS

ILLUSTRATIONS—CONTINUED

ILLUSTRATIONS—CONTINUED

ILLUSTRATIONS—CONTINUED

TABLES

TABLES—CONTINUED

APPENDIXES

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

by

David D. Drummond

EXECUTIVE SUMMARY

A study was conducted of the water-supply potential of the aquifer system in Calvert, Charles, and St. Mary's Counties. The water needs of this area are supplied by the Piney Point, Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers. Declining water levels and elevated arsenic concentrations in the Aquia aquifer have prompted water-supply managers to consider shifting some ground-water withdrawals from the Aquia aquifer to the deeper Upper Patapsco and Lower Patapsco aquifers. This report presents an assessment of the potential for these aquifers to meet future water demands of the area, given several scenarios for ground-water development. Emphasis was placed on the Upper Patapsco and Lower Patapsco aquifers, for which critical information has been lacking, to assess their water-bearing properties throughout the region.

Data were collected from existing sources and from six test wells drilled during this project, on lithology, hydraulic parameters, geophysical logs, pumpage, water levels, and water quality. Hydrogeologic maps were constructed that show the structure, transmissivity, and head distribution of the Upper Patapsco and Lower Patapsco aquifers throughout Southern Maryland, and data for pumpage and water quality were tabulated. Connectivity of individual sand bodies within the Upper Patapsco and Lower Patapsco aquifers was demonstrated using sand-percentage analysis and hydraulic continuity relations. Hydrogeologic cross sections were also constructed to show the vertical distribution of aquifers and confining units in the region.

A ground-water flow model was developed that simulates water levels in five major aquifers in Southern Maryland. The flow model was calibrated using historical pumpage and water levels, and was then used to estimate future water levels through 2030 based on future pumpage scenarios compiled in conjunction with county planning departments. Flow-model scenarios were evaluated primarily based on the Maryland Department of the Environment regulated 80-percent management level, which restricts regional heads from declining to the tops of aquifers. Consideration was also given to the possibility of land subsidence; and of ground-water withdrawals in the deeper confined parts of aquifers reducing heads in the shallow unconfined parts of those aquifers, which may create the potential for stream-flow depletion, wetlands degradation, and river-water intrusion.

Flow-model simulations indicate that projected water demand in Calvert and St. Mary's Counties through 2030 could be met by increased pumpage from the Aquia aquifer without reducing water levels below the 80-percent management level. Shifting a portion of public-supply withdrawals from the Aquia aquifer to the Patapsco aquifers would result in an increase in available drawdown in the Aquia aquifer in many areas of Calvert and St. Mary's Counties, with minimal impact on future water levels in the Patapsco aquifers in Charles County.

In Charles County, withdrawals from the Magothy aquifer in the Waldorf area cannot be increased significantly above 2002 amounts without lowering water levels below the 80-percent management level by 2030. The relatively shallow depth of the Patapsco aquifers and the proximity of major pumping centers to outcrop/recharge areas limit productive capacity. Future pumpage scenarios result in drawdowns exceeding the 80-percent management level at several locations, such as Indian Head and La Plata.

Simulated future drawdowns indicate the potential for river-water intrusion into the Upper Patapsco and Lower Patapsco aquifers from the Potomac River in the Indian Head area. Simulated drawdowns also indicate the potential in shallow portions of the Patapsco aquifers for lowering the water table, which could reduce base flow to streams and reduce the amount of water available in wetlands where ground-water inflow provides moisture for plants. These issues could not be specifically addressed in the context of a large regional study, but require additional examination. Alternative water-supply options should be evaluated in Charles County, such as utilizing the Patuxent aquifer, or replacing current production well fields with new wells in the Patapsco aquifers located farther southeast.

INTRODUCTION

The water needs of Calvert, Charles, and St. Mary's Counties (referred to in this report as Southern Maryland) (fig. 1) are predominantly supplied by five major aquifers. From shallow to deep, these are the Piney Point, Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers (tab. 1). Declining water levels and water-quality issues in the Aquia aquifer have prompted water-supply managers to shift a portion of ground-water withdrawals from the Aquia aquifer to the deeper Upper Patapsco and Lower Patapsco aquifers. As of 2002, cones-of-depression have formed in the Aquia aquifer centered at Lexington Park (200 feet [ft] below sea level), the Magothy aquifer at Waldorf (90 ft below sea level), the Upper Patapsco aquifer at La Plata (136 ft below sea level), and the Lower Patapsco aquifer at La Plata (200 ft below sea level). Because of these concerns, a study was undertaken to assess the water-supply potential of these aquifers, and to provide water-supply managers with information necessary for long-term planning.

PURPOSE AND SCOPE

The purpose of this report is to present the conclusions of a 5-year study that focused on the water-supply potential of the Piney Point, Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers (the five major aquifers in Southern Maryland) (fig. 2). Information is included on the hydrogeology, population trends, and pumpage trends in Southern Maryland. A ground-water flow model was developed to simulate future ground-water conditions, and estimate the impact of projected pumpage on water levels in the study area. The Patuxent aquifer is described briefly, but is not included in the flow model. The bedrock units underlying the Coastal Plain aquifers are not addressed in this report. The results of the study are summarized and discussed with respect to the water-management issues of the major aquifers in Southern Maryland.

In addition to this Report of Investigations, a Basic Data Report is in preparation that will provide data collected from six exploratory test wells drilled into the Patapsco aquifer as a part of this study (fig. 3). An Administrative Report (Drummond, 2005) presented the background and conclusions of the study; some of the material from the Administrative Report is included in this report.

LOCATION OF STUDY AREA

The study area comprises three counties in Southern Maryland: Calvert, Charles, and St. Mary's Counties. This area is bounded by the Chesapeake Bay to the east, the Potomac River to the south and west, and Anne Arundel and Prince George's Counties to the north (fig. 1). The Commonwealth of Virginia lies across the Potomac River, and Washington, D.C. is about 15 miles (mi) to the north. The total area of the three counties is 1,044 square miles (mi^2). The area of the ground-water flow model extends from 76°00' to 77°30' longitude, and 37°50' to 39°00' latitude, and is 6,642 mi^2.

METHODS OF INVESTIGATION

The hydrogeology of the study area was investigated in three phases: data collection for six deep test wells drilled through the Patapsco Formation; interpretation of test-well data and incorporation of the data into a regional aquifer framework; and development of a ground-water flow model. Well-construction information for selected wells cited in this report is tabulated in Appendix A. Six test wells were drilled in cooperation with the U.S. Geological Survey (USGS) as a part of this study to obtain hydrogeologic information on the Upper Patapsco and Lower Patapsco aquifers in Southern Maryland. Well-construction information is summarized in table 2. Two wells were drilled in each county; four were screened in the Lower Patapsco aquifer, and two were screened in the Upper Patapsco aquifer (fig. 2). Each well was drilled to a depth of about 1,650 ft, into the Lower Patapsco aquifer, and sediment samples were collected at 10-foot or 20-foot intervals to describe lithologies and to investigate the age and depositional environment of the sediments using microfossil analysis. Geophysical logging (gamma-radiation, spontaneous potential, single-point resistance, and multi-point resistivity) was conducted on the uncased boreholes, and screen depths were chosen based primarily on geophysical logs.

An aquifer test, consisting of a 24-hour pumping phase and 24-hour recovery phase, was conducted to determine transmissivity and specific capacity for each well. Water samples were obtained near the end of each pumping interval for chemical analysis. Continuous water-level recorders were installed on the six wells to determine short-term fluctuations and long-term trends. The recorders were removed in late 2005; periodic measurements will be taken to document future water-level trends.

Drill cuttings from the test wells were described in the field and selected samples were further examined with a binocular microscope. Selected subsamples were sent to Dr. Gilbert Brenner of the State University of New York at New Paltz for analysis of pollen and spore assemblages (palynomorphs) and stratigraphic analysis. Lithologic data, pollen data, and geophysical logs were used to determine the contacts of stratigraphic units and hydrogeologic units. These contacts were incorporated into a series of regional cross sections, based on geophysical logs, that show the structural relations of the hydrogeologic units in the area. Structure-contour maps for the Upper Patapsco and Lower Patapsco aquifers were developed to correlate data within the study area to the surrounding area. Water levels for the test wells and other observation wells were plotted as hydrographs to show short-term and long-term trends. Water levels were also used to plot potentiometric maps, which in turn were used to develop and calibrate the ground-water flow model. Data from the aquifer tests were plotted on semi-logarithmic graphs and transmissivity values were estimated using the straight-line method of Cooper and Jacob (1946). A Geographic Information System (GIS) was used for storage and analysis of many types of hydrogeologic data. It was also used to create flow-model input data sets and to display model output maps.

A ground-water flow model was constructed and used to simulate ground-water flow and hydraulic heads in all major aquifers in the study area (except the Patuxent aquifer). Visual Modflow (Waterloo Hydrologic, Inc., 2000) was used for the simulations. The flow model was calibrated using historical pumpage and head data, and was then used to simulate a range of future conditions. A series of eight major future pumpage scenarios was developed in conjunction with county planning officials, and ground-water conditions were simulated through 2030 to provide an estimate of future ground-water levels in response to projected ground-water withdrawals.

PREVIOUS INVESTIGATIONS

Darton (1896) provided the first description of the aquifers of the Atlantic Coastal Plain region, and listed information for some of the deepest wells in Maryland for that time. Clark and others (1918) studied the ground-water resources of Maryland, as well as Washington, D.C. and Delaware. Martin and Ferguson (1953) described the ground-water and surface-water resources of St. Mary's County. Otton (1955) conducted the first comprehensive study of the hydrogeology in Southern Maryland, and provided the first potentiometric maps for the region. Hansen (1968) developed a cross-sectional network of the subsurface in Southern Maryland using geophysical logs. Slaughter and Otton (1968) reported on the availability of ground water in Charles County. Glaser (1969) studied the petrology and depositional environment of the Potomac Group and Magothy Formation in Maryland and Virginia. Weigle and others (1970) published hydrologic atlases that compiled data on ground-water and surface-water resources in Southern Maryland. Mack and Mandle (1977) simulated water levels in the Magothy aquifer in Southern Maryland through 2000, based on projected population growth and pumpage increases. Williams (1979) simulated water levels in the Piney Point aquifer in Southern Maryland and the Eastern Shore. Chapelle and Drummond (1983) simulated water levels in the Piney Point and Aquia aquifers in Southern Maryland, and described the geochemistry of these aquifers. Hansen and Wilson (1984) summarized the data from a test well drilled to basement at Lexington Park. Mack (1988) described the hydrogeologic characteristics of the Patapsco aquifers at Chalk Point. McCartan (1989a, 1989b) mapped the surficial geology of Charles County and St. Mary's County.

Wilson and Fleck (1990) assessed the hydrogeology of the aquifers in the Waldorf area of Charles County. Trapp (1992) developed a hydrogeologic framework for the Atlantic Coastal Plain from North Carolina north to New York. Glaser (1994) mapped the surficial geology of Calvert County. Fleck and Vroblesky (1996), as part of a Regional Aquifer-system Analysis, simulated ground-water flow in all of the Coastal Plain aquifers of Maryland, Delaware, and the District of Columbia. Hansen (1996) refined the hydrostratigraphic framework of the Piney Point and Aquia aquifers in Calvert and St. Mary's Counties. Achmad and Hansen (1997) evaluated the water-supply potential of the Piney Point and Aquia aquifers in Calvert and St. Mary's Counties, and simulated future water levels through 2020. Hiortdahl (1997) investigated the hydrogeology of the Potomac Group aquifers in the Indian Head area of northwestern Charles County. Andreasen (1999) evaluated the water–supply potential of the Lower Patapsco and Patuxent aquifers in the Indian Head—Bryans Road area of Charles County. Andreasen (2003, 2004) conducted optimization analyses of ground-water withdrawals in the Lower Patapsco aquifer at Waldorf, and the Lower Patapsco and Patuxent aquifers at Bryans Road Service area (both in Charles County).

ACKNOWLEDGMENTS

Cooperative funding for this study was provided by the County Commissioners of Calvert, Charles, and St. Mary's Counties; the Maryland Department of Natural Resources; and the U.S. Department of the Interior, Geological Survey. Additional funding was provided by Chesapeake Ranch Estates. Sites for test-well drilling were provided by the Calvert County Department of Public Works, Charles County Public Schools, Chesapeake Ranch Water Company, the Maryland Department of Natural Resources, and St. Mary's County Metropolitan Commission.

Field data collection was conducted by Nadine Calis, Karen Jennings, Brandon Fewster, Barbara Cooper, and David Bolton, all currently or formerly of the Maryland Geological Survey (MGS). GIS support services were provided by Mary Valentino of the Center for Geographic Information Sciences at Towson University. Judith Wheeler of the U.S. Geological Survey (USGS) provided historical pumpage data for flow-model calibration. Stephen Curtin, also of the USGS, performed geophysical logging of the test wells, and provided historical water-level data for flow-model calibration. Donajean Appel of the MGS assisted in preparation of the tables and other aspects of the report. The manuscript was reviewed by David Andreasen, David Bolton, Emery Cleaves, and Harry Hansen, all currently or formerly of the MGS; John Grace of the Maryland Department of the Environment (MDE); and Charles Heywood of the USGS.

Special thanks go to the homeowners in Calvert, Charles, and St. Mary's Counties who patiently endured round-the-clock test-drilling operations in their neighborhoods.

HYDROGEOLOGY

The Southern Maryland study area (fig. 1) is located within the Atlantic Coastal Plain Province, and is underlain by a wedge-shaped body of sediments, which generally thickens and deepens to the southeast. These sediments include layers of gravel, sand, silt, and clay, and were deposited on a subsiding basement surface underlain by diverse bedrock formations (Hansen and Edwards, 1986). Bedrock emerges at land surface along the Fall Line, which approximately follows Interstate 95 in Maryland and Virginia (fig. 1). The bedrock surface in the study area attains its greatest depth in southern Calvert and St. Mary's Counties, where it was encountered in a test well at Lexington Park at a depth of 2,515 ft below sea level (Hansen and Wilson, 1984). Based on limited seismic-survey data, the basement surface dips eastward and may be 100 to 200 ft deeper at the Chesapeake Bay shoreline (Hansen, 1978; Hansen and Edwards, 1986).

HYDROGEOLOGIC FRAMEWORK

Sand and gravel layers form aquifers, which transmit and produce water to wells, and silt and clay layers form confining units (or aquicludes), which inhibit the movement of ground water. Seven aquifers underlie the study area, all of which are used for water supply (to varying degrees) in different parts of the study area (fig. 2, tab. 1). From shallowest to deepest, these aquifers are the Surficial (or Water-table), Piney Point, Aquia, Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers. The crystalline and rift-basin sedimentary rocks (Hansen and Edwards, 1986; Hansen, 1988) that underlie the Coastal Plain sediments are not considered potential sources of water. Although in places aquifers are in direct contact with other aquifers, they are generally separated by confining units.

This report focuses mainly on two aquifers in the Patapsco Formation, which are referred to as the Upper Patapsco aquifer and the Lower Patapsco aquifer. These aquifers are generally separated by a layer of predominantly silty and clayey material, which is referred to as the Middle Patapsco confining unit. The aquifers above the Patapsco Formation have been described extensively in previous reports (see Previous Investigations), and only brief descriptions for these aquifers are included here. New data and interpretations for these shallower aquifers are included in this report. The Patuxent aquifer, which underlies the Patapsco aquifers, is not included in the ground-water flow model, but may be developed more extensively in the future as an alternative to shallower aquifers. Information on the depositional environment, water levels, and water quality of the Patuxent aquifer is included in this report.

CROSS SECTIONS

Four hydrogeologic cross sections were constructed to show the structure and geometry of the major hydrogeologic units in Southern Maryland (figs. 4, 5, 6, and 7). The sections are based on gamma-ray geophysical logs obtained from existing deep wells and from the six test wells drilled for this project. Locations of the cross sections are shown in figure 3, along with additional data points used to construct structure-contour maps. Section A-A′ (fig. 4) trends east to west through northern Charles County, southern Prince George’s County, and central Calvert County. Cross sections B-B′ (fig. 5), C-C′ (fig. 6), and D-D′ (fig. 7) trend generally north to south, through central Charles County, northern Charles County to southern St. Mary’s County, and southern Anne Arundel County through Calvert County, respectively.

Formation and hydrogeologic-unit contacts were determined using previous hydrogeologic studies, lithologic and palynologic data from the six test wells, and regional structure-contour maps, as well as geophysical-log data. These contacts do not always conform to inferred lithologic changes in the gamma logs, because some generalization was necessary in order to determine contacts that conform with the diverse sources of data. Formation designations based on palynologic data from the test wells are shown on the sections. Hydrogeologic unit contacts generally conform to formation contacts, but in some instances hydrogeologic units comprise multiple formations. For instance, the Piney Point aquifer includes sediments of the Piney Point, Nanjemoy, and Calvert Formations. In other instances, formations are subdivided into several hydrogeologic units, such as the division of the Patapsco Formation into two aquifers. Shallower aquifers above the Potomac Group were not the focus of the study, but were included in the ground-water flow model, and brief descriptions are provided in the following section. The Upper and Lower Patapsco aquifers are described in more detail in the subsequent section, along with the Patuxent aquifer, which is the deepest member of the Potomac Group.

AQUIFERS ABOVE THE POTOMAC GROUP

Surficial Aquifer

The Surficial aquifer is exposed at the land surface, and receives recharge directly from precipitation. Hydrogeologic processes such as evaporation, transpiration to plants, and base flow to streams occur within the Surficial aquifer. It provides recharge to deeper aquifers, either as leakage through intervening confining units or as direct infiltration where it directly contacts an underlying aquifer. The Surficial aquifer is tapped by some irrigation wells and older farm and domestic wells, but is not widely used for potable water supply because of its vulnerability to contamination and reduced dependability during droughts. Water is also withdrawn from the Surficial aquifer to dewater gravel pits in mining operations.

The Surficial aquifer comprises a variety of geologic materials, which have been variously characterized in different reports and maps (McCartan, 1989a, 1989b; Glaser, 2003). For modeling purposes, the Surficial aquifer is defined in this report as the Holocene, Pleistocene, and Pliocene deposits that blanket much of the region; and the shallow portions of older sedimentary deposits where they exhibit unconfined hydraulic conditions. This definition includes all unconfined materials in a single aquifer, irrespective of stratigraphic relations.

The altitude of the water table (potentiometric surface in the Surficial aquifer) was estimated from topographic contours and perennial streams using a GIS (ARCGIS 8.3) analysis (fig. 8). Where a topographic contour crosses a perennial stream, that intersection was used as a control point to contour the water-table elevation. In the interfluves, the water-table elevation was constrained to be higher than the stream elevation, but lower than the land-surface elevation.

Water levels in the Surficial aquifer fluctuate seasonally due primarily to cyclic variations in evapotranspiration (figs. 9 and 10). Precipitation is fairly constant throughout the year in Maryland. During the growing season, plants consume water within their root zones, and the water table declines. When the growing season is over, recharge from precipitation goes into storage, and the water table rises. The water table also varies from year to year, with a higher water table in years with abundant precipitation. Hydrographs from shallow wells open in the Surficial aquifer do not show a long-term decline in the water table, which suggests that pumpage withdrawals from deeper confined aquifers are not exceeding the recharge capacity of the shallow system.

Piney Point Aquifer

The Piney Point aquifer, as described in this report, includes sandy sediments of the upper parts of the Nanjemoy Formation, the Piney Point Formation, and the lower, sandy units of the Calvert Formation. In some publications it is referred to as the Piney Point-Nanjemoy aquifer (Chapelle and Drummond, 1983; Achmad and Hansen, 1997). The Piney Point aquifer was named by Otton (1955), and was further investigated in Southern Maryland by Williams (1979), Chapelle and Drummond (1983), Hansen (1996), and Achmad and Hansen (1997). Only a brief description and new information on its hydrogeology are included in this report.

The Piney Point aquifer is overlain by the Chesapeake confining unit in Calvert and St. Mary’s Counties. The Nanjemoy Formation is exposed at the surface in central Charles County where it is chiefly a silty, clayey, fine sand, but the Piney Point aquifer exists only in the subsurface in Maryland, and is recharged entirely by leakage through confining units. Although a few major users in southern Calvert and St. Mary’s Counties pump from the Piney Point aquifer, it is primarily used for domestic water supply. The Piney Point aquifer is present in eastern Charles County, but is not a major water producer there.

The northwestern extent of the Piney Point aquifer (fig. 11) is based on a map in Achmad and Hansen (1997) that shows approximate cumulative sand thicknesses at selected well sites. This line represents the northwestern extent of most sandy, water-bearing units in the Nanjemoy, although a few domestic wells may be screened in minor sands northwest of this line. The altitude of the top and bottom of the Piney Point aquifer were derived from Achmad and Hansen (1997). The altitude of the bottom of the aquifer was calculated by subtracting the total thickness from the altitude of the top (Achmad and Hansen, 1997). The altitude of the top ranges from about 100 ft above sea level in northern Charles County to 310 ft below sea level in southern St. Mary’s County.

Transmissivity of the Piney Point aquifer within the study area ranges from 100 to 700 feet squared per day (ft^2/d), and up to 5,000 ft^2/d on the Eastern Shore (Achmad and Hansen, 1997).

Water levels have declined in the Piney Point aquifer in most of the study area since the 1970's, caused by steadily increasing ground-water withdrawals as population has increased. For example, the water level in well CA Fd 51 at Calvert Cliffs State Park dropped from about 12 ft above sea level in 1980 to about 2 ft below sea level in 2005 (fig. 12). The decline has leveled off somewhat since 2000. Near Lexington Park, however, water levels reached a low of about 33 ft below sea level in the late 1980's, then recovered to about 20 ft below sea level by 2000. This recovery was caused by a reduction in public-supply withdrawals from the Piney Point aquifer in the Lexington Park area.

The potentiometric surface in the Piney Point aquifer in 2002 shows a cone-of-depression, 74 ft below sea level centered at Cambridge, in Dorchester County, where it is pumped heavily for the town water supply (fig. 11). In Southern Maryland, a broad cone-of-depression, 20 to 30 ft below sea level, extends from southern St. Mary's County to southern Calvert County. The Piney Point aquifer is used extensively in this area for domestic and small commercial water supplies. In northern Calvert County, the Piney Point aquifer is used primarily for domestic supply.

Production well SM Ef 89, screened in the Piney Point aquifer at Great Mills (in St. Mary's County), has an anomalously high yield (455 gallons per minute [gpm]) and specific capacity (22.75 gallons per minute per foot [gpm/ft]) (Achmad and Fewster, 2003). Originally thought to be screened in the Aquia aquifer because of its high production capacity, the well's screened interval recorded on the driller's completion report was confirmed to be in the Piney Point aquifer. Chemical analysis for silica and potassium yielded values of 24.1 and 12.6 milligrams per liter (mg/L), respectively. Concentrations of these constituents are generally higher in the Piney Point than in the Aquia (Drummond, 1984), and the analysis is consistent with water derived from the Piney Point aquifer. A water-level measurement taken in this well on June 17, 2004 of 33 ft below sea level conforms to the potentiometric surface of the Piney Point aquifer (fig. 11), but not the Aquia aquifer.

