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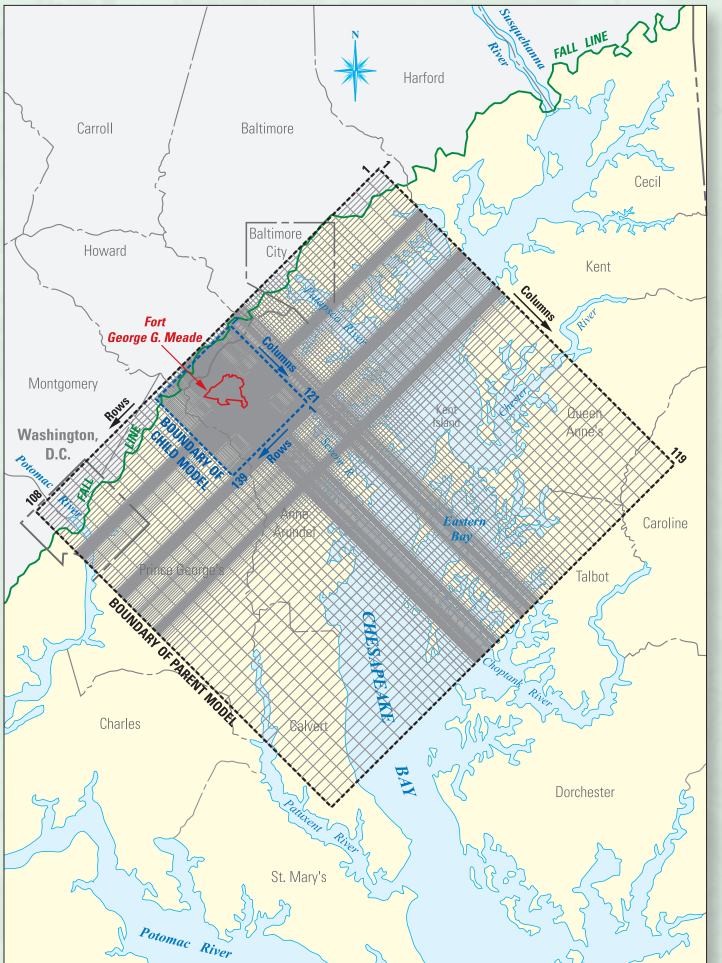
Simulation of Groundwater Flow to Assess Future Withdrawals Associated with Base Realignment and Closure (BRAC) at Fort George G. Meade, Maryland



Scientific Investigations Report 2010–5186

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

Cover. Map showing parent and child model grids.

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
million gallons (Mgal)	3,785	cubic meter (m^3)
	Flow rate	
gallon per day (gal/d)	0.003785	cubic meter per day (m^3/d)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day (m/d)
	Transmissivity*	
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)
	Leakance	
foot per day per foot [(ft/d)/ft]	1	meter per day per meter [(m/d)/m]
inch per year per foot [(in/yr)/ft]	83.33	millimeter per year per meter [(mm/yr)/m]

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83). Latitude and longitude are expressed in degrees-minutes-seconds or in decimal degrees. When expressing longitude in decimal degrees, the West/East suffix is replaced by a negative sign in the Western Hemisphere.

Altitude, as used in this report, refers to distance above the vertical datum.

*Transmissivity: The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [(ft^3/d)/ft^2]ft. In this report, the mathematically reduced form, foot squared per day (ft^2/d), is used for convenience.

Simulation of Groundwater Flow to Assess Future Withdrawals Associated with Base Realignment and Closure (BRAC) at Fort George G. Meade, Maryland

By Jeff P. Raffensperger, Brandon J. Fleming, William S.L. Banks, Marilee A. Horn, Mark R. Nardi, and David C. Andreasen

Abstract

Increased groundwater withdrawals from confined aquifers in the Maryland Coastal Plain to supply anticipated growth at Fort George G. Meade (Fort Meade) and surrounding areas resulting from the Department of Defense Base Realignment and Closure Program may have adverse effects in the outcrop or near-outcrop areas. Specifically, increased pumping from the Potomac Group aquifers (principally the Patuxent aquifer) could potentially reduce base flow in small streams below rates necessary for healthy biological functioning. Additionally, water levels may be lowered near, or possibly below, the top of the aquifer within the confined-unconfined transition zone near the outcrop area.

A three-dimensional groundwater flow model was created to incorporate and analyze data on water withdrawals, streamflow, and hydraulic head in the region. The model is based on an earlier model developed to assess the effects of future withdrawals from well fields in Anne Arundel County, Maryland and surrounding areas, and includes some of the same features, including model extent, boundary conditions, and vertical discretization (layering). The resolution (horizontal grid discretization) of the earlier model limited its ability to simulate the effects of withdrawals on the outcrop and near-outcrop areas. The model developed for this study included a block-shaped higher-resolution local grid, referred to as the child model, centered on Fort Meade, which was coupled to the coarser-grid parent model using the shared node Local Grid Refinement capability of MODFLOW-LGR. A more detailed stream network was incorporated into the child model. In addition, for part of the transient simulation period, stress periods were reduced in length from 1 year to 3 months, to allow for simulation of the effects of seasonally varying withdrawals and recharge on the groundwater-flow system and simulated streamflow. This required revision of the database on withdrawals and estimation of seasonal variations in recharge represented in the earlier model. The calibrated model provides a tool for future forecasts of changes in the system under different management scenarios, and for simulating potential effects of withdrawals at Fort Meade and the surrounding area on water levels in the near-outcrop area and base flow in the outcrop area.

Model error was assessed by comparing observed and simulated water levels from 62 wells (55 in the parent model and 7 in the child model). The root-mean-square error values for the parent and child model were 8.72 and 11.91 feet, respectively. Root-mean-square error values for the 55 parent model observation wells range from 0.95 to 30.31 feet; the range for the 7 child model observation wells is 5.00 to 24.17 feet. Many of the wells with higher root-mean-square error values occur at the perimeter of the child model and near large pumping centers, as well as updip in the confined aquifers. Root-mean-square error values decrease downdip and away from the large pumping centers.

Both the parent and child models are sensitive to increasing withdrawal rates. The parent model is more sensitive than the child model to decreasing transmissivity of layers 3, 4, 5, and 6. The parent model is relatively insensitive to riverbed vertical conductance, however, the child model does exhibit some sensitivity to decreasing riverbed conductance.

The overall water budget for the model included sources and sinks of water including recharge, surface-water bodies and rivers and streams, general-head boundaries, and withdrawals from permitted wells. Withdrawal from wells in 2005 was estimated to be equivalent to 8.5 percent of the total recharge rate.

Introduction

Since 2008, the U.S. Geological Survey (USGS), in cooperation with the Maryland Department of the Environment (MDE), has been investigating the potential impacts of increased groundwater withdrawals from confined aquifers in the Maryland Coastal Plain to supply anticipated growth at Fort Meade and surrounding areas, primarily within Anne Arundel County (fig. 1), as a result of the Department of Defense (DoD) Base Realignment and Closure (BRAC) process. Specifically, increased pumping from the aquifers in the area could potentially reduce base flow in small streams below rates necessary for healthy biological functioning. Additionally, water levels may be lowered near, or possibly below, the top of the aquifer within the confined-unconfined transition zone near the outcrop area. To assess these potential problems, a three-dimensional groundwater flow model was modified for the Coastal Plain aquifer system in the Fort Meade area from a previous model (Andreasen, 2007). The calibrated model provides a tool for forecasting future changes in the system under different management scenarios, as well as identifying additional data that may better define the groundwater system (Alley and others, 1999).

Background

Groundwater use in Anne Arundel County is primarily from the Patuxent, lower Patapsco, upper Patapsco, Magothy, and Aquia aquifers (Andreasen, 2007). From 1980 through 2005, average annual withdrawals from these aquifers by major users (greater than 10,000 gallons per day) in Anne Arundel County (including public, industrial, commercial, and agricultural use) were 32.4 Mgal/d (million gallons per day). Pumpage from these aquifers has resulted in the development of substantial cones of depression in potentiometric surfaces (Andreasen, 2007; dePaul and others, 2008; Soeder and others, 2007).

The population of Anne Arundel County grew by 38 percent, from 370,775 to 510,878, between 1980 and 2005 (U.S. Census Bureau, 2009). Additional population growth is expected to occur as the result of the DoD BRAC process, which will bring an estimated 5,800 new jobs to Fort Meade (Maryland Department of Transportation, 2009). Andreasen (2007) developed a groundwater-flow model for the area likely to be affected by the additional water-resources demands resulting from anticipated growth. The simulations were performed using the three-dimensional numerical code MODFLOW-96 (Harbaugh and McDonald, 1996a, b). Optimization of groundwater withdrawals projected through 2044 also was conducted. The results of the previous model indicated that overall, sufficient groundwater supplies exist to meet anticipated increased demand; however, increased withdrawals may cause significant drawdown resulting in water levels falling below the regulatory management level in some areas, as well as potential adverse impacts on streamflow and increased costs of pumping.

Purpose and Scope

This report documents the design and calibration of a three-dimensional, steady-state and transient, groundwater-flow model of central Maryland, including parts of Anne Arundel, Prince George’s, Calvert, Talbot, Queen Anne’s, Kent, Baltimore, Howard, and Montgomery Counties, as well as Baltimore City and Washington, D.C. The model is based on the earlier model by Andreasen (2007), and shares several features, including model extent, boundary conditions, and horizontal and vertical discretization. The earlier model also provided initial estimates of hydraulic properties and recharge rates. The model developed for this study included an area of spatial refinement, centered on Fort Meade, which was coupled to the regional model using the shared node Local Grid Refinement (LGR) capability (Mehl and Hill, 2006, 2007) of MODFLOW-LGR. A more detailed stream network was incorporated into the refined model. In addition, for part of the transient simulation period, stress periods were reduced in length from 1 year to 3 months, to allow future investigation of the effects of seasonally varying withdrawals and recharge on the groundwater flow system and streamflow. This required revision of a withdrawal database and estimation of seasonal variations in recharge. The steps involved in spatial and temporal refinement are described in this report, as well as subsequent model calibration and sensitivity analysis.

Description of the Study Area

Fort Meade is located in western Anne Arundel County, near the Patuxent River separating Anne Arundel and Prince George’s Counties (fig. 1). The Fort is located within the Atlantic Coastal Plain Physiographic Province, although only a few miles southeast of the Fall Line, which is the boundary between the unconsolidated sediments of the Coastal Plain and the crystalline rocks of the Piedmont Physiographic Province. Northern Anne Arundel County includes outcrop and subcrop areas for the Patuxent, lower and upper Patapsco, and Magothy aquifers. Where these aquifers outcrop they may be considered unconfined, although locally less permeable materials may exist at the surface. Downdip (southeast) of the outcrop and subcrop areas, the aquifers become confined, although the confining units may thin and be discontinuous in some places.

Previous Investigations

The USGS Regional Aquifer-System Analysis (RASA) Program, initiated in 1978, systematically studied the Nation’s most important aquifer systems following a congressional mandate to develop quantitative appraisals of the major groundwater systems of the United States (Trapp and Meisler, 1992). During 1979–87, the USGS conducted a regional analysis of the northern Atlantic Coastal Plain as part of the RASA Program. The major focus of the study was to develop an understanding of the groundwater flow system and the

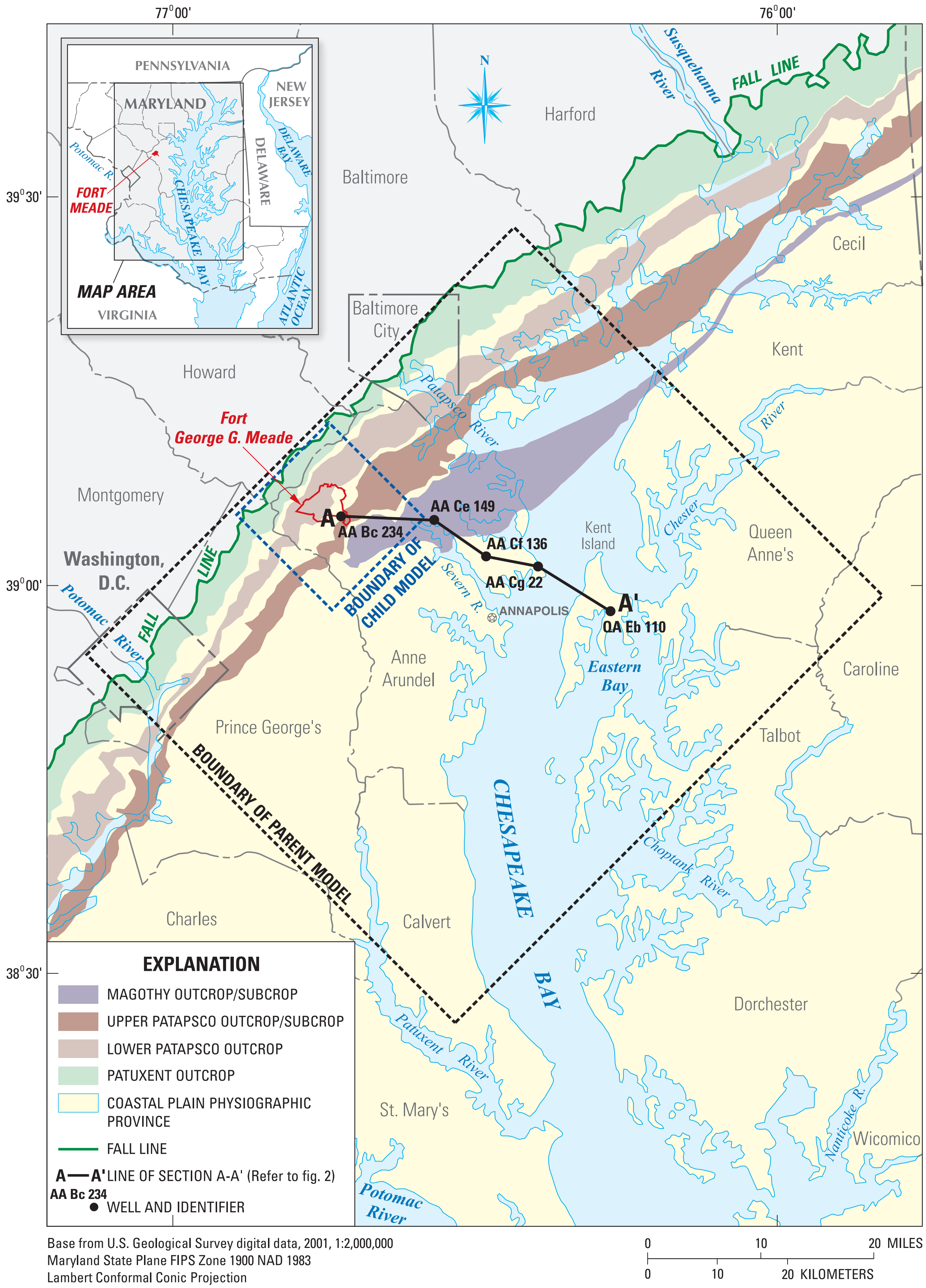


Figure 1. Location of boundaries of parent and child models, major outcrops, line of section A-A′, and Fort George G. Meade, Anne Arundel County, Maryland.

way that it responds to pumping (Trapp and Meisler, 1992). The study's objectives included defining the hydrogeologic framework of regional aquifers and confining units and constructing models of groundwater flow at regional and local scales. Vroblesky and Fleck (1991) described the hydrogeologic framework of the Coastal Plain in Maryland, Delaware, and Washington, D.C. The regional model (from Long Island, New York to North Carolina) is described in Leahy and Martin (1993). A more local-scale model for Maryland, Delaware, and Washington, D.C., is described in Fleck and Vroblesky (1996). This model was relatively coarse, with each cell 3.5 mi (miles) on a side, and was quasi-three-dimensional, so that confining units were not modeled as having storage or horizontal permeability, but only a vertical "leakance." The model was used to estimate pre-pumping conditions and water budgets, as well as changes during pumping (1900–80) and sources of water to pumping wells.

The water-supply potential of the Potomac Group aquifers (Patuxent and Patapsco aquifers) was investigated by Mack and Achmad (1986), who developed a numerical groundwater-flow model that was used to estimate the effects of planned future withdrawals. Achmad (1991) modeled a smaller part of the same system, focusing on water-supply potential of the Patapsco aquifer in Glen Burnie, Anne Arundel County. Other studies that investigated water-supply issues, the groundwater-flow system, or water quality using some form of modeling include Wilson and Achmad (1995), Fleck and Andreasen (1996), and Andreasen (2002). More recently, Andreasen (2007) reported on a model developed for the area in Anne Arundel County likely to be affected by the additional water-resources demands resulting from anticipated growth. That model forms the basis for this study.

Hydrogeologic Framework

Anne Arundel County is part of the mid-Atlantic Coastal Plain, which consists mainly of unconsolidated deposits of gravel, sand, silt, and clay. The sediments are complexly stratified, forming a sequence of aquifers and confining beds that extend from Virginia to New Jersey (Leahy and Martin, 1993). An important aspect of the geologic framework is that the Coastal Plain sediments dip and thicken toward the east and southeast, forming a wedge that thins to a feather edge against the consolidated rocks of the Piedmont, and thickens toward the Atlantic Ocean. In Anne Arundel County, the Coastal Plain deposits range in thickness from a few tens of feet along the northwestern boundary with Howard County to as much as 2,500 ft (feet) in southeastern Anne Arundel County (Vroblesky and Fleck, 1991).

The surficial aquifer (water-table aquifer) is unconfined throughout the study area, and consists of alluvium and terrace deposits (table 1). Thickness of the surficial aquifer is highly variable. The surficial aquifer overlies several aquifers and confining units, which may outcrop or subcrop the surficial aquifer.

The Aquia aquifer consists of glauconitic, greenish to brown sand with indurated layers in middle and basal parts (Andreasen, 2002; Hansen, 1974; Soeder and others, 2007). The altitude of the top of the Aquia aquifer decreases from its outcrop area in central Anne Arundel County to approximately 250 ft below sea level in southern Anne Arundel County. The aquifer dips to the southeast at approximately 22 ft/mi (feet per mile).

In Anne Arundel County, the Matawan Formation underlying the Aquia aquifer consists of dark gray and black silty clay, and is an effective confining unit restricting flow between the Aquia and the deeper Magothy aquifer, although some inter-aquifer flow may occur with increased hydraulic gradient between these aquifers (Andreasen, 2002). The Magothy aquifer, part of the late Cretaceous-age Magothy Formation, consists of light gray to white sand, interbedded with layers of black and gray lignitic clay. Pyrite is a common accessory mineral. Massive beds of well-sorted, coarse-grained sands characterize the Magothy aquifer. In the Annapolis area of Anne Arundel County, the Magothy aquifer consists predominantly of one continuous sand layer, whereas in southern Anne Arundel County, two discrete sand layers are present (Andreasen, 2002). Where present, the confining unit between the Magothy and upper Patapsco aquifers also is effective at restricting inter-aquifer flow. On Broadneck Peninsula, and perhaps elsewhere, however, the contact between the Magothy and upper Patapsco aquifers is sand-on-sand, resulting in a direct hydraulic connection (Mack and Andreasen, 1991). The altitude of the top of the Magothy aquifer decreases from its outcrop area in central Anne Arundel County to approximately 200 ft below sea level in east-central Anne Arundel County (figs. 1, 2). The aquifer dips to the southeast at approximately 30 ft/mi.

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

The Potomac Group of Lower Cretaceous age occurs at the base of the Coastal Plain and makes up over half of its total thickness. In Anne Arundel County, the Potomac Group can be subdivided into the Patapsco Formation, Arundel Clay, and Patuxent Formation (Glaser, 1969; Hansen, 1968). Sandy strata in parts of these formations transmit water and form aquifers. In this report, three Potomac Group aquifers (the upper Patapsco, lower Patapsco, and Patuxent) are evaluated (table 1, fig. 2). The upper Patapsco aquifer consists of multiple sand layers and lenses within the upper part of

Table 1. Stratigraphic units, hydrogeologic units, and model layers in Anne Arundel County, Maryland.

[Modified from Andreasen, 2007; Soeder and others, 2007]

<table>
<tr><th>System</th><th>Series</th><th colspan="2">Group or formation</th><th>Hydrogeologic unit
(model layer)</th></tr>
<tr><td>Quaternary</td><td>Holocene
Pleistocene</td><td colspan="2">Alluvium and terrace deposits</td><td>Surficial aquifer
(Layer 1)</td></tr>
<tr><td rowspan="4">Tertiary</td><td rowspan="2">Eocene</td><td colspan="2">Nanjemoy</td><td rowspan="2">Nanjemoy and Marlboro clay confining units</td></tr>
<tr><td colspan="2">Marlboro Clay</td></tr>
<tr><td rowspan="2">Paleocene</td><td colspan="2">Aquia</td><td>Aquia aquifer
(Layer 2)</td></tr>
<tr><td colspan="2">Brightseat</td><td>Brightseat confining unit</td></tr>
<tr><td rowspan="9">Cretaceous</td><td rowspan="3">Upper Cretaceous</td><td colspan="2">Severn</td><td>Monmouth aquifer</td></tr>
<tr><td colspan="2">Matawan</td><td>Matawan confining unit</td></tr>
<tr><td colspan="2">Magothy</td><td>Magothy aquifer
(Layer 3)</td></tr>
<tr><td rowspan="6">Lower Cretaceous</td><td rowspan="6">Potomac
Group</td><td rowspan="4">Patapsco</td><td>Magothy-Patapsco confining unit</td></tr>
<tr><td>upper Patapsco aquifer
(Layer 4)</td></tr>
<tr><td>Patapsco confining unit</td></tr>
<tr><td>lower Patapsco aquifer
(Layer 5)</td></tr>
<tr><td>Arundel Clay</td><td>Arundel Clay confining unit</td></tr>
<tr><td>Patuxent</td><td>Patuxent aquifer
(Layer 6)</td></tr>
</table>

the Patapsco Formation. The upper Patapsco aquifer was described by Mack and Achmad (1986) as “one of the best water-bearing formations in Anne Arundel County,” although they noted that it is much more limited in aerial extent than the deeper lower Patapsco and Patuxent aquifers. The upper Patapsco consists of the same type of fluvial, interbedded, fine- to medium-grained sand, silt, and clay layers as the lower Patapsco. The altitude of the top of the upper Patapsco aquifer decreases from its outcrop area in central Anne Arundel County to approximately 425 ft below sea level in east-central Anne Arundel County (figs. 1, 2). The aquifer dips to the southeast at approximately 40 ft/mi.

