Department of Natural Resources
Resource Assessment Service
MARYLAND GEOLOGICAL SURVEY
Richard Ortt, Director

ADMINISTRATIVE REPORT 20-02-01

SIMULATED MAXIMUM WITHDRAWALS FROM THE UPPER PATAPSCO, LOWER PATAPSCO, AND PATUXENT AQUIFER SYSTEMS IN ANNE ARUNDEL COUNTY, MARYLAND

By

David C. Andreasen

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

DNR Publication No. 12-020620-208

2020

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KEY RESULTS

Anne Arundel County relies heavily on withdrawals from the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems for public water supply. In 2018, approximately 33.5 million gallons per day were withdrawn from Anne Arundel County Department of Public Works well fields in the central and northern part of the county. Remaining available drawdown in 2018 in the well fields before water levels reach management levels ranges from 24 to 193 feet in the Upper Patapsco aquifer system, 150 to 500 feet in the Lower Patapsco aquifer system, and 100 to 960 feet in the Patuxent aquifer system.

A previously constructed groundwater-flow model (MODFLOW) was revised, verified for calibration, and used to estimate maximum withdrawals from the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems at existing Anne Arundel County Department of Public Works well fields (Arnold, Broad Creek, Crofton Meadows and Severndale), and at future well fields (Crownsville and Millersville). Results of the modeling show that a total of 114.4 million gallons per day can be withdrawn from the well fields before water levels reach management levels in one or more of the aquifers. As a result of the simulated leakage between aquifers, the amount that can be withdrawn from deeper aquifers is controlled, in part, by the available drawdown in shallower aquifers. The simulated maximum withdrawal is approximately 1.7 times greater than the 2086 build-out value of 66.5 million gallons per day and approximately 3.4 times greater than the amount pumped in 2018. Simulated water levels are as deep as 155, 295, and 480 feet below sea level in the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively. Drawdown of this magnitude has the potential to cause land subsidence, saltwater intrusion, and well interference with other groundwater users.

The simulated net water budget for the modeled aquifer system for the maximum-withdrawal scenario indicates that recharge applied to the water-table aquifer (100 percent of net inflow to the model) is balanced by a net outflow to rivers (46 percent), wells (31 percent), and constant-head and head dependent boundaries (22 percent and 1 pecent, respectively). As withdrawals increased under the maximum withdrawal scenario, net flow to rivers and constant-head boundaries decreased. The maximum withdrawals result in an approximate 14-percent reduction in net river discharge from the 2018 amount.

Groundwater travel times from Anne Arundel County Department of Public Works well fields pumped in the maximum withdrawal scenario were calculated using the groundwater-flow model and the particle-tracking code MODPATH. In the Upper Patapsco aquifer system well fields, the minimum travel time from model boundaries (water-table aquifer or brackish tidal surface water) is 30 years for Severndale, 75 years for Arnold, and 277 years for Broad Creek. In the Lower Patapsco aquifer system well fields, the minimum travel times from model boundaries is 135 years for Arnold, 277 years for Broad Creek, 94 years for Crofton Meadows, 144 years for Crownsville, 70 years for Millersville, and 97 years for Severndale. In the Patuxent aquifer system well fields, the minimum travel times from model boundaries is 459 years for Arnold, 375 for Broad Creek, 244 for Crofton Meadows, 234 for Crownsville, and 193 years for Millersville. The well fields with the shortest travel times (less than 100 years) to the water-table aquifer (recharge area) and brackish tidal surface water include the Upper Patapsco well fields at Arnold (75 years to brackish Magothy River) and Severndale (30 years to recharge area), and the Lower Patapsco aquifer wells fields at Crofton Meadows, Millersville, and Severndale (94, 70, and 97 years to recharge area, respectively). Travel times from well fields to model boundaries under the maximum-withdrawal scenario range from approximately 1.4- to 16-times less than under 2018 pumping conditions and 1.1- to 9.9-times less than under 2086 build-out pumping conditions.

INTRODUCTION

Anne Arundel County Department of Public Works (AADPW) relies almost entirely on groundwater for its municipal water supply. In 2018, approximately 33.5 million gallons per day (Mgal/d) was pumped from three aquifer systems (Upper and Lower Patapsco, and Patuxent) tapped by AADPW production wells, providing drinking water to approximately 116,000 customers (population of ~430,000) (Edward Cope, Anne Arundel County Department of Public Works, written commun., 2019). A relatively small amount (average of approximately 0.01 Mgal/d) was imported from the surface-water-sourced Baltimore City water system in 2018. Projected groundwater withdrawals may increase to approximately 67 million gallons per day at build-out (Malcolm Pirnie, Water Division of Arcadis, 2016). In 2017, a MODFLOW (McDonald and Harbaugh, 1988) groundwater-flow model constructed by the Maryland Geological Survey (Andreasen, 2017) indicated that projected 2086 build-out withdrawals will not cause water levels to fall below the 80-percent management level in all three aquifer systems, with the exception of the Upper Patapsco at the Severndale well field. However, sufficient supply capacity is available in the Lower Patapsco aquifer system at Severndale to shift the Upper Patapsco withdrawals (0.4 million gallons per day by 2086) to the Lower Patapsco. Groundwater levels simulated for 2086 build-out were as low as approximately 100, 170, and 228 feet below sea level in the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems, respectively. Drawdown from current water levels was as great as approximately 80, 130, and 200 feet in the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems respectively. The 2017 model also evaluated the potential effects of the increased withdrawals on domestic wells. The simulated drawdown at the projected build-out amount did not adversely affect domestic-well operation. Simulated water levels remained above well screens and casing-diameter reductions (telescoping wells) in the 3,154 domestic wells estimated to be screened in the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems in areas updip (to the northwest) of the well fields. Of the total number of domestic wells only approximately 3 percent were determined to be telescoping. Simulated water levels remained at least 20 ft above well screens and casing-diameter reductions in all but six wells.

OBJECTIVE AND SCOPE OF WORK

The objectives of the study are to estimate, using a steady-state groundwater-flow model, maximum possible withdrawal rates from the major Anne Arundel County well fields (existing and future) tapping the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems before simulated water levels reach the 80-percent management level. The existing well fields include Arnold, Broad Creek, Crofton Meadows, and Severndale and the future well fields include Crownsville and Millersville (fig. 1). The study focuses on estimating groundwater levels, drawdown, and water budget in the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems in Anne Arundel County, Maryland. The study also addresses how the withdrawals could potentially affect groundwater levels in surrounding areas, baseflow in streams, and water levels in the overlying Magothy aquifer. In addition, the study estimates groundwater-flow travel times (advective flow) for groundwater path lines terminating at Anne Arundel County well fields.

LOCATION OF STUDY AREA

The study area includes the major AADPW well fields in the central portion of Anne Arundel County (fig. 1). A groundwater-flow model used in the study includes the entirety of Anne Arundel County and portions of Baltimore, Calvert, Howard, Kent, Prince George’s, Queen Anne’s, and Talbot Counties, and Baltimore City.

AVAILABLE DRAWDOWN

Groundwater withdrawals in confined aquifers of Maryland’s coastal plain are managed such that groundwater levels are maintained above a prescribed management level. The management level is defined as 80 percent of the difference between the top of the aquifer and the pre-pumping water level. The 80-percent management level, acting as a buffer against de-watering of the saturated aquifer sands, constrains the maximum water-supply capacity of the aquifer. Assessing whether withdrawals have exceeded aquifer-supply capacity as defined by the management level requires sustained monitoring and assessment of groundwater levels at both regional and local scales. For this study, the amount of remaining available drawdown (difference between the current water level and the 80-percent management level) in 2018 in the Upper Patapsco, Lower Patapsco, and

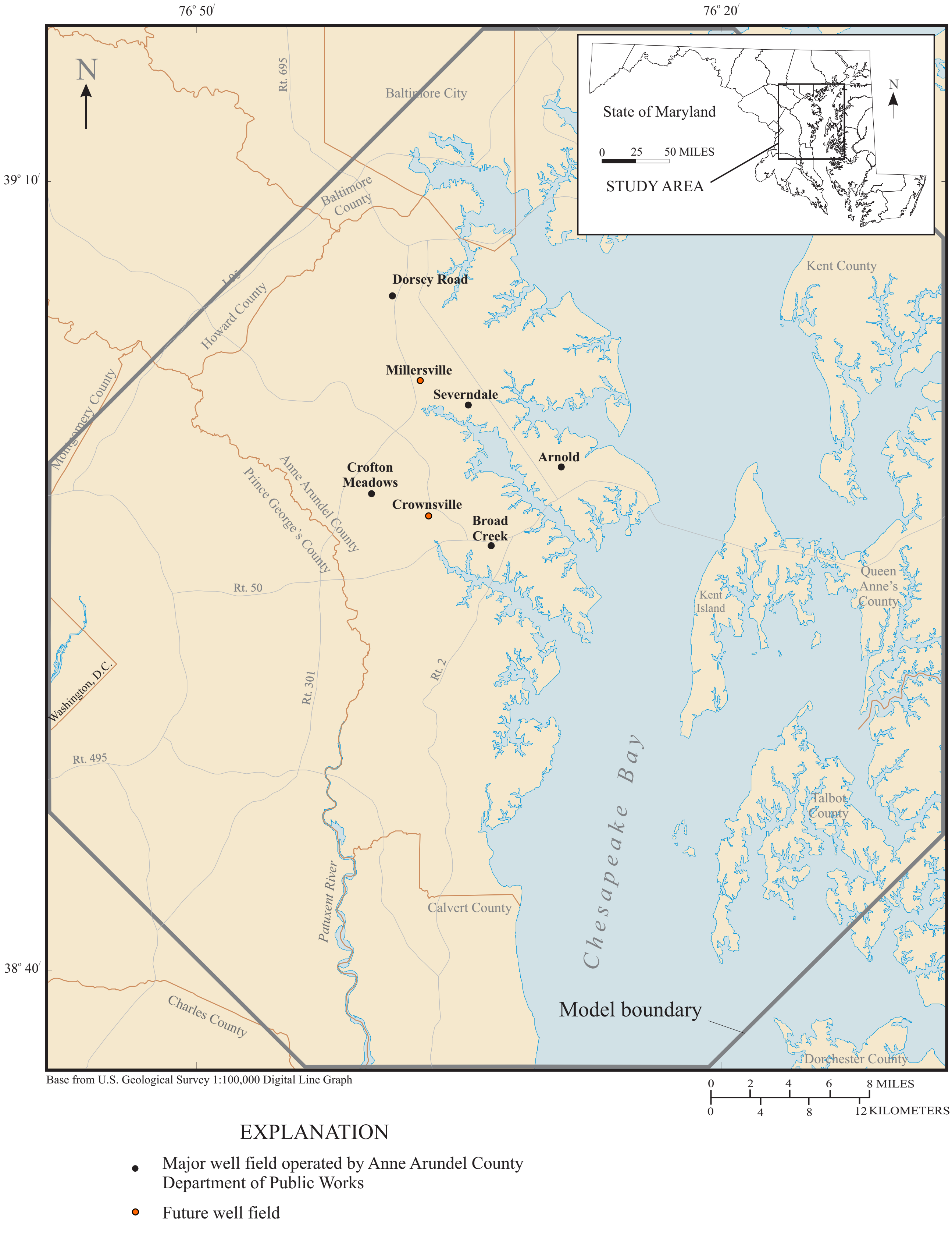


Figure 1. Location of study area.