Aquia Aquifer

The Aquia aquifer includes sandy sediments of the Aquia Formation in eastern Charles County, all of Calvert County, and most of St. Mary's County (fig. 13). It undergoes a transformation (facies change) to predominantly finer-grained sediments in southeastern St. Mary's County, where it is not used for water supply. It outcrops or subcrops in a southwest to northeast trending band, roughly 10 mi wide, from Virginia through northern Charles County to Prince George's and Anne Arundel Counties, and the Eastern Shore of Maryland. The generalized outcrop/subcrop area for the Aquia aquifer shown in this report was derived from Chapelle and Drummond (1983) for Anne Arundel and Queen Anne's Counties; and from geologic maps of Charles and Prince George's Counties (McCartan, 1989a; Glaser, 2003) for those counties. The Aquia aquifer also extends into Delaware, where it is named the Rancocas aquifer (Cushing and others, 1973). The hydrogeology of the Aquia aquifer has been described by Otton (1955), Chapelle and Drummond (1983), Hansen (1996), and Achmad and Hansen (1997). Only a brief description and new information on its hydrogeology are included in this report.

The Aquia aquifer is generally separated from the overlying Piney Point aquifer by the Marlboro Clay and lower, clayey parts of the Nanjemoy Formation, referred to as the Nanjemoy confining unit. The Aquia aquifer is separated from the underlying Magothy aquifer (where it exists) by clayey and silty sediments of the Brightseat and Severn Formations, and clayey units of the upper part of the Magothy Formation. Where the Magothy aquifer is absent (southern Calvert County and most of St. Mary's County), the Aquia aquifer is separated from the underlying Upper Patapsco aquifer by clayey units of the Brightseat Formation and upper, clayey units of the Patapsco Formation. The clayey material separating the Aquia aquifer from underlying aquifers is referred to as the Brightseat confining unit.

The Aquia aquifer is used extensively for domestic and major-user supplies in Southern Maryland, as well as in Virginia and the Eastern Shore of Maryland. It is not generally used for water supply west of U.S. Route 301 in Charles County. Transmissivity of the Aquia aquifer within the study area ranges from 400 to 2,000 ft^2/d, and up to 5,000 ft^2/d on the Eastern Shore (Achmad and Hansen, 1997).

Since 1975, water levels have declined in the Aquia aquifer by about 100 ft at Solomons in Calvert County (well CA Gd 6) and by 65 ft and 90 ft at Leonardtown (well SM Dd 50) and Lexington Park (well SM Df 71), respectively, in St. Mary's County (fig. 14). These are all areas where the Aquia aquifer is heavily pumped for public supplies and other uses. A deep cone-of-depression (as much as 200 ft below sea level) has formed in the Aquia aquifer in the Lexington Park/Solomons area of St. Mary's and Calvert Counties, where it is heavily pumped for public, commercial, and military supplies (fig. 13). Domestic wells are also screened in the Aquia aquifer in this area, and declining water levels have caused failures in some wells due to outmoded construction techniques (telescoping wells).

Water quality in the Aquia aquifer is generally good (for an extensive discussion, see Chapelle and Drummond, 1983). However, arsenic concentrations in some places exceed the U.S. Environmental Protection Agency Maximum Contaminant Level (MCL) of 10 micrograms per liter (µg/L) for public water supplies. Because of these considerations, water-supply managers in Calvert and St. Mary's Counties are seeking to shift some ground-water usage from the Aquia aquifer to the deeper Patapsco aquifers. This shift of pumpage from the Aquia should also reduce (and perhaps reverse) water-level declines, and ameliorate problems for domestic-well users.

Magothy Aquifer

The Magothy aquifer underlies the Aquia aquifer, and is separated from it by the Brightseat confining unit. The Magothy aquifer primarily comprises the sandy portion of the Magothy Formation. In this report, the Magothy aquifer in the Waldorf area also includes overlying Upper Cretaceous sands that Fleck and Wilson (1990) referred to as the Monmouth aquifer. The Magothy aquifer pinches out (decreases to zero thickness) in central Charles County, northern St. Mary's County and southern Calvert County (figs. 6, 7, and 15), but is used extensively for domestic and public supplies in northeastern Charles County, northern Calvert County, southeastern Prince George's County, and southern Anne Arundel County. The Magothy aquifer crops out only in central Anne Arundel County, and does not receive recharge directly within the study area.

Test well SM Bc 39, in northern St. Mary's County, penetrated about 10 ft of dark gray lignitic clay (640 to 650 ft below land surface) and 20 ft of medium to coarse light-colored, pyritic sand (650 to 670 ft below land surface). These sediments have been tentatively assigned to the Magothy Formation. This well is about 5 mi south of the southern extent of the Magothy aquifer drawn by Mack and Mandle (1977), and indicates that the Magothy extends at least a few miles into northern St. Mary's County. Maps of the Magothy aquifer in this report show the revised extent of the Magothy aquifer.

Within the study area, the top of the Magothy aquifer ranges from about 50 ft below sea level in northwestern Charles County to about 700 ft below sea level in southeastern Calvert County, and the thickness ranges from 0 ft at the edge of the aquifer's extent to a little over 50 ft at Waldorf (Mack and Mandle, 1977). The bottom of the Magothy aquifer ranges from about sea level in northern Charles County to about 720 ft below sea level in eastern Calvert County. The Magothy attains its maximum thickness of 200 ft in the Annapolis area of central Anne Arundel County.

The transmissivity of the Magothy aquifer in the study area ranges from zero where it pinches out, to about 7,000 ft^2/d in northern Calvert County (Mack and Mandle, 1977; Mack and Achmad, 1986). The Magothy attains its maximum transmissivity of 12,000 ft^2/d, where it is thickest, in central Anne Arundel County (Mack, 1974). Mack and Mandle (1977) did not report measured values of storage coefficient for the Magothy aquifer, but used a value of 0.0003 for the confined part of the aquifer. Hansen (1972) reported a storage coefficient of 0.0001 for the Magothy aquifer north of the study area, and Andreasen (2002) used this value in a flow model in southern Anne Arundel County.

The potentiometric surface of the Magothy aquifer in 2002 shows a cone-of-depression in the Waldorf area, which was 90 ft below sea level (fig. 15). The Magothy is heavily pumped in this area for the public-supply system. Elsewhere in the study area, heads range from about 50 ft above sea level near the outcrop area in Anne Arundel County to about 40 ft below sea level in central Calvert County.

Hydrographs of two wells screened in the Magothy aquifer show significant head declines over the past several decades (fig. 16). Heads in well CA Dc 35, at Scientists Cliffs, declined from about 10 ft above sea level in 1975 to about 35 ft below sea level in 2005. Although a few major users withdraw water from the Magothy aquifer in northern Calvert County, the head decline at Scientists Cliffs is probably caused primarily by cumulative pumpage increases throughout the extent of the Magothy aquifer. Heads in well CH Bf 134, at

Waldorf, declined from about 10 ft above sea level in 1975 to about 80 ft below sea level in 2005. The decline at Waldorf was caused by significant population growth and increased pumpage for the public-supply water system in central Charles County. In recent years, increased water demand has been met by increasing withdrawals from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers; as a result, heads in the Magothy aquifer have tended to stabilize at Waldorf (fig. 16).

POTOMAC GROUP AQUIFERS

Sediments of the Patapsco Formation are divided into four hydrogeologic units in this report. From shallow to deep, these units are the Upper Patapsco confining unit, the Upper Patapsco aquifer, the Middle Patapsco confining unit, and the Lower Patapsco aquifer (fig. 2). This division was used by Mack and Achmad (1986) in a study of the Potomac Group aquifers in northern Anne Arundel County. They noted that sands in the Patapsco Formation form two distinct aquifers that are hydraulically separated. Andreasen (1999) generally followed this classification in researching the hydrogeology of northwestern Charles County, although that study was restricted to the Lower Patapsco and Patuxent aquifers. No attempt was made in the previous studies to correlate the units between Anne Arundel County and Charles County. In this study, additional data were collected at six sites in Calvert, Charles, and St. Mary's Counties, which has helped clarify the relation of these aquifers throughout the region. This section describes the regional depositional setting of Potomac Group sediments, geometry of individual sand bodies within the formation, lithologic and hydraulic characteristics of the units, and descriptions of the aquifers.

Regional Setting

Coastal Plain sediments of Maryland were deposited on the subsiding margin of the Atlantic plate. Richards (1948) documented a structural depression in the Middle Atlantic area, with an axis trending southeastward through the Delmarva Peninsula, which he named the Salisbury Embayment. Deposition within the Salisbury Embayment created a wedge-shaped body of sediments, which generally deepens to the southeast with a gentle slope of about 25 to 65 feet per mile (ft/mi) (Glaser, 1969). North of the embayment axis, structure contours generally trend northeast, indicating a deepening of the formations to the southeast. On the southern flank of the embayment, structural contours swing to the south and southeast, and the formations become shallower to the southwest (Hansen, 1978).

Hansen and Edwards (1986) presented evidence of a buried rift basin beneath Southern Maryland, extending northeast through the Eastern Shore of Maryland and Delaware. It may be the northeast extension of the Taylorsville and Richmond Basins, which are exposed at the surface in Virginia (Hansen, 1988). High-angle reverse faulting associated with these rift basins was documented in northern Charles County and Prince George's County by Jacobeen (1972), and in central St. Mary's and Calvert Counties by Hansen (1978). The latest significant activity of these faults was probably late Cretaceous or early Paleocene. These faults may influence the hydrogeology in places by partially offsetting aquifer and confining-unit layers, or by warping more competent beds.

Lower Cretaceous sediments of the Maryland Coastal Plain were deposited in a fluvial-deltaic environment, which extended throughout the mid-Atlantic region. Hansen (1969) determined that the delta system in Maryland was dominated by a major axial river in the Baltimore area, and smaller distributary channels to the northeast (Harford County) and southwest in Southern Maryland. Proximity to the major channel near Baltimore gave rise to high-energy braided-channel stream types, dominated by sand and gravel point-bar deposits. Toward the southwest in Southern Maryland, Potomac Group sediments are dominated by lower-energy deposits of floodplain and meandering stream environments. These sediments in Southern Maryland have a higher percentage of clay/silt lithologies than in the Baltimore area, and a lower percentage of sands and gravels. These trends are reflected in the lower transmissivities of the Patuxent and Patapsco aquifers in Southern Maryland, compared with areas in Baltimore and northern Anne Arundel County.

The source area for Potomac Group sediments was primarily the Piedmont rocks of Maryland and Virginia, to the northwest of the Coastal Plain (Glaser, 1969). Additional material was contributed by the Appalachian region during later Patapsco deposition, and possibly from reworked older Potomac Group sediments. Marginal marine sediments, such as glauconitic and calcareous sands, may also have been deposited by the sporadic, progressive encroachment of the sea during Patapsco time, particularly in eastern Maryland (Anderson and others, 1948).

Streams that supplied sediment for the Potomac Group in Maryland generally flowed eastward to southeastward (Glaser, 1969). Channel sands that form the aquifers in the Potomac Group therefore are probably elongated in the eastward to southeastward direction, although insufficient subsurface data are available to corroborate the orientation of individual sand bodies.

Geometry of Potomac Group Sands

The geometry of individual sand bodies that comprise the Patapsco aquifers affects the hydraulic characteristics of the aquifers in several ways. The extent and degree of connectedness of the sand bodies at the local scale will have a strong influence on the results of aquifer pumping tests. Most aquifer-test analysis techniques assume that the aquifer has constant thickness and infinite lateral extent, or that simple boundary conditions exist within the sphere of influence of the test. Examples of simple boundaries would be a straight recharge boundary such as a river, or a linear no-flow boundary, such as an impermeable valley wall. More complex aquifer geometries, such as gradual thinning and irregular boundary conditions, complicate the interpretation of aquifer-test results.

Sand-body geometry can also affect development of the ground-water flow model. Elongate sand bodies oriented in the same direction may impart a regional anisotropy on the transmissivity field. The degree of connectedness of individual sand bodies may also influence the method of dividing the geologic section into aquifer layers.

Empirical solutions derived from modern fluvial analogs have been developed to estimate the dimensions of ancient sand deposits, such as widths of channel-belt sands (Bridge and Mackey, 1993; Bridge, 2003). An example is provided by Fielding and Crane (1987), who developed bivariate regression equations to relate bank-full channel depth to channel-belt width for various types of modern and ancient fluvial channel deposits (fig. 17). Their Case 2b applies to point-bar deposits in meandering channels. Hansen (1969) postulated that the Southern Maryland area occupies the upper flood plain and lower flood plain environments of a deltaic sequence, and that meandering streams predominated in most of the area. Fielding and Crane's (1987) equation for meandering streams is:

$$CBW_m=64.6H_m^{1.54} \qquad (1)$$

where

CBW_m = channel-belt width (in meters)

H_m = channel depth (in meters).

They theorize that, because channel deposits accrete vertically as well as laterally, channel depth is a fraction of sandstone thickness that, on average, is 0.55. Entering this fraction into equation (1) yields:

$$CBW_m=64.6(0.55ST_m)^{1.54} \qquad (2)$$

where

ST_m = sand thickness (in meters).

Table 3 shows calculated values for sand-body widths for typical values of sand thickness observed in the Patapsco Formation in Southern Maryland. Sand-body thicknesses of 20 to 30 ft would indicate sand-body widths for meandering streams of about ¼ to ½ mi (Case 2b, table 3). Table 3 also shows calculated sand-body widths for braided stream channels (Case 3), and an average of all stream types (Case 2a) (Fielding and Crane, 1987). Case 3 calculations would apply to areas closer to Baltimore, such as northern Prince George's and Anne

Arundel Counties, where Hansen (1968) speculates that higher energy depositional environments gave rise to braided-channel stream types. Case 2a encompasses all stream types, including straight non-migrating streams of laterally restricted fluvial environments.

Lorenz and others (1985) relate bankfull channel widths to depths using a relationship from Leeder (1973):

$$BCW_m = 6.8h_m^{1.54} \qquad (3)$$

where

BCW_m = bankfull channel width (in meters)

h_m = bankfull channel depth (in meters)

and an equation from Leopold and Wolman (1960):

$$CBW_m = 7.44\ BCW_m^{\ 1.01} \qquad (4)$$

to relate meander amplitude (channel-belt width) to channel width. Ignoring the exponent of the nearly linear equation, and substitution of equation (3) yields

$$CBW_m = 50.6\ h^{\ 1.54} \qquad (5)$$

where

CBW_m = channel-belt width (in meters)

which is similar to equation (2) derived from Fielding and Crane (1987). Lorenz and others (1985) do not correct sand-body thickness for the vertical accretion factor of Fielding and Crane (1987), but they do employ a factor of 0.9 to correct for compaction in the conversion of channel depth (original sand thickness) to sandstone thickness. Compaction of sands in the Patapsco Formation may have occurred, but this factor was not included in calculations in table 3. Bridge and Mackey (1993) summarize mathematical relationships between various channel dimensions for numerous studies, and note the wide variance in the derived parameters.

It should be noted that the above analysis estimates sand body widths for “ideal” depositional conditions. Sand bodies that comprise the Potomac Group aquifers may have different dimensions because the ideal channel-sand deposition may have been aborted before reaching full size, or may be truncated by subsequent avulsions (abrupt changes in the course of a stream). On the other hand, sand bodies observed in the field may be the result of stacked meander sequences (Andreasen, 1999), and have greater thicknesses and widths than those determined above. Figure 18 is a schematic cross section that shows individual sand bodies that are generally interconnected within aquifer layers, but disconnected within confining units. Although some sand bodies appear to be disconnected in the two-dimensional cross section, they are likely to be connected in the three-dimensional matrix. Other types of sand bodies, such as natural levees and crevasse splays, may also be present beside the point-bar sequences that probably comprise the bulk of the Potomac Group aquifers.

The estimated widths of sand bodies (¼ to ½ mi) indicate that aquifer tests are likely to be affected by localized boundaries. Gradual reduction in sand thickness and truncation of sand bodies would produce partial no-flow boundaries that are within the sphere of influence of some pumping tests.

Lithology

Lithologic characteristics of Patapsco sediments were determined by examining drill cuttings from six test wells drilled for this study (Calis and Drummond, in preparation). Lithologic descriptions were made on-site of washed, undried samples using a hand lens. Selected intervals were examined later in more detail on dried samples using a binocular microscope.

Because samples were taken from drill cuttings (no cores were obtained), sediments from shallower intervals were apparently mixed with sediments of the specified intervals. In particular, glauconite was observed in many samples from the Patapsco Formation. Glauconite is abundant in the shallower marine units (Nanjemoy, Piney Point, and Aquia Formations) but is not expected to occur widely in the fluvial-deltaic depositional environments of the Patapsco Formation. Glauconite has not been documented in outcrop or core samples of the Potomac Group in Maryland. However, as Hansen and Wilson (1984) noted, it is possible that sporadic marine incursions could have introduced rare glauconite into the fluvio-deltaic environments of the Potomac Group. Brenner's identification of several species of Lower Cretaceous dinoflagellate cysts in a sample from well SM Dd 72 (1,130 to 1,150 ft) provides evidence for shallow marine sediments in the Patapsco Formation (Calis and Drummond, in preparation; Appendix C).

Recovery of representative fine-grained samples was also problematic. Clays and silts were often disaggregated by the drill bit, and incorporated into the drilling fluid. Some fragments of intact clay samples were recovered, and these were used to describe clayey intervals. However, clay lithologies are probably underrepresented in the lithological descriptions, based on comparison with geophysical logs.

Sands of the Patapsco Formation in the six test wells range from very fine to very coarse, and except for some accessory minerals (for instance, pyrite and goethite), are detrital in origin. They are generally gray or greenish-gray in appearance, but in some cases are yellowish to reddish brown. These colors are typical of paleosols, and may represent fossil soil profiles imprinted on fluvial sediments that accumulated and weathered in a setting characterized by varying drainage conditions (Retallack, 1986; Bridge, 2003; Kraus and Hasiotis, 2006). Sorting characteristics could not be determined due to mixing of sediments in drill cuttings. Gravel and pebbles up to 35 millimeters (mm) in diameter are sporadically present, and may be underrepresented in sample descriptions due to settling in the drilling-fluid column and difficulty in bringing them to the surface. Sands are predominantly subangular to subrounded quartz grains, with minor amounts of accessory minerals. Quartz grains are mostly clear and colorless (occasionally with black inclusions), with some frosted white grains, and some with yellowish to dark-brown iron coatings. Some clear grains are stained green, yellow, lavender, and blue.

Common accessory grains include pyrite, lignite, and muscovite. Rare accessory grains include chert, biotite, goethite, and feldspar. Fragments of several types of cemented sandstone are common. Cement in these fragments variously includes hard, yellow to dark reddish brown iron oxide; hard white to gray calcareous matrix (exhibited effervescence when wetted with dilute hydrochloric acid); and soft, friable non-calcareous matrix. The sand fraction from several intervals in different test borings included spherical, sand-sized grains of grayish-white sandstone. Although the origin of the accessory grains and fragments is uncertain, the presence of pyrite, lignite, and goethite, and non-calcareous aggregates is consistent with a paleosol origin (Bridge, 2003).

Clays of the Patapsco Formation are extremely variable, in both color and texture. The predominant clay lithology encountered in the test holes is medium to dark gray silty clay. Other common colors include light greenish gray, light to dark reddish brown, and mottling with gray, brown, yellow, white, pink and purple. Most clays are silty and/or sandy, but some samples appear to be nearly pure clay, hard and crumbly. Some of these clays have a waxy, slickensided aspect, which, along with variegated coloration and mottling, is typical of alluvial soils (Bridge, 2003). Common accessory grains in the clays include pyrite, lignite, and muscovite. Glauconite was commonly observed in clay samples from the Patapsco Formation, but it is uncertain if any was in-situ material.

Aquifer Tests

Aquifer tests were performed on the six test wells drilled during this project. Each test consisted of a 24-hour pumping phase, followed by a 24-hour recovery phase. During the pumping phase, the well was pumped at a constant rate; discharge was monitored with an orifice meter, and checked periodically with a 55-gallon drum and stopwatch. During the pumping and recovery phases, water levels were measured using an electric tape, and for five of the six wells, a pressure transducer and digital recording device were used.

Results of the tests were analyzed using the method developed by Cooper and Jacob (1946). In this method, measured water levels are plotted against time on semi-logarithmic axes (figs. 19 to 24). If the assumptions of the method are met, drawdowns plot in a straight line, and transmissivity is calculated from the slope of the line and discharge rate, according to the formula:

$$T = 35.3 \times Q/\Delta s \qquad (6)$$

where

T = transmissivity, in ft^2/d,

Q = pumping rate, in gallons per minute,

Δs = drawdown in one log cycle, in ft.

Assumptions of this method are that: 1) the aquifer is homogeneous and infinite in lateral extent with constant thickness; 2) the well screen fully penetrates the aquifer; 3) the well is completely developed; and 4) there are no other influences on water levels, such as tidal or barometric effects, recharge events, or nearby pumpage. All test wells are located at least five miles from other pumping wells, and the Patapsco aquifers are fully confined, so pumpage and recharge did not affect test results. Well SM Dd 72 is about ½ mi from Breton Bay, and a semi-diurnal tidal fluctuation is superimposed on pumping and recovery data in the test of that well. The pumping and recovery phases of the test each covered two complete tide cycles, and the effect was visually corrected. Although none of the well screens penetrated the entire aquifer thickness, most screens included the full thickness of the sand body that forms the aquifer at each location, and partial penetration is not considered a factor in data analysis.

Incomplete well development may be a factor in analysis of the aquifer tests because of well-construction techniques. Drilling continued below the depth intervals that were eventually screened, and drilling fluid had several days to several weeks to invade the aquifer sands. The problem was particularly acute in wells CA Db 96 and CH Cg 24, which were screened in the Upper Patapsco aquifer, but drilling continued to the Lower Patapsco aquifer, and the screen intervals were open to drilling fluid for several weeks. Because of construction problems, the screened interval in well CH Bg 17 was also open to drilling fluid for several weeks before the well was developed. These factors make it difficult to remove all drilling fluid from the aquifer sands during well development. Aquifer tests performed in wells that have not been completely developed will underestimate transmissivity. In addition, changes in fluid density of water in the well bore, caused by changes in water temperature, may also cause water-level fluctuations during the tests.

The extreme variability of Potomac Group sands leads to significant difficulties in interpreting aquifer-test data. As discussed previously, the individual sand bodies that make up the aquifers are limited in lateral extent, have complex localized boundaries, and are lithologically heterogeneous. Furthermore, individual sands may coalesce to form stacked sandy sequences. These factors create variable hydraulic boundaries that are impossible to characterize with the sparse data available, but may strongly influence aquifer-test results if they are sufficiently close to the test wells. The concept of a unique transmissivity value, where neither a constant thickness nor a hydraulic conductivity can be defined, may not be valid.

Nevertheless, transmissivities were calculated from aquifer tests for the six test wells. For flow-modeling purposes, transmissivity values must be mapped and entered throughout the modeled extent of each aquifer. A "composite" transmissivity value was assigned for the aquifer screened at each test-well site, based on various slopes of the drawdown and recovery phases of each test, and circumstances for each test. Data from all six tests showed nonlinearities in Cooper-Jacob plots. In the tests for wells CH Cg 24 (fig. 22) and SM Bc 39 (fig. 23), the nonlinearities are minor, and transmissivity values (1,000 and 640 ft^2/d, respectively) were based on averages of pumping and recovery results.