The confining layer separating the lower and upper Patapsco aquifers was described by Mack and Achmad (1986) as massive beds of clay with low vertical hydraulic conductivity, although some layers within the confining unit are more permeable. The lower Patapsco aquifer consists of multiple sand layers and lenses within the lower part of the Patapsco Formation. Despite the finer-grained nature of the sediments, Mack and Achmad (1986) reported that the lower Patapsco aquifer is capable of yielding 0.5 to 2 Mgal/d from individual wells in most locations where it has been tested in Anne Arundel County. The altitude of the top of the lower Patapsco aquifer decreases from its outcrop area in north-central Anne Arundel County to approximately 925 ft below sea level in east-central Anne Arundel County (figs. 1, 2). The aquifer dips to the southeast at approximately 60 ft/mi.

The Arundel Clay separates the lower Patapsco and Patuxent aquifers and is an effective confining unit. The Arundel Clay in the Fort Meade area consists of dark gray, white, and reddish tan, tough, massive clay containing lignite and siderite concretions (Staley and others, 2009). The predominantly clayey unit is interbedded with layers of silt, sand, and gravel.

The Patuxent aquifer, deepest of the Coastal Plain aquifers, is underlain by consolidated rock of suspected Triassic,

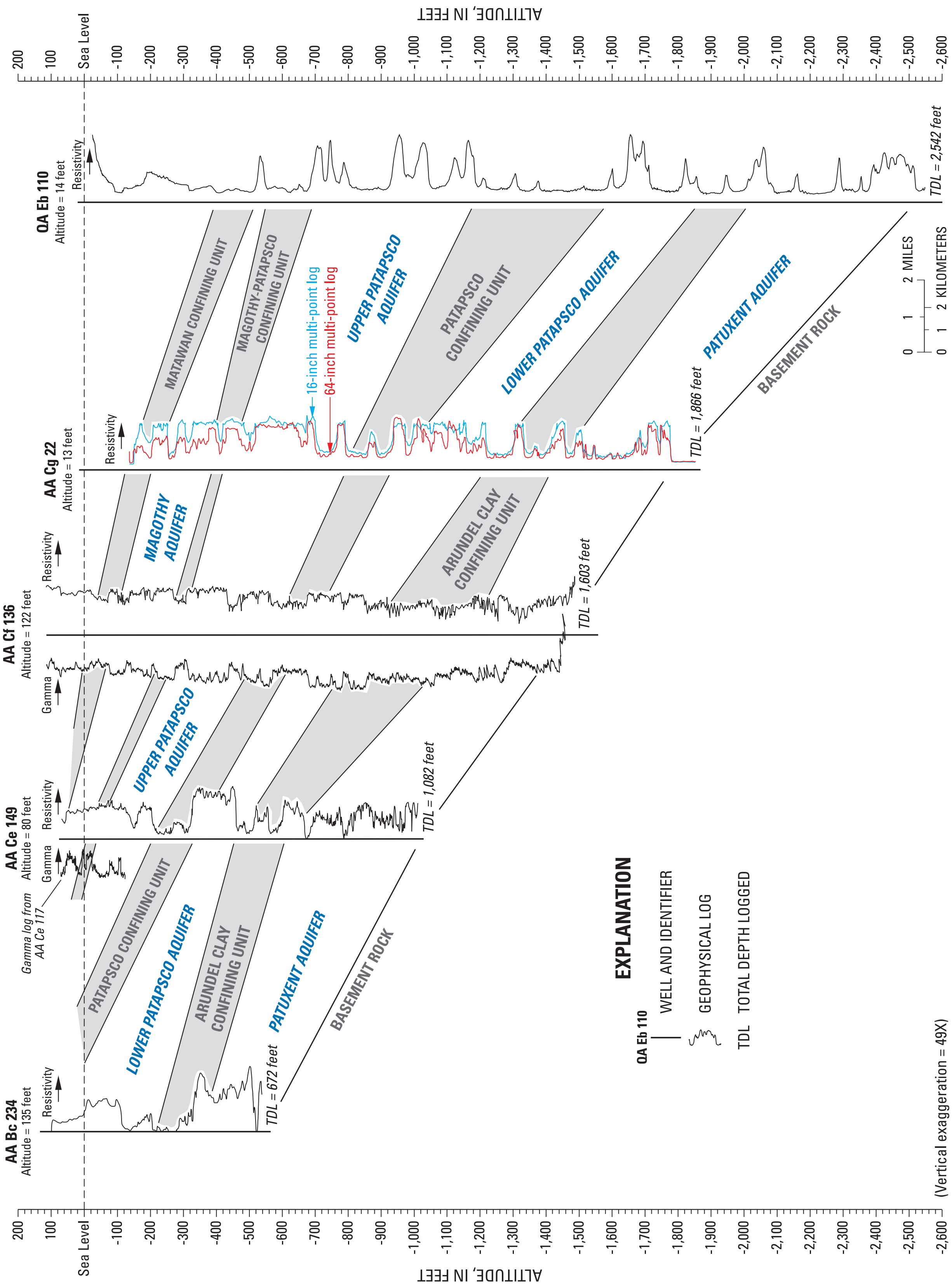


Figure 2. Hydrogeologic section A-A' from Fort Meade, Anne Arundel County, to Kent Island, Queen Anne's County, Maryland (modified from Andreasen, 2007).

Lower Paleozoic, and (or) Precambrian age (Hansen and Edwards, 1986). The lithology of the Patuxent Formation was described by Glaser (1969) as a medium-grained to coarse-grained sand or pebbly sand and gravel, interbedded with relatively thin, pale-gray clays. The formation is composed of generally finer-grained sands in the upper part, where it is overlain and confined by the Arundel Clay. The general lack of silt and clay in the lower part of the Patuxent Formation indicates that the sands were deposited in a relatively high-energy, fluvial, and deltaic environment (Glaser, 1969). The altitude of the top of the Patuxent aquifer decreases from its outcrop area in north-central Anne Arundel County to approximately 1,425 ft below sea level in east-central Anne Arundel County (figs. 1, 2). The aquifer dips to the southeast at approximately 70 ft/mi.

Simulation of Groundwater Flow

A refined numerical finite-difference groundwater-flow model was developed for the area surrounding Fort Meade in Anne Arundel County. An earlier model developed by Andreasen (2007) forms the basis for the model described herein. The following sections describe the conceptual model and the model design, including discretization, local grid refinement, boundary conditions, hydraulic properties, stresses, and model calibration. A single simulation is presented, with an initial steady-state stress period followed by transient stress periods spanning the years 1900 through 2005, which cover the historical development of the aquifers. One purpose of the transient simulation period was to calibrate the model to measured (observed) water levels for the modeled area recorded since 1947.

The model was constructed in several phases. The first phase was the conversion of the Andreasen (2007) MODFLOW-96 (Harbaugh and McDonald, 1996a, b) model files to MODFLOW-2005 (Harbaugh, 2005). The original model discretization, properties, and water budget were maintained. The second phase prepared the model to be used with the LGR capability of MODFLOW-LGR. In LGR terminology, the local, refined-grid model is referred to as the child model and the larger model to which it is linked is referred to as the parent model. In this report, the term “BRAC model” refers to the coupled parent and child models. Application of LGR began with the creation of all MODFLOW-2005 model package files for the child model. For most model properties, child model cells inherited parent model cell properties; the exception was for river reaches, which were significantly refined and based on NHDPlus (U.S. Environmental Protection Agency, 2007). The next phase was to create the MODFLOW-LGR package file and to test coupled model execution. Once the coupled parent and child models were running successfully, the period 1980–2005 was refined from annual to quarterly stress periods. The final phase consisted of making adjustments to the child model properties to calibrate the model.

Conceptual Model

The conceptual model for this study is similar to that described by Andreasen (2007). The conceptual model describes the geometry of the system and, qualitatively, the sources, sinks, and stores of water in the system. The conceptual model synthesizes what is known about the system, including the hydrogeologic framework—recharge conditions, hydraulic properties, and discharge conditions (including withdrawal rates). The conceptual model forms the basis for the construction of the quantitative numerical groundwater-flow model.

The model encompasses a layered system representing the wedge of Coastal Plain sediments beginning at the Fall Line and extending and thickening to the southeast. The basement rocks are considered impermeable and are not specifically represented in the model. Model aquifer layers include the surficial water-table aquifer and the Aquia, Magothy, upper Patapsco, lower Patapsco, and Patuxent aquifers (table 1). Recharge to aquifers occurs mainly in the outcrop areas where the aquifers are considered effectively unconfined (fig. 1), although recharge to the confined aquifers may also occur where vertical hydraulic gradients favor downward groundwater flow across confining units. Recharge to the water-table aquifer occurs as direct percolation of infiltrating precipitation. Constant-head boundaries representing surface-water bodies may be either sources or sinks of water to the model. Pre-pumping groundwater movement was generally downdip, with some movement possible across confining units upward into Chesapeake Bay. As the model does not extend to the Atlantic Ocean, the downdip margins of the model domain are represented by general-head boundaries. Discharge from the groundwater system may occur to streams, rivers, and other surface-water bodies, or be removed by withdrawal from wells or across the general-head boundaries. Groundwater withdrawals from wells are a significant stress on the system, and hydraulic gradients in aquifers near large pumping centers may be reversed, relative to pre-pumping conditions, in some areas (Soeder and others, 2007).

Model Design

The design of the groundwater-flow model includes horizontal and vertical discretization of the subsurface representing the aquifer and confining unit layers, boundary conditions, hydraulic properties for the layers, such as transmissivity, and river reaches. Additional information, representing stresses to the system, also is required. The model includes effective recharge, or that portion of infiltrating water that recharges the groundwater system after evapotranspiration, and does not explicitly simulate processes occurring in the unsaturated zone. These elements are sufficient to define the steady-state, pre-pumping system. Additional information is required for the transient period, including time-varying stresses, boundary conditions, and aquifer storage properties. The model does not simulate flow in confining units directly, but instead uses a quasi-three-dimensional approach to move water vertically between aquifers.

Model Grid and Local Grid Refinement

The parent model grid consists of 119 columns and 108 rows with total area encompassed by the model extent of 2,446 mi^2 (square miles) (fig. 3). Within the parent model, in the area covering Fort Meade, the child model grid consists of 121 columns and 139 rows and an area of 137 mi^2 (fig. 4). Using LGR (Mehl and Hill, 2002; Mehl and others, 2006; Mehl and Hill, 2006, 2007), the columns and rows in the child model are refined by a factor of three, resulting in nine child model grid cells to every one parent model grid cell within the refined area. The parent model was designed with variable grid spacing to provide greater detail near the major well fields operated by Anne Arundel County (Andreasen, 2007). This spacing is reflected down into the child model, with the smallest grid cell having dimensions of 175 by 200 ft. The vertical component of the child model is not refined. Both parent and child models have six layers representing the water-table aquifer (layer 1), the Aquia aquifer and water-table aquifer (layer 2), the Magothy aquifer (layer 3), the upper Patapsco aquifer (layer 4), the lower Patapsco aquifer (layer 5) and the Patuxent aquifer (layer 6) (table 1).

Boundary Conditions

Layer 1 (fig. 5) has active water-table cells (blue), constant-head cells representing the tidal rivers and Chesapeake Bay (orange), and inactive cells (light green). Layer 2 (fig. 6) has a band of inactive cells (light green) separating the water table (blue) from the southern constant-head cells that represent the Aquia aquifer. This inactive band of cells eliminates horizontal flow between the two parts of the model in this layer (Andreasen, 2007). The active cells in layer 2 (blue) have hydraulic properties that allow for recharge to the deeper aquifers outcropping and subcropping in the layers below. Layers 3 (fig. 7), 4 (fig. 8) and 5 (fig. 9) have zones (dark green) with hydraulic properties allowing for recharge to outcrop areas of the layers below. Layer 6 has only active and inactive cells with constant-head and general-head boundaries (fig. 10). All active cells in layers 3 through 6 are modeled as confined aquifers.

All inactive cells in layers 1 and 2 are no-flow boundaries. Inactive cells in layers 3–6 are no-flow boundaries unless adjacent to general-head boundaries (black dots). General-head boundaries were applied to areas of the model where natural boundaries did not exist. General-head boundary values were adjusted during the transient simulation period (1900–2005) to account for changes in head over time (as with the original model).

Hydraulic Properties

The hydraulic properties of an aquifer system govern the storage and transmission of groundwater. Hydraulic properties input into the model include hydraulic conductivity for the water-table aquifer, transmissivity for the remaining confined aquifers, specific yield for the water-table aquifer, and storage coefficient [the product of specific storage and aquifer (or cell) thickness] for the remaining confined aquifers. The model uses the quasi-three-dimensional approach (Harbaugh, 2005) to treat the confining units. In this approach, the confining units are not modeled as separate layers, and they do not have storage capacity. Instead, the effect of confining units on the transmission of groundwater is limited to restricting vertical flow between two aquifers, controlled by the vertical leakance (defined as the vertical hydraulic conductivity divided by the flow distance) assigned to the aquifer layer with a quasi-three-dimensional confining unit below it.

Hydraulic properties in the BRAC model are very similar to those in the Andreasen (2007) model, with child model cells inheriting properties from the parent cells. In a water-table aquifer, transmissivity is a product of the horizontal hydraulic conductivity of the aquifer and its saturated thickness. In model layer 1 (water-table aquifer), the horizontal hydraulic conductivity was set at 35 ft/d (feet per day). This value, selected through model calibration (Andreasen, 2007), is within a typical range for a sand aquifer (Freeze and Cherry, 1979). Model layer 2, underlying the water-table aquifer represented in model layer 1, was assigned a transmissivity value of 1,000 ft^2/d (feet squared per day) through model calibration. In the confined aquifers (model layers 3, 4, 5, and 6), transmissivity is constant in time. Transmissivity arrays were developed for model input first from measured field data and then adjusted through model calibration. In the Magothy aquifer (layer 3), the simulated transmissivity ranges from less than 1,500 ft^2/d to more than 5,000 ft^2/d. In the upper Patapsco aquifer (layer 4), transmissivity ranges from less than 2,000 ft^2/d to as much as 14,000 ft^2/d. In the lower Patapsco aquifer (layer 5), transmissivity ranges from less than 2,000 ft^2/d to as much as 8,000 ft^2/d. In the Patuxent aquifer (layer 6), transmissivity ranges from less than 2,000 ft^2/d to more than 8,000 ft^2/d.

Storage coefficients assigned to the model for the confined aquifers were 0.001 for the Aquia aquifer (model layer 2), 0.0001 for the Magothy, lower, and upper Patapsco aquifers (model layers 3, 4, and 5), and 0.0009 for the Patuxent aquifer (model layer 6). These values are within the range of measured storage coefficients for these aquifers (Hansen, 1972). A specific yield of 0.25 was used for the unconfined aquifer in model layer 1. This value is within the range of specific yield for unconfined aquifers (Fetter, 1988).

To allow recharge to reach outcrop areas of the aquifers, both transmissivity (as described above) and vertical leakance were adjusted for cells in all model layers directly above the outcrop area (fig. 11). For the confined parts of the aquifers, Andreasen (2007) initially calculated vertical leakance using average model-layer thickness and estimates of vertical hydraulic conductivity. Because the clay confining beds are significantly less permeable than the sandy aquifers, vertical leakance is controlled mostly by the vertical hydraulic conductivity of the confining beds. During model calibration, the vertical leakance was adjusted. Vertical leakance values assigned to model layer 1 occur in three zones expressed in cubic feet per day per cubic foot (1/d): zone 1 ($1x10^{-8}$ 1/d), zone 2 ($1x10^{-4}$ 1/d), and zone 3 (90 1/d). Zone 1 represents the low-permeability Marlboro Clay overlying the Aquia aquifer, zone 2 in part controls the amount of recharge entering the confined aquifers, and zone 3 represents the window in the confining bed overlying the lower Patapsco aquifer in the Glen Burnie area (Wilson and Achmad, 1995). Vertical leakance values assigned to model layer 2 are: $9x10^{-6}$ 1/d, representing the Matawan Formation separating the Aquia and Magothy aquifers; $1x10^{-4}$ 1/d, representing the recharge area of the Magothy aquifer; and $8x10^{-5}$ 1/d, representing the subcrop area of the Magothy aquifer. Vertical leakance values assigned to model layer 3 are: $1x10^{-4}$ 1/d, representing the confining bed separating the Magothy and upper Patapsco aquifers; $1x10^{-3}$ 1/d, representing the sand-on-sand contact between the Magothy and upper Patapsco aquifers on Broadneck Peninsula (Mack and Andreasen, 1991); and $1x10^{-3}$ to $5x10^{-4}$ 1/d, representing the recharge area of the upper Patapsco aquifer. Vertical leakance values assigned to model layer 4 are: $2x10^{-5}$ 1/d, representing the confining bed separating the upper and lower Patapsco aquifers; 0.1 1/d, representing the window in the confining bed overlying the lower Patapsco aquifer in the Glen Burnie area; and $9x10^{-4}$ 1/d, representing the recharge area of the lower Patapsco aquifer. Vertical leakance values assigned to model layer 5 are: $2x10^{-5}$ to $4.5x10^{-12}$ 1/d, representing the confining bed separating the lower Patapsco and Patuxent aquifers; $2x10^{-4}$ 1/d, representing a paleochannel penetrating the Arundel Clay confining bed separating the lower Patapsco and Patuxent aquifers at Baltimore City (Chapelle and Kean, 1985); and $1x10^{-5}$ l/d, representing the recharge area of the Patuxent aquifer. A value of 100 1/d was assigned to the active areas of model layers 2, 3, and 4 northwest of the areas representing the Aquia, Magothy, and upper Patapsco aquifers, respectively. This relatively high value allows the transfer of recharge water from model layers 1 and 2 (water-table aquifer) to the deeper confined aquifers.

Model Stresses

MODFLOW-2005 incorporates several hydrological processes that add terms to the governing equations representing inflows or outflows (Harbaugh, 2005). These may be thought of as stresses on the system that affect groundwater flow. The model includes two natural stresses, recharge and flow to and from rivers and streams, and one human stress, withdrawal of groundwater by pumping wells.

Recharge

Recharge to the groundwater system was modeled using the recharge package (RCH) of MODFLOW-2005. Recharge to the groundwater system consists of infiltrating precipitation not lost to evapotranspiration as well as return flows from septic systems and other sources. In the original Andreasen (2007) model, recharge to the model area was estimated using hydrograph separation methods applied to streamflow records for four streams within the active part of model layer 1 (water-table aquifer): Sawmill Creek (USGS station 01589500), North River (USGS station 01590000), Western Branch at Upper Marlboro (USGS station 01594526), and Northwest Branch of the Anacostia River at Riverdale (USGS station 01649500). Mean daily discharge values for the period of record from each basin were input into the hydrograph separation program HYSEP (Sloto and Crouse, 1996). HYSEP uses these data to separate streamflow hydrographs into base-flow and surface-runoff components and performs frequency and duration analyses on both components. Using stream base flow as an estimate for net recharge implicitly accounts for return flows from septic systems and other sources.

Recharge was applied to the top of the active part of model layer 1 (water-table aquifer). The rate of recharge was adjusted during calibration of the original Andreasen (2007) model, is spatially variable, and ranges from 9 in/yr (inches per year) in southern Anne Arundel County and eastern Prince George's County to approximately 18 in/yr in northern Anne Arundel County. The annual recharge rates reported by Andreasen (2007) are used for both the parent and child models, and are held constant from year to year throughout the model simulation period.

In order to better reflect the seasonal nature of groundwater recharge, the annual recharge total was subdivided into four quarters (January–March, April–June, July–September, and October–December). In the original Andreasen (2007) model, no stress periods were shorter than 1 year. For the BRAC model, the time period 1980 through 2005 was divided into quarter-year stress periods (table 2). The fraction of annual recharge applied during each quarter was determined using the mean of the daily mean discharge exceeded 80 percent of the time (Q_{80}) for the four stream gages in the model domain for each quarter (Nelms and others, 1997). These values compare favorably with the quarterly mean base-flow values calculated by HYSEP.

Rivers

Streams and nontidal rivers were simulated using the river package (RIV) of MODFLOW-2005. For the parent model, reach locations and properties are identical to Andreasen (2007) (fig. 12). Spatial refinement in the child model allowed for incorporation of more detailed information on streams and rivers, however. River cells in the child model are based on hydrography data from NHDPlus

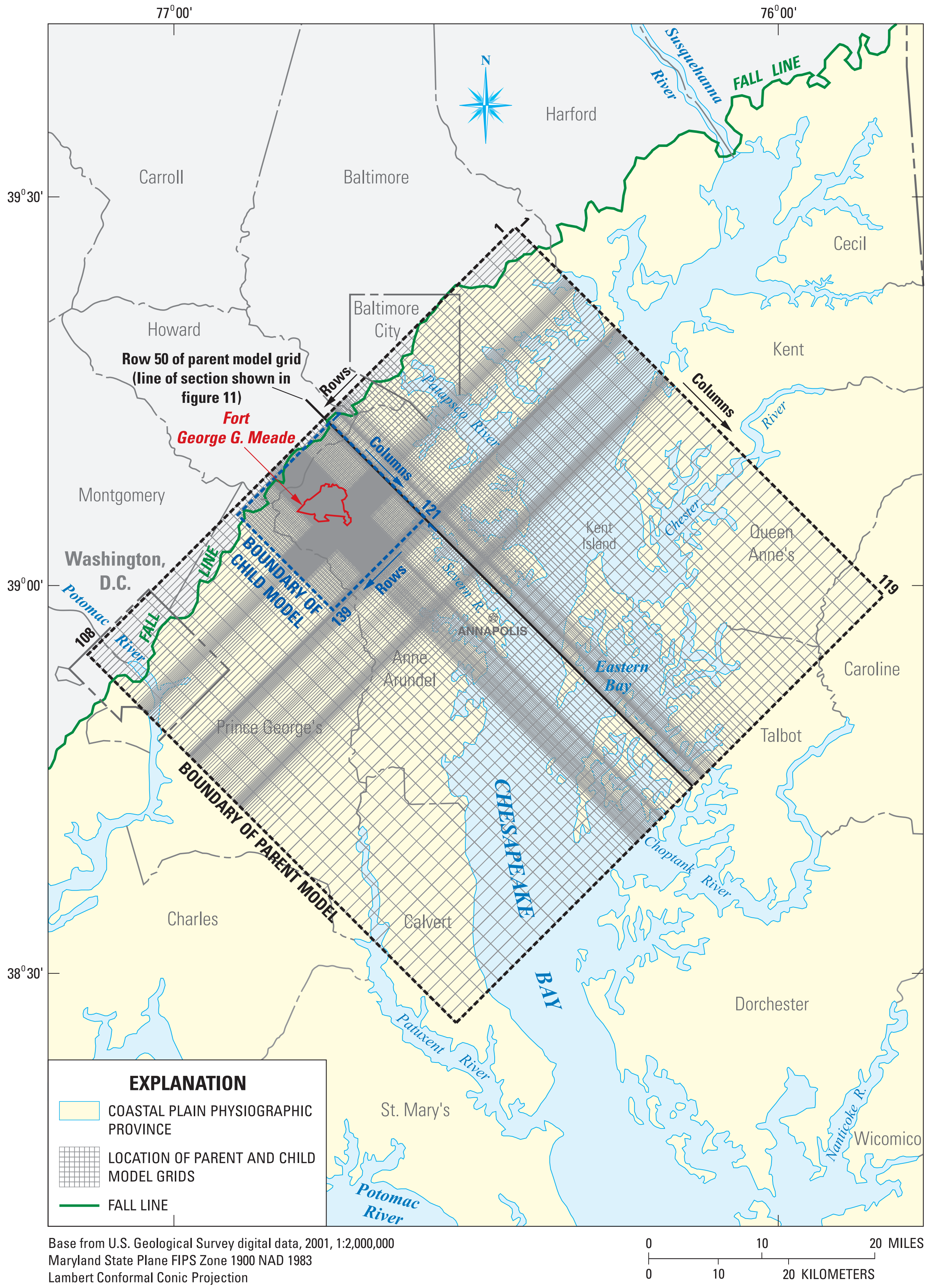


Figure 3. Parent and child model grids.