Patuxent aquifer systems was determined using potentiometric surface elevations, aquifer elevations from the GIS-based Maryland Coastal Plain Aquifer Information System (Andreasen and others, 2013), and model-simulated pre-pumping water levels from a previous groundwater-flow model (Andreasen, 2007; p. 44) (figs. 2-4).

Remaining available drawdown in 2018 in the Upper Patapsco aquifer system in Anne Arundel County ranged from zero near the outcrop area of the aquifer to approximately 500 ft in the southern-most part of the county (fig. 2). At the Arnold, Broad Creek, Gibson Island, and Severndale well fields, the remaining available drawdown was approximately 140, 183, 193, and 24 ft, respectively.

Remaining available drawdown in 2018 in the Lower Patapsco aquifer system in Anne Arundel County ranged from zero near the outcrop area of the aquifer to approximately 1,000 ft in the southern -most part of the county (fig. 3). At the Arnold, Broad Creek, Crofton Meadows, and Severndale well fields, the remaining available drawdown was approximately 470, 500, 190, and 150 ft, respectively.

Remaining available drawdown in 2018 in the Patuxent aquifer system in Anne Arundel County ranged from zero near the outcrop area to approximately 1,500 ft in the southern-most part of the county (fig. 4). At Arnold, Broad Creek, and Crofton Meadows the remaining available drawdown was approximately 820, 960, and 500 ft, respectively. The remaining available drawdown at the Dorsey Road well field is approximately 100 ft.

In all three aquifer systems, there is a relatively narrow band parallel to the aquifer outcrops where water levels are below management levels. In these areas the tops of the aquifers are relatively shallow, therefore even relatively minor amounts of drawdown can cause water levels to fall below the management level. In the analysis performed here, the potentiometric surfaces and layer elevations may not have the level of granularity necessary to resolve in enough detail the shallow areas near aquifer outcrops. The accuracy and lack of resolution of the estimated pre-pumping water levels used to calculate the management level may also limit accuracy in those shallow areas.

GROUNDWATER-FLOW MODEL

The maximum rates of withdrawals from the existing AADPW well fields at Arnold, Broad Creek, Crofton Meadows, Severndale, and future well fields at Crownsville and Millersville were evaluated using a groundwater-flow model (MODFLOW) previously constructed by the Maryland Geological Survey (Andreasen, 2007). The model consists of 61,000 cells and six layers representing (from shallow to deep) the water table, Aquia, Magothy, Upper and Lower Patapsco, and Patuxent aquifer systems. Model-cell size is variable with dimensions ranging from 360 by 390 ft at Anne Arundel County well fields to as much as 4,800 ft by 9,400 ft in locations along the model boundary. The 2007 model, revised in 2017 (Andreasen, 2017), was updated for this study. The model simulates groundwater flow in the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems as well as the Magothy aquifer. The water-table aquifer, consisting of the outcrop areas of the Aquia, Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers along the outcrop areas of the intervening confining layers, is also represented in the model as an active layer. The confined Aquia aquifer is represented in the model as a layer with specified (constant) heads varied over time.

Model Revisions

Several revisions were made to input arrays and time discretization prior to the predictive model simulations. Changes made to the model are described below.

Time Discretization

The transient model simulation period of the 2017 model was extended from 1900-2015 to 1900-2018 by adding three stress periods of one-year duration each with two time steps per year. The additional stress periods allowed for input of 2016-2018 well withdrawals.

Pumpage

Pumpage represented in the model was entered for the additional stress periods (2016-2018) (app. A). The pumpage represents reported annual-average withdrawals for appropriated use greater than 10,000 gallons per day. Total pumpage in the model declined slightly from 50 Mgal/d in 2015 to 47.5 Mgal/d in 2018. Pumpage from the AADPW well fields increased from 30 Mgal/d in 2015 to 34 Mgal/d in 2018. The greatest amount pumped by AADPW well fields in 2018 was from the Lower Patapsco aquifer at 19.7 Mgal/d, followed by the Patuxent aquifer at 10.7 Mgal/d, and the Upper Patapsco aquifer at 3.6 Mgal/d. The total number of appropriated users withdrawing water within the model area increased from 75 in 2015 to 86 in 2018. Self-supplied, domestic withdrawals from the Magothy, Upper Patapsco, Lower Patapsco, and Patuxent aquifers were not included in the model because the effects of those withdrawals on the flow system were considered minimal (Andreasen, 2007).

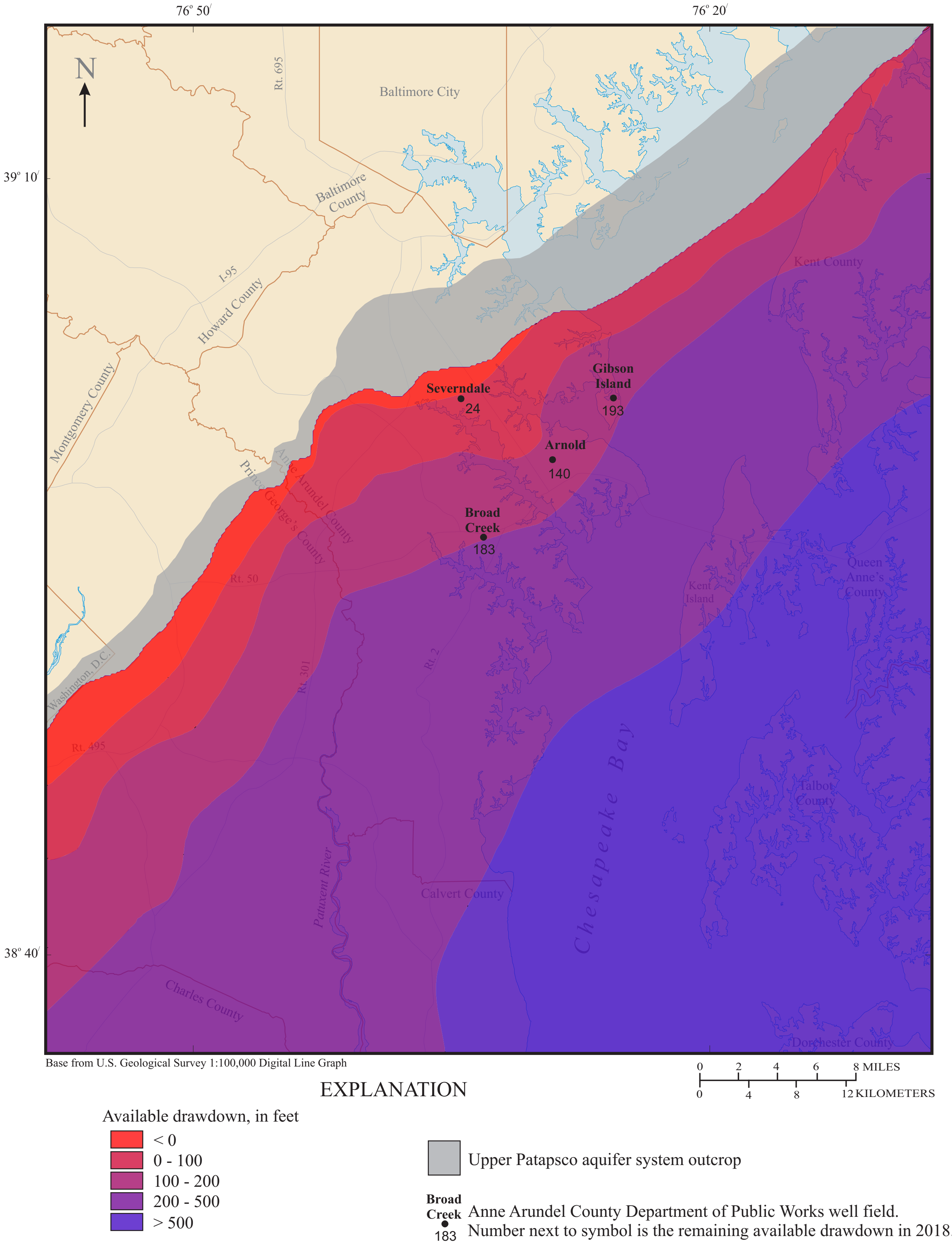


Figure 2. Remaining available drawdown in 2018 in the Upper Patapsco aquifer system.