In the aquifer tests for wells CA Db 96 (fig. 19) and CH Bg 17 (fig. 21), curves in the data are reflected in the pumping and recovery data, and show similar trends; that is, slopes increased with later time, indicating a decrease in transmissivity as the test progressed. Composite transmissivities of 380 ft^2/d and 200 ft^2/d were calculated for these two wells, respectively. This curvature is interpreted as a decrease in transmissivity with distance from the test well. Wilson (1986) noted a similar steepening of data plots in the aquifer test for well CH Bf 146, screened in the Lower Patapsco aquifer near Waldorf. He attributed this effect to a hydrologic boundary caused by either a change in texture to finer sediments or a lateral truncation of the sand screened in the test well. Andreasen (1999) also noted this effect in test wells CH Bc 75 and CH Bc 78, screened in the Patuxent aquifer near Chapmans Landing. He attributed the steepening of slope to either updip thinning of the sandy interval, or vertical offset of aquifer beds caused by faulting. A sharp break in the slope of test data would indicate a no-flow boundary; however, a gradual curvature in test data indicates a gradual thinning or change to finer sediments.

Aquifer-test data for wells CA Fd 85 (fig. 20) and SM Dd 72 (fig. 24), both screened in the Lower Patapsco aquifer, also show significant nonlinear responses, but the data show differences between the drawdown and recovery phases of the tests. The recovery test for well CA Fd 85 shows a downward curvature, in which transmissivity appears to increase in the later stages of the test. This pattern resembles results for a nearby recharge boundary, although no such boundary is likely to exist in this strictly confined hydrologic setting. The curvature may also be caused by an increase in transmissivity with distance from the well, such as a thickening of the sandy interval, or a gradual coarsening of the sediments. The downward curvature seen in the recovery data is not reflected in the data for the drawdown phase of the test, which is difficult to explain. Short-term water-level changes, on the order of ½ ft, are caused by barometric fluctuations, which may partially account for the irregularities. The composite transmissivity value of 2,700 ft^2/d determined for this site is based on a generalized average of slopes from different stages of the aquifer test.

Aquifer-test data for well SM Dd 72 (fig. 24) also show dissimilarity between the drawdown and recovery phases of the test. Water levels at this well exhibit semi-diurnal fluctuations of less than a foot caused by tidal loading from Breton Bay, which is about ½ mi away. These fluctuations, in addition to barometric fluctuations, may account for some of the dissimilarity. The drawdown phase of the test shows a moderate steepening of the curve, indicating a decrease in transmissivity with distance from the well. This curvature is not reflected in the recovery data, which is essentially linear when corrected for tidal fluctuations. The composite transmissivity value of 4,000 ft^2/d determined for this well is based on a generalized average of slopes from different stages of the aquifer test, although more weight was given to the recovery test.

Differentiation of the Upper and Lower Patapsco Aquifers

The division of the Patapsco Formation into the Upper and Lower Patapsco aquifers is based on hydraulic characteristics and structural relations. The two aquifers are lithologically similar, and cannot be routinely distinguished by examining drill cuttings from the units. Similarly, the units within the Patapsco Formation cannot be distinguished on the basis of pollen assemblages or other paleontologic evidence, although the Patapsco Formation can be distinguished from the deeper Arundel and Patuxent Formations using pollen. The Patapsco Formation was subdivided into palynozones (IIa, IIb, IIc, and III) based on fossil pollen and spore assemblages in a few wells (Calis and Drummond, in preparation); however, these palynozones probably do not correspond with the hydrogeologic units delineated in this report.

Potentiometric surfaces of the Upper and Lower Patapsco aquifers are similar, but show some distinctive differences. Both surfaces show cones-of-depression centered in the Waldorf-La Plata area where ground-water withdrawals are greatest. However, the deepest head in the Lower Patapsco aquifer is 191 ft below sea level, whereas in the Upper Patapsco aquifer, the deepest head is only about 130 ft below sea level. Heads in the two aquifers are also significantly different near the Morgantown power plant in southern Charles County, and at Annapolis.

Water levels in wells screened in the Upper Patapsco and Lower Patapsco aquifers at the same location also indicate that the aquifers are hydraulically disconnected. Hydrographs for wells in four of these clusters show distinct trends that would not be evident if the units functioned as a single aquifer (fig. 25). Water levels in well CH Be 60, screened in the Upper Patapsco aquifer at Smallwood West, declined steadily from about 20 ft below sea level in 1987 to 42 ft below sea level in 2007, while water levels in well CH Be 58, screened in the Lower Patapsco aquifer at the same location, dropped from 20 ft below sea level to nearly 200 ft below sea level during the same time period. Water levels in well QA Eb 111, screened in the Upper Patapsco aquifer at Chester in Queen Anne's County, declined steadily from 1980 until 1999, then recovered a few feet when much of the pumpage from the Upper Patapsco aquifer at Stevensville, a few miles away, was shifted to the Lower Patapsco aquifer. Water levels in well QA Eb 112, screened in the Lower Patapsco aquifer at Chester also declined steadily during that period, but were a few feet above water levels in the Upper Patapsco aquifer until the shift in pumpage occurred. At that time, water levels in well QA Eb 112 quickly dropped to a few feet below levels in well QA Eb 111, then continued to decline. Water-level trends in well clusters at St. Paul (in central Charles County) and Bowie (in northern Prince George's County) also show differences between the Upper and Lower Patapsco aquifers. These differences in water-level trends indicate that the two aquifers are hydraulically disconnected, at least locally, and function as separate aquifers.

Hydraulic connectivity of individual sand bodies within the Upper Patapsco and Lower Patapsco aquifers was corroborated by analysis of sand percentages. Mathematical models have been developed to simulate the distribution, dimensions, and connectivity of channel-belt sand bodies that comprise fluvial aquifers. Process-based models simulate the fluvial processes that control the distribution and geometry of channel-belt sands, and can be used to generate theoretical distributions of sand bodies in alluvial sequences (Mackey and Bridge, 1995). Bridge and Mackey (1993) show that alluvial sand bodies generated by a process-based model are largely unconnected in cross section when sand percentage is less than 40 percent. They report that connectivity increases with sand percentage up to 75 percent, where all channel-belt sand bodies are connected. Stochastic models using "percolation theory" to determine the probability of randomly distributed sand bodies being connected show similar results. King (1990) and Berkowitz and Balberg (1993) show that sand bodies randomly distributed in a three-dimensional lattice become increasingly connected when sand percentage reaches a threshold of 27.6 percent and 31.2 percent, respectively. These studies suggest that aquifer layers in the Patapsco Formation should have minimum sand percentage values of at least 27 percent to 40 percent for the assumption of hydraulic connectivity to be valid. Conversely, confining units should have sand percentages below these values for the assumption of aquifer separation to be valid.

Sand percentages were calculated for the hydrogeologic units in the Patapsco Formation from multi-point resistivity logs. These were used to estimate the connectivity of aquifer intervals and confining-unit intervals. Sand percentages were estimated using the inflection method of Lynch (1962) for 16 multi-point resistivity logs (where available) for the wells shown on cross sections in figures 4 through 7. Sand thicknesses of individual beds were corrected for bed-thickness effects (Keys and MacCary, 1971), and averaged for each of the units. Logs that partially penetrated hydrogeologic units were included if they penetrated a significant portion of the unit. This method may underestimate total sand thickness of some units because the resistivity deflection disappears or reverses for sand beds thinner than the tool electrode spacing (1.3 ft for the 16-inch tool and 5.3 ft for the 64-inch tool [Keyes and MacCary, 1971]).

The Upper Patapsco aquifer averaged 46.4 percent sand for 16 well-log intervals, which indicates general hydraulic connectivity of the individual sand bodies within the aquifer. The Lower Patapsco aquifer averaged 40.8 percent sand for 12 well-log intervals, which indicates borderline connectivity based on the process-based model (Bridge and Mackey, 1993), but general connectivity based on stochastic models (King, 1990; Berkowitz and Balberg, 1993). Sand percentages for the Upper Patapsco and Middle Patapsco confining units averaged 4.2 and 10.9 percent, respectively, indicating poor connectivity of the isolated sand bodies within these units, and general disconnectivity between the Upper and Lower Patapsco aquifers.

The delineation of top and bottom structure-contour maps for the Upper Patapsco and Lower Patapsco aquifers was based on geophysical logs, lithologic logs, and regional structural relations. Unlike shallower aquifers, such as the Aquia, which was deposited in a shallow marine environment and predominantly comprises a single sand layer, the Patapsco aquifers are composed of multiple interconnected sand bodies that do not form continuous surfaces. Delineation of top and bottom surfaces for the Patapsco aquifers is somewhat arbitrary in places because aquifer boundaries do not always coincide with boundaries of sand bodies. For example, hypothetical test borings A, B, and C, shown in the conceptual cross section (fig. 18), intercept different sand bodies within the Upper Patapsco and Lower Patapsco aquifers. It would be impossible to define continuous top surfaces for these aquifers based on the shallowest sand layer encountered in each boring, and some regional generalization is necessary to delineate structure-contour maps. It is even possible that a boring would not encounter any sand layers within an aquifer's boundaries, such as hypothetical boring C in the Lower Patapsco aquifer (fig. 18). Similar relations apply to the bottoms of aquifers.

The basis for aquifer delineation may be important in managing ground-water withdrawals in the Upper Patapsco and Lower Patapsco aquifers. As explained in the section of this report entitled Ground-Water Management, ground-water withdrawals are managed to prevent water levels from declining below the 80-percent management level, which is based on the prepumping potentiometric surface and the top-of-aquifer surface. If the aquifer top were defined by the top of the shallowest sand layer (such as hypothetical boring A in fig. 18), a well located at that site would appear to have more available drawdown than if the aquifer top were defined by regional structure, as shown.

Upper Patapsco Aquifer

The Upper Patapsco aquifer underlies the Magothy aquifer where the Magothy is present, and is separated from it by clayey units in the top of the Patapsco Formation and bottom of the Magothy Formation (fig. 2). These clayey units are referred to collectively as the Upper Patapsco confining unit. Where the Magothy aquifer is absent, the Upper Patapsco aquifer is overlain by the Aquia aquifer, and is separated from it by the Brightseat confining unit, and clays in the top of the Patapsco Formation. The Upper Patapsco aquifer includes sandy beds in the upper part of the Patapsco Formation, which is the upper unit of the Potomac Group. Individual sand units of the Upper Patapsco aquifer are impossible to delineate with the data currently available; however, they appear to be sufficiently interconnected at the regional scale to form a single aquifer.

The Upper Patapsco aquifer extends to the northeast through Prince George's and Anne Arundel Counties, and beneath the Chesapeake Bay to the Eastern Shore of Maryland. It extends southwest across the Potomac River, but in Virginia, the Potomac Group is not subdivided into the Upper Patapsco, Lower Patapsco, and Patuxent aquifers as it is in Maryland. The bluffs along the Potomac River in northwestern Charles County contain outcrops of the upper part of the Potomac Group, and the Upper Patapsco aquifer outcrops and subcrops in this area. It also subcrops beneath the Potomac River, and river-water intrusion has occurred in the Indian Head area from the tidal part of the river (Hiortdahl, 1997). Outcrop and subcrop areas provide recharge to the deep, confined Potomac Group aquifers, but have not been mapped explicitly. The generalized outcrop/subcrop areas of the Upper Patapsco and Lower Patapsco aquifers shown in this report were derived by extrapolating the structure contours of top and bottom surfaces to the land surface. These outcrop/subcrop areas include areas that are overlain by thin layers of other units, and are not shown on geologic maps (McCartan, 1989a; Glaser, 2003).

Within the study area, the top of the Upper Patapsco aquifer ranges from 50 ft above sea level in northwestern Charles County to about 750 ft below sea level in central Calvert County (fig. 26). It is 1,024 ft below sea level at Cambridge on the Eastern Shore. The -600 ft contour shown in figure 26 swings eastward in southern St. Mary's County to accommodate values in the Leonardtown and Lexington Park area that are shallower than suggested by regional relations. These beds are noted in wells SM Bc 39, SM Dd 72 and SM Ef 56 in cross-section C-C′ (fig. 6) and in wells CA Fd 85, SM Df 100, and SM Df 84 in cross-section D-D′ (fig. 7). This trend suggests additional sandy beds in the Upper Patapsco aquifer not present elsewhere in the region. Hansen and Wilson (1984) tentatively assigned these beds to the Mattaponi (?) Formation, a name Cederstrom (1957) assigned to non-marine and shallow-marine units that occur between the Aquia Formation and the Potomac Group in the Northern Neck of Virginia. In this report, the Mattaponi(?) Formation is included in the Upper Patapsco aquifer.

Within the study area, the bottom of the Upper Patapsco aquifer ranges from about 100 ft below sea level in western Charles County to about 1,000 ft below sea level in eastern Calvert County (fig. 27). The bottom altitude is 1,640 ft below sea level at Cambridge. The thickness of the Upper Patapsco aquifer in the study area ranges up to 330 ft at Cedar Point on NAS (Naval Air Station) Patuxent River. On the Eastern Shore, it is over 600 ft thick.

Transmissivity distribution of the Upper Patapsco aquifer in Southern Maryland was determined by assembling data from previously published reports and other sources on file at MGS. These data were supplemented by transmissivity calculations for test wells CA Db 96 and CH Cg 24. Transmissivity of the Upper Patapsco aquifer in the study area ranges from less than 500 ft^2/d in western Charles County to more than 3,000 ft^2/d in Calvert and St. Mary's Counties (fig. 28). In northern Anne Arundel County, transmissivity of the Upper Patapsco aquifer attains a maximum of over 10,000 ft^2/d. Because of the complex boundaries previously discussed, and wide variation in measured values, it may not be possible to accurately map transmissivity on a regional basis. Some modifications of the transmissivity distribution were made during calibration of the ground-water flow model.

The Upper Patapsco aquifer is used extensively for public supply in central Charles County. It is also pumped heavily by major users in Prince George's and Anne Arundel Counties north of the study area, and by domestic users in Charles County. A few major users pump the Upper Patapsco aquifer in Calvert and St. Mary's Counties, and it is used on the Eastern Shore of Maryland as far south as Crisfield, in Somerset County. The Upper Patapsco aquifer is also used on the Northern Neck of Virginia.

Water levels have declined significantly in the Upper Patapsco aquifer since pumping began in northwestern Charles County. A cone-of-depression has formed in the Upper Patapsco aquifer, centered in the La Plata area, which was 136 ft below sea level in 2002 (fig. 29). This cone-of-depression probably extends northwest to the Potomac River, where it may induce river-water intrusion. It may extend southeast to the Lexington Park area, where withdrawals for public supply began in the early 2000's.

Hydrographs of observation wells screened in the Upper Patapsco aquifer show a steady decline in heads, even in areas where major withdrawals have not occurred. At La Plata, where the Upper Patapsco is heavily pumped, water levels have declined from about 22 ft below sea level in 1969 to about 140 ft below sea level in 2004 (fig. 30). At Randle Cliff, in Calvert County, where the aquifer has been minimally developed, the water level has declined from about 15 ft above sea level in 1975 to 17 ft below sea level in 2004. At Lexington Park, in St. Mary's County where the aquifer had not been used until the early 2000's, the water level declined from about 8 ft below sea level in 1983 to about 45 ft below sea level in 2004. These water-level declines are probably caused by distant pumpage, and indicate hydraulic continuity of the aquifer on a regional scale.

Hydrographs for test wells CA Db 96 and CH Cg 24 show a seasonal fluctuation superimposed on a general decline of about 1 foot per year (ft/yr) (fig. 31). Although the seasonal fluctuation corresponds to the fluctuation in the Surficial aquifer, the Upper Patapsco aquifer is strictly confined, and is not strongly influenced hydraulically by the water table. The fluctuation is more likely the result of seasonal variations in pumpage from water-supply wells at La Plata, and the Chalk Point Power Plant, located halfway between wells CA Db 96 and CH Cg 24.

Water quality in the Upper Patapsco aquifer is generally good, based on analyses of 19 wells in the study area. Chemical analyses of water from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers are shown in appendix B, and the locations of sampled wells are shown in figure 32. Total dissolved solids (TDS) (based on residue on evaporation at 180° Celsius [C]) are low, ranging from 126 to 349 mg/L. The pH in water from most wells ranges from 7.0 to 8.5, but well SM Ff 36, in southern St. Mary's County, had a pH of 9.8. This pH is anomalously high, and may be a result of sampling error, or may be caused by invasion of cement grout in the water sample. No MCLs were exceeded in water from the Upper Patapsco aquifer (although not all regulated constituents were tested), but Secondary Maximum Contaminant Levels (SMCLs) were exceeded for iron (4 of 11 samples) and manganese (1 of 11 samples).

Piper diagrams were prepared for water analyses from the Upper Patapsco, Lower Patapsco, and Patuxent aquifers. These diagrams display the chemical character of the water on two ternary diagrams—one for cations and one for anions—and a central diamond, which combines the ionic types. Hydrochemical facies are shown as areas on the diagrams that have distinct water chemistries. For instance, water samples of the sodium-bicarbonate hydrochemical facies plot in the lower right section of the cation triangle, the lower left area of the anion triangle, and the bottom part of the central diamond.

Samples that were not analyzed for calcium, magnesium, sodium, potassium, sulfate, or chloride were excluded from the Piper diagrams. Samples that included these constituents but were missing alkalinity analyses were included in the diagrams, and bicarbonate was calculated from the other ions to achieve a charge-balance error of zero. Analyses in which the charge-balance error was greater than 5 percent were excluded from the Piper diagrams.

Water samples in the Upper Patapsco aquifer are primarily classified as sodium/potassium-bicarbonate hydrochemical facies (fig. 33). However, about half of the samples show a trend away from sodium/potassium, toward a ratio of 40 to 50 percent calcium and 60 to 40 percent magnesium. This trend suggests a primary source of sodium and potassium, and a secondary source that is approximately equal in calcium and magnesium. A nearly identical trend is displayed by water from the Upper Patapsco aquifer in Kent County (Drummond, 1998), and Queen Anne's and Talbot Counties (Drummond, 2001). Drummond (2001) cites the dissolution of aluminosilicates, such as albite and anorthite, as possible sources of calcium; however, these minerals do not contain magnesium, so the source of this constituent is uncertain. Biotite is a possible source of magnesium, but was rarely observed in drill cuttings from the six test wells, and Glaser (1969) noted muscovite as the only mica observed in outcrop of the Potomac Group sands. The water samples with elevated levels of calcium and magnesium do not show a clear trend in spatial distribution.

The calcium/magnesium component could be derived from leakage from confining units. If interstitial water in the overlying or underlying confining unit is a calcium/magnesium-bicarbonate facies, the mixing of water of this type with sodium/potassium-bicarbonate water indigenous to the aquifer would produce the observed trend in cations. Marine units such as the Aquia and Brightseat Formations, overlie the Upper Patapsco aquifer in some parts of the study area. These units contain shell material, and could supply the calcium/magnesium component to water chemistry in the Upper Patapsco aquifer. Chemical analyses of pore water squeezed from Potomac Group clays (Hansen and Wilson, 1984) show a similar trend toward a calcium/magnesium component, and suggest that clays from confining units or interbedded fine-grained material may supply this component. Cation-exchange processes could also produce this trend, where sodium and potassium in the water would exchange for calcium and magnesium on exchange sites in intercalated clays or iron oxide coatings on sand grains of the aquifer matrix.

Lower Patapsco Aquifer

The Lower Patapsco aquifer underlies the Upper Patapsco aquifer, and is separated from it by clayey units in the middle part of the Patapsco Formation, referred to as the Middle Patapsco confining unit. The Lower Patapsco aquifer comprises sandy units in the lower part of the Patapsco Formation. Like the Upper Patapsco aquifer, the Lower Patapsco aquifer is composed of numerous sandy beds, which may be hydraulically separated locally, but coalesce on a regional scale to form a single aquifer.

Potomac Group sediments extend to the southwest of the study area into Virginia, but correlation to aquifers from Maryland is uncertain. The Lower Patapsco aquifer also extends northeast to northern Anne Arundel County, but correlation across southern Prince George's County, where data are scarce, is also uncertain. It extends across the Chesapeake Bay to Queen Anne's and Kent Counties on the upper Eastern Shore of Maryland, but, because of sparse data, its hydraulic character on the lower Eastern Shore is uncertain.

Within the study area, the top of the Lower Patapsco aquifer ranges from about 100 ft below sea level in western Charles County to about 1,400 ft below sea level in eastern Calvert County (fig. 34). The top is 1,795 ft below sea level at Cambridge. The bottom of the Lower Patapsco aquifer ranges from about 200 ft below sea level in western Charles County to about 1,700 ft below sea level in eastern Calvert County, and 2,055 ft below sea level at Cambridge (fig. 35). It attains its greatest thickness of about 380 ft in the Hollywood area of St. Mary's County.

Transmissivity of the Lower Patapsco aquifer in the study area ranges from less than 500 ft^2/d in northwestern Charles County to 4,000 ft^2/d in St. Mary's County (fig. 36). Transmissivity ranges up to 5,000 ft^2/d in northern Anne Arundel County, and 4,000 ft^2/d in Queen Anne's County. On the Northern Neck of Virginia, the middle Potomac aquifer was simulated with a transmissivity of up to 12,000 ft^2/d by Harsh and Laczniak (1990) based on model calibration. The middle Potomac aquifer of Virginia is tentatively correlated with the Lower Patapsco aquifer of Maryland in this report, and these transmissivity values were assimilated into the contour map. Because of the fluvial-deltaic depositional environment of Patapsco sediments, transmissivity values calculated from aquifer-test data vary widely, sometimes over relatively short distances.

Water levels have declined significantly in the Lower Patapsco aquifer, especially in the northwestern Charles County area where a cone-of-depression has formed that was nearly 200 ft below sea level in 2002 (fig. 37). This cone-of-depression extends northwest to the Potomac River, and probably to the outcrop area in Virginia and Prince George's County.

Hydrographs of wells screened in the Lower Patapsco aquifer in Charles County show rapid head declines from the late 1980's through the mid-1990's, followed by slower declines until present (fig. 38). In Charles County, water levels in the Lower Patapsco aquifer have declined about 150 ft at St. Charles (well CH Be 58) from 1986 to 2005, and about 50 ft at Potomac Heights (well CH Bc 24) near Indian Head from 1988 to 2005. The Lower Patapsco aquifer is used extensively in central and northwestern Charles County, but not elsewhere in the study area, and no long-term water-level data are available for the Lower Patapsco aquifer in Calvert or St. Mary's Counties.

Hydrographs of four test wells screened in the Lower Patapsco aquifer show steady declines over several years of available record, even in Calvert and St. Mary's Counties where the aquifer is not used for water supply (fig. 31). These declines are caused by increased withdrawals from the Lower Patapsco aquifer in Anne Arundel and Prince George's Counties, and indicate that the aquifer is hydraulically connected on a regional scale. Wells CA Fd 85 and SM Dd 72 show nearly identical responses to barometric effects, and a decline of about 1.2 ft/yr. Wells CH Bg 17 and SM Bc 39, which are closer to the pumping center, show greater declines of 2.2 and 1.5 ft/yr, respectively. These wells show similar barometric fluctuations seen in wells CA Fd 85 and SM Dd 72. Well CH Bg 17 may show a seasonal fluctuation similar to that seen in the Upper Patapsco test wells, although less than 2 years of data is available for this well, and the fluctuation is not as apparent.