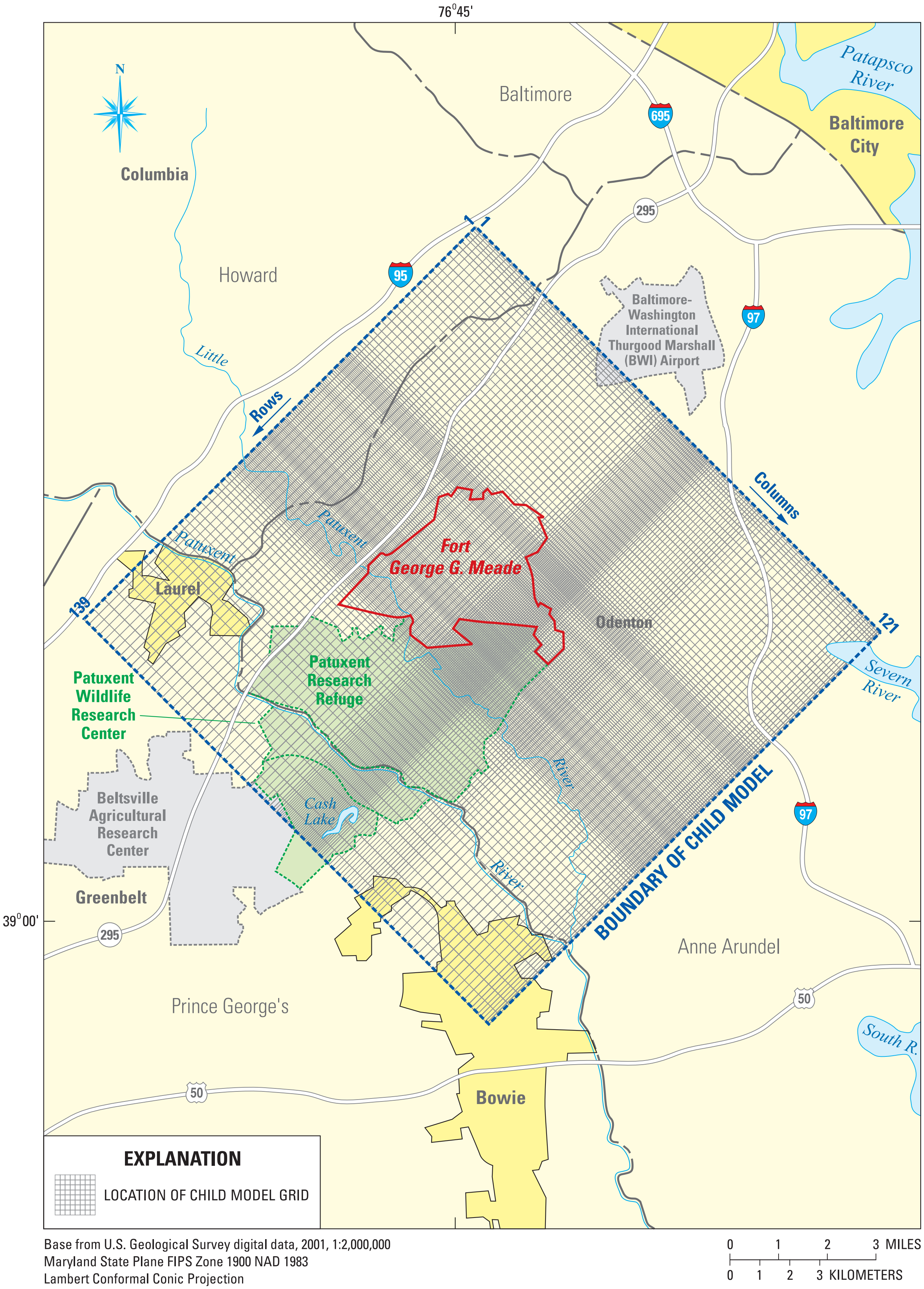


Figure 4. Child model grid.

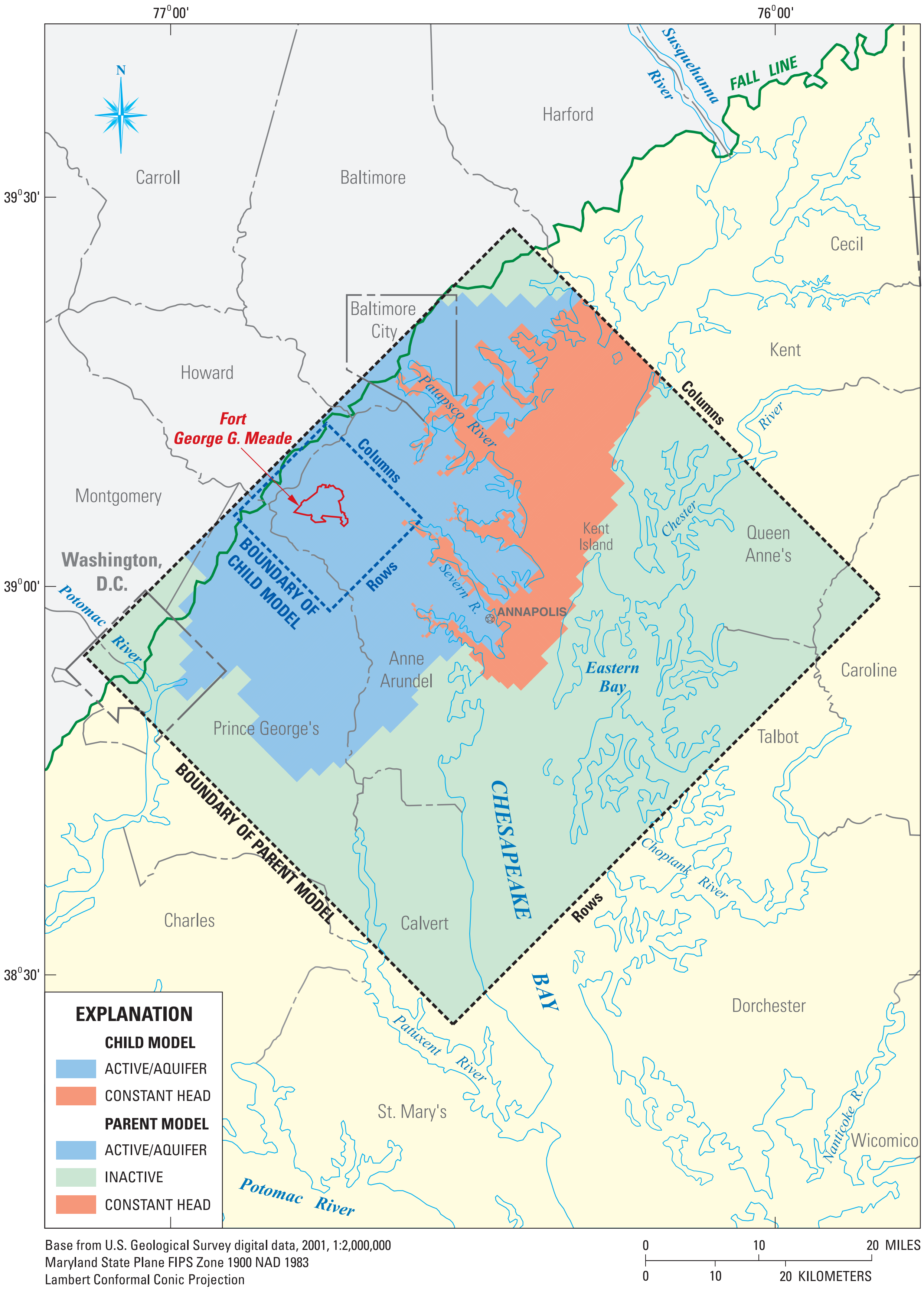


Figure 5A. Parent and child model cell designations for layer 1, the water-table aquifer, indicating active, inactive, and constant-head cells.

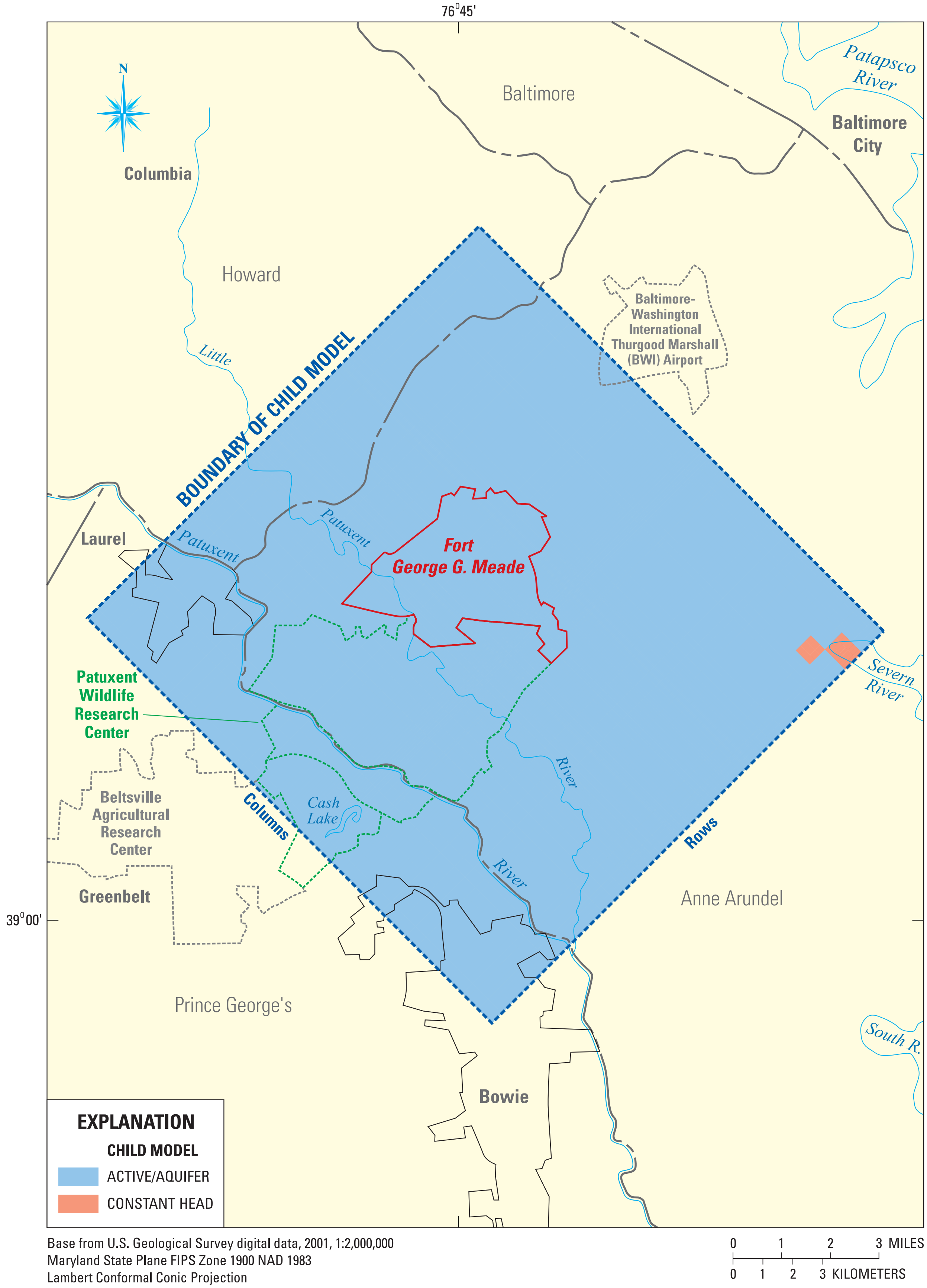


Figure 5B. Child model cell designations for layer 1, the water-table aquifer, indicating active and constant-head cells.

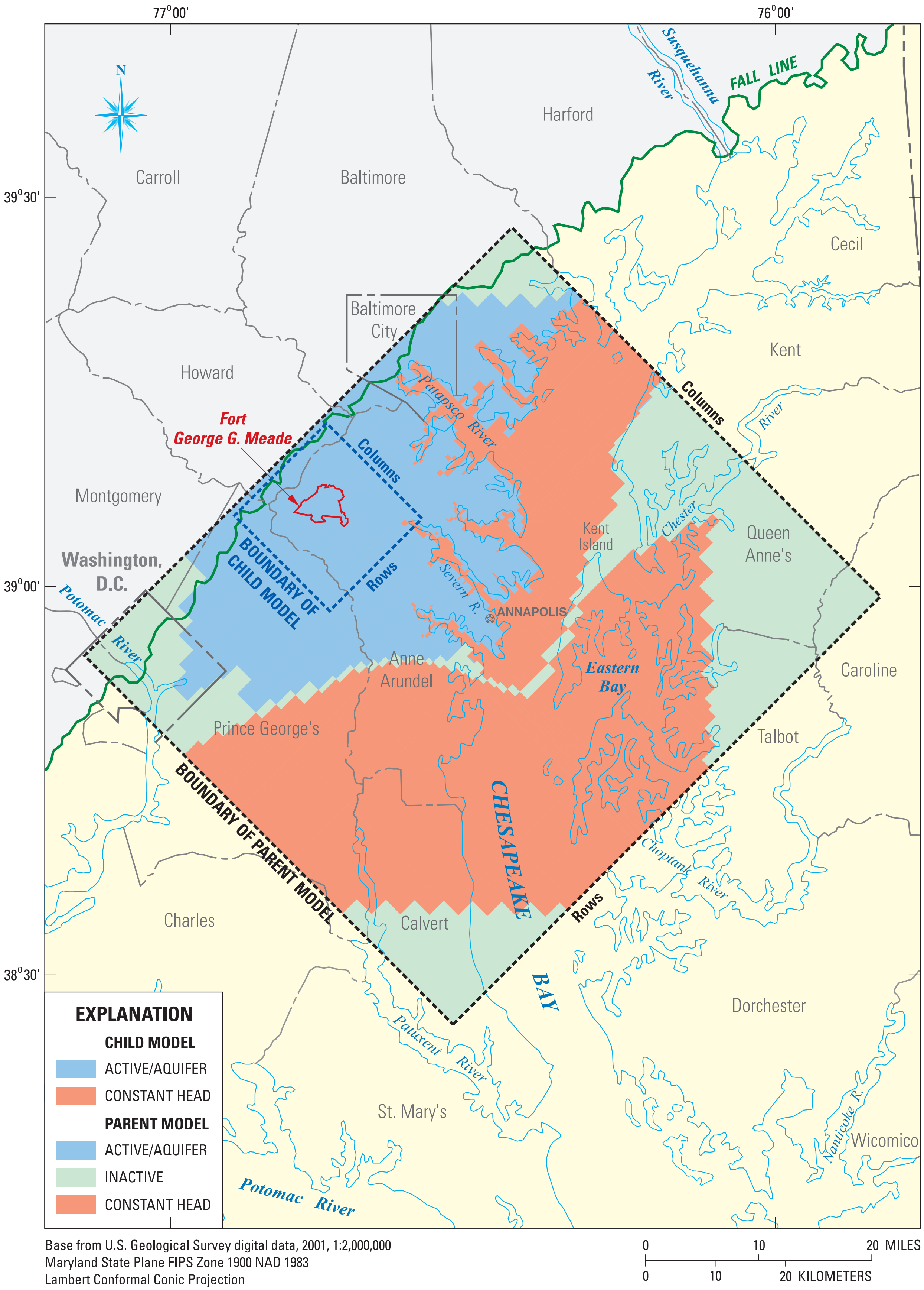
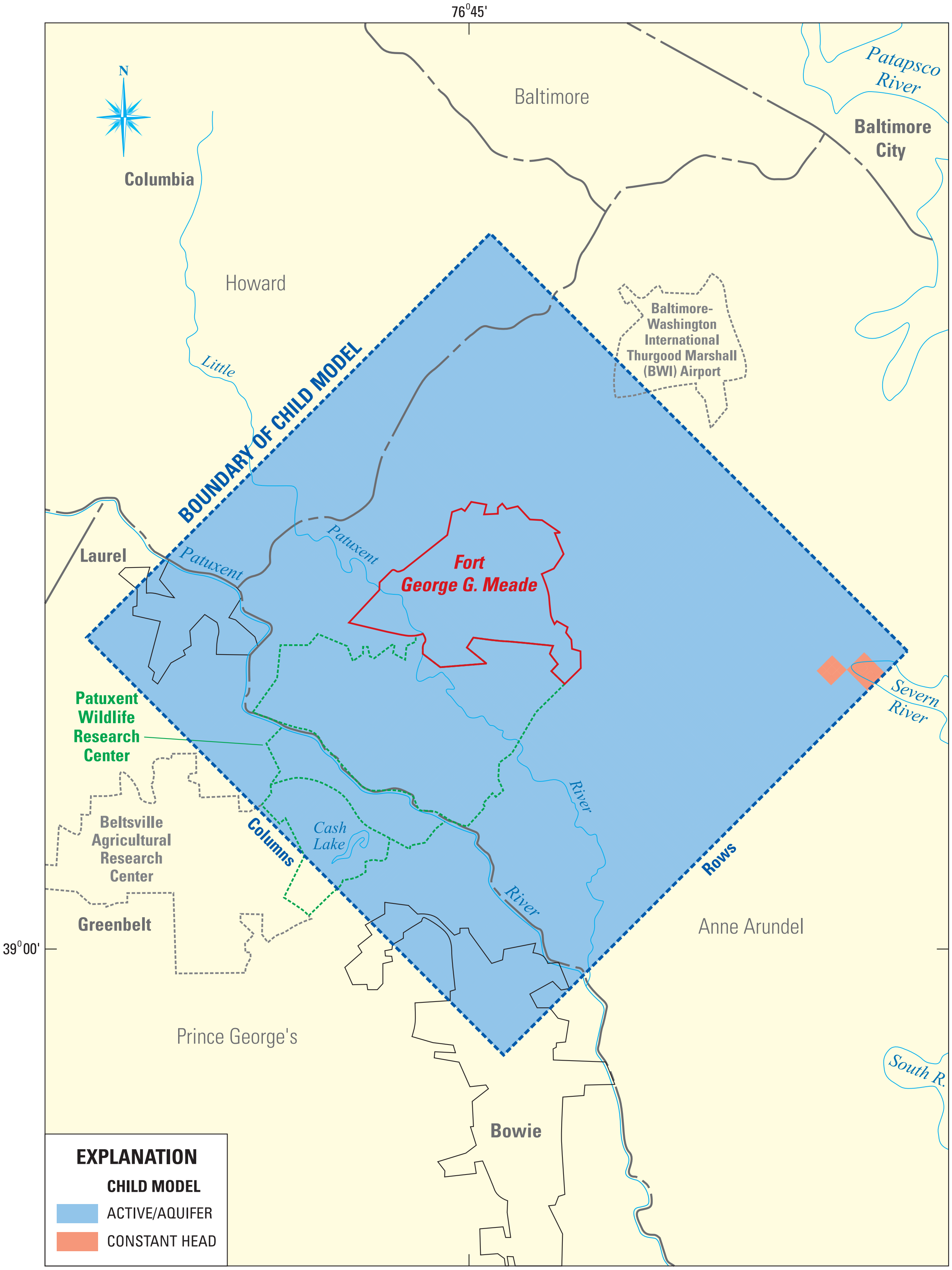


Figure 6A. Parent and child model cell designations for layer 2, the Aquia aquifer and water-table aquifer, indicating active, inactive, and constant-head cells.



Base from U.S. Geological Survey digital data, 2001, 1:2,000,000
Maryland State Plane FIPS Zone 1900 NAD 1983
Lambert Conformal Conic Projection

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Figure 6B. Child model cell designations for layer 2, the Aquia aquifer and water-table aquifer, indicating active and constant-head cells.

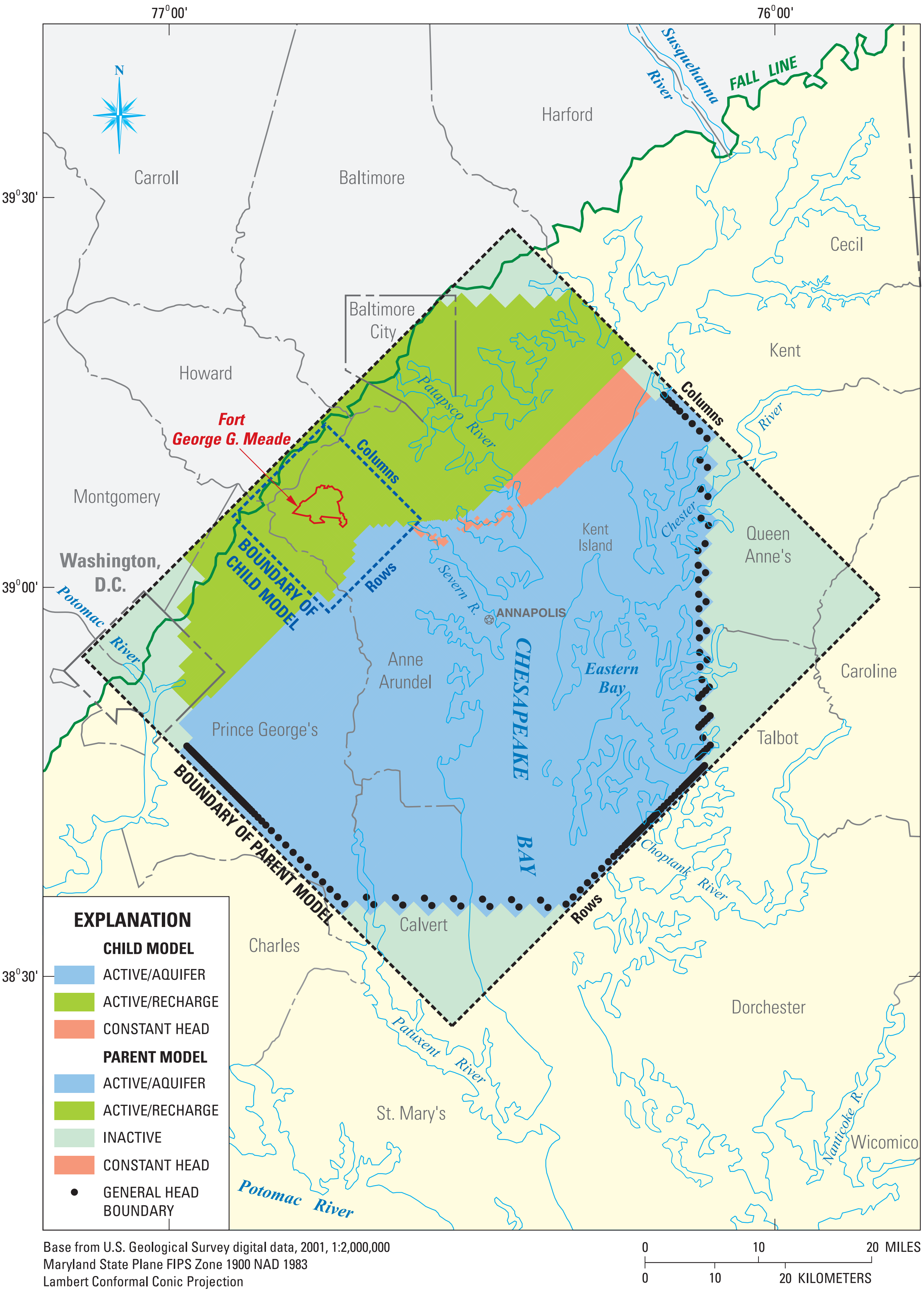


Figure 7A. Parent and child model cell designations for layer 3, the Magothy aquifer, indicating active, active/recharge, inactive, constant-head, and general-head boundary cells.