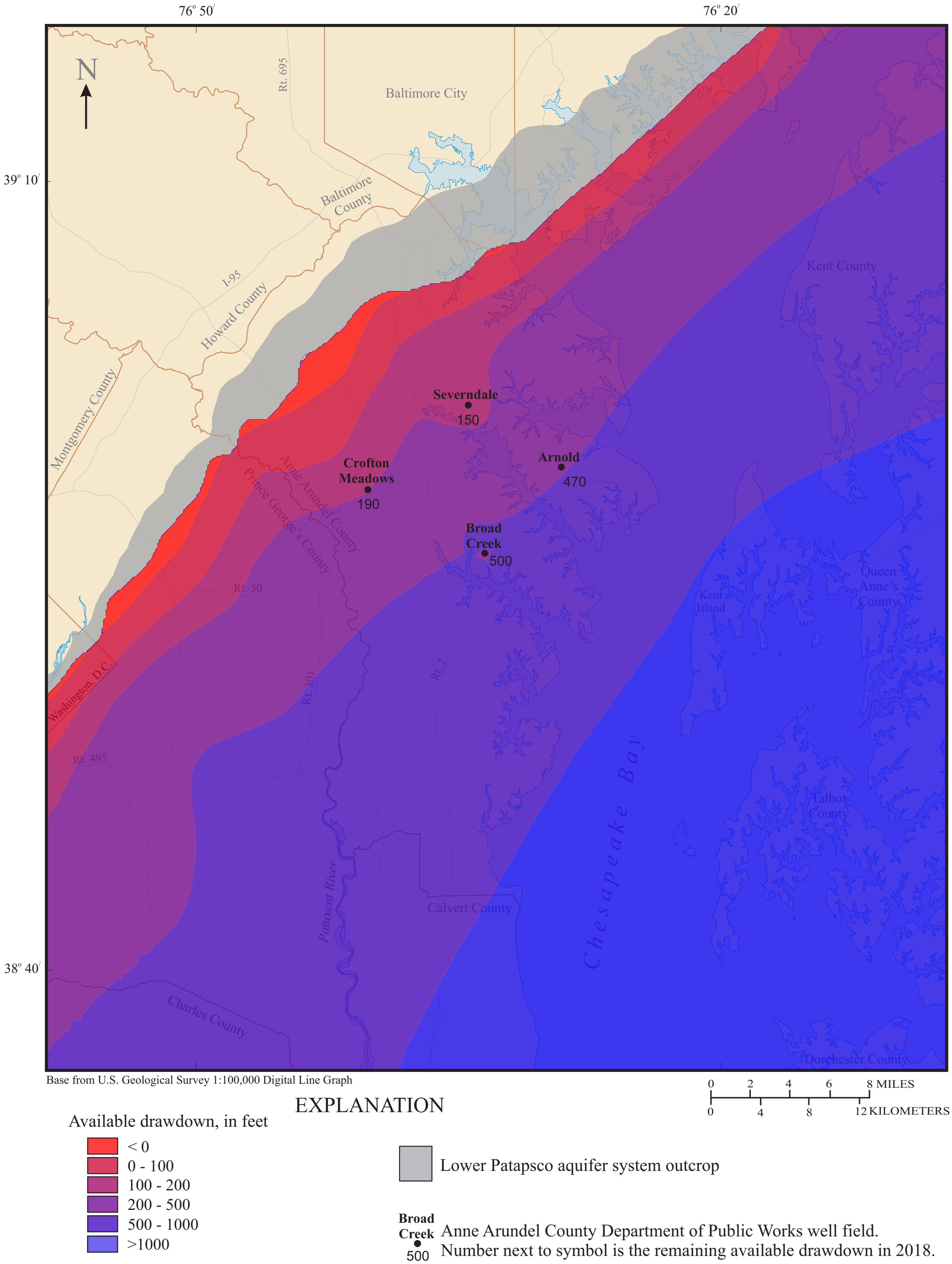


Figure 3. Remaining available drawdown in 2018 in the Lower Patapsco aquifer system.

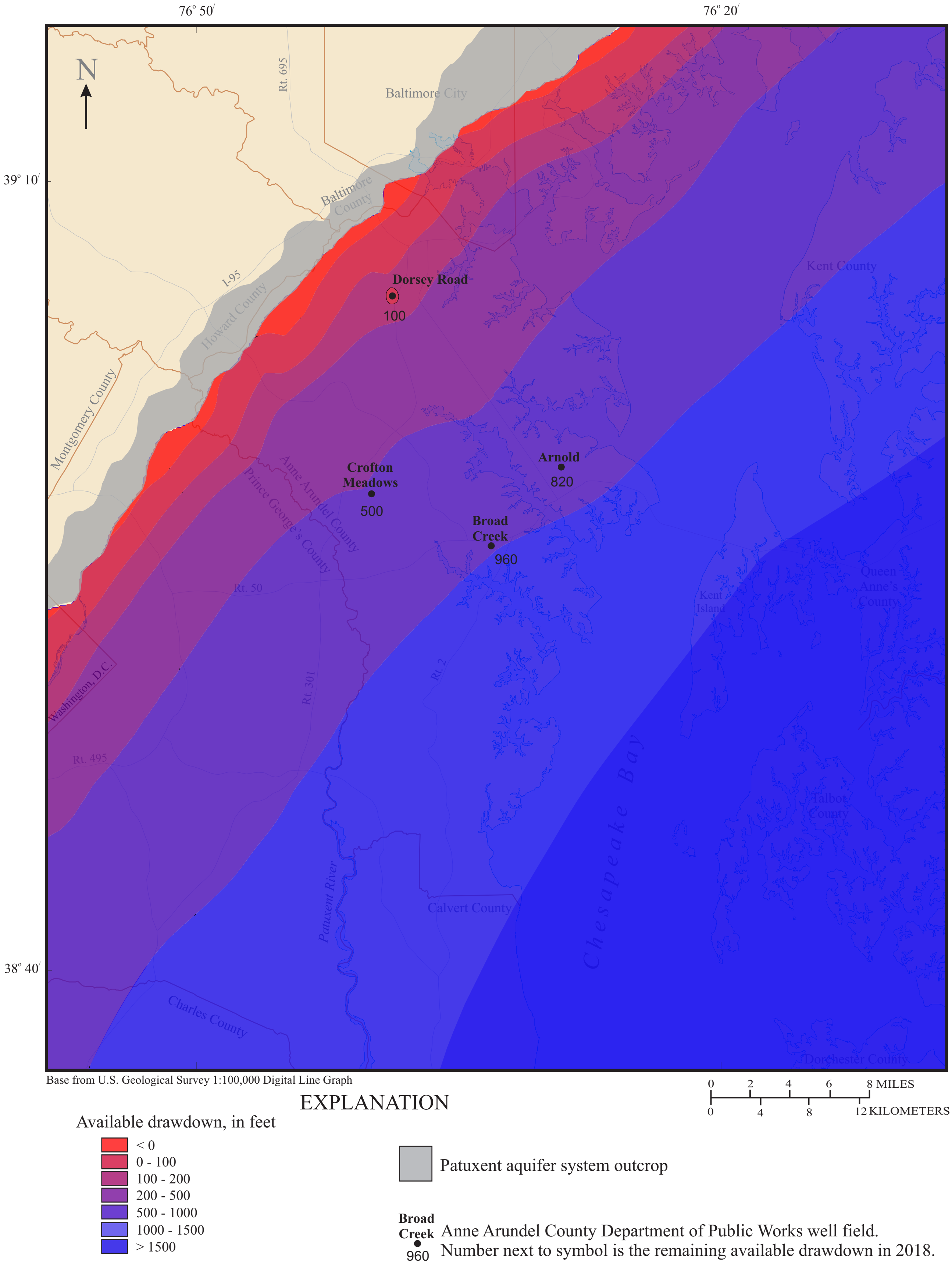


Figure 4. Remaining available drawdown in 2018 in the Patuxent aquifer system.

Verification of Model Calibration

To verify the calibration of the revised model, simulated water levels were compared to observed water levels for the extended time period. Water levels from a total of 49 wells were used in verifying model calibration (tab. 1). The locations of the wells are given in Andreasen (2017, p. 12). Model calibration was assessed by examining trends in simulated heads versus observed heads (figs. 5-7; tab. 1) as well as by a statistical analysis of simulated versus observed head at the end of the simulation period (2018). Overall, a good match was attained between simulated and observed heads. The root-mean-square-error and correlation coefficient is 8.9 ft and 0.98 respectively, and the median of the absolute difference between simulated and observed heads is 4.4, 7.9, 4.8, and 9.4 ft for the Magothy aquifer, Upper and Lower Patapsco aquifer systems, and Patuxent aquifer system respectively. In comparison to the previously calibrated model (Andreasen, 2017, p. 10), the overall head match is similar for the Magothy, slightly less for the Upper Patapsco and Patuxent, and greater for the Lower Patapsco. As a result, it was concluded that additional model calibration was not required.

Limitations of Quasi-3D Representation

The groundwater-flow model as originally designed is a quasi-3d representation of the aquifer system where confining units are not explicitly modeled, but instead represented by a leakance term (Andreasen, 2007, pgs. 34 and 44). In a quasi-3D model, aquifer-confining unit pairs are represented in a layer-cake structure. This model conceptualization assumes orders of magnitude contrast between hydraulic conductivity of aquifer and confining unit, resulting in flow in the aquifer to be essentially horizontal and flow in the confining unit (leakage) to be essentially vertical, and that the flow in the confining unit is at steady state. Under these assumptions, aquifers are coupled to one another only through the leakage terms.

One limitation of the quasi-3D modeling scheme is that water from storage within the confining units is not represented in the model. Additionally, each aquifer is represented by one model layer; therefore, interbedded clay/silt layers within the aquifers (potentially an additional source of water to wells) are also not represented. These model limitations are relevant to the fluvial sediments of the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems, where multiple sand layers are interbedded with clay/silt beds. Water derived from storage within the low permeability confining units may contribute significant quantities of water to pumping wells in the Atlantic coastal plain sediments (Masterson and others, 2016). The lack of stored water in confining units and interbedded clay/silt layers was compensated in the model during calibration by increasing leakage (higher leakance values) in order to attain a match between simulated and observed heads. Consequently, this condition may exaggerate the hydraulic connection between aquifers. Since the time the model was constructed (2005-2006) there has been an increased recognition of the potential importance of stored water in confining units related to groundwater supply, and for the critical need of field data to characterize the hydraulic properties of these low permeability sediments (Shedlock and others, 2007). Regardless of these limitations imposed by the quasi-3D representation, the model does provide for a reasonable approximation of aquifer heads as the relatively close match between simulated and observed heads demonstrate.

SIMULATION OF MAXIMUM WITHDRAWALS IN THE UPPER PATAPSCO, LOWER PATAPSCO, AND PATUXENT AQUIFER SYSTEMS

A model simulation was run to estimate the total amount of water available from the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems from AADPW well fields before water levels reach the management level constraint. The AADPW well fields pumped in the scenario include Arnold, Broad Creek, Crofton Meadows, and Severndale (fig. 1). Two future well fields at Crownsville and Millersville were also included in the scenario. The transient (1900-2018) flow model was modified to operate in steady-state mode where outflow is balanced by inflow with no change in storage (equilibrium conditions). Heads at general-head boundaries along the northeast, southeast, and southwest sides of the model in the Magothy, Upper and Lower Patapsco and Patuxent aquifers were adjusted to levels consistent with regional water-level trends observed over the past ~10 years. The time-specified heads representing those in the Aquia aquifer were held constant at approximate 2018 levels to reflect the overall stabilization in Aquia heads observed in observation wells throughout the region. Withdrawals at AADPW independent well fields at Gibson Island, Harundale, Herald Harbor, Stevenson Road, and Telegraph Road were held constant at maximum design rates of 0.86, 2.95, 1.0, 1.0, and 1.0 Mgal/d, respectively. Withdrawals from those well fields total 6.8 Mgal/d (0.86 Mgal/d from the Upper Patapsco at Gibson Island, and 6 Mgal/d from Lower Patapsco aquifer at Harundale, Herald Harbor, Stevenson Road, and Telegraph Road). AADPW well fields at Dorsey Road (Patuxent aquifer) and Severndale (Upper Patapsco) were not

Table 1. Comparison of observed and simulated water levels (2018).