Water quality in the Lower Patapsco aquifer is generally good (app. B). The pH of 60 water samples from wells in Southern Maryland ranged from 6.8 to 8.7, and TDS range from 122 to 768 mg/L. No MCLs were exceeded in these samples, although not all regulated constituents were tested. SMCLs were exceeded for iron (12 out of 40 samples) and manganese (5 of 41 samples). Arsenic concentrations were below detection levels in water from all seven wells sampled (detection levels range from 0.2 to 1.0). Gross alpha- and gross beta-particle analyses from four samples ranged from 1.4 to 6.4 and 2.0 to 5.6 picocuries per liter (pCi/L), respectively, and were well below MCLs.

A Piper diagram (fig. 39) shows that water from the Lower Patapsco aquifer is primarily in the sodium/potassium-bicarbonate hydrochemical facies. Four samples show a trend in cation composition away from sodium and potassium and toward a mixture of calcium and magnesium, similar to that seen in the Upper Patapsco aquifer. The reason for the trend in the Lower Patapsco aquifer is probably the same as in the Upper Patapsco; that is, leakage of calcium/magnesium water from confining units, or cation exchange processes within the aquifer. All four samples with elevated calcium and magnesium levels in the Lower Patapsco aquifer are in the updip portion of the aquifer, close to the Potomac River.

Although most samples plot in the bicarbonate water type for anions (as in the Upper Patapsco aquifer), a significant trend toward chloride is also apparent. Elevated chloride concentrations occur mostly in the extreme northwestern part of Charles County, and probably relate to river-water intrusion from the Potomac River. Hiortdahl (1997) attributed high chloride concentrations in this area to river-water intrusion, citing high pumpage rates at the Indian Head Naval Ordnance Station, and shallow, semi-confined hydraulic conditions in the vicinity of the Potomac River. A few elevated chloride samples occur farther downdip in the Lower Patapsco aquifer. These may be attributable to leakage from the underlying Patuxent aquifer, or relic parcels of brackish water from former high stands of sea level, as discussed for the Patuxent aquifer.

Patuxent Aquifer

The Patuxent aquifer underlies the Lower Patapsco aquifer, and is separated from it by the Arundel confining unit. The Patuxent aquifer is the deepest Coastal Plain aquifer in the study area, and rests on the bedrock surface. It is pumped by a few wells in northwestern Charles County, but is not used elsewhere in the study area. The Patuxent aquifer is a potential future water source in Charles County where the shallower aquifers have been extensively developed, and its depth is not prohibitive. In Calvert and St. Mary's Counties, however, it probably will not be used for water supply until the shallower Patapsco aquifers are developed.

The Patuxent Formation probably extends throughout the entire Maryland Coastal Plain, but downdip data are too sparse to map the presence of the Patuxent aquifer southeast of Charles County. The top of the Patuxent aquifer ranges from about 400 ft below sea level in northwestern Charles County to 1,846 ft below sea level at Chalk Point, in southernmost Prince George's County (Andreasen, 1999). Hansen and Wilson (1984) did not differentiate between the Arundel and Patuxent Formations in test well SM Df 84 at Lexington Park; however, examination of their reconstructed geologic log and geophysical logs for the well suggests that the top of the Patuxent aquifer is between 1,950 and 2,050 ft below sea level. The bottom of the Patuxent aquifer cannot be mapped with currently available data, but the top of basement rock ranges from about 600 ft below sea level in northwestern Charles County to 2,453 ft below sea level at Chalk Point, in southernmost Prince George's County (Andreasen, 1999) and 2,515 ft below sea level at Lexington Park (Hansen and Wilson, 1984). The basal 30 ft of the Coastal Plain at Lexington Park was tentatively assigned by Hansen and Wilson (1984) to the "Waste Gate Formation", the updip edge of an Early Cretaceous unit that thickens eastward beneath the Eastern Shore of Maryland (Hansen, 1984). The Patuxent aquifer outcrops along the inner edge of the Fall Line in Virginia, Washington, D.C., and northwestern Prince George's County.

Transmissivity values estimated by Andreasen (1999) for the Patuxent aquifer in Charles and Prince George's Counties and northern Virginia range from 80 to 4,400 ft^2/d. Water levels measured in the Patuxent aquifer in 2002 range from 4 ft below sea level to 35 ft below sea level in northwestern Charles County (fig. 40). Water levels measured in Prince George's, Anne Arundel, and Queen Anne's Counties are within 6 ft of sea level. Water-level declines in four wells screened in the Patuxent aquifer in Charles and Prince George's Counties range from about 0.5 ft/yr in well CH Da 18 to 3 ft/yr in well CH Bc 77 (fig. 41).

Analyses of water from seven wells screened in the Patuxent aquifer in Charles County show good water quality, with pH ranging from 7.3 to 7.9 and TDS ranging from 214 to 602 mg/L (app. B). No MCLs were exceeded in these analyses, but SMCLs were exceeded in one well for iron, and in one well for manganese. No analyses are available for arsenic concentrations in the Patuxent aquifer in the USGS database, but samples from two production wells in northwestern Charles County (wells CH Bd 58 and CH Cc 36) were below the detection level of 2 µg/L.

A Piper diagram indicates that water in the Patuxent aquifer is of the sodium bicarbonate hydrochemical facies (fig. 42). However, the anions show a trend toward chloride, similar to that seen in the Lower Patapsco aquifer. All analyses have elevated chloride concentrations, ranging from 16 to 96 mg/L. Elevated chloride concentrations do not appear to be clustered near the Potomac River, as they are in the Lower Patapsco aquifer. The highest concentration is near La Plata (96 mg/L), which is about 10 mi downdip from the river.

The Patuxent aquifer was not screened or sampled for water quality at well SM Df 84 in Lexington Park, but Hansen and Wilson (1984) estimated TDS and specific conductance using the Dual Induction-SFL electric log for several sandy intervals in the Patuxent and Waste Gate Formations. They determined that these intervals contain brackish water with specific conductance estimated to range from about 2,500 to 4,300 microsiemens per centimeter (µS/cm), and TDS concentrations estimated to range from about 1,500 to 2,650 mg/L. They also report that pore water squeezed from clayey core samples from the Patuxent and Waste Gate Formations is also brackish, with estimated TDS concentrations ranging from 887 to 2,176 mg/L.

The source of brackish water in the Patuxent aquifer in Southern Maryland is uncertain, but it may be the updip portion of a wedge of salty water from the Atlantic Ocean that extends beneath the Eastern Shore of Maryland. Hansen and Wilson (1984) note that sodium and chloride concentrations generally increase with depth at well SM Df 84. Brackish water is also present at the base of the Potomac Group aquifers on the upper Eastern Shore of Maryland (Otton and Mandle, 1984). Drummond (1998) speculated that this might be a relic of a previous high stand of sea level, in which the aquifers were inundated by seawater, but not yet entirely flushed out with fresh water. A similar situation may occur in the Patuxent aquifer of Southern Maryland. If the presence of brackish water is confirmed in the downdip areas of the Patuxent aquifer, it may constrain development of the aquifer for water supply.

Thick, dense clays and silts of the Arundel confining unit separate the Patuxent aquifer from overlying aquifers (predominantly the Lower Patapsco aquifer), and probably do not allow much leakage. The Waste Gate Formation and bedrock underlie the Patuxent aquifer, and are not considered potential sources of water.

GROUND-WATER MANAGEMENT

Effective management of ground-water resources requires the consideration of several important factors that may limit the amount of water that can be safely withdrawn from the aquifer system. These water-management criteria may affect production wells, or may affect other users and resources many miles from the production wells themselves. Five water-management criteria were identified that could constrain future development of the ground-water supply: the 80-percent management level, impacts on other ground-water users, brackish-water and river-water intrusion, a lowered water table, and land subsidence.

WATER-MANAGEMENT CRITERIA

80-Percent Management Level

Currently, the primary criterion for evaluating water-appropriation permit applications in the confined aquifers of the Maryland Coastal Plain is the 80-percent management level. The Maryland Department of the Environment (MDE) defines this level at a given location as 80 percent of total available drawdown, measured from the prepumping water level to the top of the aquifer (Code of Maryland Regulations [COMAR] 26.17.06.D(4)) (fig. 43). MDE regulates ground-water users to prevent the regional potentiometric surface from declining below this level. A new user (or existing user applying to increase its withdrawal) would not be granted a permit if the proposed withdrawal rate is predicted to cause the regional head to fall below the management level. This regulation is intended to prevent water levels from declining below the top of an aquifer, and thus causing partial dewatering of the aquifer near large ground-water users. Dewatering of confined aquifers is also prevented by COMAR 26.17.06.D(5), which prohibits the installation of a well pump below the top of the aquifer. The 80-percent management level is not applied in the outcrop area nor the shallow confined portions of an aquifer because the regional head is near the top of the aquifer even without the influence of pumping. The cumulative effect of many production wells on water levels in the shallow portions of confined aquifers is not considered in application of the 80-percent management level.

The 80-percent management level for each aquifer can be mapped as an 80-percent management surface throughout the extent of the aquifer from maps of prepumping head and altitude of the aquifer top. Measured and simulated heads can be compared with the 80-percent management surface to determine remaining available drawdown for specified times. In areas where the top of an aquifer is poorly defined, the 80-percent management surface will also be poorly defined.

The 80-percent management surface for the Piney Point aquifer (fig. 44) ranges from about sea level in northern Calvert County to 250 ft below sea level in southern St. Mary's County. The 80-percent management surface for the Aquia aquifer (fig. 45) ranges from about 50 ft above sea level in northwestern Charles County to about 400 ft below sea level in southern St. Mary's County. The 80-percent management surface for the Magothy aquifer (fig. 46) ranges from about sea level in northern Charles County to 500 ft below sea level in southern Calvert County. The 80-percent management surface for the Upper Patapsco aquifer (fig. 47) ranges from about 100 ft above sea level in northern Charles County to about 600 ft below sea level in eastern Calvert County. The 80-percent management surface for the Lower Patapsco aquifer (fig. 48) ranges from about 100 ft below sea level in northwestern Charles County to about 1,150 ft below sea level in southeastern Calvert County.

Impacts on Other Users

Excessive drawdowns may create other undesirable effects that should be taken into consideration, but are difficult to evaluate on a regional basis. In some areas, wells have been constructed with 4-inch diameter casing near the land surface that reduces to a 2-inch diameter below that to save on construction costs; these are referred to as "telescoping wells." A submersible pump is typically installed in the 4-inch part of the well. If the water level falls below the reduction point in such a well, the pump cannot be lowered further, and the well must be replaced. This is not a problem with the ground-water resource, but may cause significant economic impact in areas where telescoping wells are common. In situations where a large user withdraws a quantity of ground water unprecedented for an area, MDE regulations require the user to financially mitigate the impacts of that withdrawal on other users (COMAR 26.17.06.05.D(1)).

Lowered Water Table

Although the water table (potentiometric surface in the Surficial aquifer) generally remains constant despite head declines in deeper confined aquifers, it is possible, through cumulative regional withdrawals, to lower the water table at some locations. The consequences of a lowered water table may include reduced base flow to streams, a decrease in water available for plant transpiration, and altered ecology of wetlands, where ground water provides inflow to the wetland (Tiner, 1988). These processes are complex and localized, and cannot be adequately addressed in a regional study of this scope. MDE regulations prohibit ground-water withdrawals that would affect the use of watercourses and lakes by other people (COMAR 26.17.06.05.D(2)). However, this regulation does not address the potential cumulative impact of thousands of users in the confined part of an aquifer on surface-water resources in the unconfined part.

At one location near Glen Burnie in northern Anne Arundel County, withdrawals from a well field pumping from the Lower Patapsco aquifer drastically reduced the stream flow in nearby Sawmill Creek (Achmad, 1991). The well field was abandoned, and stream flows returned to normal. No other instances of stream-flow reduction or wetland degradation caused by ground-water withdrawals have been documented in the Maryland Coastal Plain.

The potential impact of ground-water withdrawals on the water table can be tracked in the future by continuing to monitor water levels in wells in the outcrop areas of major aquifers where shallow monitoring wells exist, and installing and monitoring wells in aquifer outcrop areas where data are lacking. The future impact of increased ground-water withdrawals on water-table elevations could be evaluated by developing a ground-water flow model that simulates the shallow subsurface processes of recharge to the water table, evapotranspiration, base flow to streams, and discharge of ground water to estuaries.

Intrusion of Brackish Water or River Water

Potentiometric heads reduced below sea level in shallow aquifers may induce brackish-water intrusion near tidal estuaries or river-water intrusion near non-tidal rivers. River-water intrusion has been documented in the Lower Patapsco aquifer in the Indian Head area of northwestern Charles County, along the Potomac River (Hiortdahl, 1997). Heads have already declined below sea level in this area in the Upper Patapsco and Lower Patapsco aquifers, and increased future withdrawals will lower heads further. Both of these aquifers are unconfined or semi-confined in this area, and continued river-water intrusion is a possibility. The Potomac River is tidally influenced fresh water in the area of the cones-of-depression in northwestern Charles County. Potomac River water has average salinity values of 0.09 and 0.23 parts per thousand (ppt) at two sites in this area (Maryland Department of Natural Resources, 2005a, 2005b). River-water intrusion into the aquifers may cause the ground water to be unsuitable for some uses, including human consumption. Brackish-water intrusion is not likely to occur in other parts of the study area because the large cones-of-depression occur in the confined parts of the aquifers, and overlying confining units would prevent downward migration of salty water. Brackish-water intrusion has been documented in the Aquia aquifer in Anne Arundel County near the Chesapeake Bay (Fleck and Andreasen, 1996), Baltimore Harbor (Chapelle, 1985), and Kent Island (Drummond, 1988). MDE regulations (COMAR 26.17.06.D(7)) prohibit ground-water withdrawals that would cause brackish-water intrusion. More detailed studies are required to determine the extent and potential for brackish-water or river-water intrusion near the tidal rivers of Southern Maryland.

Land Subsidence

Land subsidence in the Maryland Coastal Plain may be caused by large head declines as a result of water withdrawals if sediments are compressed due to loss of hydrostatic pressure (Davis, 1987). Subsidence in Maryland may also be caused by the continued isostatic adjustment of the land surface to the most recent glaciation cycle. During parts of the Pleistocene Epoch, much of the northern United States and Canada was covered by an ice sheet, which depressed the land surface in that area and caused an upward bulge in the land surface to the south of the ice sheet. Melting of the ice sheet resulted in a "rebound" of the land surface that was once covered by ice, and subsidence of the land surface south of that area (Sella and others, 2007). Other processes, such as dewatering of organic soils and dissolution of soluble earth materials, may also cause land subsidence in some areas, but they are not likely to be significant in the Maryland Coastal Plain. Possible consequences of land subsidence include lowered land-surface elevation, encroachment of bay water, and a decrease in inelastic storage of confining units and clayey parts of aquifers.

Land subsidence has not been documented in Maryland, but it is a possibility near the deep cones-of-depression in Charles and St. Mary's Counties. Achmad and Hansen (1997) estimated that water levels reduced to the 80-percent management level near Lexington Park could result in land subsidence of 0.73 to 1.09 ft, but that this is not likely to cause severe engineering problems. Assuming 1 ft of subsidence takes place over 50 years (from 1980 when water levels at Lexington Park first exceeded the preconsolidation stress of 65 ft below sea level, to 2030), the rate of subsidence would be about 6 millimeters per year (mm/yr). Holzer (1981) noted that pumpage-induced sediment compaction is relatively small until water-level declines exceed the previous maximum stress on the sediments, which is referred to as the preconsolidation stress. Davis (1987) estimated that, for the Atlantic Coastal Plain, the preconsolidation stress equivalent is about 65 ft below sea level. Some shoreline slopes in the Chesapeake Bay region are nearly flat, and a small relative rise in sea level can cause a significant loss of horizontal shoreline (Nerem and others, 1998). Because of a time lag caused by drainage of thick clay beds, subsidence rates are likely to be less than this estimate, and would continue even after water levels in the aquifers have stabilized.

Subsidence was documented by Pope and Burbey (2004) at two sites in Virginia. Extensometer-well records indicate total land subsidence of 24.2 mm from September 1979 through December 1995 (1.5 mm/yr) at Franklin, and 50.2 mm from June 1982 through December 1995 (3.7 mm/yr) at Suffolk. Large ground-water withdrawals from the Cretaceous middle Potomac aquifer (possibly correlating to the Lower Patapsco aquifer in Maryland), primarily from paper mills at those sites, caused drawdowns of 200 ft and 131 ft, respectively. Sediment compaction, which manifests as subsidence at the land surface, occurs chiefly in clay beds, and does not significantly affect the hydraulic properties of the aquifers (Alley and others, 1999). Land subsidence could be evaluated by the installation and monitoring of extensometer wells at Lexington Park and La Plata, by high-precision global positioning system (GPS) surveys, and by remote sensing applications such as InSAR (a satellite imagery technique).

POPULATION TRENDS

The population of the three Southern Maryland counties increased from 64,626 in 1950 to 281,320 in 2000 (tab. 4) (U.S. Census Bureau, 1995, 2003). Charles County experienced the most growth, its population increasing by 97,131, or 415 percent during that time period. Calvert County's population increased by 62,463, or 516 percent, and St. Mary's County's population increased by 57,100, or 196 percent. Figure 49 shows historical and projected population for the three counties from 1900 through 2030.

Population data were used to estimate domestic pumpage for the historical model calibration periods of 1952, 1982, 1994, and 2002. Table 4 shows intercensal population estimates for 1982 (U.S. Census Bureau, 1992) and 1994 (U.S. Census Bureau, 2000) and the interpolated 1952 population that were used for domestic pumpage calculations. Table 4 also shows the estimate (U.S. Census Bureau, 2003) for July 1, 2002, which was used for domestic pumpage calculations for 2002, and as a base figure for future pumpage projections. As of March 2007, the U.S. Census estimates for the 2002 population in Calvert, Charles, and St. Mary's Counties (U.S. Census Bureau, 2007) had been revised slightly (less than 1 percent in all counties) from figures accessed in 2003. The population estimates used in table 4 were archived by the U.S. Census Bureau as "vintage 2002" figures (U.S. Census Bureau, 2003).

Population projections were used to estimate future domestic and public-supply pumpage. Population projections for 2010, 2020, and 2030, broken down by election district, were obtained from each of the county planning departments (Calvert County Department of Planning and Zoning, Charles County Department of Planning and Growth Management, and St. Mary's County Department of Land Use and Growth Management, written communications, 2004). Election district boundaries are shown in figures 57 to 61. Increases over 2002 populations were used to estimate domestic pumpage and public-supply pumpage for those years. Calvert County changed the boundaries of its election districts in 2002; the old election districts are used throughout this report.

Table 5 shows 2000 population figures from the Census Bureau for each election district in Calvert, Charles, and St. Mary's Counties. Population distribution among election districts was used to estimate domestic-pumpage distribution for historical and future flow-model simulations. Census Bureau population estimates for 2002 were not subdivided by election district, so the percentage increase from 2000 to 2002 for each county was multiplied by the election-district populations of 2000 to obtain estimates of election-district populations for 2002. Table 5 also shows the projected populations for each election district, and the fractional increases over 2002 populations for 2010, 2020, and 2030. Fractional increases from 2002 to 2030 range from 1.10 in Charles County Election District 10 to 2.04 in Charles County Election District 9 (increases of 10 percent to 104 percent). County populations increase by 24 percent, 59 percent, and 42 percent for Calvert, Charles, and St. Mary's Counties, respectively, from 2002 to 2030.

GROUND-WATER PUMPAGE

Ground-water pumpage is an important input parameter to the flow model for historical calibration of the model and for simulating future water levels in response to projected pumpage amounts. Pumpage is broadly divided into two categories: domestic pumpage, which is withdrawn from individual homeowners' wells for household supplies; and major-user pumpage, which is withdrawn from production wells for public-supply, commercial, military, and industrial users.

Major Users

Major users (those users pumping an average of 10,000 gallons per day [gpd] or more) are regulated by MDE, are required to obtain Ground-water Appropriation Permits (GAPs), and submit reports of monthly pumpage amounts to MDE. Pumpage data collected by MDE are acquired by the USGS and maintained in a statewide database, which also stores user locations and aquifer assignments (Judith Wheeler, written commun., 2002-2004). Pumpage data for major users from 1900 through 1980 were compiled by Wheeler and Wilde (1989). These data were used to construct model-input data sets for the simulation periods 1952, 1982, 1994, and 2002. In some cases, pumpage figures were revised, based on discussions with water-supply operators. Total pumpage for major users in each county for each historical stress period is shown in table 6. Pumpage amounts for individual major users are tabulated for the Piney Point, Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers in Appendixes D, E, F, G, and H, respectively. Locations of major users are shown for each aquifer in figures 50, and 52 through 55. Figure 51 shows the locations of individual wells for well fields at Solomons, Chesapeake Ranch, Lexington Park, NAS Patuxent River, and Leonardtown, and pumpage amounts for these wells are tabulated in Appendix I. Wells within each of these well fields are separated by large enough distances to be simulated separately in the flow model.

Future public-supply pumpage was estimated using population projections for 2010, 2020, and 2030. The fractional increase of population from 2002 population for each election district was multiplied by 2002 pumpage amounts for public-supply users within the relevant district. Pumpage amounts for major users that were not listed as public supply in 2002 were not increased in the future simulations. Although commercial, military, and industrial water use will probably increase in the future, it is difficult to predict where and when increases will occur because they are not directly related to population increases. Water use outside of the study area was also kept at 2002 levels for future simulations. Significant future increases in pumpage in counties outside the study area (particularly southern Anne Arundel County) may cause additional drawdown to that simulated in the flow model. Andreasen (2002) estimated an increase of 0.8 million gallons per day (mgd) in southern Anne Arundel County from 2000 to 2020, due to a projected population increase of 32,750. He simulated an additional drawdown of 22 ft if the water were withdrawn from the Aquia aquifer, or 20 ft if withdrawn from the Magothy aquifer. Additional drawdown caused by pumpage increases in other nearby counties would be somewhat less, due to smaller projected population increases, and greater distances from the study area. Total major-user pumpage for each county for each future stress period is shown in tables 7a-c.

Domestic Pumpage Distribution

Domestic pumpage is not reported to MDE, so the distribution and amounts were estimated from well records and population figures. Well drillers in Maryland are required to obtain a permit prior to drilling a well, and to submit a completion report after drilling a well. These documents are maintained at MDE, and the information from them is compiled in a database that includes approximate well location, depth drilled, screen settings, and yield characteristics. The number of domestic wells drilled in each 10,000-foot Maryland grid block was tallied, the number of wells in each aquifer was estimated from screen-depth and elevation information, and a conversion factor was used to calculate pumpage. Because the data include significant uncertainties in location, and land-surface elevation is unknown, a generalized method was developed to determine the distribution of wells in each aquifer.