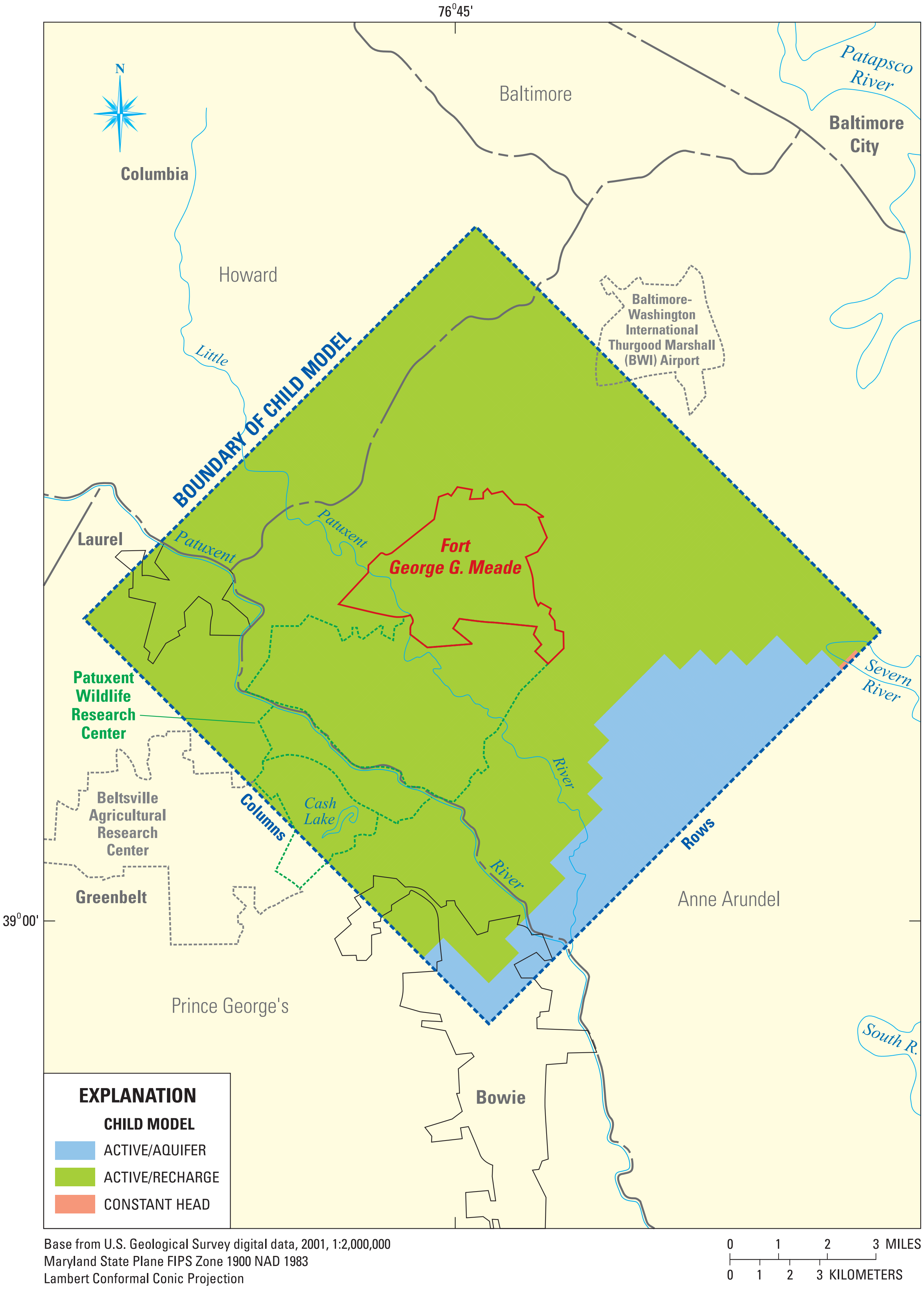


Figure 7B. Child model cell designations for layer 3, the Magothy aquifer, indicating active, active/recharge, and constant-head cells.

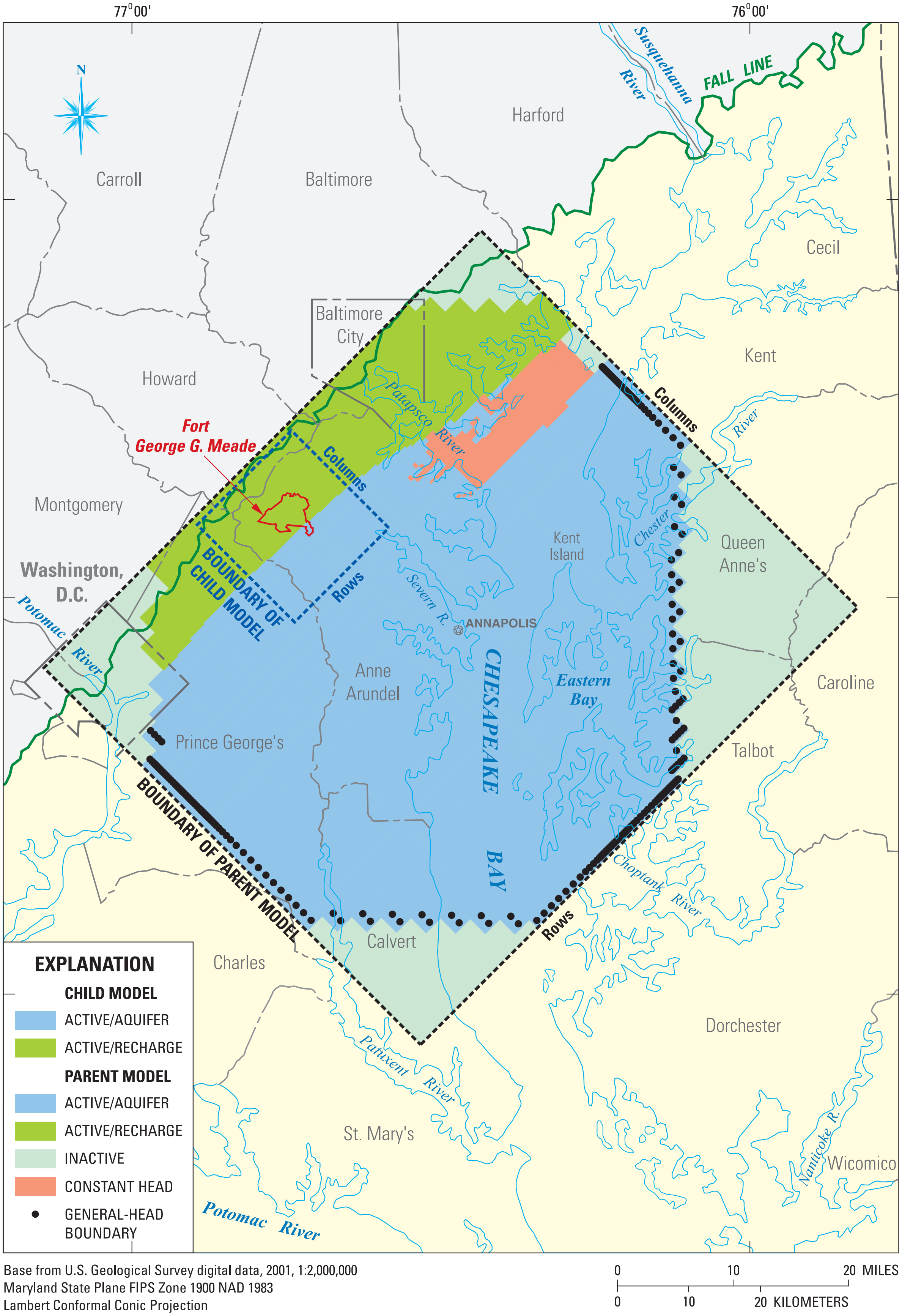
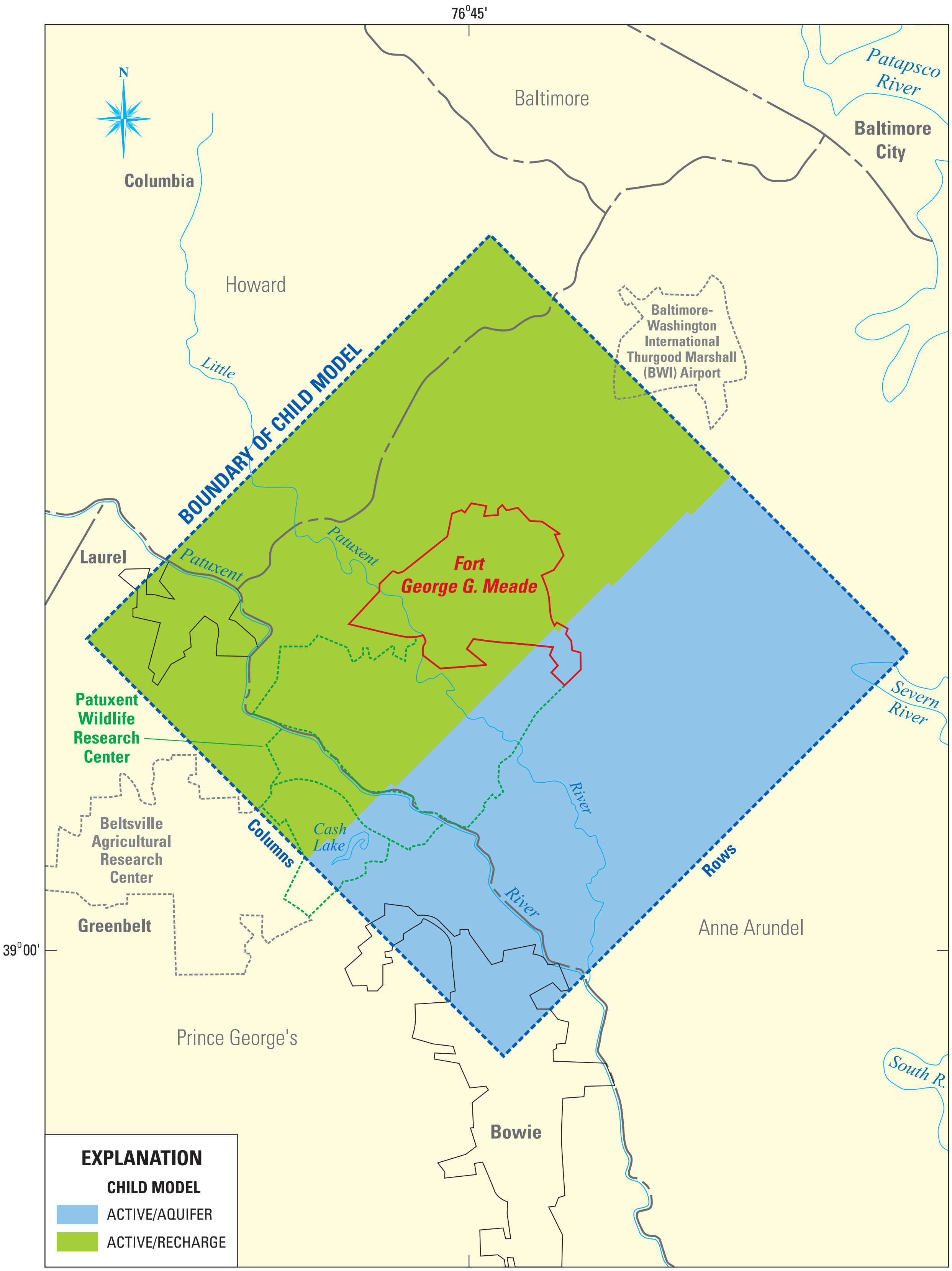


Figure 8A. Parent and child model cell designations for layer 4, the upper Patapsco aquifer, indicating active, active/recharge, inactive, constant-head, and general-head boundary cells.



Base from U.S. Geological Survey digital data, 2001, 1:2,000,000
Maryland State Plane FIPS Zone 1900 NAD 1983
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Figure 8B. Child model cell designations for layer 4, the upper Patapsco aquifer, indicating active and active/recharge cells.

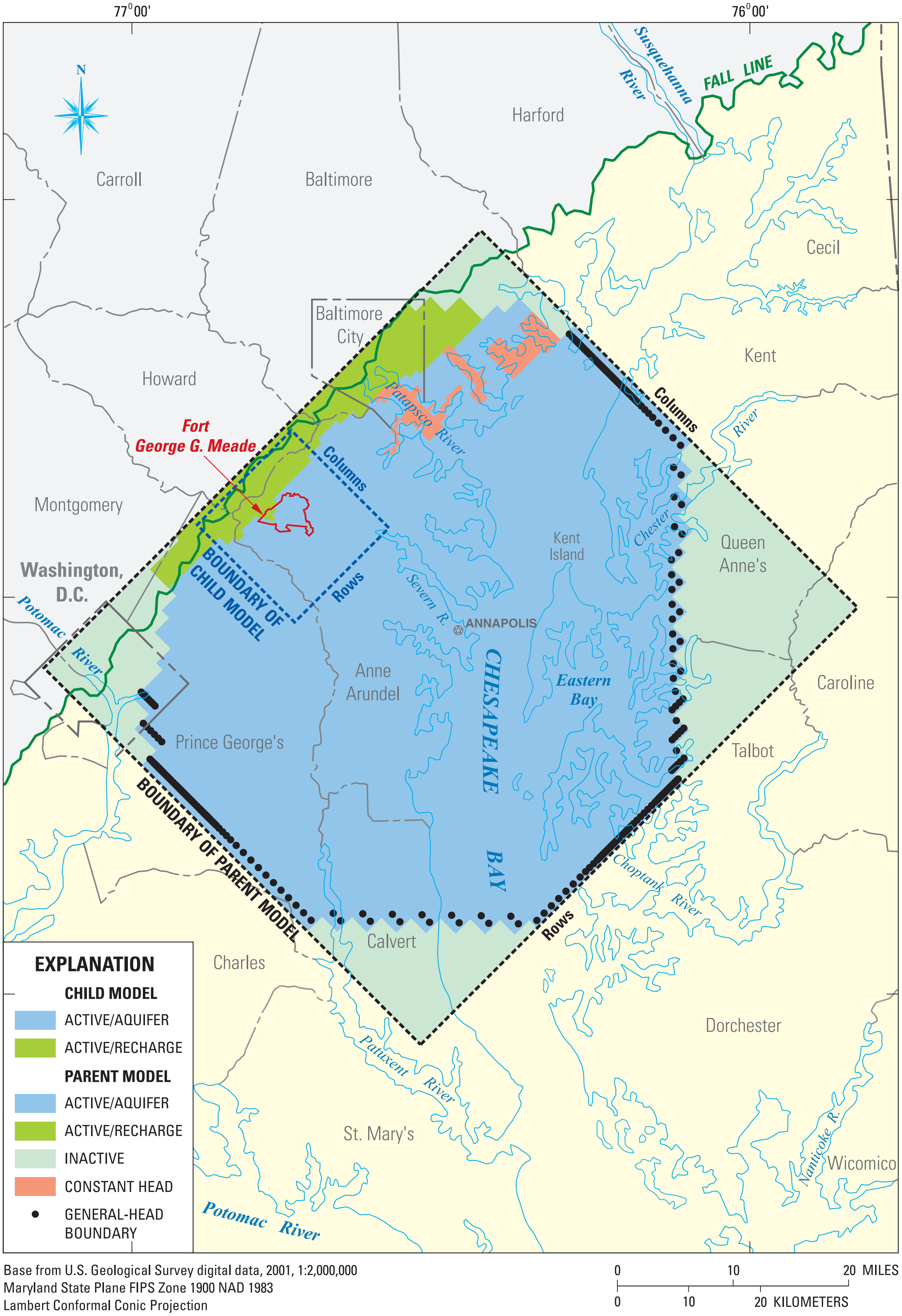


Figure 9A. Parent and child model cell designations for layer 5, the lower Patapsco aquifer, indicating active, active/recharge, inactive, constant-head, and general-head boundary cells.

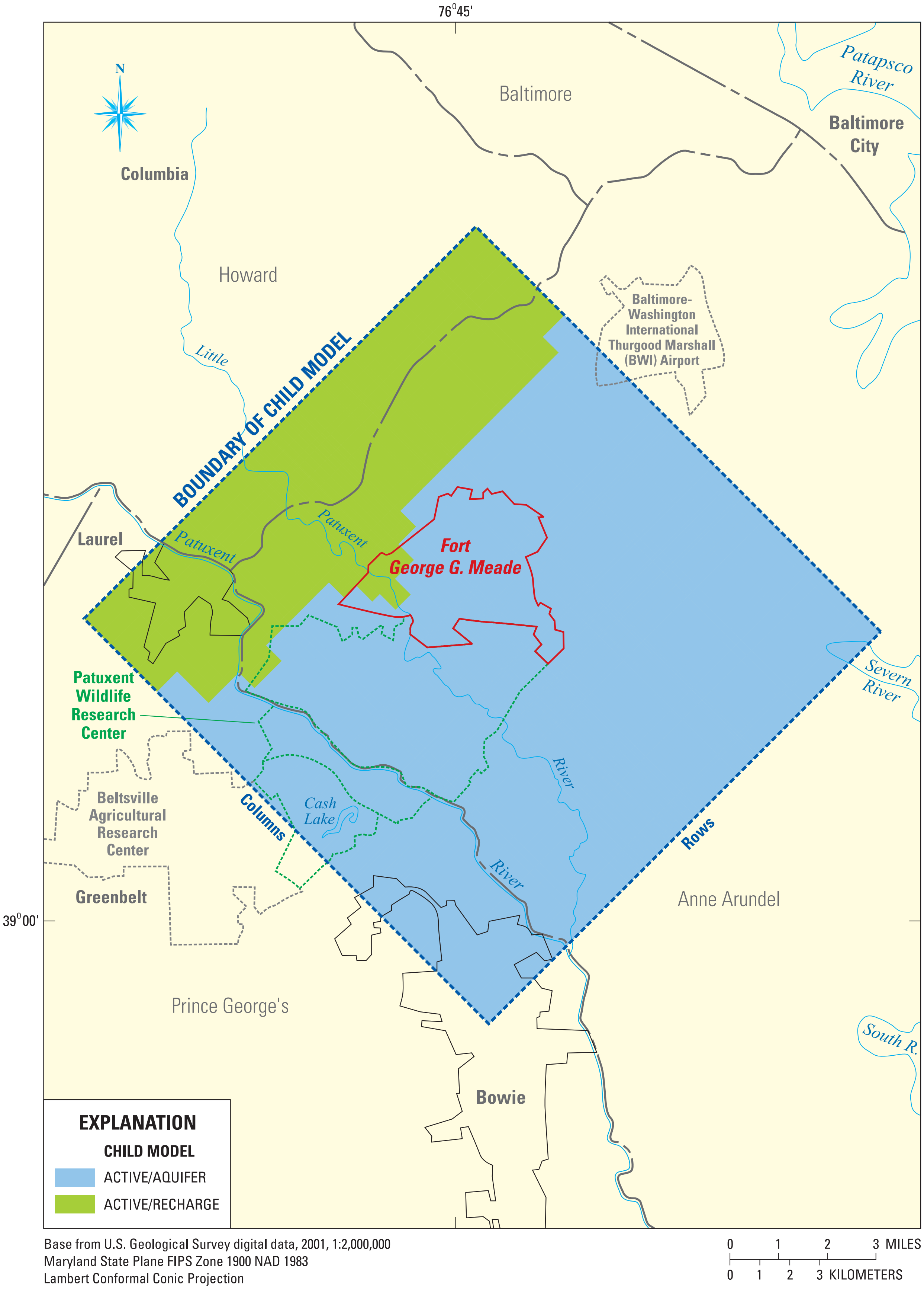
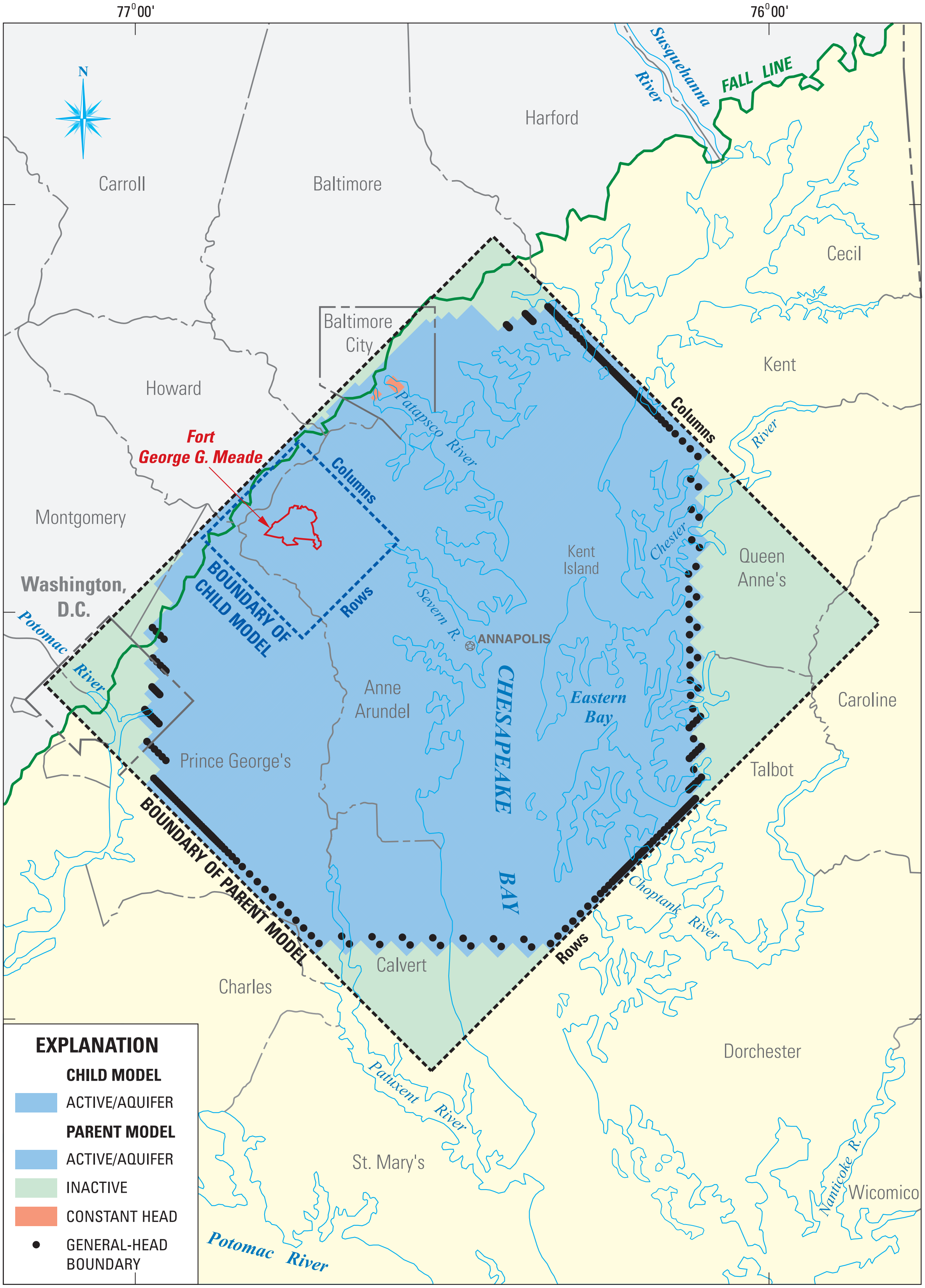


Figure 9B. Child model cell designations for layer 5, the lower Patapsco aquifer, indicating active and active/recharge cells.