Well number	Model cell (row, column, layer)	Observed water level, feet related to sea level	Simulated water level, feet related to sea level	Difference between observed and simulated water level, feet
Magothy aquifer				
AA Cc 117	84,44,3	43.29	46.38	3.09
AA Cd 78	59,49,3	34.94	36.51	1.57
AA Cf 99	35,87,3	-23.76	-30.80	7.04
AA Dd 42	88,69,3	3.68	3.60	0.08
AA De 103	85,93,3	-14.59	-15.35	0.76
AA Df 79	54,92,3	-19.41	-25.11	5.70
AA Ed 39	96,93,3	-7.96	-6.59	1.37
AA Fe 47	95,100,3	-18.64	-23.55	4.91
CA Bb 10	103,105,3	-38.93	-43.32	4.39
CA Bb 23	102,99,3	-22.66	-28.68	6.02
CA Cc 56	102,108,3	-39.97	-45.61	5.64
KE Cb 97	2,95,3	3.94	-6.30	10.24
PG Cf 33	96,47,3	53	51.65	1.35
PG De 21	102,67,3	32.12	24.59	7.53
PG Fe 30	106,91,3	-9.89	-13.95	4.06
PG Gf 35	106,102,3	-38.59	-44.83	6.24
QA Ea 27	28,100,3	-22.11	-24.39	2.28
Median of the absolute difference between simulated and observed heads				4.39
Upper Patapsco aquifer system				
AA Bd 159	46,33,4	38.02	51.17	13.15
AA Ce 120	54,58,4	5.28	-3.04	8.32
AA De 128	86,92,4	-13.72	-19.18	5.46
AA De 95	63,81,4	-19.43	-29.27	9.84
AA Df 19	45,94,4	-21.48	-29.09	7.61
AA Ec12	100,90,4	-3.68	-5.17	1.49
KE Cb 36	1,91,4	-5.95	-9.74	3.79
KE Db 40	5,95,4	-10.59	-16.38	5.79
PG De 33	102,58,4	53.61	35.22	18.39
QA Eb 111	19,102,4	-22.8	-31.44	8.64
Median of the absolute difference between simulated and observed heads				7.96
Lower Patapsco aquifer system				
AA Ad 102	33,13,5	71.33	61.90	9.43
AA Ad 109	31,20,5	41.68	50.60	8.92
AA Bd 157	46,33,5	38.08	34.61	3.47
AA Cc 40	76,29,5	90.31	71.54	18.77
AA Cc 89	92,42,5	-6.29	-0.43	5.86
AA Ce 94	48,50,5	-91.96	-95.21	3.25
AA Ce 124	54,58,5	-24.31	-27.98	3.67
AA Cf 137	39,80,5	-66.25	-67.13	0.88
AA Cg 23	24,94,5	-36.56	-29.16	7.40
PG Be 14	95,18,5	105.86	107.21	1.35
PG Ed 34	105,56,5	-8.15	15.73	23.88
QA Eb 112	19,102,5	-31.97	-32.97	1.00
Median of the absolute difference between simulated and observed heads				4.76
Patuxent aquifer system				
AA Ad 29	28,21,6	-56.06	-37.20	18.86
AA Cb 1	93,23,6	15.88	14.81	1.07
AA Cc 102	92,42,6	-45.83	-50.56	4.73
AA Ce 117	48,50,6	-34.18	-23.44	10.74
AA Cf 166	35,86,6	-67.85	-75.85	8.00
AA Cg 22	24,94,6	-50.28	-37.74	12.54
AA De 203	63,80,6	-53.65	-36.30	17.35
BA Gf 11	11,33,6	-4.94	1.87	6.81
PG Cf 66	97,43,6	-36.65	-39.53	2.88
QA Eb 110	19,102,6	-12.68	-29.24	16.56
Median of the absolute difference between simulated and observed heads				9.37

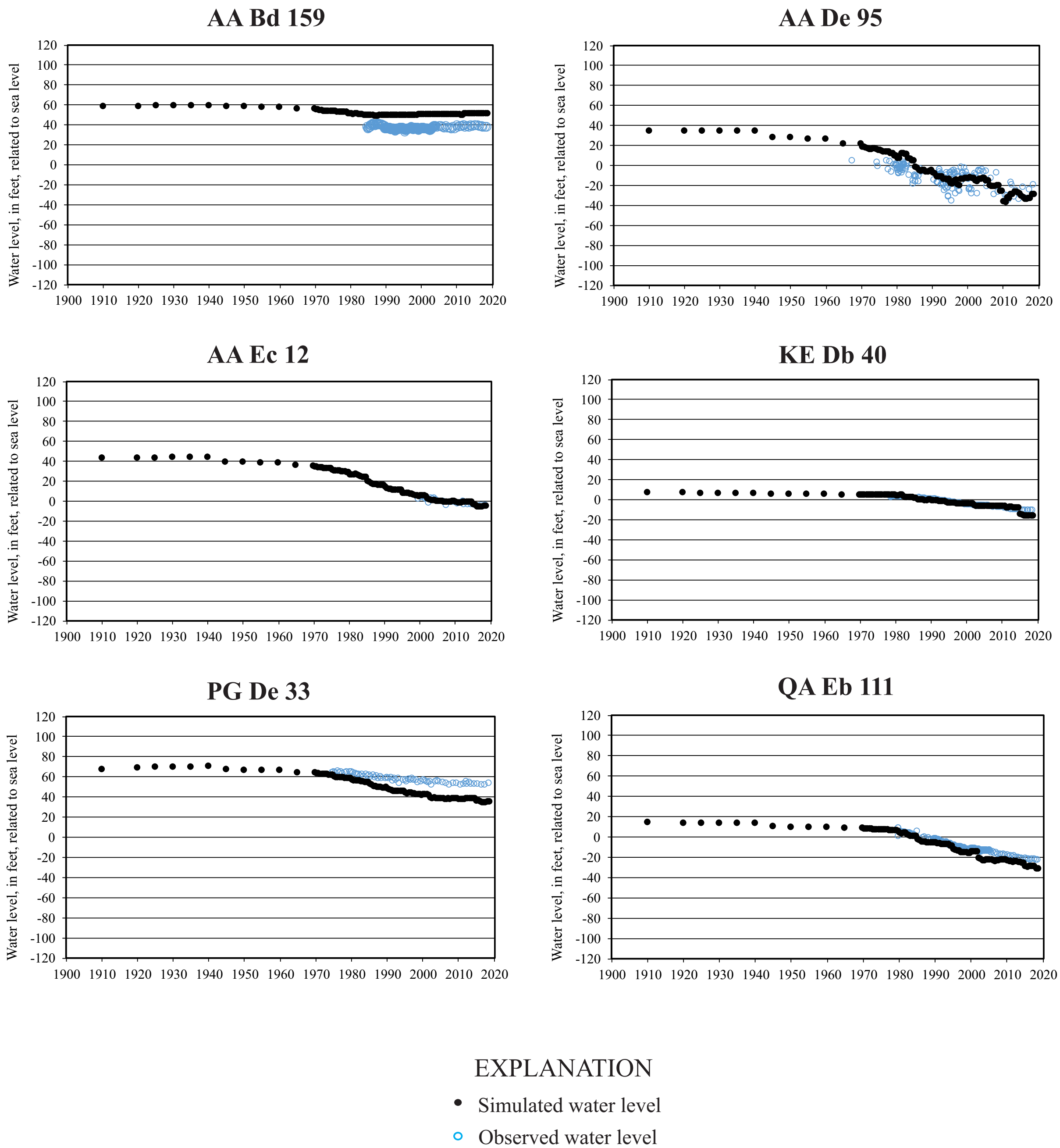


Figure 5. Hydrographs of observed and simulated water levels in wells screened in the Upper Patapsco aquifer system, 1900-2018.

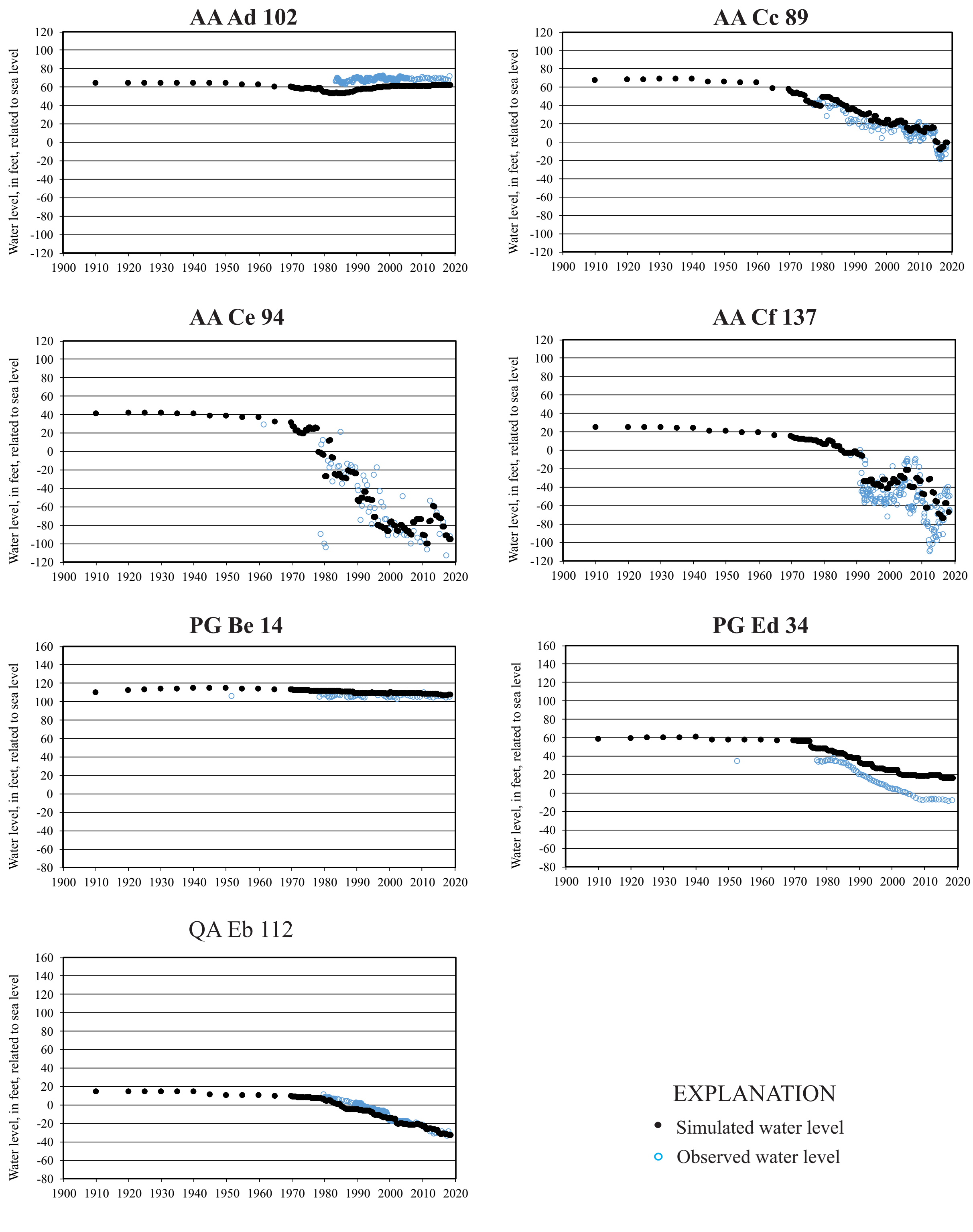


Figure 6. Hydrographs of observed and simulated water levels in wells screened in the Lower Patapsco aquifer system, 1900-2018.