All well records for Calvert, Charles, and St. Mary's Counties were loaded into a spreadsheet. Wells were removed if they were not identified as domestic-use wells, were missing depth or location data, or had locations outside of their respective counties. Wells were also removed if they were listed as replacement wells. Replacement wells generally do not specify the wells they replaced, so it is uncertain whether the replacement well and the original well were screened in the same aquifer. In such cases, such as a shallow dug well being replaced by a deeper well in a confined aquifer, some domestic pumpage may have been attributed to the wrong aquifer. However, if replacement wells were included in this analysis, they would cause duplication of wells, and this was considered a greater source of error than misattribution of aquifers.

The well records were then sorted by location data into 10,000-foot grid blocks of the Maryland Grid Coordinate system. This system is based on the 1927 datum of the Maryland State Plane projection. Because precise location and elevation data were not available for each well, the altitudes of the well screens could not be determined exactly, and, therefore, could not be compared directly to aquifer structure-contour maps to determine the aquifer in which each well is screened. Instead, the depths of domestic wells in each 10,000-foot grid block were plotted as a histogram, and the percentage of wells screened in each aquifer was estimated visually. To demonstrate this method, histograms of well depths from two grid blocks in northern Calvert County are shown in figure 56. The depths of the Piney Point and Aquia aquifers, based on the land-surface elevation at the center of each grid block, are also shown. Hydrogeologic units become progressively deeper to the southeast in this area.

In grid block 310.890, most of the domestic wells are between 200 and 450 ft deep, and they were all assigned to the Aquia aquifer. Some wells appear to be screened below the bottom of the Aquia aquifer; however, the land-surface elevation at the center of the grid block (33 ft above sea level) is not representative of all wells in the block, and wells with higher land-surface elevations require greater screen depths to reach the aquifer. Well depths in grid block 280.920 are nearly all between 200 and 350 ft deep. All of these wells were assigned to the Piney Point aquifer, although some appear to be screened below the bottom of the aquifer. This discrepancy may be partially attributable to uncertainties in land-surface elevation (as described for the Aquia aquifer in grid block 310.890). However, some of the wells in this area are actually screened in sandy portions of the lower Nanjemoy Formation, which is included in the Nanjemoy confining unit in hydrogeologic section D-D' (fig. 7). Achmad and Hansen (1997) characterize this section in northern Calvert County as a confining bed with minor aquifers, and indicate cumulative sand thicknesses of up to 30 ft.

This method produces acceptable results in Calvert and St. Mary’s Counties where only the Piney Point and Aquia aquifers are used for domestic supply and the aquifers are separated by a significant confining unit. In Charles County, however, the Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers are all used, and they are separated by thin confining units (or in some cases a confining unit may be absent). In this area, particularly in western Charles County, the depth histograms do not show distinct clusters for each aquifer. Rather, a conglomerate cluster is displayed over a range of aquifer depths, and more interpretation was required to determine the fraction of wells in each aquifer than was necessary in Calvert and St. Mary’s Counties.

This method probably provides a good estimate of the proportion of wells in each aquifer for a given area. However, the method underestimates the total number of domestic wells because many wells were excluded from the analysis due to missing or erroneous data. The total number of wells for each county was therefore adjusted based on census data. The U.S. Census of 1990 (U.S. Census Bureau, 1992) includes data on the number of housing units with domestic wells (the 2000 census omitted this crucial data item) and provides an indirect means of comparison. The number of domestic wells calculated from the above analysis was tallied for each county through 1990, and compared to 1990 census data for housing units with private wells. The undercount ratio for each county was used to adjust 2002 data upward to more realistic numbers.

The number of wells, corrected to census data, was used to estimate domestic pumpage distribution for each aquifer in each county (figs. 57 to 61). Pumpage for each domestic well was estimated to be 162 gpd by multiplying average per capita water use (60 gpd) (Andreasen, 2002) by the average household size of 2.7 for the region. The number of estimated domestic wells for each 10,000-foot grid square is shown by shading the square. Locations of “delegate wells,” which represent all domestic pumpage within a cell as a single withdrawal in the flow model, are also shown in figures 57 through 61.

Historical domestic pumpage for the model-calibration periods was estimated using county population estimates (tab. 4) and the 2002 pumpage distribution. The fraction of 2002 population for 1952, 1984, and 1992 was multiplied by 2002 pumpage amounts to obtain domestic pumpage amounts for each of those years. The distribution of pumpage, spatially and between aquifers, was assumed to be the same as in 2002.

Future domestic pumpage was estimated in a similar way. The fractional population increase for each election district (tab. 5) was multiplied by the 2002 domestic pumpage distribution to obtain domestic pumpage estimates for 2010, 2020, and 2030. As with historical pumpage estimates, the distribution of pumpage spatially and between aquifers was assumed to be the same as in 2002. Total projected pumpage amounts for each county are shown in tables 7a-c as Simulation 1.

FLOW-MODEL SIMULATIONS

A ground-water flow model was developed to simulate flow and heads in the major aquifers used in the Southern Maryland area. Visual Modflow version 2.8.2 (Waterloo Hydrogeologic, Inc., 2000) was used for all simulations. The hydrogeologic, layered structure of aquifers and confining units was entered into the model, hydraulic characteristics were assigned to the layers, and boundary conditions were entered at the edges of the model (fig. 62). The model was calibrated by simulating prepumping and historical pumping conditions, and matching simulated heads with measured heads. The calibrated model was then used to simulate future ground-water heads in response to various pumping scenarios. Estimates of future ground-water pumpage were entered into the model for stress periods ending in 2010, 2020, and 2030 (tab. 7a-c). Flow and heads were simulated at the end of each stress period, and heads at critical locations were compared with the 80-percent management level.

Visual Modflow differs from the original USGS Modflow model in several significant aspects. Visual Modflow provides many pre-processing and post-processing functions to aid with model setup and analysis. Also, Visual Modflow requires the user to enter arrays for top and bottom altitudes of all model layers, and hydraulic conductivity zones for each layer. The model calculates transmissivity and leakance based on layer thickness and hydraulic conductivity. Thus, transmissivity and leakance are not entered explicitly in Visual Modflow. Similarly, storage coefficient is not entered explicitly in Visual Modflow; zones of equal specific storage are entered for each layer, and Visual Modflow calculates storage coefficient from specific storage and layer thickness.

FLOW-MODEL SETUP

Model Area and Grid

The flow model covers an area of 6,642 mi^2, between latitudes 37° 50′ and 39° 00′, and longitudes 76° 00′ and 77° 30′ (fig. 1). The model area includes Calvert, Charles, and St. Mary's Counties, but extends north to Washington, D.C., east to the Cambridge area, and south and west to include parts of Virginia. The model area was extended beyond the limits of the study area so that the model boundaries would have minimal effect on model results in the area of main interest.

The model area was divided into a finite-difference grid with square, regularly-spaced grid cells ½ mi on each side. The grid was placed in a north/south, east/west orientation, with the horizontal direction (164 columns) slightly larger than the vertical direction (162 rows).

Boundary Conditions

Boundary conditions were entered at the top, bottom and lateral edges of the model domain (fig. 62). The top of the model was entered as a specified-head boundary (model layer 1) that provides recharge to deeper aquifer layers. The estuaries (Chesapeake Bay, the Potomac River and other tidal rivers) were entered as a constant head at sea level. The water level in these estuaries varies semidiurnally with tidal fluctuations, and in response to major storm events, but averages around sea level. Eustatic sea-level rise may have a significant effect on the surficial boundary over a period of centuries, but not in the few decades simulated in the flow model. Titus and Narayanan (1995) estimate a future sea-level rise of 10 to 12 inches (in.) per century.

The Surficial aquifer (the land portion of the model area) was simulated as a constant-head boundary of the water-table altitude. The water-table altitude was estimated using a GIS process that incorporated land-surface elevation and altitudes of perennial streams. The water-table altitude fluctuates seasonally, and from year to year due to variations in precipitation and evapotranspiration, but over the long term the water table has not shown a decreasing trend (fig. 10). As future ground-water withdrawal rates approach maximum sustainable levels, increased head gradients in the confined aquifers may cause declines in the water-table altitude in places, and the assumption of a constant-head boundary in the Surficial aquifer should be reevaluated with future data. In order to simulate water-level changes in the Surficial aquifer, it must be simulated as an active model layer, with flux components (recharge, evapotranspiration, and base flow to streams) entering and leaving the model.

The bottom of the model, which is the Arundel Clay, was represented as a no-flow boundary, assuming that the thick, low-permeability clay and silt of this unit would not allow significant leakage between the Lower Patapsco aquifer and the underlying Patuxent aquifer. Andreasen (1999) simulated a leakance value of 1×10^{-10} ft^{-1} for the Arundel confining unit throughout most of Charles County, with some areas ranging up to 9×10^{-7} ft^{-1}. Given a thickness of the Arundel of 100 ft, these leakance values yield a range in vertical hydraulic conductivity of about 1×10^{-4} to 1×10^{-8} feet per day (ft/d). This range is consistent with low-permeability materials such as clay, shale, and unfractured metamorphic and igneous rock (Freeze and Cherry, 1979, p. 29; Morris and Johnson, 1967).

The Fall Line was simulated as a no-flow boundary because the Coastal Plain aquifers do not extend northwest of this line. In areas where an aquifer extends beyond the model edges, the boundary was simulated with a head-dependent flux boundary (referred to as a General Head Boundary, or GHB). The flux (or ground-water flow) into or out of the model at this boundary was calculated by the model using conductance and head values entered at the GHB boundary, and the head calculated within the model domain. Conductance values were generally entered as 500 ft^2/d, which allows model heads to differ slightly from heads entered at the boundary. Heads entered at the GHB boundaries were estimated from potentiometric maps where available, and from previous modeling studies (Williams, 1979; Mack and Achmad, 1986; Fleck and Vroblesky, 1996) where potentiometric maps are not available. No-flow boundary conditions were entered where model edges truncate confining units, because flow is predominantly vertical in the confining units.

Layering Scheme

The vertical section was divided into 11 model layers, in which each major aquifer is represented by a model layer, alternating with model layers representing confining units (fig. 62). From top to bottom, the layering scheme comprises the Surficial, Piney Point/Nanjemoy, Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers. The intervening confining units are the Chesapeake, Nanjemoy, Brightseat, Upper Patapsco, and Middle Patapsco confining units. The Arundel confining unit was designated a no-flow boundary, and neither it nor the Patuxent aquifer was simulated in this model.

Some aquifers and confining units do not extend throughout the entire model area. However, the model layers must extend throughout the entire active region of the model to provide vertical flow between hydrologic units that are present. In areas where a unit thins laterally to zero thickness (and in reality is not present), a minimum thickness of 1 ft was maintained, the horizontal hydraulic conductivity was assigned a very low value (1×10^{-7} ft/d) to prevent horizontal flow, and the vertical hydraulic conductivity was assigned a very high value (100 ft/d) to allow vertical flow (leakage). This is necessary to allow vertical flow through the model layer, even where the hydrogeologic unit is absent. In areas where an aquifer undergoes a facies change (the unit is present but not as an aquifer) the true thickness of the layer was entered, and it was assigned horizontal and vertical hydraulic conductivity values appropriate for a confining unit.

An altitude array was entered into Visual Modflow for the bottom of each model layer. The top of each layer was defined by the bottom of the overlying layer. Thickness of each layer was determined in model calculations by subtracting the altitude of the bottom from the top, and a minimum thickness of 1 ft was specified so that layers would extend throughout the active model region. Land-surface elevation (or sea level for the estuaries) was entered to define the top of model layer 1 (the Surficial aquifer). For flow-modeling purposes, the bottom of the Surficial aquifer was arbitrarily defined as 50 ft below land surface, except where this would put it above the water table, and cause problems in the initial model run due to “dry cells.” In these areas, the bottom of the Surficial aquifer was placed 1 ft below the water table, which was simulated as a constant-head boundary. Because the Surficial aquifer comprises such a wide variety of geologic materials, its hydraulic characteristics are also extremely variable. However, it was designated a constant-head boundary, not an active model layer, so it was not necessary to enter hydraulic properties in the flow model.

Time Discretization

The historical (calibration) model simulation ran from 1900 until 2002. Although no pumping records exist for the period before 1900, the population at that time was only 15 percent of the 2002 population (tab. 4), and this is considered a prepumping condition. An initial steady-state prepumping stress period was run prior to 1900. The period 1900 to 2002 was divided into four stress periods, ending at 1952, 1982, 1994, and 2002. These periods correspond to previous studies that produced potentiometric maps for the region (Otton, 1955; Chapelle and Drummond, 1983; Achmad and Hansen, 1997). Potentiometric maps for each aquifer were generated by the flow model at the end of each stress period, and simulated heads at observation wells were compared to measured heads for the appropriate time during model calibration. Each stress period was divided into 10 equal time steps, although heads were not generally evaluated for each time step.

For future scenarios, three stress periods were simulated, starting in 2003 and ending at 2010, 2020, and 2030, to correspond with population projections. Each stress period was divided into 10 equal time steps, and heads were calculated at the end of each time step. For each aquifer, potentiometric maps were generated, which show heads at the end of each stress period.

Pumpage Simulation

Ground-water pumpage was entered in the flow model at discrete points that correspond to well locations. Pumpage was held constant during each stress period described above. Major-user pumpage was entered for the location and aquifer of each GAP in the study area, and for the surrounding counties in Maryland. Many GAPs include multiple production wells, but most of those were simulated as single wells in the model. A few GAPs include multiple wells that are widely dispersed; for these GAPs, pumpage at individual wells was simulated. Total major-user pumpage simulated for 2002 was 3.36 mgd, 9.02 mgd and 5.29 mgd for Calvert, Charles, and St. Mary's Counties, respectively (tab. 6).

Domestic pumpage was simulated differently than major-user pumpage. There are too many domestic wells to simulate individually, so "delegate wells" were used to represent pumpage from many individual domestic wells. The number and distribution of delegate wells were based on the estimated pumpage distribution in election districts and aquifers shown in table 4 and figures 57 through 61. Each delegate well represents 250 domestic wells pumping 162 gpd each in 2002. The pumping rate was estimated from a per-capita water-use rate of 60 gpd (Andreasen, 2002) multiplied by an average household size for the region of 2.7. Delegate wells were placed in such a way as to approximate population centers reliant on domestic supply; more delegate wells were placed in these areas and fewer were placed in less-populated areas and areas reliant on public-water supply.

For historical (1952, 1982, and 1994) and future (2010, 2020, and 2030) stress periods, the same distribution of delegate wells was used as in the 2002 stress period. However, the rate of withdrawal at each well was adjusted to reflect the difference in population from the 2002 population. For historical simulations, the fraction of the 2002 population for each county (shown in tab. 4) was multiplied by the 2002 withdrawal rate for each delegate well to obtain withdrawal rates for 1952, 1982, and 1994. For future simulations, the fractional increase over the 2002 population for each election district in each county (shown in tab. 5) was multiplied by the 2002 withdrawal rate for each delegate well to obtain withdrawal rates for 2010, 2020, and 2030.

Hydraulic Properties

Hydraulic properties were initially entered into the model for aquifers and confining units, and then adjusted in some cases during model calibration. Properties for each model layer include horizontal hydraulic conductivity, vertical hydraulic conductivity, and specific storage. Visual Modflow calculates transmissivity from horizontal hydraulic conductivity and layer thickness; leakance from vertical hydraulic conductivity and thickness; and storage coefficient from specific storage and thickness.

Effective hydraulic conductivity zones for initial model input were derived from transmissivity, leakance, and top and bottom structure-contour maps. The effective hydraulic conductivity is an average value for the entire aquifer thickness, so that when multiplied by the thickness (altitude of the top minus altitude of the bottom of the aquifer) it yields the transmissivity for the aquifer. The effective hydraulic conductivity is generally lower than the conductivity of individual sand layers within the aquifer. A GIS process was used to calculate horizontal hydraulic conductivity distribution for each aquifer throughout the model area according to the equation:

$$K_{he} = T/(t-b) \qquad (7)$$

where

K_{he} = effective horizontal hydraulic conductivity, in ft/d

T = transmissivity, in ft^2/d

t = altitude of the top of the aquifer, in ft

b = altitude of the bottom of the aquifer, in ft

The aquifers were then divided into zones based on ranges of effective hydraulic conductivity.

No data are available for the vertical hydraulic conductivity (K_v) of these aquifers, but Freeze and Cherry (1979) show that core samples of clay show horizontal-to-vertical anisotropy values generally below 10, and layered sands can exceed 100. A value of 10 for horizontal-to-vertical anisotropy was used to calculate vertical hydraulic conductivity for all aquifers. Because flow is predominantly horizontal in aquifers, K_v is not as important as horizontal hydraulic conductivity (K_h) in aquifers. Similarly, because flow is predominantly vertical in confining units, K_h is less important than K_v in confining units.

Effective horizontal hydraulic conductivity zones for the Piney Point and Aquia aquifers were initially derived from transmissivity distributions from Achmad and Hansen (1997), and for the Magothy aquifer from Mack and Mandle (1977). Effective horizontal hydraulic conductivity zones for the Upper Patapsco and Lower Patapsco aquifers were initially derived from transmissivity distributions shown in the Hydrogeology section of this report. These zones were revised during calibration of the flow model. Maps showing the final calibrated distribution of effective horizontal hydraulic conductivity for the five aquifers are shown in figures 63 to 67, and ranges of calibrated hydraulic conductivity values for each aquifer are summarized in table 8.

Initially, a single value of vertical hydraulic conductivity was entered for each confining unit, then zones with differing values were created and revised during model calibration. Initial vertical hydraulic conductivity values were derived for the Chesapeake and Nanjemoy confining units from Achmad and Hansen (1997), and for the Brightseat confining unit from Mack and Mandle (1977). Initial values for the Upper Patapsco and Middle Patapsco confining units were derived from Wilson and Fleck (1990), and Andreasen (1999), respectively.

Storage coefficient values for each model layer were calculated by Visual Modflow from layer thickness (derived from top and bottom altitudes of the aquifer) and zones of specific storage entered in model calibration. A single value of specific storage was entered for all aquifer and confining unit layers (2×10^{-6} ft^{-1}).

Critical Locations

Results of model simulations were evaluated by comparing simulated heads with the 80-percent management levels at critical locations. If the simulated regional head falls below the 80-percent management level at a critical location, the pumpage that caused the exceedence is considered excessive. Critical locations were selected where drawdowns are most likely to exceed management levels, or where future pumpage scenarios may cause significant additional drawdown (fig. 68). The flow model calculated average head values for model cells, each of which is ½ mile by ½ mile and covers an area of ¼ mi^2. Heads will be deeper near heavily pumped wells than model-calculated cell averages. Model-calculated heads near pumping centers are somewhat dependent on grid spacing; a model with smaller grid cells would average heads over a smaller area than a model with larger cells, and would simulate heads at pumping wells more accurately.

Regional head is not formally defined in MDE regulations, and is determined on a case-by-case basis. Because a consistent methodology was needed for this evaluation, the simulated head averaged over an area of ¼ mi^2 was considered to represent the "regional head" and was compared with the 80-percent management level. Trescott and others (1976) present a method for calculating the effective radius from a hypothetical well (i.e., the distance from the well at which the model-calculated cell head applies). Applying their equation 12, $r_e = r_l/4.81$ (where r_e is the effective radius and r_l is the cell width) yields an effective radius for this flow model of 549 ft. This calculation indicates that the model-calculated head would apply at a distance of 549 ft from a production well.

MDE regulations prohibit a well pump from being installed below the top of an aquifer in which the well is screened, thus preventing the partial dewatering of the aquifer near the production well. This restriction acts as an additional constraint on withdrawal rates of production wells; however, this constraint can generally be overcome by installing additional production wells in a well field, and effectively distributing the drawdown over a larger area. Because the majority of future pumpage increases will probably be met by installing new production wells, the top-of-aquifer restriction was not considered to be a constraint on withdrawal amounts.

MODEL CALIBRATION

The ground-water flow model was calibrated by entering historical pumpage for the period 1900 through 2002, running the model using initial estimates of model inputs, and comparing model-calculated heads with measured heads at the end of each stress period. Based on residuals (the difference between measured and calculated heads), adjustments were made to model inputs, and the process was repeated until a good match was obtained between measured and calculated heads. Inputs that were adjusted during model calibration were primarily horizontal hydraulic conductivity for the aquifers, vertical hydraulic conductivity for the confining units, and to a lesser extent, lateral flow boundaries. Inputs that were not adjusted during calibration include storativity, altitude of aquifer tops and bottoms, and altitude of the water table (constant-head boundary in layer 1).

The statistical parameters mean error (ME) and root-mean-square (RMS) were calculated for each aquifer and each stress period to provide a quantitative assessment of model calibration (tab. 9). The ME is the average of all residuals (differences between calculated and observed head values) and is calculated as

$$ME = \frac{1}{n}\sum_{i=1}^{n}\left(H_{c_i} - H_{o\,i}\right), \qquad (8)$$

where

ME = mean error, in ft

H_{ci} = calculated head at observation well *i,* in ft

H_{oi} = observed head at observation well *i*, in ft

n = number of observation wells

The ME indicates whether calculated head values are generally too high (positive ME) or too low (negative ME). The RMS indicates how far calculated values are from observed values, irrespective of the mathematical sign of the differences, according to the equation

$$RMS = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(H_{c_i} - H_{o_i}\right)^2}, \qquad (9)$$

where

RMS = root mean square, in ft

H_{ci} = calculated head at observation well *i,* in ft

H_{oi} = observed head at observation well *i*, in ft

n = number of observation wells

RMS values are always positive, and lower values indicate a better fit of calculated heads to observed heads than higher values.

Although model results were evaluated at the end of each stress period (1900, 1952, 1982, 1994, and 2002), greater weight was given to the last stress period. More head measurements were available for this period, and pumpage data were considered more reliable than for previous periods. Figures 69 through 73 show simulated prepumping heads for the five modeled aquifers. The simulated prepumping head distributions were used to develop the 80-percent management surfaces shown in figures 44 through 48. The simulated prepumping potentiometric surface in the Piney Point aquifer (fig. 69) ranges from sea level near the Potomac and Patuxent Rivers and the Chesapeake Bay to about 80 ft above sea level near the updip truncation of the aquifer. This pattern of high heads in areas of high surface elevation and low heads in areas of low surface elevation is a subdued form of the water-table configuration, and indicates an influence of the water table on heads in the Piney Point aquifer. The simulated prepumping potentiometric surface in the Aquia aquifer (fig. 70) ranges from about sea level near the Potomac River to more than 70 ft above sea level in some parts of the outcrop area. The simulated prepumping potentiometric surface in the Magothy aquifer (fig. 71) ranges from about 20 ft above sea level near the Chesapeake Bay to more than 120 ft above sea level near the outcrop area. The simulated prepumping potentiometric surfaces in the Upper and Lower Patapsco aquifer (figs. 72 and 73) are similar, and each ranges from about 20 ft in southern St. Mary's County to over 120 ft above sea level in Prince George's County.