Base from U.S. Geological Survey digital data, 2001, 1:2,000,000
Maryland State Plane FIPS Zone 1900 NAD 1983
Lambert Conformal Conic Projection

Figure 10A. Parent and child model cell designations for layer 6, the Patuxent aquifer, indicating active, inactive, constant-head, and general-head boundary cells.

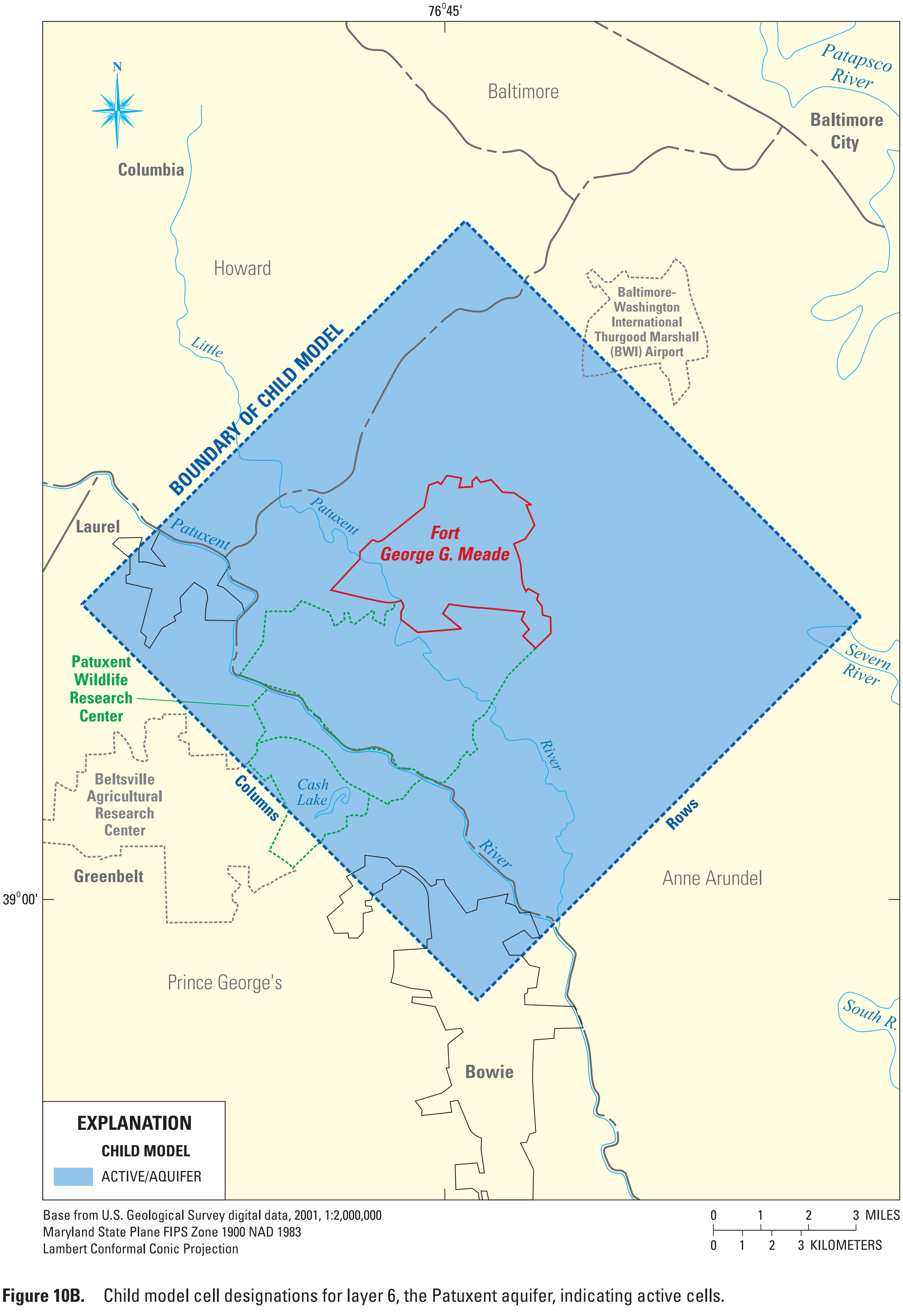


Figure 10B. Child model cell designations for layer 6, the Patuxent aquifer, indicating active cells.

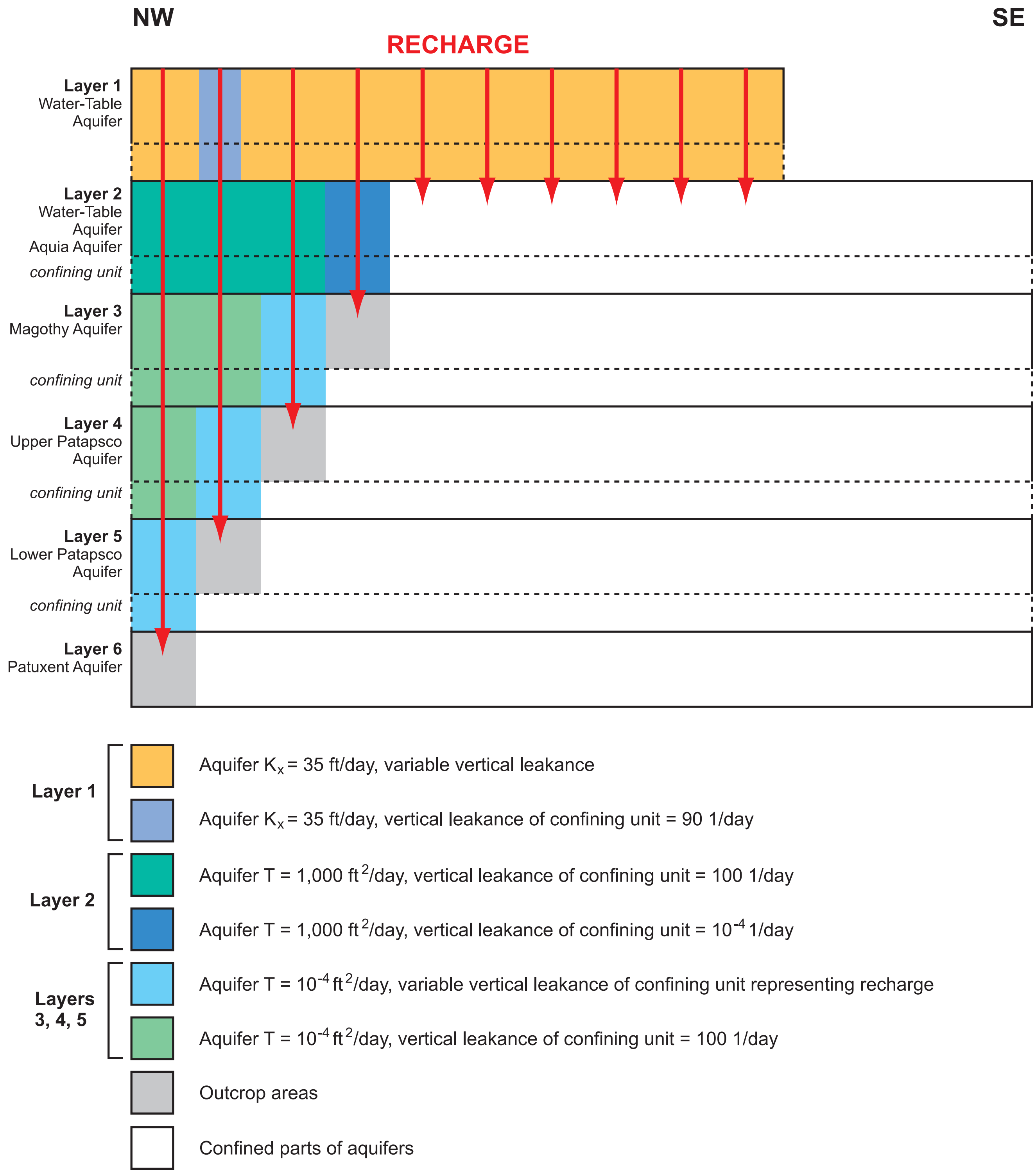


Figure 11. Schematic cross section along model row 50 showing model layers and properties in the updip parts of the aquifers.

Table 2. Stress periods with respective time periods.

[n/a, not applicable]

Stress period number(s)	Steady or transient	Time period	Length of each stress period(s)
1	Steady	n/a	n/a
2	Transient	1900–1919	20 years
3–7	Transient	1920–1969	10 years
8–17	Transient	1970–1979	1 year
18–121	Transient	1980–2005	0.25 year

(U.S. Environmental Protection Agency, 2007). A total of 3,368 individual reaches were represented in the child model (fig. 13): small reaches (less than 10 ft in length) were not represented in the model.

Data from NHDPlus was used to estimate reach geometry and riverbed conductance in each child model cell (CRIV):

$$CRIV = \frac{KWL}{M}$$

where *K* is the vertical hydraulic conductivity of the riverbed, *W* is the river width, *L* is the river reach length, and *M* is the riverbed thickness. Digital Elevation Model (DEM) data were used to determine the river bottom elevation for each child model cell. River stage was assumed to be 2.0 ft above the river bottom. Reach length, *L*, was determined from the intersection of the NHDPlus streams with the child model cells. The thickness of the riverbed, *M*, was assumed to be constant (2.0 ft) because no information was available. The product of the remaining terms in *CRIV*, *K* and *W*, was considered an adjustable parameter during model calibration. The river width, *W*, was initially arbitrarily set equal to the mean annual flow value for the reach from NHDPlus to represent a simple scaling of *CRIV* with flow. The vertical hydraulic conductivity of the riverbed, *K*, was assumed to be constant (0.1 ft/day) for all reaches; the value of *K*x*W* was determined during model calibration.

Reported Withdrawals

Reported groundwater withdrawals from the Magothy, upper Patapsco, lower Patapsco, and Patuxent aquifers by users permitted to withdraw more than 10,000 gal/d (gallons per day) were input to the model. These data were identified through compilation and analysis of water-use and related data from State, private, and Federal databases. Three major state programs in Maryland maintain databases used to identify water users and those who withdraw water. These programs and databases include the following:

1. The water-allocation permitting and reporting program and the water-use database (Regulatory Analysis Management System–RAMS);
2. The well construction permitting program and database; and
3. The Maryland drinking water program and the Public Drinking Water Information System (PDWIS) database.

The other database used was the Maryland version of the USGS Water Use database MD SWUDS (old) (Site-Specific Water-Use Data System), which is part of the USGS National Water Information System (NWIS). Data describing major users who withdraw groundwater were integrated from all four data sources, analyzed for completeness and accuracy, and entered into MD SWUDS (new). Data were retrieved from MD SWUDS (new) into a SWUDS Data Warehouse. Data on the quantity of water withdrawn by wells were made consistent with data in spreadsheets used in the Andreasen (2007) model.

Wells in the well construction permit database were matched to the Water Appropriation Permit database by their Water Appropriation Identification Number (WAPID), which appears in both databases. When aquifer information was not available from the USGS Groundwater Site Inventory database (GWSI), it was obtained from RAMS. When locations were not available from GWSI, they were obtained from the well construction database. Community water systems (CWSs) were matched with the Water Appropriation Permit information, usually by owner name, with the PDWIS database information given higher credibility for location information for active wells.

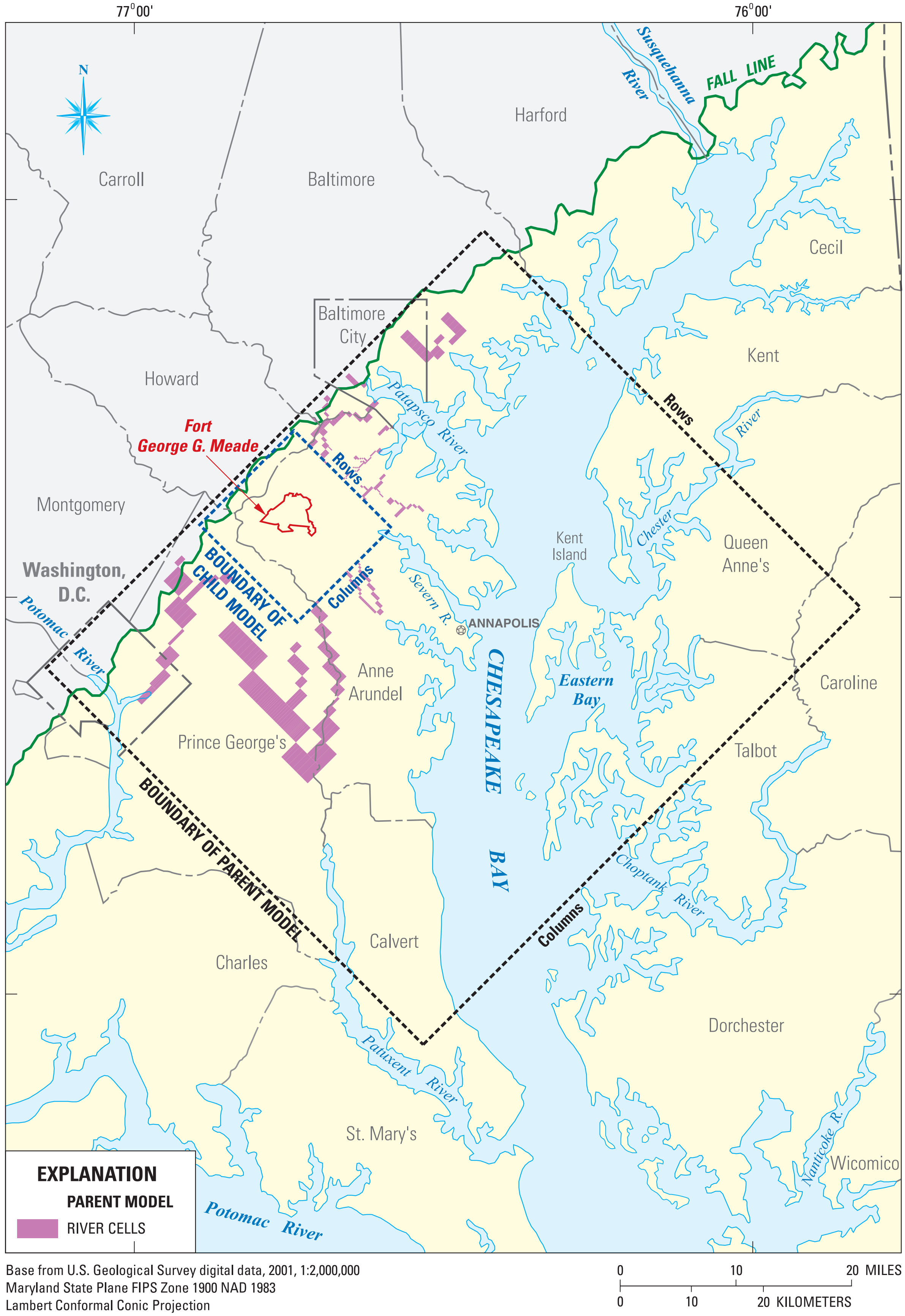
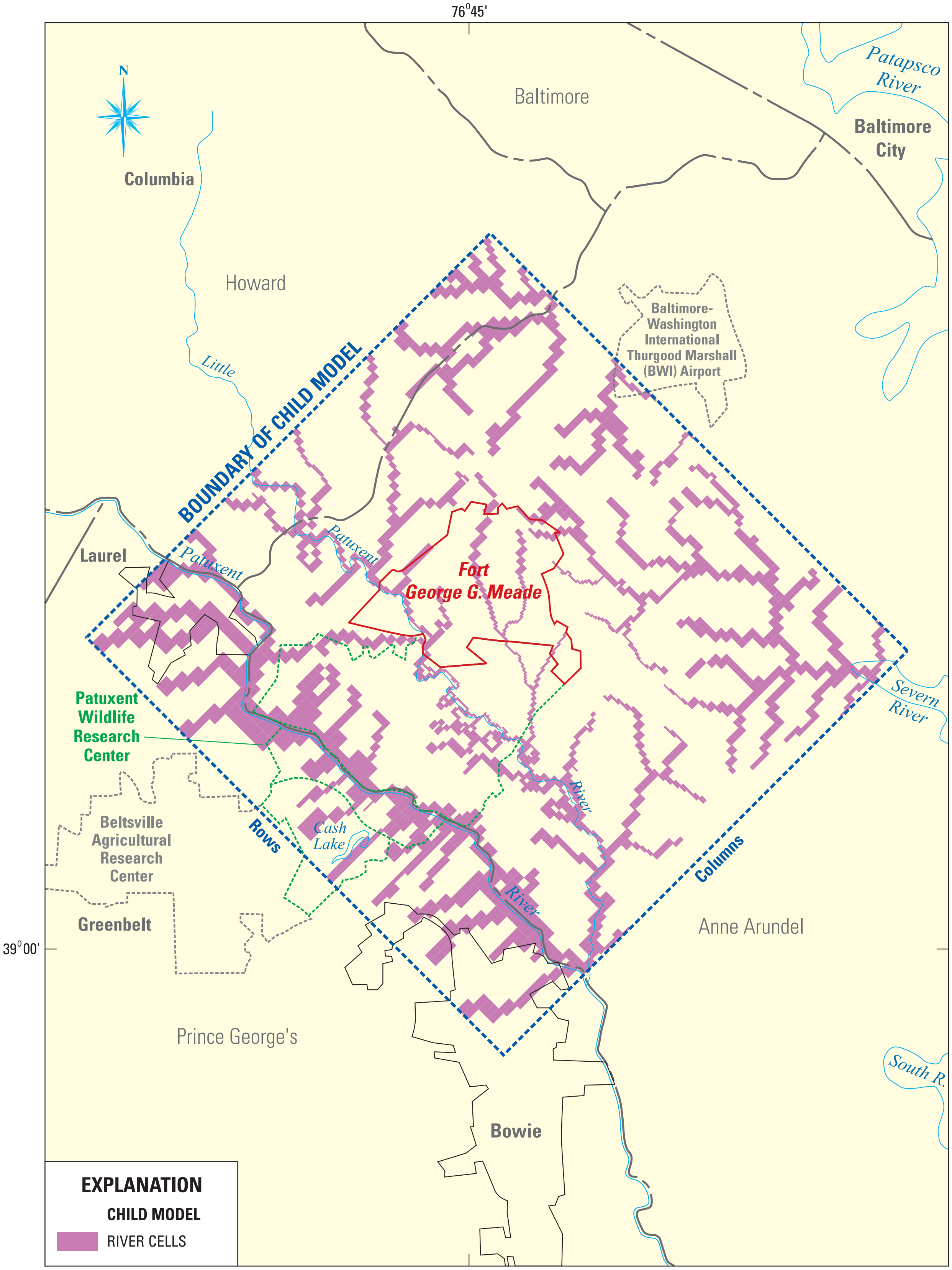


Figure 12. River cells in the parent model.



Base from U.S. Geological Survey digital data, 2001, 1:2,000,000
Maryland State Plane FIPS Zone 1900 NAD 1983
Lambert Conformal Conic Projection

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Figure 13. River cells in the child model.

MD SWUDS (old) contains information on the quantity of total groundwater or surface-water withdrawal by permit through 2005. MD SWUDS (new) was developed to take advantage of the capabilities of SWUDS to track the movement of water from site to site. The groundwater-permit withdrawal values were divided among the active wells or inactive wells included in the groundwater-flow model and entered into MD SWUDS (new) as water being conveyed from a specific well to a site representing the permit. Withdrawal data were assigned to model cells representing the pumping wells (Appendix A).

Model Calibration

For the original model (Andreasen, 2007), the following parameters were manually calibrated to match simulated and observed water levels and stream base flows: recharge, riverbed hydraulic conductivity, hydraulic conductivity and specific yield of model layer 1, transmissivity of model layers 2 through 6, general-head boundary conductance in model layers 3 through 6, vertical leakance between all model layers, and the storage coefficients of model layers 2 through 6. The model was considered calibrated when the lowest value of the root-mean-square error (RMSE) between observed and simulated water levels was obtained, and river flow reasonably matched base flow to the four streams in the model area. It should be noted that a manual model calibration approach might not provide optimal parameter values; as a result, different combinations of hydraulic properties and stresses may simulate the same water levels and stream base flow.