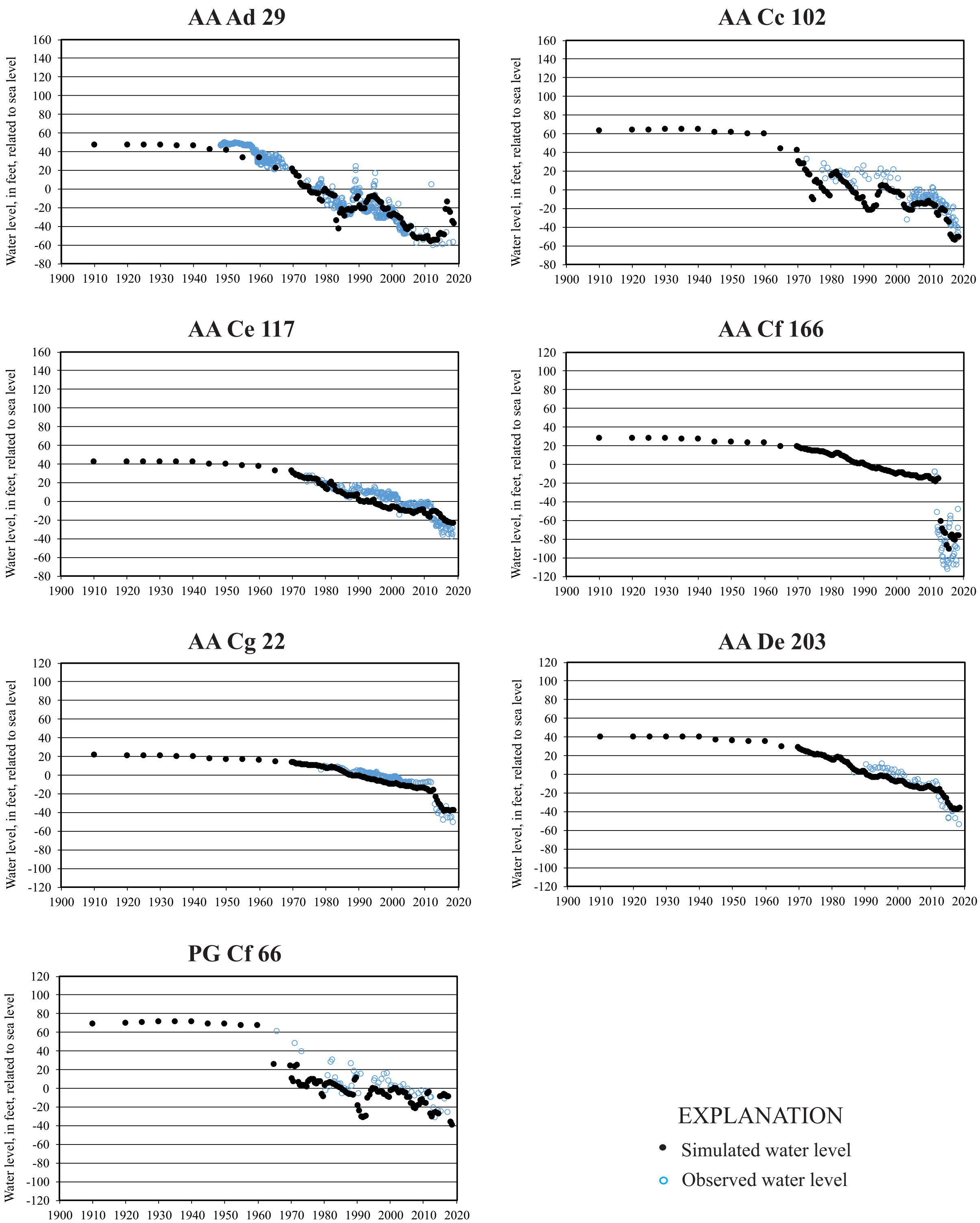


Figure 7. Hydrographs of observed and simulated water levels in wells screened in the Patuxent aquifer system, 1900-2018.

pumped during the simulation. The Dorsey Road well field was not pumped because it is planned to be discontinued, and the Upper Patapsco aquifer at Severndale was not pumped because of the limited amount of available drawdown at that location. Withdrawals from wells other than those operated by the AADPW were held constant at permitted average-day appropriation amounts totaling 25 Mgal/d (app. A). Recharge applied to the water-table aquifer was held constant at linear rates ranging from 9 to 18 inches per year as assigned in the calibrated model (Andreasen, 2007, p. 41).

During the model simulation, withdrawals from the existing AADPW wells were set at a minimum to the rates pumped during a previous model simulation of projected 2086 withdrawals at build-out (tab. 2)(Andreasen, 2017, tab. 5). As withdrawals were increased to determine the maximum total rate possible, withdrawals from individual AADPW wells were allowed to increase up to their design rates. In addition, hypothetical wells were added to each existing well field along with future well fields at Crownsville and Millersville in order to reach total withdrawals.

The management constraints which control the maximum allowable withdrawal rates were defined as the 80-percent management level measured at a distance of approximately one-quarter mile updip (to the northwest) of each AADPW well field. This is the area around each well field where water levels would likely reach the management level first given that the aquifers are shallowest (less available drawdown) on the updip side.

Results of the modeling show that a total of 114.4 Mgal/d can be withdrawn from the AADPW well fields Arnold, Broad Creek, Crofton Meadows, Severndale, and future Crownsville and Millersville before water levels reach a management level constraint (tab. 3). The simulated maximum withdrawal is approximately 1.7 times greater than the 2086 build-out value of 66.5 Mgal/d and approximately 3.4 times greater than the amount pumped in 2018 (tab. 3). As a result of leakage between aquifers caused by the withdrawals, the amount of water that can be withdrawn from the deeper aquifers (Lower Patapsco and Patuxent aquifers) is controlled, in part, by the available drawdown in the shallower Upper Patapsco aquifer. In the simulated maximum scenario for the AADPW well fields, the Lower Patapsco aquifer is pumped at the highest rate (66 Mgal/d) which is 26.8 Mgal/d greater than the build-out amount of 39.2 Mgal/d and 46.9 Mgal/d greater than the 2018 amount of 19.1 Mgal/d. The Patuxent aquifer is pumped at 41 Mgal/d which is 21 Mgal/d greater than build-out of 19.7 Mgal/d and 33.5 Mgal/d greater than the 2018 amount of 7.4 Mgal/d. Withdrawals from the Upper Patapsco aquifer did not surpass the build-out amount of 7.6 Mgal/d because of the management level constraints. The maximum withdrawal scenario represents one possible pumping scheme; however, it is possible that additional water could be withdrawn through alternative schemes whereby withdrawals are further balanced between deep and shallow aquifers.

Water levels

In the Upper Patapsco aquifer system, simulated water levels under the maximum withdrawal scenario are as deep as 135 ft below sea level (Arnold) and 155 ft below sea level (Broad Creek) (fig. 8). The water level in the Upper Patapsco aquifer at Severndale is approximately 27 ft below sea level. A single cone of depression is centered on the Broad Creek well field. The withdrawals result in approximately 70 and 110 ft of drawdown at Arnold and Broad Creek, respectively, from 2018 water levels.

In the Lower Patapsco aquifer system, simulated water levels under the maximum withdrawal scenario are as deep as 295 ft below sea level (Arnold), 285 ft below sea level (Broad Creek), 260 ft below sea level (Crownsville), 230 ft below sea level (Crofton Meadows), 107 ft below sea level (Millersville), and 170 ft below sea level (Severndale) (fig. 9). A large cone of depression is formed with two depressions greater than 200 ft below sea level. Compared to 2018 water levels, the simulated withdrawals result in approximately 200 ft of additional drawdown at Arnold, Broad Creek, Crofton Meadows, and Crownsville, and about 100 and 40 ft of additional drawdown at Millersville and Severndale, respectively.

In the Patuxent aquifer system, simulated water levels under the maximum withdrawal scenario are as deep as 480 ft below sea level (Arnold), 420 ft below sea level (Broad Creek), 370 ft below sea level (Crownsville), 296 ft below sea level (Crofton Meadows), and 193 ft below sea level (Millersville) (fig. 10). A large cone of depression is formed with two depressions greater than 300 ft below sea level. Compared to 2018 water levels, the withdrawals result in over 300 ft of additional drawdown at Arnold, Broad Creek, and Crownsville, and approximately 200 and 160 ft of additional drawdown at Crofton Meadows and Millersville, respectively, from 2018 water levels.

The simulated water levels are model-cell averages (heads averaged over model cell areas); therefore, water levels are deeper closer to actual pumping wells within the model cells. Water levels inside the pumping well will be even deeper, depending on the efficiency of the well.

Table 2. Maximum withdrawal rates at individual AADPW production wells.