Simulated water levels are compared with observed water levels through time for 12 observation wells in figure 74. Water-level trends are simulated closely in most observation wells for the available periods of record. Simulated water levels at well CA Gd 6 in southern Calvert County are significantly lower than observed water levels for the 1952 and 1982 calibration times, perhaps because of inaccuracies in estimated pumpage for those time periods. Simulated heads are compared with all observed heads for 2002 in figure 75 for each of the modeled aquifers, and for the model as a whole. The dashed line in each plot represents a "perfect-fit line"; if a simulated head matches an observed head exactly, it would fall on this line. Simulated heads greater than observed heads plot above this line, and simulated heads less than observed heads fall below this line. If simulated heads are generally higher than observed heads, the mean error (tab. 9) would be positive. Data points are distributed fairly evenly about the "perfect-fit line" for all aquifers, and for the model as a whole, which is reflected in mean error values close to zero for all aquifers (tab. 9). The greater degree of scatter about the "perfect-fit line" for the Lower Patapsco aquifer is reflected in the relatively high RMS value shown in table 9.

Figures 76 through 80 show simulated heads as potentiometric contour lines and measured water levels at observation wells for 2002. Calibration is considered good for the Aquia and Magothy aquifers. These aquifers are fairly homogeneous, and can be easily characterized by model layers. The RMS for these aquifers was 9.1 ft and 7.5 ft, respectively, for the final stress period of model calibration (2002) (tab. 9). The mean error for these aquifers was 2.7 ft and 1.2 ft for the same stress period. Calibration is considered fair for the Piney Point aquifer, which does not have as extensive data coverage as the Aquia and Magothy aquifers. The RMS and ME for the Piney Point aquifer were 12.0 and 1.9 ft, respectively, for 2002. Simulated heads in northern Calvert County are fairly deep due to numerous domestic wells in the area tapping the Piney Point aquifer. Although no observed water levels were available during model calibration, a subsequent measurement of 18 ft below sea level in October, 2005 (David Andreasen, Maryland Geological Survey, written commun., 2006) indicates that heads are not as deep as simulated. In addition, heads near well SM Ef 89 near Great Mills in St. Mary's County, were difficult to calibrate. The anomalously high withdrawal rate of that well could not be simulated with transmissivity values reported in the study area. Vertical hydraulic conductivity of the overlying confining unit in this area was increased to allow greater vertical leakage from the Surficial aquifer.

Calibration is also fair for the Upper Patapsco and Lower Patapsco aquifers. Sparse data are available for these aquifers in many parts of the study area, and existing data indicate that the aquifers are extremely variable, with significant vertical and lateral heterogeneities. The variability of these aquifers makes them difficult to characterize as model layers in a study of this scale. The RMS for the final stress period was 10.5 and 16.7 ft for the Upper Patapsco and Lower Patapsco aquifers, and the mean error was –1.0 and –3.4, respectively. Residuals (differences between measured and simulated heads at observation wells) range as high as 24 ft in the Upper Patapsco aquifer, and 39 ft in the Lower Patapsco aquifer. Numerous adjustments of horizontal hydraulic conductivity were necessary to calibrate these two layers. Some adjustments in the vertical hydraulic conductivity zones of overlying confining units were also necessary for calibration. Although the model may not accurately simulate measured heads at some individual wells, it is considered suitable to characterize the regional flow system, and to evaluate the production capabilities of the aquifer system.

Sensitivity Analysis

A sensitivity analysis was performed on the calibrated flow model to determine the inputs with greatest influence on model behavior. Additionally, the sensitivity analysis indicates the degree of error in output that could be caused by inaccuracies in model input. The sensitivity analysis was performed by globally changing a single model input, within the reasonable range of values for the input, and noting the change in mean error and root-mean-square (tab. 10). Each input was increased by two levels and decreased by two levels, and the results plotted in graphs shown in figure 81. Model inputs that were included in the sensitivity analysis are K_h, K_v, specific storage (S_s), heads at lateral boundaries (H_b), conductance at lateral boundaries (C_b), and heads at the constant-head boundary in the Surficial aquifer (H_c). Values for K_h, K_v, S_s, and C_b were each increased by 50 percent and 100 percent, and decreased by 25 percent and 50 percent. Values for H_b and H_c were increased by 2 ft and 5 ft, and decreased by 2 ft and 5 ft.

The sensitivity analysis indicates that the flow model is most sensitive to K_h. When K_h was decreased by 50 percent, the RMS for the entire model increased from 11.0 to 43.3, and the mean error decreased from 0.6 to -26.5. When K_h was increased by 100 percent, the RMS increased to 27.5, and the mean error increased to 18.9. The flow model is moderately sensitive to K_v. When K_v was decreased by 50 percent, the RMS increased to 26.3, and the mean error decreased to -18.8. When K_v was increased by 100 percent, the RMS increased to 23.8, and the mean error increased to 17.6. The model was relatively insensitive to S_s, H_b and H_c.

Mass Balance

Flux components for the flow model were calculated to determine the relative quantities of water entering and leaving the flow model, and to ensure that these fluxes do not exceed reasonable amounts. Model boundaries can supply an infinite amount of water to the model domain, and if these quantities are unrealistic, results will not be accurate. Calculations of flux components were made for the entire model area, at the end of each stress period, and summarized in table 11.

Mass-balance calculations show that in the prepumping period, the majority of water entered the model domain from the constant-head boundary in model layer 1 (2.1 million cubic feet per day [ft^3/d], or 78 percent of total flux), with the rest entering from lateral boundaries (22 percent). As pumpage increased through 2002, water entering the model from the constant-head boundary increased to 4.7 million ft^3/d, although the percentage of total flux decreased to 65 percent. Water entering the model from the lateral boundaries increased to 1.9 million ft^3/d, and the percentage increased to 26 percent. Water influx from storage increased from zero to 9 percent from 1900 to 2002. No water entered the model from wells, because all were withdrawal wells, with no injection wells.

Most water also left the model domain (outflux) during the prepumping period through the constant-head boundary (1.7 million ft^3/d, or 64 percent) with some water leaving the model through the lateral boundaries (0.9 million ft^3/d, or 35 percent). Pumpage from wells increased to 5.8 million ft^3/d in 2002, which was the major outflux component, with 81 percent of the total. Outflux for the constant-head boundary decreased to 0.3 million ft^3/d (4 percent of total outflux), and outflux through the lateral boundaries increased slightly to 1.1 million ft^3/d, but the percentage of total outflux decreased to 15 percent. Water exiting the model domain to storage was insignificant throughout the simulations.

Flow components for individual aquifers simulated in the flow model are shown in table 12. Values are shown for recharge (water entering the aquifer directly from the Surficial aquifer), leakage through the overlying confining unit, leakage through the underlying confining unit, pumpage, storage, flow through the lateral model boundaries (general head boundaries) and other components (primarily water entering or leaving the aquifer where it is laterally truncated). Table 12 shows that under prepumping conditions water generally enters the confined aquifers as recharge and leakage from underlying units; and leaves the aquifers as leakage to overlying units, and through lateral boundaries. Under pumping conditions most water enters the confined aquifers as leakage through the overlying confining units. Although in most of these aquifers water can directly enter from the outcrop area as recharge, downward leakage is applied over a much larger area, and is the predominant component of inflow. Some water also enters the aquifers under pumping conditions through the lateral boundaries. Although storage is not actually inflow to the aquifers, the flow model treats it as a water source during pumping conditions. In the pumping scenarios, most water leaves the aquifers as pumpage, but some water also leaves most aquifers (except the Lower Patapsco aquifer, which is underlain by a no-flow boundary) as leakage to underlying units.

Flux calculations were also made for 2002 conditions in small (1 mi^2), selected areas to ensure that water is not entering the model domain from the constant-head boundary in unreasonable amounts. This flux represents recharge to the confined aquifer system from the Surficial aquifer. No actual measurements of flux are available to compare directly to model-calculated values, so flux values were compared to average precipitation for the area. Significant amounts of water that enter the Surficial aquifer as precipitation are removed as base flow to streams and evapotranspiration, so recharge flux should be well below average precipitation. Locations of zones (fig. 82) were chosen in areas where flux rates are expected to be highest, and in some typical areas for comparison.

Flux rates for the 13 selected zones range from 0.1 to 10.7 inches per year (in/yr) (fig 82). The maximum flux rate, near Bowie in Prince George's County, is about 22 percent of average precipitation recorded at Mechanicsville (47.52 in/yr near Charlotte Hall in northern St. Mary's County). For comparison, precipitation at Mechanicsville in 2002, a severe drought year, was 38.78 in/yr, or an 18-percent reduction from average yearly precipitation. Although the maximum flux is on the same order as average precipitation for the area, most fluxes are much lower, and indicate that recharge flux rates for the model do not exceed reasonable limits.

Remaining Available Drawdown in 2002

Figures 83 through 87 show maps of simulated remaining available drawdown for 2002 for each of the modeled aquifers. Remaining available drawdown is the amount of drawdown that remains above the 80-percent management level for a given aquifer (fig. 43), based on simulated potentiometric surfaces. Negative values indicate that the simulated heads are below the 80-percent management level. The 80-percent management regulation is not applied in areas in the vicinity of an aquifer's outcrop.

Remaining available drawdown in the Piney Point aquifer (fig. 83) ranges from no remaining drawdown in northern Calvert County to about 240 ft in southern St. Mary's County. As discussed in the Model Calibration section, simulated heads are probably too deep in this area, and there is probably more remaining available drawdown than indicated in this simulation. In the Aquia aquifer, remaining available drawdown in 2002 (fig. 84) ranges from no remaining drawdown near Waldorf to 380 ft in southern St. Mary's County. No measured water levels were available for model calibration near Waldorf, and simulated heads may be too low in this area. The Aquia aquifer is not generally used for water supply in this area, and the relatively deep water levels simulated in the Aquia aquifer are caused by downward leakage to the Magothy aquifer. The Magothy aquifer is pumped heavily in this area with heads as deep as 115 ft below sea level. Simulated remaining available drawdown in the Magothy aquifer (fig. 85) ranges from 0 ft near the outcrop area to about 470 ft in eastern Calvert County. Remaining available drawdown in the Upper Patapsco aquifer (fig. 86) ranges from no remaining drawdown near Indian Head (near the outcrop area) to 550 ft in eastern Calvert County. Remaining available drawdown in the Lower Patapsco aquifer (fig. 87) ranges from 30 ft near Indian Head to about 1,100 ft in southeastern Calvert County.

FUTURE PUMPAGE SCENARIOS

A series of eight major pumpage scenarios was developed that incorporates estimates of future pumpage derived from population projections, planned areas of growth, and hypothetical new users. The pumpage scenarios are summarized in table 13. Four of the pumpage scenarios included ranges of pumping conditions. Hypothetical new pumping centers were added in some scenarios to evaluate the impact of additional major withdrawals. All pumpage scenarios were simulated with the calibrated flow model, and the results were evaluated in terms of the 80-percent management level at critical locations in the study area. All scenarios simulate the time period 2003 through 2030. Pumpage was entered for an 8-year period, 2003 to 2010, and two

10-year periods, 2011 to 2020, and 2021 to 2030. Pumpage was held constant during each of these stress periods, and heads were calculated at the end of each period.

Results of the simulations are presented in several ways. Potentiometric surface maps show simulated water levels at the end of a stress period for a specific aquifer, similar to measured potentiometric-surface maps for historical time periods. Drawdown maps show the difference in water levels from the 2002 potentiometric surface to the relevant simulated time period. Simulated head at a specified location may be derived by subtracting the drawdown from the 2002 potentiometric surface at that location. Positive drawdowns indicate declining water levels, and negative drawdowns indicate recovering water levels. Remaining-available-drawdown maps show the amount of drawdown that remains above the 80-percent management level at a given time. Negative values of remaining available drawdown indicate that the simulated water level is below the management level, and there is no remaining available drawdown.

Results of future model simulations were also evaluated by comparing simulated heads with management levels at critical locations. If the simulated regional head falls below the 80-percent management level at a critical location, the pumpage that caused the exceedence is considered excessive. Critical locations were selected where drawdowns are most likely to exceed management levels, or where future pumpage scenarios may cause significant additional drawdown. These locations are shown in figure 68, and information for each location is shown in table 14, including the 80-percent management level, simulated prepumping head and the altitude of the top of the aquifer used to calculate management level. Critical locations were chosen at the centers of major cones-of-depression, hypothetical new production wells, and one area in northern Calvert County where numerous domestic wells in the Aquia aquifer have reduced the potentiometric surface without forming a typical cone-of-depression. Withdrawals would be considered excessive if they are predicted to cause water levels to exceed the management level, and alternative pumpage distributions should be sought.

Tables 15 and 16 show simulated heads and remaining available drawdown, respectively, for each scenario for 2030, at each critical location. Where simulated drawdown exceeds the management level (remaining available drawdown is negative), the value is indicated with an asterisk, and, where it exceeds the top of the aquifer, it is indicated with a dagger. MDE prohibits the placement of a well pump below the top of the aquifer in which the well is screened, which prevents water levels from actually falling below the top of the aquifer.

Pumpage was increased for future scenarios only for domestic and public-supply wells within the study area (tab. 7a-c). Other major users within the study area and all users outside the study area were held at 2002 withdrawal rates, which may cause underestimates of drawdown in future simulations. In addition, the general-head boundaries at the lateral edges of the model, which approximate pumpage outside the model area, were also held at 2002 head conditions. Underestimates would probably be greatest near areas of adjacent counties that are likely to experience high growth rates in the next several decades. Additional model simulations could be performed to estimate the effect of future pumpage increases outside the study area on water levels within the study area.

The first simulation (Scenario 1) represents “base conditions”, and simulates the most likely set of conditions without shifting pumpage to deeper aquifers. Each subsequent simulation is a variation of the base conditions, and incorporates a change in a single aspect of future conditions. The results of the subsequent simulations can be compared to the results of Scenario 1 to evaluate the relative effects of the range of possible future conditions.

In addition to the eight major pumping scenarios, a preliminary simulation (Scenario 0) was run in which 2002 pumpage was continued unchanged from 2003 through 2030. This simulation indicates the future residual drawdown that would occur even if pumpage were not increased above 2002 levels.

Scenario 1

Scenario 1 represents pumpage increases to accommodate projected population increases through 2030 without making major changes to the water-production infrastructure. Pumpage at domestic “delegate” wells (an explanation of delegate wells is provided in the Pumpage Simulation section) and public-supply production wells was increased proportionate to population projections for each county election district. Pumpage at all other major users (commercial, agricultural, and military) within the study area, as well as all pumpage outside the study area, was held constant at 2002 rates. Boundary conditions at the top of the model (constant head for the water-table aquifer and estuaries) and sides of the model (general head at the lateral boundaries) also were held at 2002 levels.

Results of Scenario 1 for 2030 are shown in figures 88 through 102, and summarized in tables 15 and 16. Figures 88 through 92 show the simulated potentiometric surfaces of the five major aquifers in Southern Maryland based on the conditions outlined for Scenario 1, and figures 93 through 97 show drawdowns for the simulation period 2003 to 2030. Figures 98 through 102 show simulated remaining available drawdown in 2030 for each aquifer.

Heads in the Piney Point aquifer decline to as much as about 60 ft below sea level in central St. Mary's County and more than 100 ft below sea level near Prince Frederick in Calvert County, primarily due to increases in domestic pumpage in those areas (fig. 88). Drawdowns are as much as about 20 ft in central St. Mary's County and 50 ft in central Calvert County. About 74 ft of drawdown is still available at Town Creek in St. Mary's County (critical location 26). Figure 98 shows an area in northern Calvert County where drawdown in the Piney Point aquifer exceeds the management level by 40 ft and remaining available drawdown is negative. As discussed in the Model Calibration section, simulated heads are probably too deep in this area, and there is probably more remaining available drawdown than indicated in this simulation.

In the Aquia aquifer, the cone-of-depression centered at Lexington Park (critical location 19) has deepened to almost 250 ft below sea level, which is about 60 ft deeper than in 2002 (fig. 89). About 109 to 117 ft of available drawdown remains as of 2030 at the center of the cone-of-depression. At Prince Frederick (critical location 3), head has declined to about 120 ft below sea level, with 141 ft of remaining available drawdown. In eastern Charles County and northern St. Mary's County, heads in the Aquia aquifer have declined to 100 ft below sea level, due to increased domestic pumpage and leakage to the underlying Magothy aquifer. Figure 99 indicates that drawdown in the Aquia aquifer exceeds the management level by more than 100 ft in the Waldorf area, (remaining available drawdown is negative) due to leakage downward into the Magothy aquifer. The area where drawdown exceeds the 80-percent management level is within 10 mi of the outcrop area, and it is unclear whether the 80-percent management criterion would apply here. The Aquia aquifer is not generally used for water supply in this area, and no observation wells in the Aquia aquifer were available for model calibration. Remaining available drawdown in the Aquia aquifer ranges up to about 380 ft in southern St. Mary's County.

In the Magothy aquifer, head has declined to as much as 215 ft below sea level in the Waldorf area (critical location 12) by 2030 (fig. 90). This drawdown exceeds the 80-percent management level by nearly 40 ft (tab. 16). This drawdown is caused by a population increase of nearly 100 percent in central Charles County (tab. 5) and corresponding increase in public-supply pumpage. It should be noted that MDE has imposed a cap of 2.87 mgd on ground-water withdrawals from the Magothy aquifer in the Waldorf area, and would not allow the increases simulated in this scenario. Remaining available drawdown in the Magothy aquifer ranges from below zero in the Waldorf area to about 450 ft in eastern Calvert County (fig. 100).

A drawdown of 80 ft has reduced heads in the Upper Patapsco aquifer to about 195 ft below sea level in the cone-of-depression centered near La Plata (critical location 10) (fig. 91). This leaves only about 10 ft of remaining available drawdown at this site. In the Lexington Park area (critical location 27), a small cone-of-depression has formed in the Upper Patapsco aquifer, which is 81 ft below sea level by 2030, caused by increased pumpage at the Lexington Park water system. The cone-of-depression centered at Waldorf reaches southeast to the Lexington Park area, and indicates some drawdown there. The management level is about 450 ft below sea level at Lexington Park, so there is still 370 ft of available drawdown in 2030. The cone-of-depression centered at Waldorf also extends northwest to the Potomac River and the outcrop/recharge area of the Upper Patapsco aquifer. This may produce undesirable consequences such as a declining water table and river-water intrusion. Remaining available drawdown in the Upper Patapsco aquifer ranges from about –150 ft in the Indian Head area to about 550 ft in eastern Calvert County (fig. 101).

In the Lower Patapsco aquifer, increased public-supply withdrawals in central Charles County have caused drawdowns of 140 ft between 2002 and 2030 in the cone-of-depression in the Waldorf-La Plata area (critical location 14) (fig. 97). Heads have declined to 315 ft below sea level at the deepest part of the cone, although 281 ft of available drawdown remain there in 2030 (tabs. 15 and 16). Farther northwest in the Indian Head area (critical location 13), heads have declined to 166 ft below sea level, which is 37 ft below the management level, and at the top of the aquifer. However, simulated heads are probably too deep there because simulated withdrawals from the military base at Indian Head are concentrated in one model cell, whereas in reality they are distributed over a larger area. The simulated cone-of-depression in the Lower Patapsco aquifer extends northwest beyond the Potomac River to the outcrop/recharge area of the aquifer. As in the Upper Patapsco aquifer, this may produce undesirable consequences such as a declining water table and river-water intrusion. Remaining available drawdown in the Lower Patapsco aquifer ranges from -100 ft in Washington, D.C. to about 1,060 ft in eastern Calvert County (fig. 102).

Scenario 2

Scenario 2 incorporates additional increases of pumpage within the study area to account for possible underestimates in future withdrawal rates. Scenario 2a increases all pumpage within the study area by 10 percent over pumpage in Scenario 1, and Scenario 2b increases pumpage by 20 percent over pumpage in Scenario 1. Pumpage outside the study area but within the model area was held constant at 2002 rates.

Results for Scenario 2 are similar to Scenario 1, but drawdowns are greater in all five aquifers. For example, drawdowns for 2002 to 2030 in Scenario 2b are greater than 40 ft in the Piney Point aquifer at Lexington Park (fig. 103), and 100 ft in the Aquia aquifer at Lexington Park and central Charles County (fig. 104). Simulated heads in the Piney Point aquifer exceed the management level in northern Calvert County in Scenario 2, but are probably too deep, as discussed for Scenario 1. Management levels are not exceeded in the Aquia aquifer in this scenario, although only 42 ft of available drawdown remains at Charlotte Hall in the Aquia aquifer (critical location 23). In the Magothy aquifer, drawdown for 2002 to 2030 is greater than 160 ft at Waldorf (critical location 12), and the management level is exceeded by over 90 ft (fig. 105; tab. 16). Water levels are below the top of the Magothy aquifer in this simulation (tabs. 15 and 16). In the Upper Patapsco aquifer, drawdown between 2002 and 2030 is greater than 100 ft in the La Plata area (critical location 10) (fig. 106), and the management level is exceeded by 30 ft (tab 16). In the Lower Patapsco aquifer, drawdown for 2002 to 2030 is greater than 200 ft in the Waldorf-La Plata area (fig. 107), and remaining available drawdown at Bensville (critical location 15) is 77 ft. The management level at Indian Head (critical location 13) is exceeded by 72 ft, and the water level is below the top of the Lower Patapsco aquifer there.

Scenario 3

Scenario 3 represents decreases of pumpage within the study area to account for possible overestimates in future withdrawal rates. Scenario 3a decreases pumpage within the study area by 10 percent from pumpage in Scenario 1, and Scenario 3b decreases pumpage by 20 percent from pumpage in Scenario 1. Pumpage outside the study area but within the model area was held constant at 2002 rates.

In Scenario 3, heads in all five aquifers are shallower than in Scenario 1. In the Piney Point aquifer, drawdown for 2002 to 2030 is about 5 ft at Lexington Park and about 15 ft in northern Calvert County in Scenario 3b (fig. 108). Drawdown in the Aquia aquifer is about 10 ft at Lexington Park (fig. 109), and in the Magothy aquifer, about 50 ft at Waldorf for Scenario 3b (fig. 110). Drawdown in the Upper Patapsco aquifer is about 40 ft at La Plata for Scenario 3b (fig. 111). In Scenario 3a (10-percent decrease in projected pumpage), drawdown exceeds the management level by 20 ft in the Lower Patapsco aquifer at Indian Head, and by 12 ft in the Magothy aquifer at Waldorf. In Scenario 3b (20-percent decrease in projected pumpage), drawdown exceeds the management level only at Indian Head, and only by 2 ft (fig. 112, tab. 16).

Scenario 4

In Scenario 4, all major users are pumping at their “average GAP rates.” The average GAP rate is the greatest pumping rate, averaged over an entire year, allowed under the permit as regulated by MDE. Domestic pumpage increases with population growth, as in Scenario 1. The average GAP rate is generally lower than the “maximum GAP rate,” which is the maximum rate allowable for the month of greatest withdrawals. Although the average GAP rate is greater than 2002 pumpage for most users, the average GAP rate is exceeded by many users in some future scenarios. This indicates that either GAP rates of existing users would have to be increased to accommodate future population growth, or permits would need to be issued for new users.