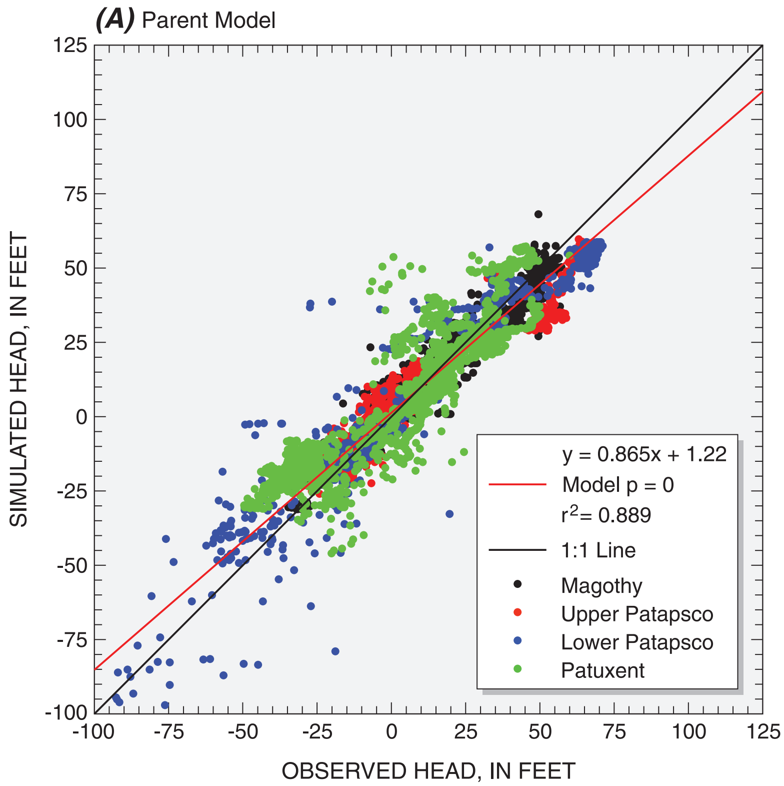
The overall model RMSE reported by Andreasen (2007) was 9.34 ft, based on 5,330 observations from 62 wells. Simulated base flow was 8 percent greater at Sawmill Creek, 2 percent greater at Northwest Branch of the Anacostia River at Riverdale, and 14 percent lower at Western Branch at Upper Marlboro compared to measured base flow. Simulated base flow was within 1 percent of measured base flow at North River.

In developing the BRAC model, it was not considered necessary to adjust layer hydraulic properties, because the BRAC and Andreasen (2007) models are essentially identical at the regional (parent model) scale. The greatest difference between the two models is the inclusion of many more stream reaches in the child model. Initial model runs with an estimated constant riverbed conductance for the child model stream reaches indicated that this difference resulted in a substantially altered water budget for the model. Therefore, the riverbed conductance was adjusted (by adjusting the product of the riverbed vertical hydraulic conductivity and river width terms) until the overall water budget for the combined parent and child models was similar to that of the Andreasen (2007) regional model.

The BRAC model makes use of the Observation Process introduced in MODFLOW-2000 (Hill and others, 2000), which provides the capability to compare model-calculated heads. The Observation Process computes simulated equivalent values, based on observation well location relative to the node and time. The observed and simulated equivalent heads are written to a file. Another program, written for this study, computes RMSE and other model fit statistics, by well, layer, stress period, and for the overall model. The parent and child models were analyzed separately. For the parent model, 7,797 observations from 55 wells were available. For the child model, 1,412 observations from 7 wells were used.

The RMSE values for the parent and child model are 8.72 and 11.91 feet, respectively. Comparing simulated and observed hydraulic heads or water levels for all layers with observation wells and for the entire simulation period (fig. 14), the correlation coefficients (r^2) for the parent and child models are 0.889 and 0.864, respectively. However, the slope of the regression line is 0.865 for the parent model and 0.639 for the child model and this indicates a tendency to over-simulate low heads and (or) under-simulate high heads. There are also differences in how the model performs for each aquifer (layer). In the child model, for example, heads are under-simulated for two wells in the lower Patapsco aquifer (groups of blue symbols to the upper right in figure 14B). The observed water levels in the Patuxent aquifer (green symbols) are generally lower than simulated values at lower water levels. A similar pattern can be noted for lower Patapsco and Patuxent aquifer observations in the parent model as well (fig. 14A). It is important to note that the observations are all weighted the same, and are not randomly distributed in space or time.

Observed and simulated water levels in parent (fig. 15) and child (fig. 16) models at selected observation sites show general agreement. Overall rates of decline are similar. Water levels in observation well AA Ce 94 (fig. 15C), for example, declined from 30 ft to almost -100 ft between 1961 and 2005, and the simulated water levels show approximately the same decline. RMSE values for the 55 parent model observation wells range from 0.95 to 30.31 ft; the range for the 7 child model observation wells is 5.00 to 24.17 ft (table 3). Many of the wells with higher RMSE values occur at the perimeter of the child model and near large pumping centers (fig. 17), as well as updip in the confined aquifers. RMSE values decrease downdip and away from the large pumping centers. The model is very sensitive to withdrawal rates, as will be discussed in the next section. Uncertainty in withdrawal rates may be manifested in the model as error. For the period 1980–82, for example, there are known reporting problems for some permits for wells in Anne Arundel County (John Smith, Maryland Department of the Environment, written commun., September 9, 2009). In some cases, it is apparent that pumping is either not reported or under-reported for this period. As a result, the simulation shows recovery near these wells between 1980 and 1982, which is not seen in the nearby observation wells (AA Ce 114 and AA Ce 120 in figure 15 and AA Cc 80 in figure 16).



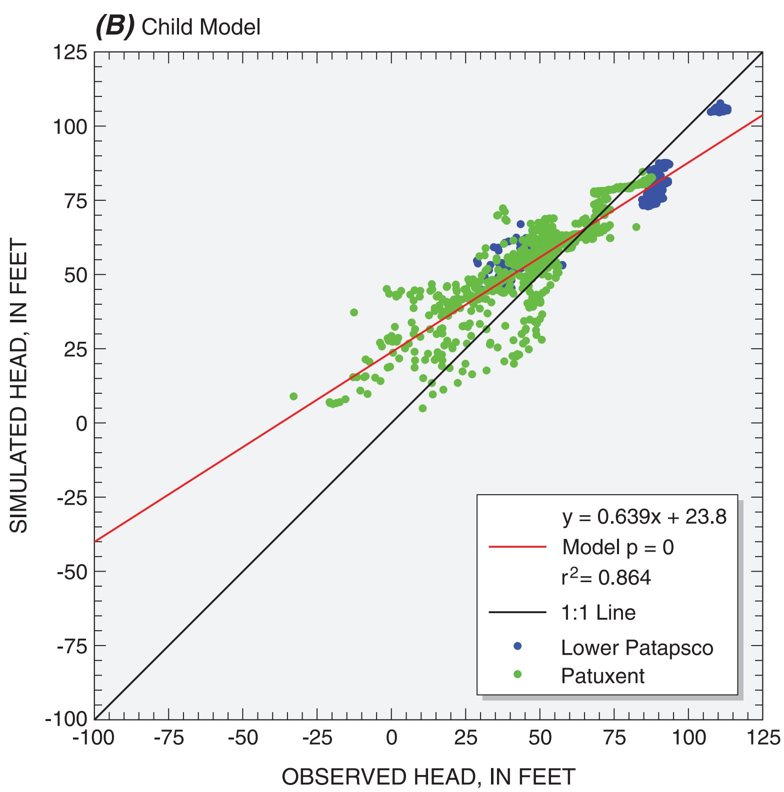


Figure 14. Comparison of simulated and observed water levels for the *(A)* parent and *(B)* child models.

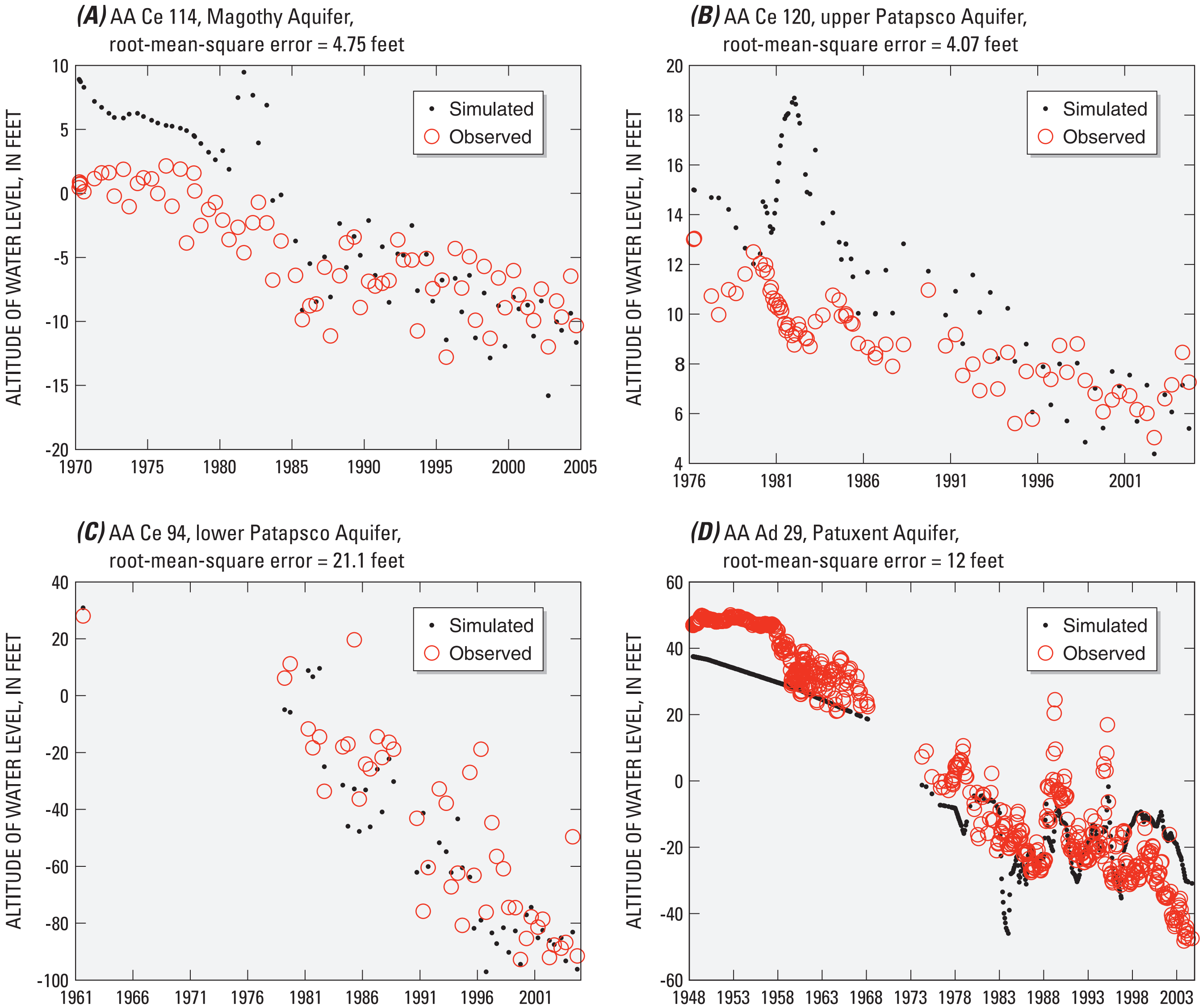


Figure 15. Hydrographs of simulated and observed water levels for four wells within the parent model: *(A)* AA Ce 114, layer 3; *(B)* AA Ce 120, layer 4; *(C)* AA Ce 94, layer 5; and *(D)* AA Ad 29, layer 6.

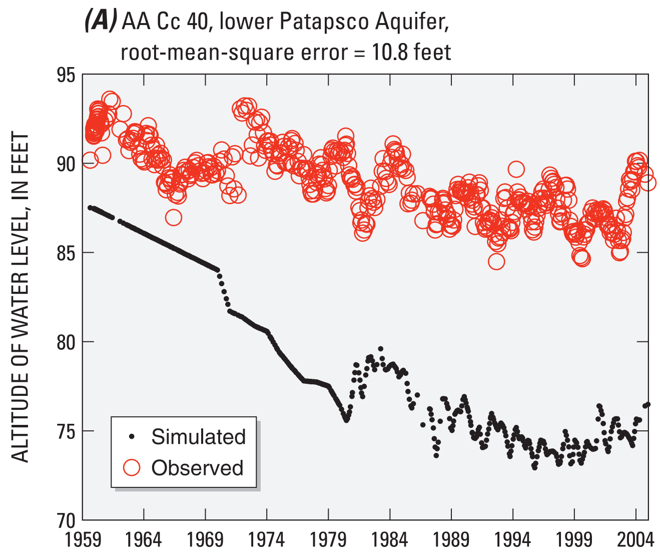


Figure 16. Hydrographs of simulated and observed water levels for two wells within the child model: *(A)* AA Cc 40, layer 5; and *(B)* AA Cc 80, layer 6.

Table 3. Root-mean-square error (RMSE) values for all observation wells.

[USGS, U.S. Geological Survey]

USGS well name	USGS site number	Latitude (decimal degrees)	Longitude (decimal degrees)	Model	Layer	Aquifer	RMSE (feet)
AA Cc 117	390103076402603	39.01761	-76.67358	Parent	3	Magothy	4.71
AA Cd 78	390238076373301	39.04400	-76.62552	Parent	3	Magothy	7.91
AA Ce 114	390130076311501	39.02511	-76.52052	Parent	3	Magothy	4.75
AA Cf 99	390150076283002	39.03067	-76.47468	Parent	3	Magothy	3.98
AA Cg 8	390125076240502	39.02372	-76.40107	Parent	3	Magothy	4.21
AA Dd 42	385808076373502	38.96900	-76.62608	Parent	3	Magothy	3.01
AA De 103	385512076331603	38.92011	-76.55413	Parent	3	Magothy	4.11
AA Df 79	385905076293601	38.98483	-76.49302	Parent	3	Magothy	4.17
AA Ed 39	385210076371002	38.86956	-76.61913	Parent	3	Magothy	4.23
AA Fe 47	384843076312601	38.81206	-76.52357	Parent	3	Magothy	3.07
CA Bb 10	384028076354201	38.67456	-76.59468	Parent	3	Magothy	6.11
CA Bb 23	384458076375501	38.74956	-76.63163	Parent	3	Magothy	5.32
CA Cc 56	383934076320001	38.65956	-76.53301	Parent	3	Magothy	4.35
KE Cb 97	391124076101001	39.19011	-76.16912	Parent	3	Magothy	6.12
PG Cf 33	385806076435303	38.96844	-76.73108	Parent	3	Magothy	9.65
PG De 21	385130076465501	38.85845	-76.78164	Parent	3	Magothy	5.59
PG Ed 50	384715076522001	38.78761	-76.87192	Parent	3	Magothy	11.39
PG Fe 30	384453076482101	38.74817	-76.80553	Parent	3	Magothy	7.47
PG Gf 35	383832076414701	38.64234	-76.69608	Parent	3	Magothy	5.65
QA Ea 27	385718076205501	38.95400	-76.34801	Parent	3	Magothy	1.99
AA Bd 99	390604076354501	39.10122	-76.59552	Parent	4	Upper Patapsco	20.09

Table 3. Root-mean-square error (RMSE) values for all observation wells.—Continued

[USGS, U.S. Geological Survey]

USGS well name	USGS site number	Latitude (decimal degrees)	Longitude (decimal degrees)	Model	Layer	Aquifer	RMSE (feet)
AA Bd 159	390737076374402	39.12705	-76.62858	Parent	4	Upper Patapsco	11.71
AA Be 102	390559076312602	39.09983	-76.52357	Parent	4	Upper Patapsco	6.63
AA Bf 3	390945076285601	39.16261	-76.48191	Parent	4	Upper Patapsco	3.85
AA Ce 70	390115076303002	39.02094	-76.50802	Parent	4	Upper Patapsco	4.93
AA Ce 120	390303076344301	39.05094	-76.57830	Parent	4	Upper Patapsco	4.07
AA Cf 121	390149076261701	39.03039	-76.43774	Parent	4	Upper Patapsco	7.65
AA De 95	385853076333001	38.98150	-76.55802	Parent	4	Upper Patapsco	7.91
AA De 128	385530076334701	38.92511	-76.56274	Parent	4	Upper Patapsco	3.32
AA Df 19	385921076270701	38.98956	-76.45079	Parent	4	Upper Patapsco	4.67
AA Ec 12	385125076404801	38.85694	-76.68000	Parent	4	Upper Patapsco	3.09
KE Cb 36	391400076101401	39.23344	-76.17023	Parent	4	Upper Patapsco	2.03
KE Db 40	390837076140401	39.14372	-76.23412	Parent	4	Upper Patapsco	0.95
PG De 33	385323076471802	38.88983	-76.78803	Parent	4	Upper Patapsco	11.75
QA Eb 111	385751076171601	38.96428	-76.28745	Parent	4	Upper Patapsco	3.61
AA Ad 102	391032076385904	39.17566	-76.64941	Parent	5	Lower Patapsco	12.11
AA Ad 109	391006076380101	39.16844	-76.63330	Parent	5	Lower Patapsco	4.10
AA Bd 109	390845076385801	39.14594	-76.64913	Parent	5	Lower Patapsco	12.03
AA Bd 157	390737076374401	39.12705	-76.62858	Parent	5	Lower Patapsco	7.68
AA Cc 40	390423076432001	39.07316	-76.72191	Child	5	Lower Patapsco	10.79
AA Cc 115	390103076402601	39.01761	-76.67358	Parent	5	Lower Patapsco	15.53
AA Ce 94	390450076343503	39.08067	-76.57608	Parent	5	Lower Patapsco	21.09
AA Cf 137	390205076292702	39.03483	-76.49052	Parent	5	Lower Patapsco	16.65
AA Cg 23	390123076241602	39.02317	-76.40413	Parent	5	Lower Patapsco	5.61
AA De 177	385852076333201	38.98122	-76.55857	Parent	5	Lower Patapsco	5.91
PG Be 14	390226076481001	39.04067	-76.80247	Child	5	Lower Patapsco	5.00
PG Cf 44	385944076433801	38.99567	-76.72691	Child	5	Lower Patapsco	13.54
PG Ed 34	384933076530001	38.82595	-76.88303	Parent	5	Lower Patapsco	16.51
QA Eb 112	385751076171602	38.96428	-76.28745	Parent	5	Lower Patapsco	3.59
AA Ac 11	391101076404001	39.18372	-76.67747	Parent	6	Patuxent	11.52
AA Ad 29	391015076373501	39.17094	-76.62608	Parent	6	Patuxent	11.98
AA Cb 1	390303076463201	39.05094	-76.77525	Child	6	Patuxent	7.45
AA Cc 80	390422076414503	39.07289	-76.69552	Child	6	Patuxent	16.69
AA Cc 102	390004076420001	39.00122	-76.69969	Child	6	Patuxent	19.12
AA Ce 117	390450076343402	39.08067	-76.57580	Parent	6	Patuxent	4.25
AA Cg 22	390123076241601	39.02317	-76.40413	Parent	6	Patuxent	1.92
AA De 203	385854076333202	38.98178	-76.55857	Parent	6	Patuxent	3.73
BA Gf 11	391356076293501	39.23233	-76.49274	Parent	6	Patuxent	15.12
5S2E-24	391349076354501	39.23039	-76.59552	Parent	6	Patuxent	5.83
PG Be 23	390213076471301	39.03705	-76.78664	Child	6	Patuxent	24.17
PG Cf 66	385745076445201	38.96261	-76.74747	Parent	6	Patuxent	30.31
QA Eb 110	385751076171603	38.96428	-76.28745	Parent	6	Patuxent	11.17

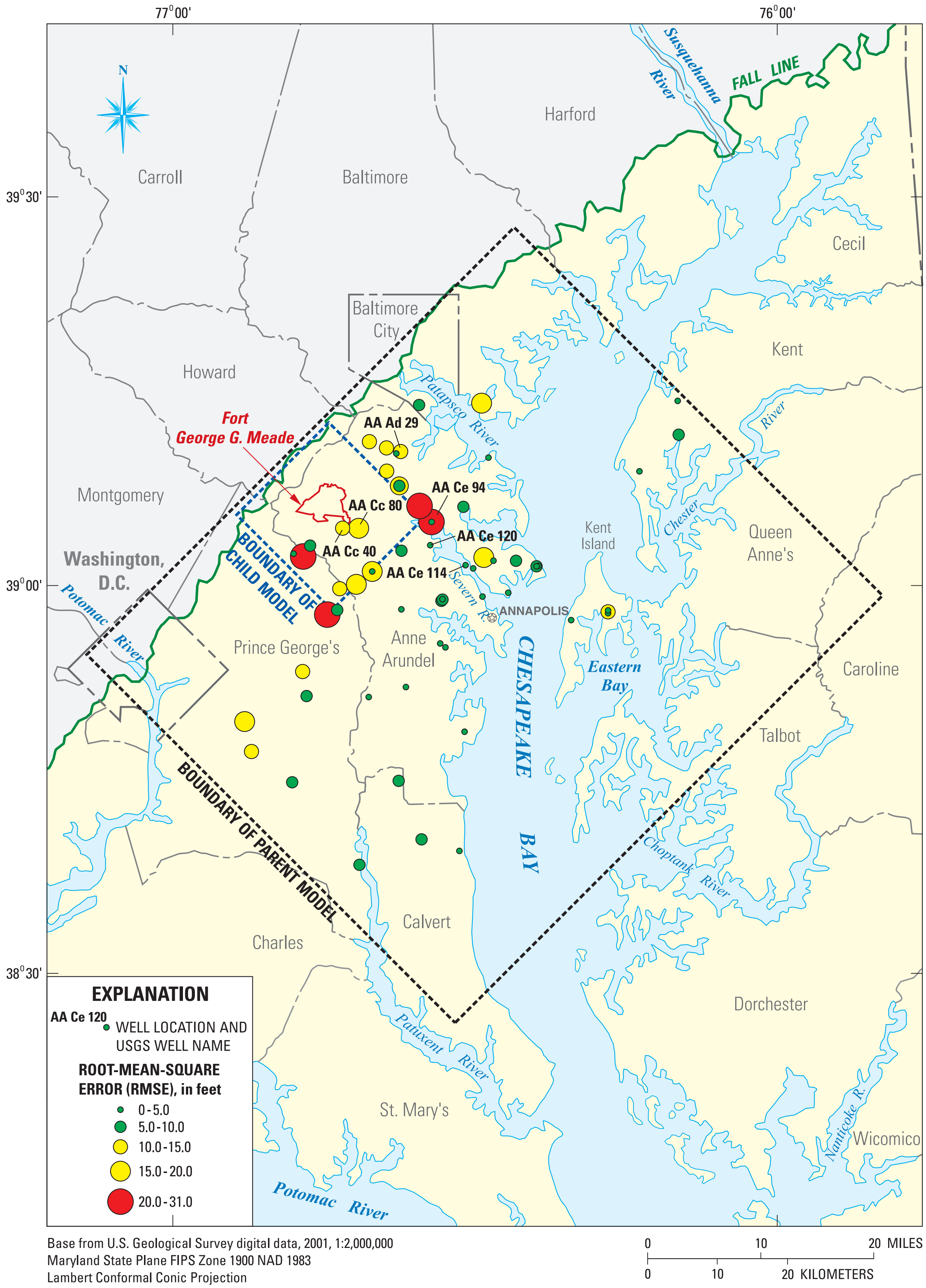


Figure 17. Location of and values for the root-mean-square error (RMSE) for 62 observation wells.