[Mgal/d, million gallons per day; ID, identification number; HW, hypothetical well]

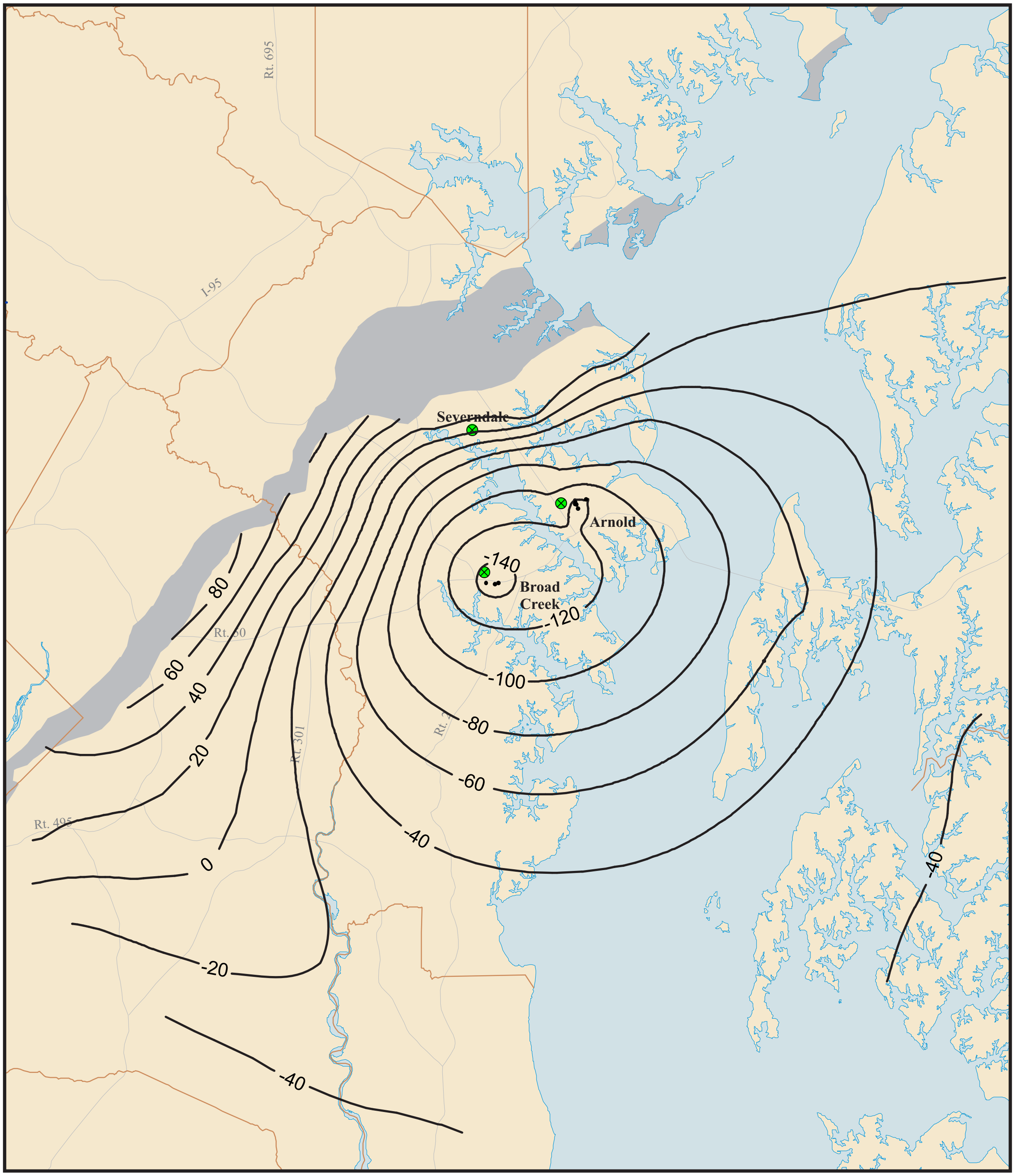
Model cell (row, column, layer)	Simulated withdrawal, Mgal/d	Well field	Aquifer	North (State plane), feet	East (State plane), feet	Well number	AADPW well ID	Well design rate, Mgal/d
39,80,4	0.98	Arnold	Ukpt	498859	1457114	AA Cf 118	AR-2	0.86
40,80,4	0.98	Arnold	Ukpt	498472	1456872	AA Cf 119	AR-1	1.44
40,81,4	0.98	Arnold	Ukpt	498295	1457265	AA Cf 120	AR-3	1.19
41,83,4	0.98	Arnold	Ukpt	497341	1457541	AA Cf 155	AR-6	1.44
35,82,4	0.98	Arnold	Ukpt	499568	1459510	AA Cf 170	AR-10	1.44
66,77,4	0.90	Broad Creek	Ukpt	479397	1435493	AA De 136	BC-3	1.44
64,80,4	0.90	Broad Creek	Ukpt	479079	1437567	AA De 97	BC-2	1.15
62,81,4	0.90	Broad Creek	Ukpt	479334	1438447	AA De 96	BC-1	1.01
35,77,5	3.46	Arnold	Lkpt	501401	1457510	HW	HW	3.46
38,77,5	3.46	Arnold	Lkpt	500183	1456530	HW	HW	3.46
42,80,5	2.45	Arnold	Lkpt	497441	1458016	HW	HW	3.46
40,80,5	2.45	Arnold	Lkpt	498712	1456876	AA Cf 142	AR-4	2.59
41,83,5	2.45	Arnold	Lkpt	497315	1457550	AA Cf 150	AR-5	3.46
35,82,5	3.46	Arnold	Lkpt	499532	1459522	AA Cf 168	AR-8	3.46
33,82,5	3.46	Arnold	Lkpt	500721	1460547	HW	HW	3.46
67,78,5	3.46	Broad Creek	Lkpt	477835	1434962	HW	HW	3.46
68,80,5	3.46	Broad Creek	Lkpt	476289	1435253	HW	HW	3.46
66,80,5	3.46	Broad Creek	Lkpt	478035	1436508	HW	HW	3.46
63,80,5	1.65	Broad Creek	Lkpt	479076	1437655	AA De 177	BC-4	2.59
65,84,5	1.65	Broad Creek	Lkpt	477311	1438148	AA De 208	BC-5	3.46
81,41,5	1.64	Crofton Meadows	Lkpt	494514	1404848	AA Cc 152	CM-10	3.26
79,42,5	1.64	Crofton Meadows	Lkpt	494983	1406302	HW	HW	3.26
84,43,5	1.64	Crofton Meadows	Lkpt	492214	1404903	AA Cc 128	CM-4	1.73
85,44,5	1.64	Crofton Meadows	Lkpt	492031	1404696	AA Cc 129	CM-5	1.87
83,46,5	1.64	Crofton Meadows	Lkpt	491936	1405830	AA Cc 140	CM-6	2.59
81,49,5	1.64	Crofton Meadows	Lkpt	491472	1408219	AA Cd 106	CM-8	2.16
85,52,5	1.64	Crofton Meadows	Lkpt	495598	1407731	HW	HW	3.26
48,49,5	0.92	Severndale	Lkpt	515934	1432209	AA Ce 122	SD-5	2.59
48,50,5	1.84	Severndale	Lkpt	515350	1432714	AA Ce 131, Well 7R	SD-6	2.88
50,50,5	0.92	Severndale	Lkpt	514974	1431904	AA Ce 121	SD-4	1.15
46,52,5	0.92	Severndale	Lkpt	515216	1434435	AA Ce 139	SD-8	2.02

Table 2. Maximum withdrawal rates at individual AADPW production wells--Continued.

Model cell (row, column, layer)	Simulated withdrawal, Mgal/d	Well field	Aquifer	North (State plane), feet	East (State plane), feet	Well number	AADPW well ID	Well design rate, Mgal/d
72,59,5	1.67	Crownsville	Lkpt	488714	1418608	HW	HW	1.67
74,61,5	1.67	Crownsville	Lkpt	486079	1419675	HW	CV-1	1.67
72,63,5	1.67	Crownsville	Lkpt	486003	1421811	HW	CV-3	1.67
69,63,5	1.67	Crownsville	Lkpt	487529	1423499	HW	CV-5	1.67
70,64,5	1.67	Crownsville	Lkpt	485979	1423347	HW	HW	1.67
69,65,5	1.67	Crownsville	Lkpt	486630	1424780	HW	HW	1.67
52,36,5	1.67	Millersville	Lkpt	521264	1419626	HW	NC-3	3.34
52,37,5	1.67	Millersville	Lkpt	522665	1421285	HW	NC-5	3.34
53,37,5	1.67	Millersville	Lkpt	524313	1418894	HW	HW	3.34
42,77,6	2.59	Arnold	Kpx	498902	1455090	HW	HW	2.59
40,79,6	2.59	Arnold	Kpx	498634	1456656	HW	HW	2.59
36,79,6	2.59	Arnold	Kpx	500278	1458127	HW	HW	2.59
41,83,6	1.40	Arnold	Kpx	497341	1457541	AA Cf 171	AR-7	2.59
35,82,6	1.59	Arnold	Kpx	499568	1459510	AA Cf 169	AR-9	1.58
65,75,6	2.16	Broad Creek	Kpx	478890	1433761	HW	HW	2.16
66,77,6	0.45	Broad Creek	Kpx	479358	1435227	HW	BC-8	1.73
63,77,6	2.16	Broad Creek	Kpx	480164	1436544	HW	HW	2.16
68,80,6	2.16	Broad Creek	Kpx	476343	1435234	HW	HW	2.16
64,83,6	1.26	Broad Creek	Kpx	477929	1438127	HW	BC-6	2.16
81,41,6	1.00	Crofton Meadows	Kpx	494539	1404944	AA Cc 151	CM-11	2.88
88,43,6	1.44	Crofton Meadows	Kpx	490630	1403192	AA Cc 107	CM-1	1.44
86,43,6	1.44	Crofton Meadows	Kpx	491570	1404133	AA Cc 103	CM-2	1.44
85,43,6	1.00	Crofton Meadows	Kpx	491987	1404594	AA Cc 105	CM-3	1.30
83,46,6	1.00	Crofton Meadows	Kpx	491900	1405882	AA Cc 138	CM-7	2.16
81,49,6	1.00	Crofton Meadows	Kpx	491490	1408275	AA Cd 107	CM-9	2.02
71,59,6	1.67	Crownsville	Kpx	489104	1419077	HW	HW	1.67
74,60,6	1.67	Crownsville	Kpx	486917	1418295	HW	HW	1.67
70,60,6	1.67	Crownsville	Kpx	488922	1420613	HW	HW	1.67
69,61,6	1.67	Crownsville	Kpx	488584	1422176	HW	HW	3.34
70,64,6	1.67	Crownsville	Kpx	486031	1423373	HW	HW	1.67
68,65,6	1.67	Crownsville	Kpx	486839	1424728	HW	HW	1.67
52,36,6	1.67	Millersville	Kpx	524078	1418842	HW	HW	3.34
52,37,6	1.67	Millersville	Kpx	522638	1421249	HW	NC-6	3.34
53,37,6	1.67	Millersville	Kpx	521061	1419638	HW	NC-4	5.01

Table 3. Withdrawal rates in the Upper Patapsco, Lower Patapsco, and Patuxent aquifers in 2018 at projected build-out and at the simulated maximum rate.

	Withdrawals, in million gallons per day (Mgal/d)														
	Upper Patapsco		Lower Patapsco						Patuxent					Total
	Arnold	Broad Creek	Arnold	Broad Creek	Crownsville	Crofton Meadows	Millersville	Severndale	Arnold	Broad Creek	Crownsville	Crofton Meadows	Millersville	
Reported 2018	2.87	0.5	4.45	2.7	0	5.2	0	6.75	2.41	0	0	4.95	0	30
Layer totals	3.4		19.1						7.4					
Simulated Build-out (2086)	4.9	2.7	9.8	3.3	5	11.5	5	4.6	2.8	0.9	5	6	5	66.5
Layer totals	7.6		39.2						19.7					
Simulated Maximum	4.9	2.7	21.2	13.7	10	11.5	5	4.6	10.8	8.2	10	6.9	5	114.4
Layer totals	7.6		66						40.9					



EXPLANATION

Upper Patapsco aquifer system outcrop

-40 Potentiometric contour of simulated water levels. Contour interval is 20 feet. Datum is sea level.