In Scenario 4, heads are shallower at most locations than in Scenario 1 because the average GAP withdrawal amounts are generally less than necessary to accommodate future population projections simulated in Scenario 1. Drawdown in the Piney Point aquifer for 2002 to 2030 is slightly less in St. Mary's County than in Scenario 1, but nearly identical in Calvert County (figs. 93, 113). Drawdown in the Aquia aquifer is only about 20 ft at Lexington Park and 40 ft in Charles County (fig. 114). Drawdown in the Magothy aquifer is only about 40 ft at Waldorf, far less than in Scenario 1 (figs. 95, 115). Drawdown in the Upper Patapsco aquifer is about the same as in Scenario 1 (figs. 96, 116), and in the Lower Patapsco aquifer, drawdown is about 100 ft in the Waldorf-La Plata area, as opposed to 140 ft in Scenario 1 (figs. 97, 117). Drawdown at Indian Head exceeds the management level by 87 ft, and the head is below the top of the Lower Patapsco aquifer.

Scenario 5

Scenario 5 represents a shift of pumpage in public-supply wells from shallower aquifers to deeper aquifers in order to reduce the decline of water levels in the shallower aquifers near major population centers. This shift would also help reduce reliance on the Aquia aquifer in locations where arsenic concentrations exceed the MCL of 10 μg/L. Scenario 5a represents a 25-percent shift of public-supply pumpage from the Aquia aquifer to the Upper Patapsco aquifer in Calvert and St. Mary's Counties, and a 25-percent shift of public-supply pumpage from the Magothy aquifer to the Lower Patapsco aquifer in Charles County. Pumpage for other major users in the study area and domestic pumpage is the same as in Scenario 1, as these users are not likely to incur the expense of constructing new, deeper wells. Scenario 5b represents a shift of 50-percent of public-supply pumpage from the Aquia aquifer to the Upper Patapsco aquifer in Calvert and St. Mary's Counties, and a 50-percent shift of public-supply pumpage from the Magothy aquifer to the Lower Patapsco aquifer in Charles County.

In Scenario 5b, maximum drawdown for 2002 to 2030 in the Piney Point aquifer is only about 40 ft in Calvert County, and near zero elsewhere (fig. 118). Drawdown for 2002 to 2030 in the Aquia aquifer is about 30 ft in northern St. Mary's County, but heads have recovered (negative drawdown) by about 10 ft in the Lexington Park and Solomons area (fig. 119). In the Magothy aquifer, drawdown for 2002 to 2030 is only about 20 ft in northern St. Mary's and Charles Counties (fig. 120). Drawdown does not exceed the management level in 2030, but only 65 ft of available drawdown remains at Waldorf. In the Upper Patapsco aquifer, drawdown for 2002 to 2030 is 120 ft in the Waldorf-La Plata area, and the management level is exceeded by about 15 ft at La Plata (fig. 121, tab 16). A cone-of-depression has formed in the Lexington Park area (critical locations 20, 22, and 27) that is 113 ft below sea level, mainly due to the shift of pumpage from the Aquia aquifer to the Upper Patapsco aquifer. In the Lower Patapsco aquifer, drawdown for 2002 to 2030 is 220 ft in the Waldorf-La Plata area (fig. 122). The management level is not exceeded in this area, but at Indian Head, it is exceeded by about 50 ft, and the water level is below the top of the Lower Patapsco aquifer. At Bensville, about 86 ft of available drawdown remains in 2030. Results for Scenario 5a fall between results for Scenarios 1 and 5b. About 13 ft of available drawdown remains at Waldorf (critical location 12). Drawdown in the Upper Patapsco aquifer at La Plata only exceeds the management level by about 3 ft. Drawdown at Indian Head exceeds the management level by 43 ft, and is below the top of the Upper Patapsco aquifer.

Scenario 6

Scenario 6 represents the addition of six public-supply wells (or well fields) at new locations, two in each county. The location, pumpage rate, and aquifer for each well were determined in conjunction with county planning officials, and are shown in table 17. The new wells were located within 1 mi of existing public water-distribution areas to avoid construction of new distribution infrastructure. Locations of the hypothetical wells are shown in figure 68, and model results are summarized in tables 15 and 16 as critical locations 8 and 9 in Calvert County, 17 and 18 in Charles County, and 29 and 30 in St. Mary's County. These new pumpage centers represent additional withdrawals over the rates simulated in Scenario 1. The pumping rate at each site was held constant throughout the entire simulation. Pumpage rates at all other sites were identical to those in Scenario 1.

In Scenario 6, simulated drawdowns for 2002 to 2030 are nearly identical to drawdowns in Scenario 1 for the Piney Point, Aquia, and Magothy aquifers (figs. 123, 124, and 125). Drawdown in the Upper Patapsco aquifer is 100 ft near La Plata, and about 40 ft near Prince Frederick (fig. 126). Increased pumpage in the Upper Patapsco aquifer in Calvert and St. Mary's Counties and increased leakage to the Lower Patapsco aquifer in Charles County cause drawdown to slightly exceed the management level for 2030 in the Upper Patapsco aquifer at La Plata (10 ft of available drawdown remained in Scenario 1). Management levels are also exceeded by 40 ft at Waldorf in the Magothy aquifer. Drawdown in the Lower Patapsco at Waldorf has increased to 160 ft in this simulation (fig. 127). Drawdown exceeds the management level by 43 ft at Indian Head in the Lower Patapsco aquifer.

Scenario 7

Scenario 7 simulates increases in pumpage at the NAS (Naval Air Station) Patuxent River. Because of uncertainties in growth at military facilities, pumpage was increased by 10 percent (Scenario 7a), and 20 percent (Scenario 7b) over 2002 rates. Locations of pumping centers within the facility, and aquifers pumped, were kept the same as in Scenario 1, which simulated 2002 conditions through 2030. All pumpage at the NAS Patuxent River was from the Piney Point and Aquia aquifers in 2002, so this simulation did not include a shift in pumpage to the Upper Patapsco aquifer. The naval base will likely shift some pumpage to the Patapsco aquifer in the future.

In Scenario 7b, drawdown is about 70 ft in the Aquia aquifer at NAS Patuxent River, near Lexington Park, or about 6 ft greater than in Scenario 1 (fig. 129). Elsewhere in the Aquia aquifer, and in all other aquifers, drawdowns are nearly identical to those in Scenario 1 (figs. 128, 130, 131, and 132).

Scenario 8

Scenario 8 represents the addition of three major users, one in each county, at new, hypothetical locations. The location, pumpage rate, and aquifer for each well were determined in conjunction with county planning officials, and are shown in table 17. Locations of the hypothetical wells are shown in figure 68, and model results are summarized in tables 15 and 16 as critical location 7 in Calvert County (Huntingtown), 16 in Charles County (Billingsley Road landfill), and 28 in St. Mary's County (Elms Property). The pumping rate at each site was held constant throughout the entire simulation. Pumpage rates at all other sites were identical to those in Scenario 1.

In Scenario 8, drawdowns in the Piney Point, Aquia, and Magothy aquifers are nearly the same as in Scenario 1 (figs. 133, 134, and 135). Additional drawdown in the Upper Patapsco aquifer is 66 ft at the Elms Property in St. Mary's County (fig. 136). Additional drawdown in the Lower Patapsco aquifer is 49 ft at Huntingtown in Calvert County (fig. 137). There are no significant effects elsewhere in those counties. In Charles County, however, the hypothetical major user is located at the Billingsley Road landfill near other critical locations in the Waldorf-La Plata area, and causes additional drawdowns at some of those locations. Additional drawdown over Scenario 1 at the hypothetical major user at the Billingsley Road landfill is about 77 ft in the Lower Patapsco aquifer, and remaining available drawdown is 383 ft. Additional drawdown at the other critical locations in Charles County range up to 30 ft at Barrington Drive and at Waldorf, both in the Lower Patapsco aquifer. Addition of the hypothetical users causes drawdown to exceed the management level slightly (0.2 ft) in the Upper Patapsco aquifer at La Plata.

DISCUSSION OF RESULTS

Results of the future pumpage simulations indicate that drawdowns in Calvert and St. Mary's Counties will not exceed the 80-percent management level under any of the scenarios considered in this study. Charles County, however, cannot supply the required water in 2030, given the simulated scenarios, without drawdowns exceeding 80-percent management levels at some locations. Future pumpage may also cause significant drawdown near the outcrop/recharge areas of the Upper Patapsco and Lower Patapsco aquifers in northwestern Charles County. Although the flow model used in this study cannot accurately simulate hydrogeologic conditions in the shallow subsurface of the outcrop areas, large increases in pumpage rates in well fields fairly close to the outcrop areas have the potential to cause detrimental effects.

In Calvert County, projected ground-water demand could be met without shifting withdrawals from the Aquia aquifer to deeper aquifers (Scenario 1). In this scenario, the deepest simulated head for 2030 is about 200 ft below sea level near Solomons, and the lowest remaining available drawdown is 141 ft at Prince Frederick (both in the Aquia aquifer). Even a 20-percent increase above the likely increase in ground-water withdrawals does not cause drawdowns to exceed management levels. Shifting 25 percent of public-supply withdrawals from the Aquia aquifer to the Upper Patapsco aquifer (Scenario 5a) increases remaining available drawdown at Prince Frederick to 157 ft, and shifting 50 percent (Scenario 5b) increases remaining available drawdown at Prince Frederick to 173 ft (about 31 ft more available drawdown than in Scenario 1). Increased withdrawals in the Upper Patapsco and Lower Patapsco aquifers in Calvert County in Scenarios 5a and 5b contribute minimally to drawdowns near the outcrop area in Charles County.

In St. Mary's County, projected ground-water demand could also be met without shifting withdrawals from the Aquia aquifer to the deeper Patapsco aquifers (Scenario 1). In this scenario, the deepest simulated regional head for 2030 is about 248 ft below sea level in the Aquia aquifer at Lexington Park, and the lowest remaining available drawdown is 71 ft (in the Aquia aquifer) at Charlotte Hall. A 20-percent increase in ground-water withdrawals (Scenario 2b) does not cause drawdowns to exceed management levels. Shifting 25 percent of public-supply withdrawals from the Aquia aquifer to the Upper Patapsco aquifer (Scenario 5a) increases remaining available drawdown at Charlotte Hall to 83 ft, and shifting 50 percent (Scenario 5b) increases remaining available drawdown at Charlotte Hall to 96 ft. Increased withdrawals in the Upper Patapsco aquifer in St. Mary's County in Scenarios 5a and 5b contribute minimally to drawdowns near the outcrop area in Charles County.

In Charles County, the proximity of the major pumping centers to the outcrop/recharge areas of the Patapsco aquifers and the relatively shallow depth of the aquifers limit their productive capabilities. Withdrawals from the Magothy aquifer in the Waldorf area cannot be increased significantly above 2002 amounts without lowering heads below management levels. Withdrawals from the Upper Patapsco aquifer in this area can be increased above 2002 amounts (there was 10 ft remaining available drawdown in Scenario 1) but probably not enough to accommodate a shift of pumpage from the Magothy aquifer. An additional model simulation could be run to estimate the additional pumpage that could be withdrawn from the Upper Patapsco aquifer in this area. Shifting pumpage from the Magothy aquifer to the Lower Patapsco aquifer (Scenarios 5a and 5b) may cause declines in the water table in the outcrop area of the Lower Patapsco aquifer and river-water intrusion from the Potomac River. A lowered water table in the outcrop area of the Patapsco aquifers may also cause reduced baseflow to streams and changes in wetland ecology where ground water is a significant source of water.

Several ground-water alternatives to the modeled scenarios are available for consideration that would help alleviate excessive drawdowns in central Charles County. Although evaluation of these alternatives was not within the scope of this study, it is prudent to mention them.

1. Some pumpage could be shifted from the Magothy, Upper Patapsco, and Lower Patapsco aquifers to the deeper Patuxent aquifer. This alternative would require more information on the hydraulic characteristics and water quality in the Patuxent aquifer.
2. Using optimization techniques, it may be possible to minimize drawdowns in the aquifers in central Charles County and avoid exceedence of the 80-percent management level (Andreasen, 2003; 2004). However, this would probably not lessen the effects of excessive drawdown in the outcrop areas.
3. Existing well fields in central and northwestern Charles County could be selectively replaced with new well fields farther southeast where aquifer tops (and management levels) are deeper and available drawdown is greater. This would effectively move the cones-of-depression to the southeast, farther from the outcrop areas of the Upper Patapsco and Lower Patapsco aquifers. Moving pumping centers to the southeast, and closer to Calvert and St. Mary's Counties, would probably cause further water-level declines in those counties.

RECOMMENDATIONS FOR FUTURE STUDY

Several issues were identified during this study that need to be addressed in further research. Flow-model simulations identified areas where water levels are likely to be drawn down below the tops of some aquifers due to future pumpage increases. This generally occurs in the shallow updip parts of confined aquifers near the outcrop areas. Although this is a normal consequence of developing confined aquifers in this hydrogeologic setting, the impacts of partial aquifer dewatering are not well understood, and current ground-water regulations do not specifically address this issue. Further study is needed to evaluate the impact of partial aquifer dewatering on aquifer hydraulics and other ground-water users.

River-water intrusion has been documented from the Potomac River in northwestern Charles County, and may be induced further by large ground-water withdrawals from well fields in central Charles County. The potential for increased river-water intrusion should be evaluated by installing test wells in this area and monitoring for key water-quality constituents. The impact on other ground-water users in this area should be assessed.

Land subsidence induced by large ground-water withdrawals is possible near the large cones-of-depression at Waldorf and La Plata in Charles County, and at Lexington Park in St. Mary's County. Land subsidence can contribute to the relative rise of sea level in coastal areas, and may have a significant impact on shorelines where slopes are low. The significance of land subsidence should be evaluated in these areas through InSAR, establishment and monitoring of high precision GPS survey lines, and/or the installation and monitoring on extensometer wells.

Large ground-water withdrawals near the outcrop areas of confined aquifers have the potential to lower the water table in the outcrop areas, cause a reduction of stream flow and a reduction of water available to some types of wetlands. The flow model used in this study could not evaluate the changes in shallow ground-water processes caused by declining heads in the confined parts of aquifers. The potential impact on these processes should be evaluated by installing shallow monitoring wells in and near the outcrop areas of these aquifers, and by studying selected watersheds within the outcrop areas. Model calibration could be improved in these areas by the installation of monitoring wells at key sites, particularly in the shallow parts of the Aquia and Piney Point aquifers.

Additional model simulations should be run to evaluate potential increases in ground-water withdrawals in counties outside the study area, and in Virginia. Although pumpage increases in these outlying areas are not likely to have a significant impact on water levels in the majority of the study area, areas adjacent to high-growth areas in other counties may be affected. Model calibration and evaluation of impacts of future population increases could be improved by a better understanding of domestic pumpage rates and distribution. Metering of selected domestic water wells would provide much needed information on water use, and the specification of the aquifer on well permits would help determine distribution of domestic pumpage. Monitoring wells and water-level data in adjacent areas of Virginia would also improve model calibration and the evaluation of future impacts of ground-water withdrawals on water levels in Virginia.

SUMMARY AND CONCLUSIONS

A study was conducted of the water-supply potential of the aquifer system in Calvert, Charles, and St. Mary's Counties. Water managers in these counties need an assessment of the effects of projected increases in water demand for several decades into the future in order to plan and install new well fields, treatment facilities, and distribution systems. The population of the three Southern Maryland counties increased from 64,626 in 1950 to 281,320 in 2000. Charles County experienced the most growth, its population increasing by 97,131, or 415 percent during that time period. Calvert County's population increased by 62,463, or 516 percent, and St. Mary's County's population increased by 57,100, or 196 percent. The population of the three counties is projected to increase to 432,600 by 2030. This report provides an assessment of the major aquifers underlying the Southern Maryland area, and their potential for supplying projected water demands.

The water needs of Calvert, Charles, and St. Mary's Counties are predominantly supplied by five major aquifers. From shallow to deep, these are the Piney Point, Aquia, Magothy, Upper Patapsco, and Lower Patapsco aquifers. The Patuxent aquifer, which underlies the Lower Patapsco aquifer, has not been developed extensively in the study area, but may be utilized in the future. Consolidated bedrock, which underlies the Patuxent aquifer, is not considered a potential source of water.

Although information on the entire regional aquifer system is included in this report, the study focused mainly on the Upper and Lower Patapsco aquifers. The Patapsco aquifers have been developed in northwestern Charles County, but not farther to the southeast in Calvert and St. Mary's Counties. Six deep test wells (each about 1,650 ft deep) were drilled during this study to obtain hydrologic data on the Patapsco aquifers, and to monitor long-term water levels as these aquifers are developed in the future.

Declining water levels and elevated arsenic concentrations in the Aquia aquifer have prompted water-supply managers to shift a portion of ground-water withdrawals from the Aquia aquifer to the deeper Upper Patapsco and Lower Patapsco aquifers. As of 2002, cones-of-depression have formed in the Aquia aquifer centered at Lexington Park (200 ft below sea level), the Magothy aquifer at Waldorf (90 ft below sea level), the Upper Patapsco aquifer at La Plata (136 ft below sea level), and the Lower Patapsco aquifer at La Plata (200 ft below sea level). Arsenic concentrations in the Aquia aquifer exceed the new U.S. Environmental Protection Agency MCL of 10 µg/L in some public-supply wells in Calvert and St. Mary's Counties, requiring water managers to either treat water from the Aquia aquifer, or to blend it with water from another source that is lower in dissolved arsenic.

Sediments of the Patapsco Formation are divided into four hydrogeologic units in this report. From shallow to deep, these units are the Upper Patapsco confining unit, the Upper Patapsco aquifer, the Middle Patapsco confining unit, and the Lower Patapsco aquifer. The division of the Patapsco Formation into the Upper and Lower Patapsco aquifers is based on hydraulic continuity within the aquifer intervals and distinct water-level trends between the aquifers. Analysis of sand percentages within hydrogeologic units corroborates general connectivity between individual sand bodies within the aquifer layers, and disconnectivity between aquifer layers.

Sediments of the Patapsco Formation were deposited in a fluvial-deltaic environment, which extended throughout the mid-Atlantic region. These sediments were dominated by lower-energy deposits of floodplain and meandering stream environments. Channel sands that form the aquifers in the Patapsco Formation are probably elongated in the eastward to southeastward direction. Given typical sand-body thicknesses of 20 to 30 ft, sand-body widths within the Patapsco aquifers are estimated to be about ¼ to ½ mi. In some cases, individual sand bodies have merged both vertically and horizontally to form more extensive multi-story sand units.

Sands of the Patapsco Formation range from very fine through very coarse. They are generally gray or greenish-gray in appearance, but in some cases are yellowish to reddish brown. Common accessory grains include pyrite, lignite, and muscovite; and rare accessory grains include chert, biotite, goethite, and feldspar. Clays of the Patapsco Formation are extremely variable, in both color and texture. The predominant clay lithology encountered in the test holes is medium to dark gray silty clay. Other common colors include light greenish gray, light to dark reddish brown, and mottling with gray, brown, yellow, white, pink and purple. These colors are characteristic of paleosols formed in floodplain deposits affected by varying drainage conditions.

Aquifer tests were performed on the six test wells screened in the Upper and Lower Patapsco aquifers. Transmissivities for the two wells screened in the Upper Patapsco aquifer are 380 and 1,000 ft^2/d. Transmissivities for the four wells screened in the Lower Patapsco aquifer range from 200 ft^2/d to 4,000 ft^2/d. Test data were difficult to interpret because of aquifer heterogeneities and varying thicknesses. Calculated transmissivities may be too low because of incomplete development of the well screens.

Within the study area, the top of the Upper Patapsco aquifer ranges from 50 ft above sea level in northwestern Charles County to about 750 ft below sea level in central Calvert County, and the bottom ranges from about 100 ft below sea level in western Charles County to about 1,000 ft below sea level in eastern Calvert County. A cone-of-depression has formed in the Upper Patapsco aquifer, centered in the La Plata area, which was 136 below sea level in 2002. This cone-of-depression probably extends northwest to the Potomac River, where it may induce river-water intrusion. At La Plata, where the Upper Patapsco aquifer is heavily pumped, water levels have declined from about 22 ft below sea level in 1969 to about 140 ft below sea level in 2004. Water quality in the Upper Patapsco aquifer is generally suitable for most purposes. TDS is low, ranging from 126 to 349 mg/L, and the pH in water from most wells ranges from 7.0 to 8.5. No U.S. Environmental Protection Agency drinking-water standards were exceeded in water from the Upper Patapsco aquifer. Water in the Upper Patapsco aquifer is primarily classified as sodium/potassium-bicarbonate hydrochemical facies.

The top of the Lower Patapsco aquifer within the study area ranges from about 100 ft below sea level in western Charles County to about 1,400 ft below sea level in eastern Calvert County, and the bottom ranges from about 200 ft below sea level in western Charles County to about 1,700 ft below sea level in eastern Calvert County. Water levels have declined significantly in the Lower Patapsco aquifer, especially in the area of northwestern Charles County where a cone-of-depression has formed that was nearly 200 ft below sea level in 2002. This cone-of-depression extends northwest to the Potomac River, and probably to the outcrop area in Virginia and Prince George's County. Water levels in the Lower Patapsco aquifer in Charles County show rapid declines from the late 1980's through the mid-1990's, then slower declines until the present. In Charles County, water levels in the Lower Patapsco aquifer have declined about 150 ft at St. Charles from 1986 to 2004, and about 50 ft at Potomac Heights near Indian Head from 1988 to 2004. Water quality in the Lower Patapsco aquifer is generally good. The pH in Southern Maryland ranges from 6.8 to 8.7, and TDS ranges from 122 to 768 mg/L. No U.S. Environmental Protection Agency drinking-water standards were exceeded in water from the Lower Patapsco aquifer; however, elevated chloride concentrations have been documented in the Indian Head area of Charles County, caused by river-water intrusion from the Potomac River. Water from the Lower Patapsco aquifer is primarily in the sodium/potassium-bicarbonate hydrochemical facies.

Five water-management criteria were identified that could constrain future development of the ground-water supply: the 80-percent management level, well failures of local ground-water users, brackish-water and river-water intrusion, a lowered water table, and land subsidence. The primary criterion for determining the productive capabilities of the confined aquifers in Southern Maryland is the 80-percent management level. The 80-percent management level for the Upper Patapsco aquifer ranges from about 100 ft above sea level in northern Calvert County to about 600 ft below sea level in eastern Calvert County. The 80-percent management level for the Lower Patapsco aquifer ranges from about sea level in northwestern Charles County to about 1,100 ft below sea level in southeastern Calvert County.

Ground-water pumpage is an important input parameter to the flow model for historical calibration of the model and for simulating future water levels in response to projected pumpage amounts. Pumpage is broadly divided into two categories: domestic pumpage, which is withdrawn from individual homeowners' wells for household supplies; and major-user pumpage, which is withdrawn from production wells for public-supply, commercial, military, and industrial users. Future public-supply pumpage was estimated using population projections for 2010, 2020, and 2030. County populations are projected to increase by 24 percent, 59 percent, and 42 percent for Calvert, Charles, and St. Mary's Counties, respectively, from 2002 to 2030. Domestic pumpage distribution and amounts were estimated from well records and population figures, and corrected to census data. The fractional population increase for each election district was multiplied by the 2002 domestic pumpage distribution to obtain domestic pumpage estimates for 2010, 2020, and 2030.