Model Sensitivity

In addition to providing a check on model calibration, sensitivity analysis helps quantify the uncertainty of the calibrated model due to uncertainty in model input parameters, stresses, and boundary conditions (Anderson and Woessner, 1992). Sensitivity analysis indicates which input parameters impact the ability of the model to match observed values (Reilly and Harbaugh, 2004). Sensitivities can be used to indicate the importance of the observations to the estimation of parameter values (Hill and Tiedeman, 2007).

Andreasen (2007) performed a sensitivity analysis on the regional model that indicated the model was sensitive to transmissivity and pumpage in model layers 3, 4, 5, and 6. The model was generally less sensitive to other parameters tested (leakance between aquifers, horizontal hydraulic conductivity of layer 1, general-head boundary hydraulic conductance, riverbed vertical hydraulic conductivity, storage coefficients, and recharge). In the current study, similar parameters were tested, however in this case, sensitivities could be determined separately for the parent and child model. The goal of the sensitivity analysis of the BRAC model was to ensure that it reproduced the results of Andreasen (2007) and to examine separately the parent and child model sensitivities to the same parameters used by Andreasen (2007). The following parameters were tested: transmissivity of layers 3, 4, 5, and 6; riverbed vertical conductance; and pumpage or withdrawal rates. For each, the parameters were adjusted for both the parent and child models; RMSE values were calculated for the overall model (the total error) as well as for each model separately (fig. 18).

Both the parent and child models are sensitive to increasing withdrawal rates. This sensitivity was discussed earlier when examining model errors in the context of simulated and observed well hydrographs. Both models are somewhat less sensitive to decreasing withdrawal rates. The parent model is more sensitive than the child model to decreasing transmissivity of layers 3, 4, 5, and 6. The parent model is relatively insensitive to riverbed vertical conductance, however, the child model does exhibit some sensitivity to decreasing riverbed conductance. This result may be expected given the large number of river reaches in the refined child model (compare figure 12 and figure 13).

Water Budget

The water budget of the groundwater-flow model describes the sources and sinks of water in the system. MODFLOW-2005 computes the water budget on a cell-by-cell basis for each stress period and time step combination. The overall model water budget also is summarized in the model output file. The net overall budgets for stress period 1 (steady state), stress period 8 (1970), and stress periods 118–121 (averaged, representing 2005) are shown in figure 19. This represents the sum of the budgets for the parent and child models. Recharge is the dominant source of water to the model. Outflows include flow to constant-head cells representing the Chesapeake Bay and tidal tributaries, and leakage to rivers. After the initial steady-state stress period, withdrawal by pumping wells is an important outflow as well. Head-dependent boundaries (general-head boundaries) are a minor source or sink, depending on the stress period. In 2005, the rate of withdrawal by pumping wells was approximately 8.5 percent of the rate of recharge. Sources of the withdrawn water include storage and reductions in flow to streams and rivers, including tidal rivers. Net outflow rates to both constant-head cells (representing tidal rivers and the Bay) and river cells were more than 5 percent lower in 2005 than in the pre-pumping time period represented by stress period 1.

Model Limitations

Numerical groundwater-flow models are one of the most robust tools for simulating the effects of withdrawals on water levels; however, there are some important limitations that should be considered. Because the model is based on a published model (Andreasen, 2007) it inherits some limitations of that model: (1) the accuracy of the model is limited by the validity of the conceptual model of groundwater flow, the hydrogeologic framework, and the input parameters such as aquifer transmissivity, confining-bed leakance, and withdrawal rates; (2) model-cell heads are averages over the cell areas; therefore, simulated heads are less representative of true heads in larger model cells; (3) accurately simulating the effects of withdrawals from the confined aquifers on stream base flow is limited since model calibration is less complete in the recharge (outcrop) areas resulting from a relative absence of head data in the water-table aquifer; and (4) use of the quasi-three-dimensional approximation, which does not include storage in confining units, may bias the model.

The LGR employed by current model has limitations as well. Spatial refinement of the model grid increased the number of cells in the area around Fort Meade, but no attempt was made to refine hydraulic properties. Therefore, although the model should provide improved simulation of the cones of depression associated with pumping wells, it does not incorporate any information on heterogeneity that is likely to exist at the smaller scale. Temporal refinement into quarterly stress periods for 1980–2005 was accomplished in two ways—by incorporating monthly data on withdrawals from permitted wells, and by varying the recharge seasonally. For the former, information existed on monthly reported withdrawals in databases that were used in this study, however, the true variation or seasonality in recharge is not known and so estimates had to be made. Furthermore, neither the model published by Andreasen (2007) nor the model developed for this study considers longer time-scale variations (years to decades) in recharge that have likely impacted the model, such as major droughts or periods of several wet years. Finally, manual model calibration approach might not provide optimal parameter values; as a result, different combinations of hydraulic properties and stresses may simulate the same water levels and stream base flow.

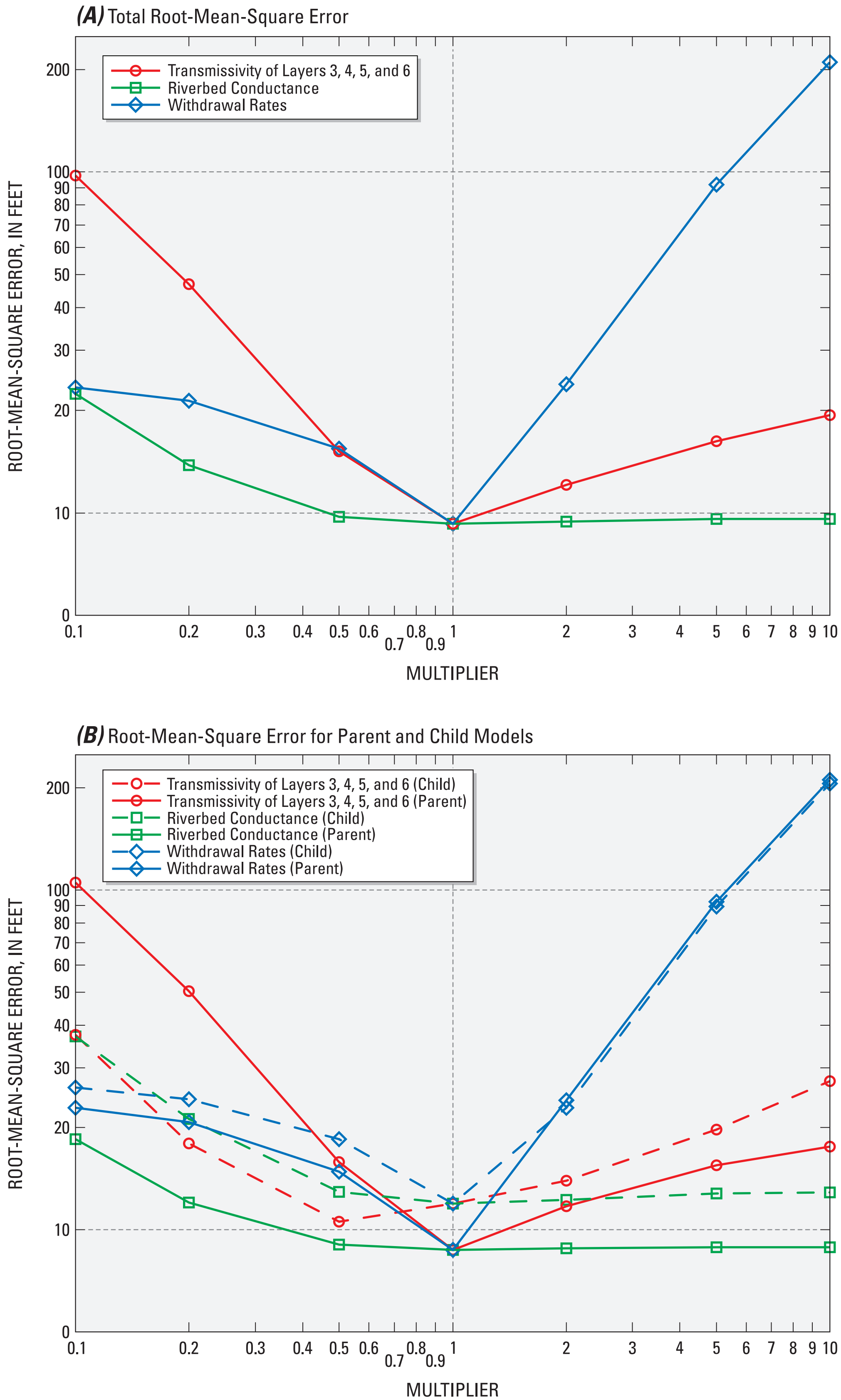


Figure 18. Results of the model sensitivity analysis showing *(A)* total and *(B)* parent and child model root-mean-square error (RMSE) values for the sensitivity-analysis simulations.

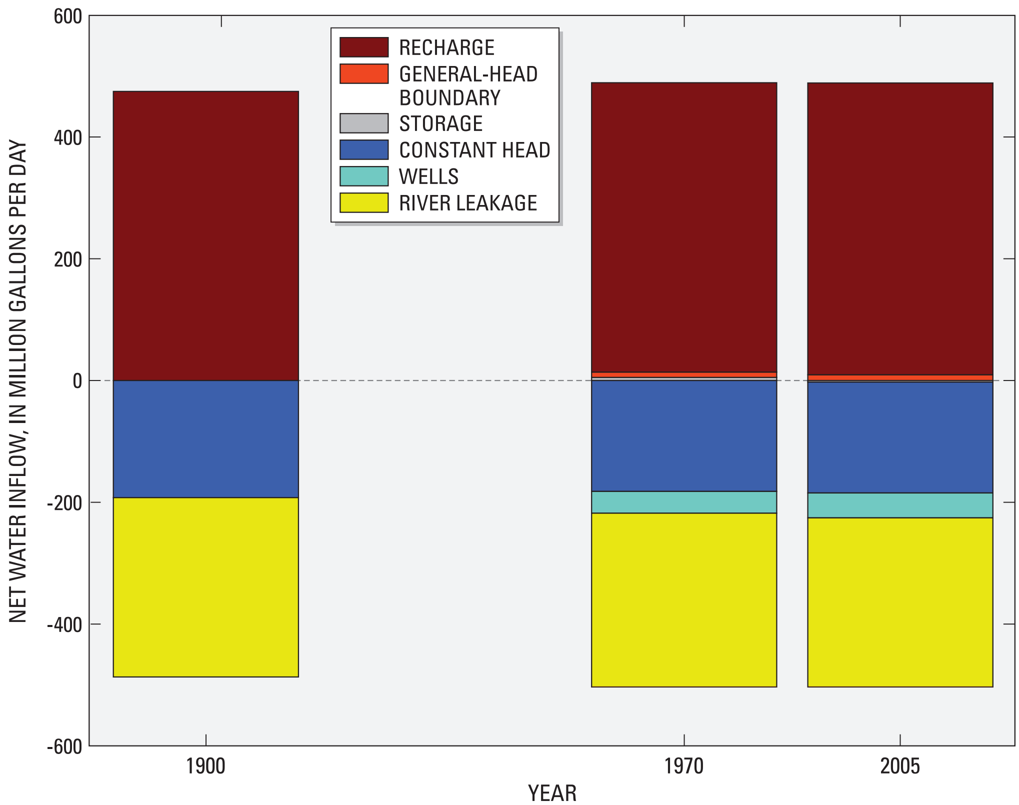


Figure 19. Net water budget for the entire model domain for stress period 1 (steady state), stress period 8 (1970), and stress periods 118–121 (averaged, representing 2005).

Summary and Conclusions

Increased groundwater withdrawals from confined aquifers in the Maryland Coastal Plain to supply anticipated growth at Fort Meade and surrounding areas as a result of the Department of Defense Base Realignment and Closure (BRAC) process may have adverse effects in the outcrop or near-outcrop area. Specifically, increased pumping from the Potomac Group aquifers could potentially reduce base flow in small streams below rates necessary for healthy biological functioning. Additionally, water levels may be lowered near, or possibly below, the top of the aquifer within the confined-unconfined transition zone near the outcrop area. A three-dimensional groundwater-flow model was compiled and refined to incorporate and analyze data on water withdrawals, streamflow, and hydraulic head in the region. The model is based on an earlier model, and shares several features, including model extent, boundary conditions, and vertical discretization (layering). The earlier model also provided initial estimates of hydraulic properties and recharge rates. The model developed for this study included an area of spatial refinement, centered on Fort Meade, which was coupled to the regional or parent model using the shared node Local Grid Refinement (LGR) capability of MODFLOW-LGR. A spatially refined stream network was incorporated into the child model. In addition, for part of the transient simulation period, stress periods were reduced in length from 1 year to 3 months, to allow for investigation of the effects of seasonally varying withdrawals and recharge on the groundwater-flow system and simulated streamflow. This required revision of the database on withdrawals and estimation of seasonal variations in recharge.

Model error was assessed by comparing observed and simulated water levels from 62 wells (55 in the parent model and 7 in the child model). The root-mean-square error values for the parent and child model were 8.72 and 11.91 feet, respectively. Root-mean-square error values for the 55 parent model observation wells range from 0.95 to 30.31 feet; the range for the 7 child model observation wells is 5.00 to 24.17 feet. Many of the wells with higher root-mean-square error values occur at the perimeter of the child model and near large pumping centers, as well as updip in the confined aquifers. Root-mean-square error values decrease downdip and away from the large pumping centers. The historical water levels observed within the model domain can be matched relatively well for both the parent ($r^2 = 0.889$) and child ($r^2 = 0.864$) models. The slope of the regression line is 0.865 for the parent model and 0.639 for the child model, indicating a tendency to over-simulate low heads and (or) under-simulate high heads.

Both the parent and child models are sensitive to increasing withdrawal rates. The parent model is more sensitive than the child model to decreasing transmissivity of layers 3, 4, 5, and 6. The parent model is relatively insensitive to riverbed vertical conductance; however, the child model does exhibit some sensitivity to decreasing riverbed conductance.

The overall water budget for the model included sources and sinks of water including recharge, surface-water bodies and rivers and streams, general-head boundaries, and withdrawals from permitted wells. Withdrawal from wells in 2005 was estimated to be equivalent to 8.5 percent of the total recharge rate.

The calibrated model provides a tool for future forecasts of changes in the system under different pumping scenarios, as well as for identifying additional data that may better define the groundwater system. Examination of model performance and a sensitivity analysis emphasizes the importance of accurate data on groundwater withdrawals.

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Appendix A

Appendix A. Withdrawal wells used in the model with corresponding groundwater appropriation permits and locations.

[USGS, U.S. Geological Survey]

Groundwater appropriation permit	USGS well name	USGS site number	Model	Layer	Row	Column	Latitude (decimal degrees)	Longitude (decimal degrees)
AA1932G001	AA Df 64	385909076281704	Parent	3	52	93	38.98595	-76.47107
AA1932G003	AA Df 101	385927076293001	Parent	4	53	91	38.99095	-76.49135
AA1932G003	AA Df 12	385900076292010	Parent	4	54	92	38.98345	-76.48857
AA1932G003	AA Df 13	385900076292011	Parent	4	54	92	38.98345	-76.48857
AA1932G003	AA Df 159	385918076295802	Parent	4	54	90	38.98833	-76.49944
AA1932G003	AA Df 160	385905076293605	Parent	4	54	91	38.98483	-76.49302
AA1932G003	AA Df 80	385905076293602	Parent	4	54	91	38.98483	-76.49302
AA1932G003	AA Df 83	385918076295801	Parent	4	54	90	38.98845	-76.49913
AA1932G101	AA Df 16	385907076281901	Parent	4	52	93	38.98539	-76.47163
AA1932G101	AA Df 65	385913076281401	Parent	4	51	93	38.98706	-76.47024
AA1947G003	AA Bb 22	390606076494001	Child	6	92	6	39.10178	-76.82747
AA1949G004	AA Cg 6	390126076235801	Parent	3	23	94	39.02400	-76.39913
AA1949G004	AA Cg 8	390125076240502	Parent	3	24	94	39.02372	-76.40107
AA1953G008	AA Ce 121	390449076344601	Parent	5	49	49	39.08039	-76.57913
AA1953G008	AA Ce 122	390454076344501	Parent	5	47	48	39.08289	-76.57774
AA1953G008	AA Ce 131	390450076343403	Parent	5	48	50	39.08067	-76.57580
AA1953G008	AA Ce 132	390450076343404	Parent	5	48	50	39.08067	-76.57580
AA1953G008	AA Ce 139	390448076341502	Parent	5	46	52	39.08011	-76.57052
AA1953G008	AA Ce 94	390450076343503	Parent	5	48	50	39.08067	-76.57608
AA1953G008	AA Ce 95	390450076343504	Parent	5	48	50	39.08067	-76.57608
AA1953G108	AA Ce 96	390450076343505	Parent	4	49	49	39.08011	-76.57885
AA1954G001	AA Cd 138	390120076361001	Parent	3	60	60	39.02233	-76.60246
AA1954G001	AA Cd 43	390112076362001	Parent	3	62	60	39.02011	-76.60524
AA1954G001	AA Cd 50	390118076361202	Parent	3	61	60	39.02178	-76.60302
AA1954G001	AA Cd 72	390113076361601	Parent	3	61	60	39.02039	-76.60413
AA1954G018	AA Cc 43	390422076414501	Child	4	69	33	39.07289	-76.69552
AA1954G018	AA Cc 79	390422076414802	Child	5	69	33	39.07289	-76.69636
AA1954G019	AA Bb 37	390826076450901	Child	5	60	8	39.14066	-76.75219
AA1954G019	AA Bb 71	390827076451201	Child	5	60	8	39.14094	-76.75303
AA1955G016	AA Bc 187	390742076410902	Child	4	55	19	39.12844	-76.68552
AA1955G016	AA Bc 88	390742076410901	Child	4	55	19	39.12844	-76.68552
AA1956G002	AA De 122	385709076345101	Parent	3	80	86	38.95261	-76.58052
AA1956G002	AA De 227	385710076344801	Parent	3	80	86	38.95289	-76.57969
AA1956G002	AA De 69	385708076345101	Parent	3	80	86	38.95233	-76.58052
AA1957G007	AA Bc 72	390851076430801	Child	5	55	10	39.14761	-76.71858
AA1958G005	AA Bd 89	390722076380901	Child	4	50	32	39.12289	-76.63552
AA1960G021	AA Cd 134	390024076352001	Parent	3	62	67	39.00678	-76.58858
AA1960G021	AA Cd 93	390024076352102	Parent	3	62	67	39.00678	-76.58885
AA1960G024	AA Bb 50	390656076462801	Child	6	75	9	39.11566	-76.77414
AA1960G024	AA Bb 54	390652076462801	Child	6	76	9	39.11455	-76.77414
AA1960G024	AA Bb 70	390652076462901	Child	6	76	9	39.11455	-76.77442

Appendix A. Withdrawal wells used in the model with corresponding groundwater appropriation permits and locations.—Continued

[USGS, U.S. Geological Survey]

Groundwater appropriation permit	USGS well name	USGS site number	Model	Layer	Row	Column	Latitude (decimal degrees)	Longitude (decimal degrees)
AA1960G024	AA Bb 75	390629076461402	Child	6	77	10	39.10816	-76.77025
AA1962G003	AA Bc 182	390634076413601	Child	4	57	25	39.10955	-76.69302
AA1962G030	AA Ae 35	391147076335001	Parent	6	18	28	39.19650	-76.56358
AA1962G030	AA Ae 36	391147076335002	Parent	6	18	28	39.19650	-76.56358
AA1963G008	AA Bc 177	390836076443101	Child	6	58	9	39.14344	-76.74164
AA1963G008	AA Bc 178	390834076442801	Child	6	58	9	39.14289	-76.74080
AA1963G008	AA Bc 260	390836076442901	Child	6	58	9	39.14344	-76.74108
AA1963G008	AA Bc 261	390837076443001	Child	6	58	9	39.14372	-76.74136
AA1963G029	AA Ce 125	390116076325203	Parent	3	55	71	39.02122	-76.54746
AA1963G029	AA Ce 98	390116076325202	Parent	3	55	71	39.02122	-76.54746
AA1965G032	AA Ec 12	385125076404801	Parent	4	100	89	38.85694	-76.68000
AA1965G032	AA Ec 21	385129076404701	Parent	3	100	89	38.85817	-76.67941
AA1965G032	AA Ec 6	385122076405801	Parent	3	100	89	38.85622	-76.68247
AA1965G032	AA Ec 7	385127076404901	Parent	3	100	89	38.85761	-76.67997
AA1965G032	AA Ec 8	385124076405001	Parent	3	100	89	38.85678	-76.68024
AA1965G033	AA Bb 64	390521076492202	Child	6	93	8	39.08928	-76.82247
AA1965G033	AA Bb 65	390530076490001	Child	6	92	8	39.09178	-76.81636
AA1965G033	AA Bb 66	390531076491401	Child	6	92	8	39.09205	-76.82025
AA1965G033	AA Bb 69	390606076490901	Child	6	91	7	39.10178	-76.81886
AA1966G027	AA Cg 18	390028076243601	Parent	4	27	95	39.00789	-76.40968
AA1966G027	AA Cg 19	390027076244001	Parent	4	27	95	39.00761	-76.41079
AA1966G028	AA Ce 119	390059076314701	Parent	3	53	75	39.01650	-76.52941
AA1966G028	AA Ce 99	390059076314801	Parent	3	53	75	39.01650	-76.52968
AA1966G048	AA Cc 62	390112076413801	Child	3	89	39	39.02011	-76.69358
AA1968G006	AA De 136	385854076340201	Parent	4	65	77	38.98178	-76.56691
AA1968G006	AA De 96	385854076332801	Parent	4	62	80	38.98178	-76.55746
AA1968G006	AA De 97	385853076333701	Parent	4	63	79	38.9815	-76.55996
AA1968G011	AA Ed 39	385210076371002	Parent	3	96	93	38.86956	-76.61913
AA1968G011	AA Ed 41	385210076371001	Parent	3	96	93	38.86956	-76.61913
AA1969G006	AA Bc 199	390953076424102	Child	6	53	9	39.16483	-76.71108
AA1969G006	AA Bc 200	390951076424701	Child	6	53	9	39.16427	-76.71275
AA1969G016	AA Bc 195	390717076422602	Child	5	57	15	39.1215	-76.70691
AA1969G016	AA Bc 169	390716076422501	Child	5	57	15	39.12122	-76.70664
AA1969G019	AA Bd 122	390952076384103	Child	5	52	26	39.13400	-76.65747
AA1969G019	AA Bd 176	390947076391601	Child	5	52	31	39.12056	-76.64389
AA1969G019	AA Bd 177	390947076391602	Parent	6	39	15	39.16316	-76.65413
AA1969G019	AA Bd 37	390951076384201	Parent	5	32	31	39.14678	-76.60969
AA1969G019	AA Bd 55	390950076384001	Parent	5	35	17	39.16427	-76.64469
AA1969G019	AA Bd 64	390952076390201	Parent	5	37	15	39.16455	-76.65025
AA1969G019	AA Bd 66	390949076392002	Parent	6	40	15	39.16372	-76.65525
AA1969G019	AA Bd 92	390949076392401	Parent	5	40	14	39.16372	-76.65636