Management water level control point

Simulated AADPW pumping well

Figure 8. Simulated water levels at maximum withdrawals in the Upper Patapsco aquifer system.

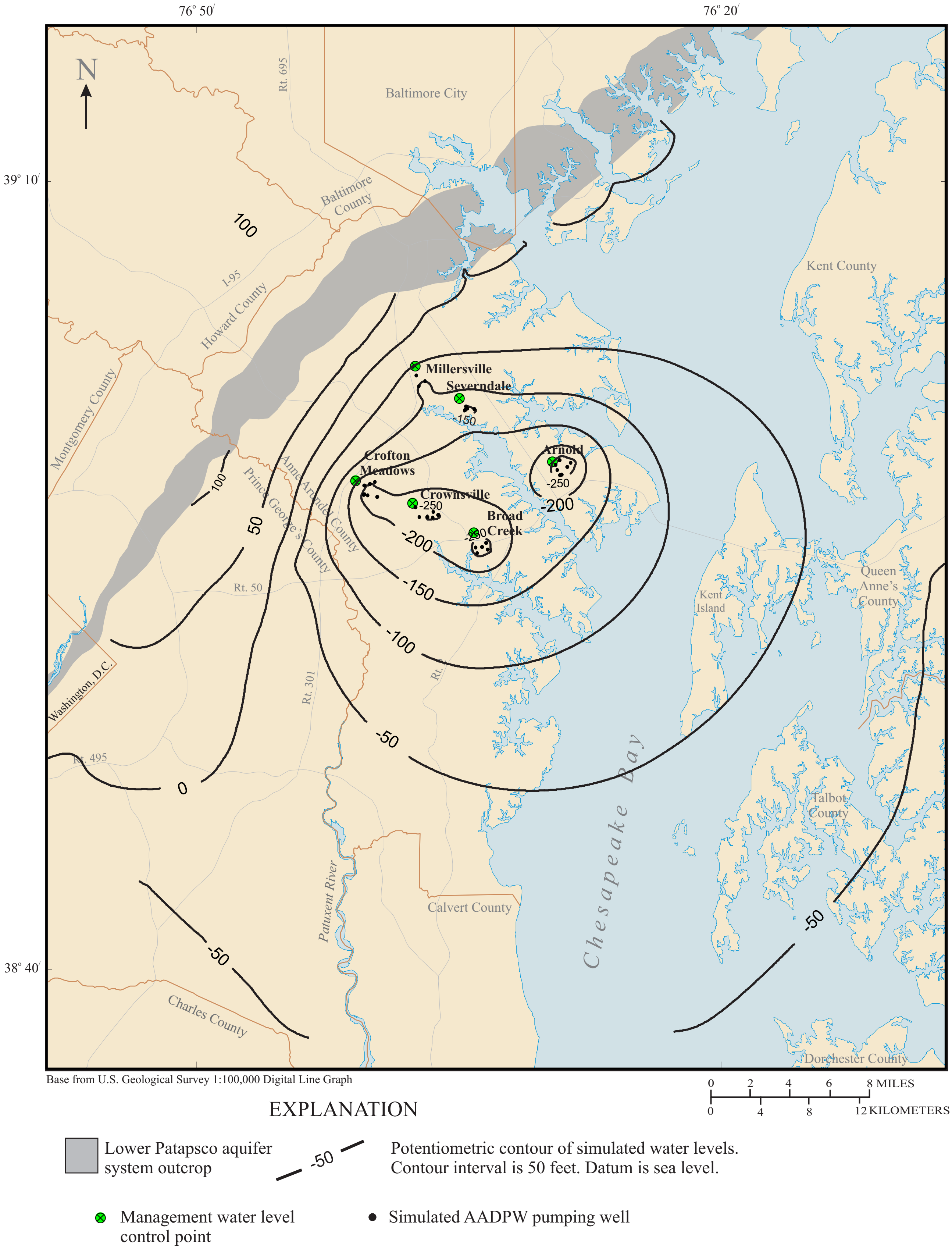


Figure 9. Simulated water levels at maximum withdrawals in the Lower Patapsco aquifer system.

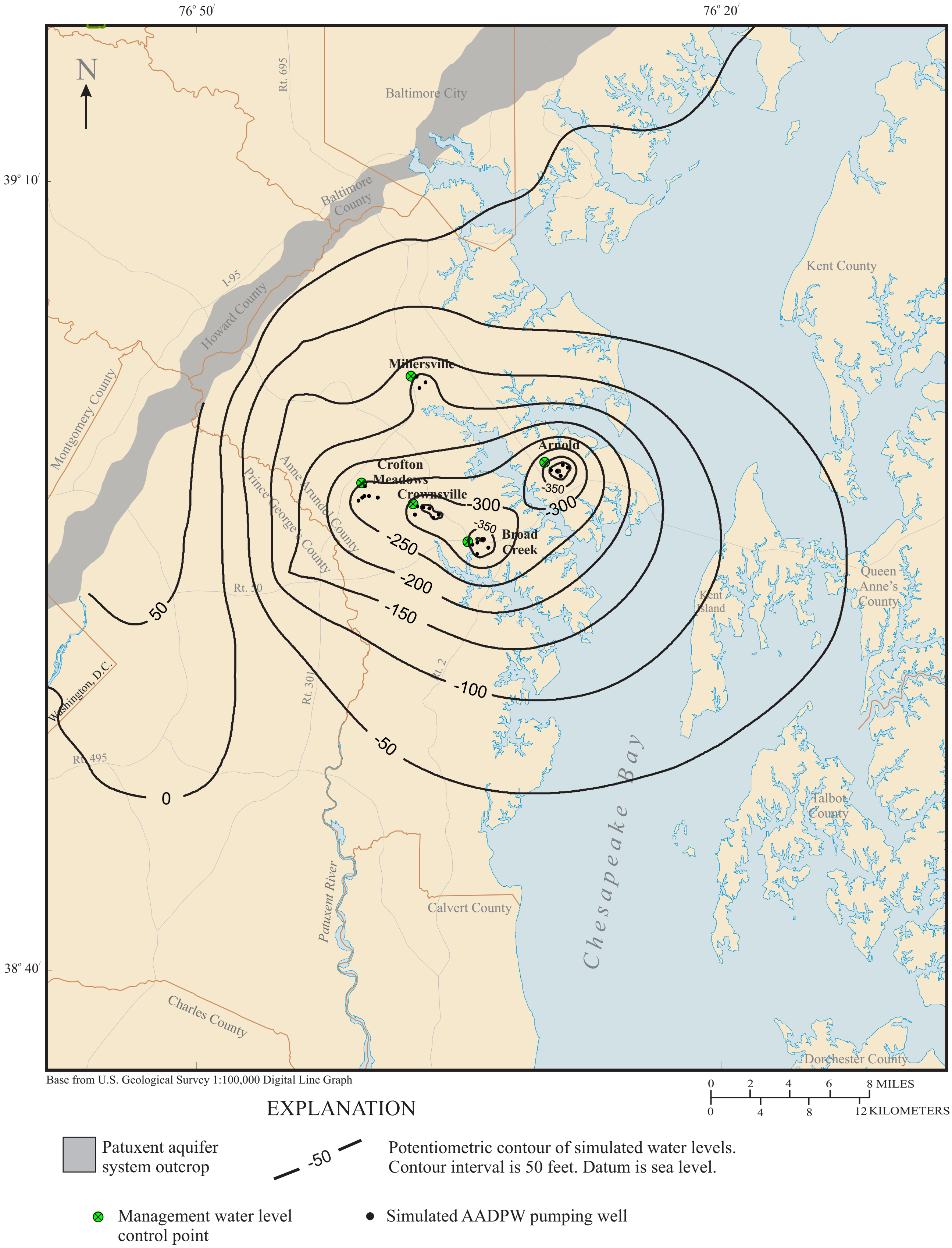


Figure 10. Simulated water levels at maximum withdrawals in the Patuxent aquifer system.

The relatively extreme amount of drawdown (up to approximately 110, 200, and 300 ft in the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems, respectively) would be greater than any that has occurred over the entire period of development of the coastal plain aquifer systems in Maryland. Drawdown at those magnitudes, especially occurring in multiple aquifers concentrated at single well fields, has the potential to cause land subsidence. A similar magnitude of drawdown (Heywood and Pope, 2009) in correlative geologic units in Virginia's southeastern coastal plain (McFarland and Bruce, 2006) resulted in an observed compaction of as much as 0.16 ft between 1982 and 1995 at an extensometer well (Eggleston and Pope, 2013). Since 1940 there may have been as much as approximately 0.6 ft of compaction in southeastern Virginia based on releveling and extensometer data (Holdahl and Morrison, 1974; Eggleston and Pope, 2013). Most of the land subsidence attributed to groundwater withdrawals is a result of compaction of confining units and clay lenses as pore pressure reduction caused by pumping propagates into the clay layers (Eggleston and Pope, 2013). The amount of compaction is controlled by the magnitude of pressure reduction (drawdown), the thickness of the clay layers, and the compressibility of the sediment. Aside from drawdown, it's unclear how these factors compare between aquifer systems in Anne Arundel County and southeastern Virginia. Additional research is needed to assess the potential for land subsidence related to groundwater withdrawals in Anne Arundel County. The Maryland Geological Survey, in cooperation with Anne Arundel County Department of Public Works, however, does continue to monitor for land subsidence at three well fields (Arnold, Broad Creek, and Crofton Meadows) using high-resolution GPS (Andreasen, 2018). Over the ~20 years of annual measurements, there has been no appreciable subsidence related to groundwater withdrawals.

Drawdown resulting from the maximum withdrawal scenario also has the potential to cause well interference with other groundwater users. The declining water levels could possibly interfere with pump operations, reduce well yields, and increase pump energy costs. In the Upper Patapsco aquifer system, well fields at City of Annapolis and U.S. Naval Academy will experience approximately 120 and 85 ft of drawdown, respectively. In the Lower Patapsco aquifer system, well fields at City of Annapolis, Stevensville, and City of Bowie will experience approximately 200, 35, and 70 ft of drawdown, respectively. Other well fields tapping the Lower Patapsco aquifer system will also experience drawdown of up to 80 ft. In the Patuxent aquifer system, the well fields at City of Bowie and Ft. Meade will experience approximately 150 and 120 ft of drawdown, respectively. Other Patuxent aquifer well fields in northern Prince George's County and northern Anne Arundel County will also experience drawdown of up to 95 ft.