A ground-water flow model was developed to simulate flow and heads in the major aquifers used in the Southern Maryland area. The hydrogeologic, layered structure of aquifers and confining units was entered into the model, hydraulic characteristics were assigned to the layers, and boundary conditions were entered at the edges of the model. The model was calibrated using prepumping and historical pumping conditions, and by matching simulated heads with measured heads. The calibrated model was then used to simulate future ground-water heads in response to various pumping scenarios. Estimates of future ground-water pumpage were entered into the model for stress periods ending in 2010, 2020, and 2030. Results of model simulations were evaluated by comparing simulated heads with management levels at critical locations. If the simulated regional head fell below the 80-percent management level at a critical location, the pumpage that caused the exceedence was considered excessive.

Eight major pumpage scenarios were developed that incorporate increases in population, and bracket the possible extremes of future pumpage conditions. The flow model calculates average head values for model cells, which are ½-mile by ½-mile. Heads are generally deeper near heavily pumping wells than model-calculated cell averages.

Scenario 1 represents pumpage increases to accommodate projected population increases through 2030 without making major changes to the water-production infrastructure. Heads in the Piney Point aquifer decline as much as about 60 ft below sea level in central St. Mary's County and 80 ft below sea level near Prince Frederick in Calvert County. In the Aquia aquifer, the cone-of-depression centered at Lexington Park has deepened to almost 250 ft below sea level, which is about 60 ft deeper than in 2002. At Prince Frederick, head has declined to about 120 ft below sea level, with 141 ft of remaining available drawdown. In the Magothy aquifer, head has declined to as much as 215 ft below sea level in the Waldorf area by 2030. This drawdown exceeds the 80-percent management level by nearly 40 ft. A drawdown of 80 ft has reduced heads in the Upper Patapsco aquifer to about 195 ft below sea level in the cone-of-depression centered near La Plata. This leaves only about 10 ft of remaining available drawdown at this site. In the Lower Patapsco aquifer, increased public-supply withdrawals in central Charles County have caused drawdowns of 140 ft between 2002 and 2030 in the cone-of-depression in the

Waldorf-La Plata area. Heads have declined to 315 ft below sea level at the deepest part of the cone, although 281 ft of available drawdown remain in 2030. The simulated cone-of-depression in the Lower Patapsco aquifer extends northwest beyond the Potomac River to the outcrop/recharge area of the aquifer. As in the Upper Patapsco aquifer, this may produce undesirable consequences such as a declining water table and additional river-water intrusion.

Scenarios 2a and 2b represent additional increases in pumpage within the study area of 10 percent and 20 percent, respectively, over Scenario 1 to account for possible underestimates in future withdrawal rates. Results for Scenario 2 are similar to Scenario 1, but drawdowns are greater in all five aquifers. Drawdowns for 2002 to 2030 for Scenario 2b are greater than 40 ft in the Piney Point aquifer at Lexington Park, and 100 ft in the Aquia aquifer at Lexington Park and central Charles County. In the Magothy aquifer, drawdown for 2002 to 2030 is greater than 160 ft at Waldorf, and the management level is exceeded by over 90 ft. In the Upper Patapsco aquifer, drawdown is greater than 100 ft in the La Plata area, and the management level is exceeded by 30 ft. In the Lower Patapsco aquifer, drawdown for 2002 to 2030 is greater than 200 ft in the Waldorf-La Plata area. The management level at Indian Head is exceeded by 72 ft, and the water level is below the top of the Lower Patapsco aquifer there.

Scenarios 3a and 3b represent decreases in pumpage within the study area of 10 percent and 20 percent, respectively, to account for possible overestimates in future withdrawal rates. Under these scenarios, heads in all five aquifers are shallower than in Scenario 1. When projected pumpage is decreased by 20 percent, drawdown exceeds the management level only in the Lower Patapsco aquifer at Indian Head, and only by 2 ft.

In Scenario 4, all major users are pumping at their "average GAP rates" (defined as the greatest pumping rate, averaged over an entire year, allowed on the permit as regulated by MDE). Under this scenario, heads are shallower at most locations than in Scenario 1 because the average GAP withdrawal amounts are generally less than necessary to accommodate future population projections simulated in Scenario 1. Drawdown in the Upper Patapsco aquifer is about the same as in Scenario 1, and in the Lower Patapsco aquifer, drawdown is about 100 ft at La Plata, as opposed to 140 ft in Scenario 1. Drawdown at Indian Head exceeds the management level by 87 ft and the head is below the top of the Lower Patapsco aquifer.

Scenarios 5a and 5b represent shifts of pumpage in public-supply wells from shallower aquifers to deeper aquifers in order to reduce the decline of water levels in the shallower aquifers near major population centers. Shifting pumpage to deeper aquifers would also reduce reliance on the Aquia aquifer in locations where arsenic concentrations exceed the MCL of 10 µg/L. Scenario 5a represents a 25-percent shift of public-supply pumpage from the Aquia aquifer to the Upper Patapsco aquifer in Calvert and St. Mary's Counties, and a 25-percent shift of public-supply pumpage from the Magothy aquifer to the Lower Patapsco aquifer in Charles County. Scenario 5b represents 50-percent shifts in pumpage at these same locations. In Scenario 5b, there is only about 40 ft of drawdown for 2002 to 2030 in the Piney Point aquifer in northern Calvert County, and none elsewhere. Drawdown for 2002 to 2030 in the Aquia aquifer is about 30 ft in northern St. Mary's County, but heads have recovered by about 10 ft in the Lexington Park and Solomons area, due to reduced pumpage in the Aquia. In the Magothy aquifer, drawdown for 2002 to 2030 is about 20 ft in northern St. Mary's and Charles Counties. Drawdown in the Magothy aquifer does not exceed the management level anywhere in 2030, but about 65 ft of available drawdown remains at Waldorf. In the Upper Patapsco aquifer, drawdown for 2002 to 2030 is 120 ft in the Waldorf-La Plata area, and the management level is exceeded by about 15 ft at La Plata, due in part to leakage to the underlying Lower Patapsco aquifer. By 2030 a cone-of-depression has formed in the Lexington Park area that is 113 ft below sea level, mainly due to the shift of pumpage from the Aquia aquifer to the Upper Patapsco aquifer. In the Lower Patapsco aquifer, drawdown for 2002 to 2030 is 220 ft in the Waldorf-La Plata area. The management level is not exceeded at La Plata, but at Indian Head, it is exceeded by about 50 ft, and the water level is below the top of the Lower Patapsco aquifer.

Scenario 6 represents the addition of six public-supply wells (or well fields) at new locations, two in each county. The location, pumpage rate, and aquifer for each well were determined in conjunction with county planning officials. The new wells were located within 1 mi of existing public water-distribution areas to avoid construction of new distribution infrastructure. Simulated drawdowns for 2002 to 2030 are nearly identical to drawdowns in Scenario 1 for the Piney Point, Aquia, and Magothy aquifers. Drawdown in the Upper Patapsco aquifer is 100 ft at Waldorf, and about 40 ft near Prince Frederick. In the Lower Patapsco aquifer at Indian Head, the 80-percent management level was exceeded by 43 ft. Drawdown in the Lower Patapsco at Waldorf increased to 160 ft in this simulation, but did not exceed the 80-percent management level.

Scenarios 7a and 7b simulate 10-percent and 20-percent increases in pumpage, respectively, at the NAS Patuxent River over 2002 rates. In Scenario 7b, drawdown is about 70 ft in the Aquia aquifer at NAS Patuxent River, or about 6 ft greater than in Scenario 1. Elsewhere in the Aquia aquifer, and in all other aquifers, drawdowns are nearly identical to those in Scenario 1. The naval base is likely to shift some pumpage from the Piney Point and Aquia aquifers to the Patapsco aquifer in the future.

In Scenario 8, three new hypothetical major users, one in each county, were added to conditions of Scenario 1. Under this scenario, drawdowns in the Piney Point, Aquia, and Magothy aquifers are nearly the same as in Scenario 1, because the hypothetical new users were added to the deeper Patapsco aquifers. Additional drawdown is 66 ft in the Upper Patapsco aquifer at the Elms Property in St. Mary's County, and 49 ft in the Lower Patapsco aquifer at Huntingtown in Calvert County. Simulated water levels at those sites are well above management levels. In Charles County, the hypothetical major user is located at the Billingsley Road landfill near other critical locations in the Waldorf-La Plata area, and causes additional drawdowns at some of those locations. Additional drawdown over Scenario 1 at the hypothetical major user at the Billingsley Road landfill is about 76 ft in the Lower Patapsco aquifer, but there is still 383 ft of available drawdown there. Additional drawdown at the other critical locations in Charles County range up to 30 ft at Barrington Drive and at Waldorf, both in the Lower Patapsco aquifer. Downward leakage to the Lower Patapsco aquifer causes the water level in the Upper Patapsco aquifer to drop slightly below the management level at La Plata.

REFERENCES

Achmad, Grufron, 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, Grufron, and Fewster, T.B., 2003, Delineation of zones of transport for public-supply wells in St. Mary's County, Maryland: Maryland Geological Survey Open-File Report No. 2003-02-16, 82 p.

Achmad, Grufron, 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.

_____ 2001, Simulated changes in water levels of the Aquia aquifer using revised water-use projections to 2025 for Calvert and St. Mary's Counties, Maryland: Maryland Geological Survey Supplemental Report No. S1/RI 64, 58 p.

Alley, W.M., Reilly, T.E., and Franke, L.O., 1999, Sustainability of ground-water resources: U.S. Geological Survey Circular 1186, 79 p.

Anderson, J.L., Gardner, J.A., Stephenson, L.W., Vokes, H.E., Lohman, K.E., Swain, F.M., Cushman, J.A., and Dorsey, Ann, 1948, Cretaceous and Tertiary subsurface geology of three deep test wells on the Eastern Shore of Maryland: Maryland Department of Geology, Mines, and Water Resources Bulletin 2, 456 p.

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

_____ 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.

_____2003, Optimization of ground-water withdrawals in the lower Patapsco aquifer, Waldorf, Maryland: Maryland Geological Survey Open-File Report No. 2003-02-17, with addendum, 51 p.

_____ 2004, Optimization of ground-water withdrawals from the Lower Patapsco and Patuxent aquifers in the Bryans Road Service Area, Charles County, Maryland: Maryland Geological Survey Administrative Report, 21 p.

Berkowitz, Brian, and Balberg, Isaac, 1993, Percolation theory and its application to groundwater hydrology: Water Resources Research, vol. 29, no. 4, p. 775-794.

Bridge, J.S., 2003, Rivers and floodplains: forms, processes, and sedimentary record: London, United Kingdom, Blockwell Publishing, 491 p.

Bridge, J.S., and Mackey, S.D., 1993, A theoretical study of fluvial sandstone body dimensions, *in* Flint, S., and Bryant, I.D., eds., The geological modeling of hydrocarbon reservoirs: International Association of Sedimentologists Special Publications 15, p. 213-236.

Cederstrom, D.J., 1957, Geology and groundwater resources of the York-James Peninsula, Virginia: U.S. Geological Survey Water-Supply Paper 1361, 237 p.

Chapelle, F.H., 1985, Hydrogeology, digital solute-transport simulation, and geochemistry of the Lower Cretaceous aquifer system near Baltimore, Maryland: Maryland Geological Survey Report of Investigations No. 43, 120 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., Mathews, E.B., and Berry, E.W., 1918, Surface and underground water resources of Maryland, including Delaware and the District of Columbia: Maryland Geological Survey Special Publication, vol. X, part II, 542 p.

Code of Maryland Regulations, 1997, Special criteria for issuance of ground water appropriation or use permit: Title 26 (Department of the Environment), Subtitle 17 (Water Management), chap. 06 (Water Appropriation or Use), Regulation 05D(1, 2, 4, 5, and 7), Supp. 10, p. 1,400-1,401.

Cooper, H.H., and Jacob, C.E., 1946, A generalized graphical method of evaluating formation constants and summarizing well-field history: American Geophysical Union Transactions, vol. 27, no. 4, p. 526-534.

Cushing, E.M., Kantrowitz, I.H., and Taylor, K.R., 1973, Water resources of the Delmarva Peninsula: U.S. Geological Survey Professional Paper 822, 58 p.

Darton, N.H., 1896, Artesian well prospects in the Atlantic coastal plain region: Washington, D.C., U.S. Geological Survey, 160 p.

Davis, G.H., 1987, Land subsidence and sea level rise on the Atlantic Coastal Plain of the United States: Environmental Geology and Water Science, vol. 10, no. 2, p. 67-80.

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.

_____ 1988, Hydrogeology, brackish-water occurrence, and simulation of flow and brackish-water movement in the Aquia aquifer in the Kent Island area, Maryland: Maryland Geological Survey Report of Investigations No. 51, 131 p.

_____ 1998, Hydrogeology, simulation of ground-water flow, and ground-water quality of the upper Coastal Plain aquifers in Kent County, Maryland: Maryland Geological Survey Report of Investigations No. 68, 76 p.

_____ 2001, Hydrogeology of the Coastal Plain aquifer system in Queen Anne's and Talbot Counties, Maryland, with emphasis on water-supply potential and brackish-water intrusion in the Aquia aquifer: Maryland Geological Survey Report of Investigations No. 72, 141 p.

_____ 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.

Fielding, C.R., and Crane, R.C., 1987, An application of statistical modelling to the prediction of hydrocarbon recovery factors in fluvial reservoir sequences, *in* Recent developments in fluvial sedimentology: Society of Economic Paleontologists and Mineralogists Special Publication No. 39, pp. 321-327.

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, with a section on Simulation of brackish-water intrusion in the Aquia aquifer in the Annapolis area using a solute-transport model, by Barry S. Smith: 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.

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

Freeze, A.R., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Glaser, J.D., 1969, Petrology and origin of Potomac and Magothy (Cretaceous) sediments, middle Atlantic coastal plain: Maryland Geological Survey Report of Investigations No. 11, 101 p.

_____ 1994, Geologic map of Calvert County: Maryland Geological Survey, scale 1:62,500.

_____ 2003, Geologic map of Prince George's County, Maryland: Maryland Geological Survey, scale 1:62,500.

Hansen, H.J., 1968, Geophysical log cross-section network of the Cretaceous sediments of southern Maryland: Maryland Geological Survey Report of Investigations No. 7, 46 p.

_____ 1969, Depositional environments of subsurface Potomac Group in southern Maryland: American Association of Petroleum Geologists Bulletin, vol. 53, no. 9, p. 1923-1937.

_____ 1972, A user's guide for the artesian aquifers of the Maryland Coastal Plain, Part two – Aquifer characteristics: Maryland Geological Survey, 123 p.

_____ 1978, Upper Cretaceous (Senonian) and Paleocene (Danian) pinchouts on the south flank of the Salisbury Embayment, Maryland, and their relationship to antecedent basement structures: Maryland Geological Survey Report of Investigations No. 29, 36 p.

_____ 1984, Hydrogeologic characteristics of the Waste Gate Formation, a new subsurface unit of the Potomac Group underlying the Eastern Delmarva Peninsula: Maryland Geological Survey Information Circular 39, 22 p.

_____ 1988, Buried rift basin underlying coastal plain sediments, central Delmarva Peninsula, Maryland: Geology, vol. 16, p. 779-782.

_____ 1996, 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 Edwards, Jonathan, Jr., 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.

Hansen, H.J., and Wilson, J.M., 1984, Summary of hydrogeologic data from a deep (2,678 ft.) well at Lexington Park, St. Mary's County, Maryland: Maryland Geological Survey Open-File Report No. 84-02-1, 61 p.

Harsh, J.F., and Laczniak, R.J., 1990, Conceptualization and analysis of the ground-water flow system in the coastal plain aquifers of Virginia and adjacent parts of Maryland and North Carolina: U.S. Geological Survey Professional Paper 1404-F, 100 p.

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.

Holzer, T.L., 1981, Preconsolidation stress of aquifer systems in areas of induced land subsidence: Water Resources Research, vol. 17, no. 3, p. 693-704.

Jacobeen, F.H., 1972, Seismic evidence for high angle reverse faulting in the Coastal Plain of Prince George's and Charles Counties, Maryland: Maryland Geological Survey Information Circular No. 13, 21 p.

Keys, S.W., and MacCary, L.M., 1971, Application of borehole geophysics to water-resource investigations: Techniques of Water-Resources Investigations of the U.S. Geological Survey, Chapter E1, 126 p.

King, P.R., 1990, The connectivity and conductivity of overlapping sand bodies *in* Buller, A.T., Berg, E., Hjelmeland, O., Kleppe, J., Torsæter, O., and Aasen, J.O., eds., North Sea oil and gas reservoirs – II: London, United Kingdom, Graham & Trotman, p. 353-361.

Krause, M.J., and Hasiotis, S.T., 2006, Significance of different modes of rhizolith preservation to interpreting paleoenvironmental and paleohydrologic settings: Examples from Paleogene paleosols, Bighorn Basin, Wyoming, USA: Journal of Sedimentary Research, vol. 76, p. 633-646.

Leeder, M.R., 1973, Fluviatile fining-upward cycles and the magnitude of paleochannels: Geological Magazine, vol. 110, p. 265-276.

Leopold, L.B., and Wolman, M.G., 1960, River meanders: Geological Society of America Bulletin, vol. 71, p. 769-794.

Lorenz, J.C., Heinze, D.M., Clark, J.A., and Searls, C.A., 1985, Determination of widths of meander-belt sandstone reservoirs from vertical downhole data, Mesaverde Group, Piceance Creek Basin, Colorado: American Association of Petroleum Geologists Bulletin, vol. 69, no. 5, p. 710-721.

Lynch, E.J., 1962, Formation evaluation: New York N.Y., Harper and Row, Inc., 422 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.

_____ 1988, Selected geohydrologic characteristics of the Patapsco aquifers at Chalk Point, Prince George's County, Maryland: Maryland Geological Survey Open-File Report No. 88-02-4, 36 p.

_____ 1999, Hydrogeologic data from the Heritage Green test site, La Plata, Maryland: Maryland Geological Survey Open-File Report No. 99-02-11, 51 p.

Mack, F.K., and Achmad, Grufron, 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 Mandle, R.J., 1977, Digital simulation and prediction of water levels in the Magothy aquifer in southern Maryland: Maryland Geological Survey Report of Investigations No. 28, 42 p.

Mackey, S.D. and Bridge, J.S., 1995, Three-dimensional model of alluvial stratigraphy: Theory and application: Journal of Sedimentary Research, vol. B65, p. 7-31.

Martin, R.O.R., and Ferguson, H.F., 1953, Water resources of St. Mary's County: Maryland Department of Geology, Mines and Water Resources Bulletin 11, 189 p.

Maryland Department of Natural Resources, 2005a, Chesapeake and coastal bays water quality conditions: Website: http://mddnr.chesapeakebay.net/bay_cond/bay_cond.cfm?param=sal&station=TF23, accessed March 25, 2005.

_____ 2005b, Chesapeake and coastal bays water quality conditions: Website: http://mddnr.chesapeakebay.net/bay_cond/bay_cond.cfm?param=sal&station=TF24, accessed March 25, 2005.

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

_____ 1989b, Geologic map of St. Mary's County: Maryland Geological Survey, scale 1:62,500.

Morris, D.A. and Johnson, A.I., 1967, Summary of hydrologic and physical properties of rock and soil materials as analyzed by the Hydrologic Laboratory of the U.S. Geological Survey 1948-60: U.S. Geological Survey Water-Supply Paper 1839-D, 42 p.

Nerem, R.S., van Dam, T.M., and Schenewerk, M.S., 1998, Chesapeake Bay subsidence monitored as wetlands loss continues: Transactions of the American Geophysical Union, vol. 79, no. 100, p. 149-156.

Otton, E.G., 1955, Ground-water resources of the southern Maryland coastal plain: Maryland Department of Geology, Mines, and Water Resources Bulletin 15, 347 p.

Otton, E.G., and Mandle, R.J., 1984, Hydrogeology of the upper Chesapeake Bay area, Maryland, with emphasis on aquifers in the Potomac Group: Maryland Geological Survey Report of Investigations No. 39, 62 p.

Pope, J.P., and Burbey, T.J., 2004, Multiple-aquifer characterization from single-borehole extensometer records: Groundwater, vol. 42, no. 1, p. 45-58.

Retallack, G.J., 1986, Fossil soils as grounds for interpreting long-term controls on ancient rivers: Journal of Sedimentary Petrology, vol. 56, p. 1-18.

Richards, H.G., 1948, Studies on the subsurface geology and paleontology of the Atlantic Coastal Plain: Philadelphia, Pa., Academy Natural Science Proceedings, vol. 100, p. 39-76.

Sella, G.F., Stein, Seth, Dixon, T.H., Craymer, Michael, James, T.S., Mazzotti, Stephane, and Dokka, R.K., 2007, Observation of glacial adjustment in "stable" North America with GPS: Geophysical Research Letters, vol. 34, L02306, doi:10.1029/2006GL027081.

Slaughter, T.H., and Otton, E.G., 1968, Availability of ground water in Charles County, Maryland: Maryland Geological Survey Bulletin 30, 100 p.

Tiner, R.W., 1988, Field guide to non-tidal wetland identification: Maryland Department of Natural Resources, and U.S. Fish and Wildlife Service, cooperative publication, 283 p. plus 198 plates.

Titus, J.G., and Narayanan, Vijay, 1995, The probability of sea level rise: U.S. Environmental Protection Agency, Global Warming Publications, EPA 230-R95-008, 186 p.

Trapp, Henry, 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, 59 p.

Trescott, P.C., Pinder, G.F., and Larson, S.P., 1976, Finite-difference model for aquifer simulation in two dimensions with results of numerical experiments, Chapter C1: Techniques of Water-Resources Investigations of the U.S. Geological Survey, 116 p.

U.S. Census Bureau, Population Division, Issued March 1992, Intercensal estimates of the resident population of states and counties, 1980-1989. Website: http://www.census.gov/popest/archives/1980s/e8089co.txt

_____ Release Date: March 27, 1995, Population of counties by decennial census: 1900 to 1990. Website: http://www.census.gov/population/cencounts/md190090.txt

_____ Release Date: March 9, 2000, County population estimates and demographic components of population change: Annual time series, July 1, 1990 to July 1, 1999. Website: http://www.census.gov/popest/archives/1990s/co-99-08/99C8_24.txt

_____ Revision Date: November 14, 2003, County population by age, sex, race, and hispanic origin: July 1, 2000 through July 1, 2002. Website: http://www.census.gov/popest/archives/2000s/vintage_2002/files/COCH_24.txt

_____ Release Date: March 22, 2007, Annual estimates of the population of counties of Maryland: April 1, 2000 to July 1, 2006. Website: http://www.census.gov/popest/counties/tables/CO-EST2006-01-24.xls

Waterloo Hydrogeologic, Inc., 2000, User's manual for Visual MODFLOW: Waterloo, Ontario, Canada, Waterloo Hydrogeologic, Inc., 285 p.

Weigle, J.M., Webb, W.E., and Gardner, R.A., 1970, Water resources of southern Maryland: U.S. Geological Survey Atlas HA-365, 3 sheets.

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., III, 1979, Simulated changes in water level in the Piney Point aquifer in Maryland: Maryland Geological Survey Report of Investigations No. 31, 50 p.

Wilson, J.M., 1986, Stratigraphy, hydrogeology, and water chemistry of the Cretaceous aquifers of the Waldorf/La Plata area, Charles County, Maryland: Maryland Geological Survey Open-File Report No. 86-02-2, 66 p.

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