Appendix A. Withdrawal wells used in the model with corresponding groundwater appropriation permits and locations.—Continued

[USGS, U.S. Geological Survey]

Groundwater appropriation permit	USGS well name	USGS site number	Model	Layer	Row	Column	Latitude (decimal degrees)	Longitude (decimal degrees)
AA1969G019	AA Bd 95	390929076391502	Parent	5	42	17	39.15816	-76.65386
AA1969G019	AA Bd 97	390921076393202	Parent	6	44	16	39.15594	-76.65858
AA1969G019	AA Bd 98	390907076390701	Parent	6	43	20	39.15205	-76.65163
AA1969G019	AA Ad 111	391011076381401	Parent	6	32	18	39.16972	-76.63722
AA1969G019	AA Ad 74	391000076384402	Parent	5	35	16	39.16677	-76.64524
AA1969G019	AA Ad 76	391009076384502	Parent	6	34	15	39.16927	-76.64552
AA1969G021	AA Bc 234	390512076434501	Child	6	73	23	39.08678	-76.72886
AA1969G021	AA Cc 120	390457076432501	Child	6	73	26	39.08261	-76.72330
AA1969G021	AA Cc 123	390419076431901	Child	6	76	29	39.07205	-76.72164
AA1969G021	AA Cc 144	390437076433001	Child	6	75	27	39.07705	-76.72469
AA1969G021	AA Bb 68	390538076453002	Child	6	79	13	39.09400	-76.75803
AA1969G021	AA Bc 164	390524076442502	Child	6	75	18	39.09011	-76.73997
AA1970G012	AA Bc 171	390525076414202	Child	5	62	29	39.09039	-76.69469
AA1970G013	AA Bf 101	390639076272102	Parent	4	18	67	39.11094	-76.45552
AA1970G013	AA Bf 51	390639076272101	Parent	4	18	67	39.11094	-76.45552
AA1970G041	AA Df 89	385934076274302	Parent	4	47	93	38.99289	-76.46163
AA1970G046	AA Bc 192	390751076435801	Child	6	59	11	39.13094	-76.73247
AA1970G046	AA Bc 193	390755076440101	Child	6	59	11	39.13205	-76.73330
AA1970G046	AA Bc 241	390752076440201	Child	6	59	11	39.13122	-76.73358
AA1970G112	AA Bc 173	390526076414102	Child	6	62	29	39.09066	-76.69441
AA1971G034	AA Cf 123	390454076254404	Parent	4	19	80	39.08178	-76.42857
AA1971G034	AA Cf 164	390454076254501	Parent	4	19	80	39.08178	-76.42885
AA1971G034	AA Cf 2	390454076254402	Parent	4	19	80	39.08178	-76.42857
AA1972G005	AA Cc 103	390057076403701	Parent	6	85	43	39.01594	-76.67663
AA1972G005	AA Cc 105	390100076403201	Parent	6	84	43	39.01678	-76.67524
AA1972G005	AA Cc 107	390047076404901	Parent	6	88	43	39.01317	-76.67997
AA1972G005	AA Cc 138	390101076401701	Parent	6	83	45	39.01705	-76.67108
AA1972G005	AA Cd 107	390055076394604	Parent	6	81	49	39.01539	-76.66247
AA1972G009	AA De 2	385913076340801	Parent	3	64	74	38.98706	-76.56857
AA1972G009	AA De 45	385920076335801	Parent	3	62	74	38.98900	-76.56580
AA1972G009	AA De 46	385915076340201	Parent	3	63	75	38.98761	-76.56691
AA1972G009	AA De 88	385915076335301	Parent	3	62	75	38.98761	-76.56441
AA1972G105	AA Cc 128	390104076402802	Parent	5	84	43	39.01789	-76.67413
AA1972G105	AA Cc 129	390103076403101	Parent	5	84	43	39.01761	-76.67497
AA1972G105	AA Cc 140	390101076401702	Parent	5	83	45	39.01705	-76.67108
AA1972G105	AA Cd 106	390055076394603	Parent	5	81	49	39.01539	-76.66247
AA1972G209	AA De 139	385912076340901	Parent	5	64	74	38.98678	-76.56885
AA1972G209	AA De 94	385916076334602	Parent	5	61	76	38.98789	-76.56246
AA1972G309	AA De 219	385915076335303	Parent	4	62	75	38.98761	-76.56441
AA1972G309	AA De 220	385912076340903	Parent	4	64	74	38.98678	-76.56885
AA1973G025	AA Bc 201	390800076424101	Child	5	56	13	39.13344	-76.71108

Appendix A. Withdrawal wells used in the model with corresponding groundwater appropriation permits and locations.—Continued

[USGS, U.S. Geological Survey]

Groundwater appropriation permit	USGS well name	USGS site number	Model	Layer	Row	Column	Latitude (decimal degrees)	Longitude (decimal degrees)
AA1973G025	AA Bc 202	390800076424102	Child	6	56	13	39.13344	-76.71108
AA1976G001	AA Cf 121	390149076261701	Parent	4	27	91	39.03039	-76.43774
AA1976G001	AA Cf 128	390149076261703	Parent	4	27	91	39.03039	-76.43774
AA1977G048	AA De 127	385633076345001	Parent	3	84	88	38.94261	-76.58024
AA1977G048	AA De 133	385633076345002	Parent	3	84	88	38.94261	-76.58024
AA1981G025	AA Bd 109	390802076392801	Parent	5	45	24	39.14594	-76.64913
AA1981G025	AA Bd 121	390802076392802	Child	5	52	26	39.13400	-76.65747
AA1981G026	AA Bc 209	390700076412701	Child	5	56	23	39.11678	-76.69052
AA1981G026	AA Bc 210	390700076412702	Child	5	56	23	39.11678	-76.69052
AA1981G026	AA Bc 215	390700076412601	Child	5	56	23	39.11678	-76.69025
AA1981G039	AA De 216	385620076333101	Parent	3	78	91	38.93900	-76.55830
AA1982G031	AA Ce 123	390303076344302	Parent	5	54	58	39.05094	-76.57830
AA1982G031	AA Ce 124	390303076344303	Parent	5	54	58	39.05094	-76.57830
AA1982G032	AA Cc 102	390004076420001	Child	6	92	42	39.00122	-76.69969
AA1982G032	AA Cc 86	390010076415702	Child	6	92	41	39.00289	-76.69886
AA1982G033	AA Ce 65	390403076325401	Parent	4	44	59	39.06761	-76.54802
AA1982G033	AA Ce 66	390401076330503	Parent	4	45	59	39.06705	-76.55107
AA1982G033	AA Ce 67	390401076330504	Parent	4	45	59	39.06705	-76.55107
AA1982G034	AA Cf 134	390121076270501	Parent	4	32	91	39.02261	-76.45107
AA1982G034	AA Cf 135	390136076271201	Parent	4	31	90	39.02678	-76.45302
AA1982G036	AA Cf 118	390207076292802	Parent	4	39	79	39.03539	-76.49079
AA1982G036	AA Cf 119	390203076292801	Parent	4	40	80	39.03428	-76.49079
AA1982G036	AA Cf 120	390203076292301	Parent	4	39	80	39.03428	-76.48941
AA1982G036	AA Cf 155	390151076292102	Parent	4	41	83	39.03094	-76.48885
AA1982G037	AA Bd 161	390852076365203	Parent	6	35	17	39.16455	-76.64441
AA1982G037	AA Bd 184	390843076362502	Child	4	52	33	39.11539	-76.64080
AA1982G037	AA Bd 36	390848076363601	Parent	5	32	32	39.14539	-76.60663
AA1982G037	AA Bd 56	390852076365202	Parent	5	35	18	39.16400	-76.64413
AA1982G037	AA Bd 63	390851076364302	Parent	5	33	31	39.14761	-76.61163
AA1982G038	AA Ad 1	391010076374601	Parent	5	30	20	39.16955	-76.62913
AA1982G038	AA Ad 23	391010076373701	Parent	5	29	21	39.16955	-76.62663
AA1982G038	AA Ad 40	391006076373402	Parent	5	29	22	39.16844	-76.62580
AA1982G038	AA Ad 41	391013076375001	Parent	5	30	20	39.17039	-76.63024
AA1982G038	AA Ad 67	391014076374501	Parent	5	29	20	39.17066	-76.62886
AA1982G038	AA Ad 68	391006076380601	Parent	5	32	19	39.16844	-76.63469
AA1982G039	AA Bd 105	390801076372302	Parent	5	44	30	39.13622	-76.63497
AA1982G040	AA Bd 107	390917076381401	Parent	5	42	32	39.13372	-76.62274
AA1982G041	AA Bc 176	390736076421602	Child	5	56	14	39.12678	-76.70414
AA1982G041	AA Bc 175	390736076421401	Child	5	56	14	39.12678	-76.70358
AA1982G042	AA Bd 61	390855076373402	Parent	5	33	30	39.14789	-76.61413
AA1982G043	AA Bd 101	390935076364302	Parent	5	36	28	39.14872	-76.62580

Appendix A. Withdrawal wells used in the model with corresponding groundwater appropriation permits and locations.—Continued

[USGS, U.S. Geological Survey]

Groundwater appropriation permit	USGS well name	USGS site number	Model	Layer	Row	Column	Latitude (decimal degrees)	Longitude (decimal degrees)
AA1982G044	AA Bd 103	390810076380702	Parent	5	28	28	39.15983	-76.61163
AA1982G044	AA Bd 162	390814076380501	Parent	5	33	30	39.14789	-76.61413
AA1982G045	AA Bd 108	390845076385801	Parent	5	37	24	39.15483	-76.63691
AA1982G069	AA Cc 127	390122076434601	Child	5	92	36	39.02289	-76.72914
AA1983G038	AA Cc 87	390422076414803	Child	6	69	33	39.07289	-76.69636
AA1983G038	AA Cc 88	390422076414804	Child	6	69	33	39.07289	-76.69636
AA1983G060	AA Bc 237	390750076442301	Child	6	60	11	39.13066	-76.73941
AA1983G060	AA Bc 251	390750076442401	Child	6	60	10	39.13056	-76.74000
AA1984G051	AA Ae 44	391120076341001	Parent	6	19	29	39.18900	-76.56913
AA1984G070	AA Ae 45	391041076322801	Parent	4	18	35	39.17816	-76.54080
AA1985G025	AA Cd 141	390356076352801	Parent	4	53	51	39.06567	-76.59080
AA1986G070	AA De 177	385852076333201	Parent	5	63	80	38.98122	-76.55857
AA1986G070	AA De 208	385834076332801	Parent	5	65	83	38.97622	-76.55746
AA1987G069	AA Cf 142	390205076292703	Parent	5	39	79	39.03483	-76.49052
AA1987G069	AA Cf 150	390151076292101	Parent	5	41	83	39.03094	-76.48885
AA1987G070	AA Ce 136	390043076345401	Parent	4	59	67	39.01206	-76.58135
AA1987G070	AA Ce 137	390043076345402	Parent	5	59	67	39.01206	-76.58135
AA1987G070	AA Ce 137	390043076345402	Parent	4	59	67	39.01206	-76.58135
AA1987G070	AA Dd 69	385800076351801	Parent	5	76	76	38.96678	-76.58802
AA1988G044	AA Fe 54	384826076332701	Parent	3	97	99	38.80734	-76.55718
AA1988G058	AA Fe 55	384956076333801	Parent	3	96	98	38.83234	-76.56024
AA1989G041	AA Fd 50	384903076391201	Parent	4	101	95	38.81761	-76.65302
AA1989G041	AA Fd 51	384903076391202	Parent	4	101	95	38.81761	-76.65302
AA1989G059	AA Bd 174	390741076383801	Parent	5	44	29	39.13722	-76.63472
AA1989G059	AA Bd 175	390714076383802	Child	5	50	30	39.12806	-76.64389
AA1990G024	AA De 205	385628076323102	Parent	4	72	92	38.94122	-76.54163
AA1990G045	AA De 217	385503076342601	Parent	3	90	92	38.91761	-76.57357
AA1990G045	AA De 226	385512076344101	Parent	2	90	91	38.92011	-76.57774
AA1990G054	AA Cc 146	390149076402101	Child	3	77	40	39.03039	-76.67219
AA1990G054	AA Cd 130	390108076395601	Parent	3	80	47	39.01889	-76.66556
AA1991G018	AA Cd 131	390336076383801	Child	4	59	39	39.06000	-76.64389
AA1991G018	AA Cd 132	390336076381402	Child	4	58	40	39.06000	-76.63722
AA1992G022	AA Fc 23	384555076401301	Parent	3	102	97	38.76539	-76.66996
AA1992G031	AA Bd 178	390655076382801	Parent	6	39	15	39.16316	-76.65413
AA1994G007	AA Bc 254	390518076415301	Child	5	64	29	39.08844	-76.69775
AA1994G007	AA Bc 255	390518076415302	Child	5	64	29	39.08844	-76.69775
AA1995G024	AA Cc 145	390119076422701	Child	5	90	38	39.02205	-76.70719
AA1997G030	AA Dc 22	385916076402201	Parent	3	91	56	38.98789	-76.67247
AA1997G030	AA Dc 23	385916076402502	Parent	3	91	56	38.98789	-76.67330
AA2004G024	AA Cd 136	390108076351601	Parent	4	58	64	39.01900	-76.58746
AA2004G024	AA Cd 137	390108076352901	Parent	4	59	63	39.01900	-76.59108

Appendix A. Withdrawal wells used in the model with corresponding groundwater appropriation permits and locations.—Continued

[USGS, U.S. Geological Survey]

Groundwater appropriation permit	USGS well name	USGS site number	Model	Layer	Row	Column	Latitude (decimal degrees)	Longitude (decimal degrees)
BA1946G003	BA Gf 210	391326076281401	Parent	6	11	36	39.22400	-76.47024
BA1946G003	BA Gf 211	391252076285901	Parent	6	12	36	39.21455	-76.48274
BA1946G003	BA Gf 212	391252076291001	Parent	6	12	35	39.21455	-76.48579
BA1946G003	BA Gf 221	391258076292901	Parent	6	12	35	39.21611	-76.49139
BA1946G003	BA Gf 222	391258076292902	Parent	6	12	35	39.21611	-76.49139
BA1946G003	BA Gf 32	391334076281401	Parent	6	10	35	39.22622	-76.47024
BA1946G003	BA Gf 35	391340076281701	Parent	6	10	35	39.22789	-76.47107
BA1956G006	BA Ff 94	391715076291401	Parent	6	7	13	39.30111	-76.48722
BA1956G006	BA Ff 95	391804076291401	Parent	6	7	13	39.30111	-76.48722
BA1956G006	BA Ff 91	391804076291402	Parent	6	7	30	39.27150	-76.45802
BA1959G009	BA Fe 68	391537076300701	Parent	5	10	23	39.26039	-76.50163
BA1969G020	BA Ff 93	391617076273002	Parent	6	8	17	39.28750	-76.48722
BA1970G006	BA Fg 176	391525076244901	Parent	6	6	37	39.25705	-76.41329
BC1956G001	1N3E-11	391805076334403	Parent	6	10	7	39.30150	-76.56191
BC1956G001	1N3E-9	391805076334401	Parent	6	10	7	39.30150	-76.56191
BC1958G001	1S3E-45	391732076335705	Parent	6	11	8	39.29233	-76.56552
BC1958G001	1S3E-46	391732076335401	Parent	6	11	8	39.29233	-76.56469
BC1958G001	1S3E-47	391737076335001	Parent	6	11	8	39.29372	-76.56358
BC1960G001	3S5E-40	391554076321601	Parent	6	11	13	39.26511	-76.53746
BC1960G001	3S5E-41	391554076322201	Parent	6	11	13	39.26511	-76.53913
BC1960G001	3S5E-42	391552076321801	Parent	6	11	13	39.26455	-76.53802
BC1960G001	3S5E-43	391556076322101	Parent	6	11	13	39.26566	-76.53885
BC1960G002	5S2E-20	391353076345301	Parent	6	15	13	39.23150	-76.58108
CA1970G004	CA Bb 23	384458076375501	Parent	3	102	99	38.74956	-76.63163
CA1970G004	CA Bb 24	384458076380001	Parent	3	102	99	38.74956	-76.63302
CA1972G002	CA Bc 7	384148076325101	Parent	3	102	106	38.69679	-76.54718
CA1972G002	CA Bc 8	384228076322901	Parent	3	101	105	38.70790	-76.54107
KE1971G004	KE Db 35	390812076141202	Parent	3	5	95	39.13678	-76.23634
KE1971G004	KE Db 55	390813076141501	Parent	3	5	95	39.13705	-76.23718
KE1971G004	KE Db 56	390812076141301	Parent	3	5	95	39.13678	-76.23662
KE1971G004	KE Db 57	390812076141401	Parent	3	5	95	39.13678	-76.23690
KE1978G102	KE Eb 14	390218076140901	Parent	3	11	100	39.03844	-76.23551
PG1956G007	PG Fd 55	384413076501501	Parent	3	107	89	38.73694	-76.83750
PG1956G007	PG Fd 67	384413076501401	Parent	3	107	89	38.73694	-76.83722
PG1958G103	PG Be 29	390140076471901	Child	6	95	27	39.02778	-76.78861
PG1961G008	PG Cf 89	385806076435303	Parent	6	96	46	38.97039	-76.72969
PG1961G008	PG Cf 35	385831076432101	Parent	5	96	44	38.96622	-76.73914
PG1961G008	PG Cf 64	385801076433101	Parent	6	96	46	38.97122	-76.72886
PG1961G108	PG Cf 78	385806076435302	Parent	5	95	46	38.97539	-76.72219
PG1961G108	PG Cf 91	385758076442201	Parent	3	96	49	38.96694	-76.72528
PG1961G108	PG Cf 66	385745076445001	Parent	6	97	42	38.96261	-76.74747

Appendix A. Withdrawal wells used in the model with corresponding groundwater appropriation permits and locations.—Continued

[USGS, U.S. Geological Survey]

Groundwater appropriation permit	USGS well name	USGS site number	Model	Layer	Row	Column	Latitude (decimal degrees)	Longitude (decimal degrees)
PG1961G108	PG Cf 93	385702076430601	Parent	4	97	42	38.96250	-76.74722
PG1961G208	PG Cf 32	385816076434501	Parent	5	96	46	38.96844	-76.73108
PG1961G208	PG Cf 33	385745076445201	Parent	3	96	46	38.96844	-76.73108
PG1961G208	PG Cf 54	385833076434801	Parent	3	96	56	38.95067	-76.71802
PG1963G003	PG Df 34	385037076430901	Parent	3	101	86	38.84372	-76.71886
PG1963G003	PG Df 36	385029076430201	Parent	3	101	87	38.8415	-76.71691
PG1970G002	PG Ef 37	384736076433401	Parent	3	103	93	38.79333	-76.72611
PG1975G006	PG Ee 57	384918076461701	Parent	3	105	90	38.75833	-76.79639
PG1975G006	PG Ee 62	384530076474701	Parent	3	103	78	38.82167	-76.77139
PG1977G008	PG Ce 50	385950076453801	Parent	4	101	40	38.92056	-76.81667
PG1977G008	PG Ce 44	385950076453802	Child	5	95	36	38.99722	-76.76056
PG1977G012	PG Fe 35	384158076483201	Parent	3	107	95	38.69944	-76.80889
PG1979G002	PG Ed 57	384719076521206	Parent	4	106	67	38.78861	-76.87000
PG1987G003	PG Ce 45	385514076490001	Child	5	95	36	38.99722	-76.76056
PG1990G012	PG Bd 45	390221076524401	Parent	6	98	9	39.03928	-76.87858
PG1990G012	PG Bd 48	390155076523401	Parent	6	99	10	39.03194	-76.87611
PG1990G012	PG Bd 49	390200076521701	Parent	6	98	10	39.03333	-76.87139
PG1990G012	PG Bd 50	390210076521501	Parent	6	98	10	39.03611	-76.87083
PG1990G012	PG Bd 51	390210076524301	Parent	6	98	9	39.03611	-76.87861
PG1990G012	PG Bd 52	390220076524201	Parent	6	98	9	39.03889	-76.87833
PG1990G012	PG Bd 61	390150076533801	Parent	6	99	8	39.03056	-76.89389
PG1990G012	PG Bd 62	390200076521001	Parent	6	98	10	39.03333	-76.86944
PG1998G006	PG Df 42	385109076434601	Parent	5	101	79	38.85261	-76.72913
PG1998G006	PG Df 42	385109076434601	Parent	6	101	79	38.85261	-76.72913
PG1998G023	PG Cd 25	385941076511301	Parent	6	100	21	38.99472	-76.85361
QA1970G102	QA Eb 173	385817076185001	Parent	4	21	101	38.97150	-76.31357
QA1984G016	QA Eb 169	385817076171501	Parent	4	18	102	38.97150	-76.28718
QA1984G016	QA Eb 170	385816076171501	Parent	4	19	102	38.97122	-76.28718
QA1985G009	QA Fa 77	385440076211801	Parent	3	45	102	38.91123	-76.35468
QA1985G024	QA Eb 162	385906076171601	Parent	4	17	101	38.98511	-76.28745
QA1985G024	QA Eb 171	385906076171602	Parent	4	17	101	38.98511	-76.28745
QA1989G024	QA Eb 166	385851076183701	Parent	4	20	100	38.98095	-76.30996
QA1989G024	QA Eb 167	385850076183601	Parent	4	20	100	38.98067	-76.30968
QA1994G007	QA Ec 91	385748076112401	Parent	4	13	106	38.96345	-76.18967
QA1994G007	QA Ec 92	385750076112501	Parent	4	13	106	38.96400	-76.18995
QA1997G050	QA Eb 184	385850076183502	Parent	5	20	100	38.98067	-76.30940

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