Available Drawdown

The amount of available drawdown remaining at the AADPW wells under the maximum withdrawal scenario is summarized in Table 4. Available drawdown was measured at approximately one-quarter mile updip (to the northwest) of each AADPW well field. In the Upper Patapsco aquifer system, the remaining available drawdown ranges from approximately 30 ft at Arnold to 40 ft at Broad Creek (fig. 11). Simulated water levels fall below the management level within a band extending parallel to the outcrop area, which includes the location of the Severndale well field. In the Lower Patapsco aquifer system, the remaining available drawdown under the maximum withdrawal scenario ranges from approximately 30 ft at Crofton Meadows to 320 ft at Broad Creek (fig. 12). In the Patuxent aquifer system, the remaining available drawdown under the maximum withdrawal scenario ranges from approximately 235 ft at Millersville to 620 ft at Broad Creek (fig. 13).

Water Budget

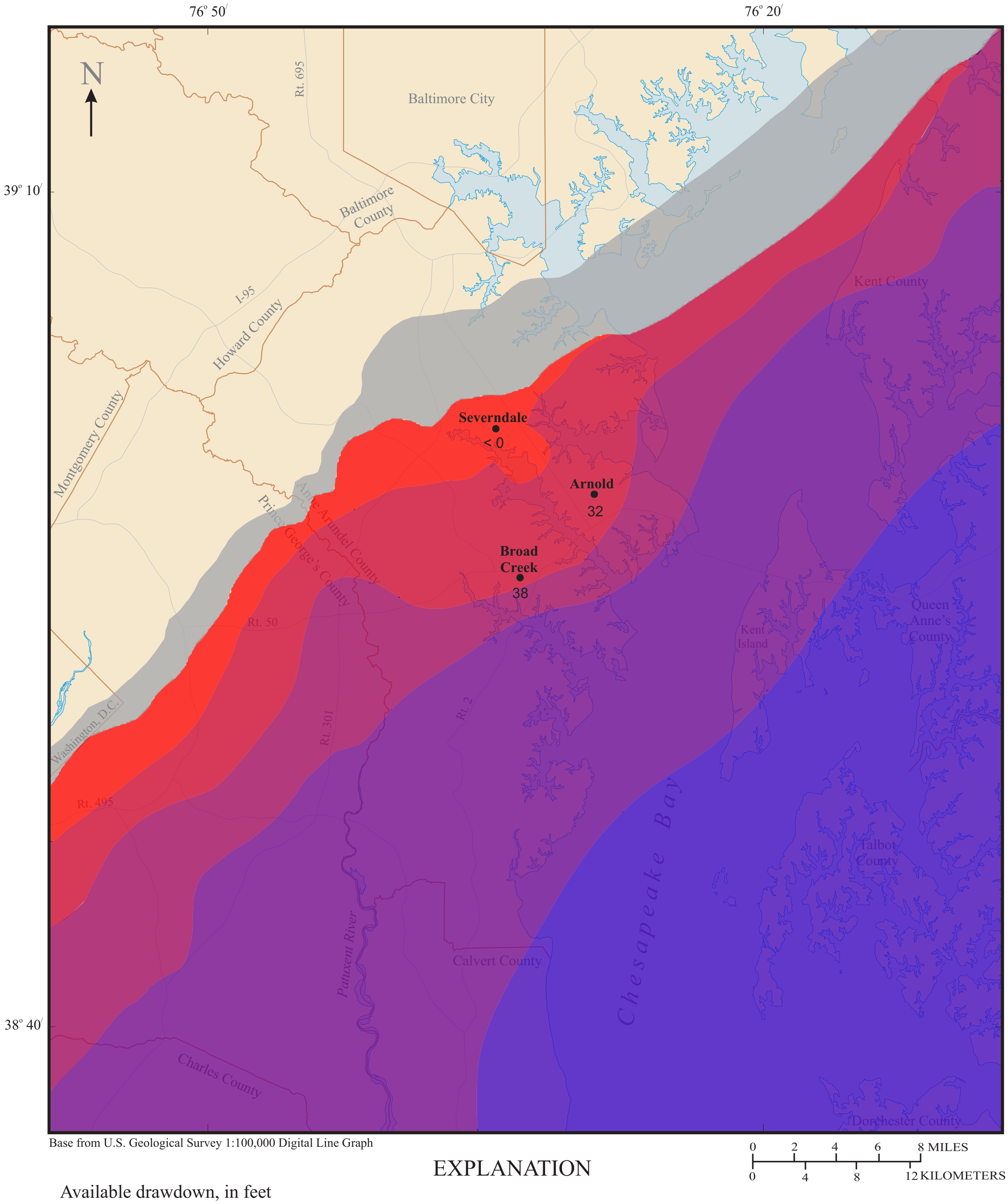
The relative amount of water flowing into and out of the modeled aquifer system (net water budget) under 2018 pumping conditions and under the steady-state maximum withdrawal simulation is shown in Figure 14. Under 2018 pumping conditions, recharge applied to the unconfined water-table aquifer accounts for all net inflow. Net outflow from the modeled aquifer system consisted of flow to rivers (baseflow) at approximately 53 percent and flow to constant-head boundaries (tidal surface water) at approximately 35 percent. Wells and head-dependent boundaries accounted for approximately 10 and 2 percent of net outflow, respectively.

Under the maximum withdrawal scenario, recharge applied to the unconfined water-table aquifer accounts for all net inflow. Net outflow from the modeled aquifer system consisted of flow to rivers (baseflow) at approximately 46 percent and flow to wells at approximately 31 percent. Constant-head boundaries (tidal surface water) and head-dependent boundaries accounted for approximately 22 and 1 percent of net outflow, respectively. As withdrawals increased under the maximum withdrawal scenario, net flow to rivers and constant-head boundaries decreased.

Modeled net discharge (baseflow) to rivers in 2018 was approximately 34.2 x 10^6 ft^3/d (~253

Table 4. Remaining available drawdown at maximum withdrawal rates.

Well field	Remaining available drawdown, ft
Upper Patapsco aquifer system	
Arnold	32
Broad Creek	38
Severndale	<0
Lower Patapsco aquifer system	
Arnold	260
Broad Creek	318
Crofton Meadows	33
Crownsville	113
Millersville	58
Severndale	116
Patuxent aquifer system	
Arnold	534
Broad Creek	621
Crofton Meadows	313
Crownsville	434
Millersville	235



EXPLANATION

Available drawdown, in feet

- < 0
- 0 - 100
- 100 - 200
- 200 - 500
- > 500

Upper Patapsco Aquifer Outcrop

Number next to well field name is the amount of available drawdown, in feet

Figure 11. Simulated remaining available drawdown at maximum withdrawal (steady state) in the Upper Patapsco aquifer system.

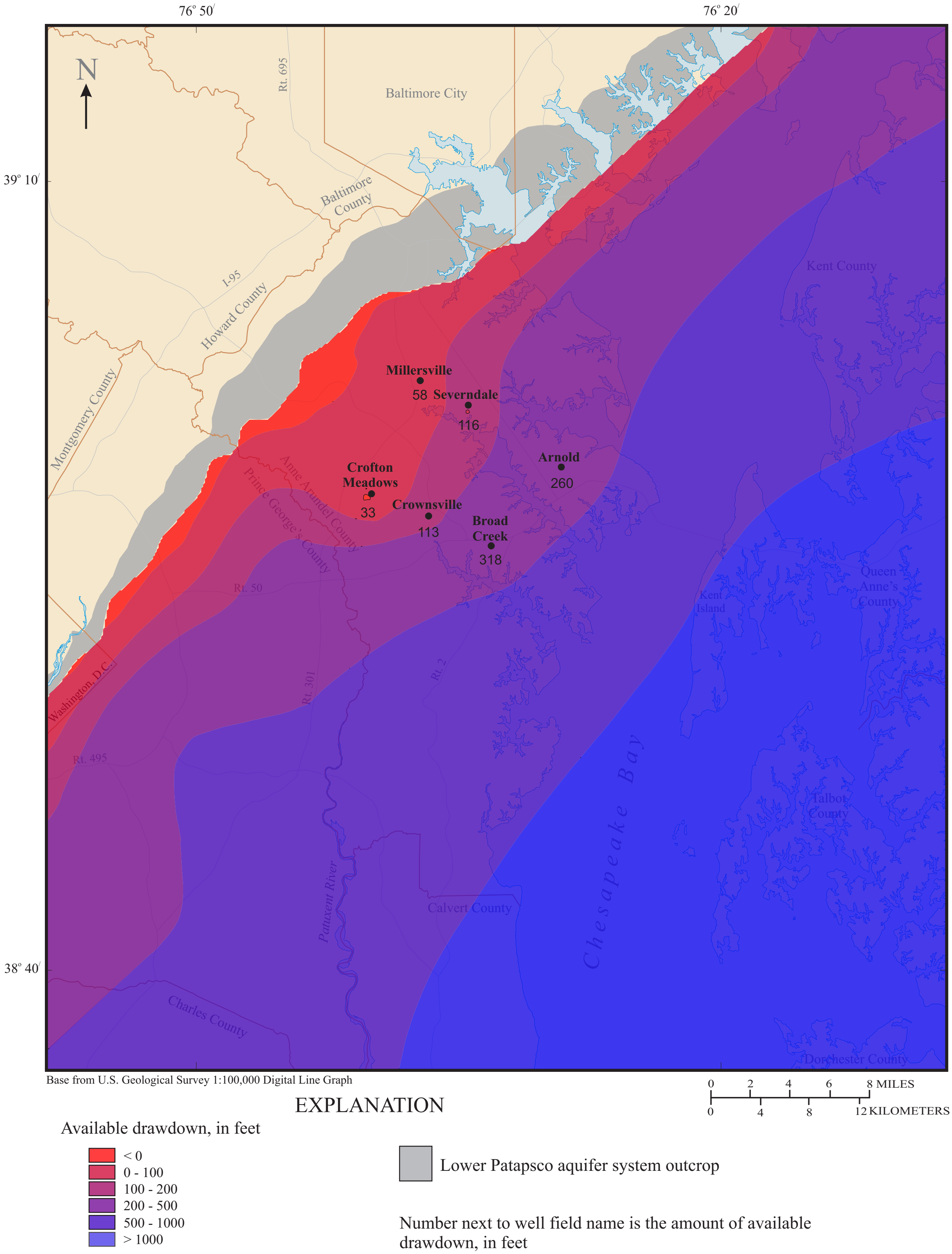


Figure 12. Simulated remaining available drawdown at maximum withdrawals (steady state) in the Lower Patapsco aquifer system.

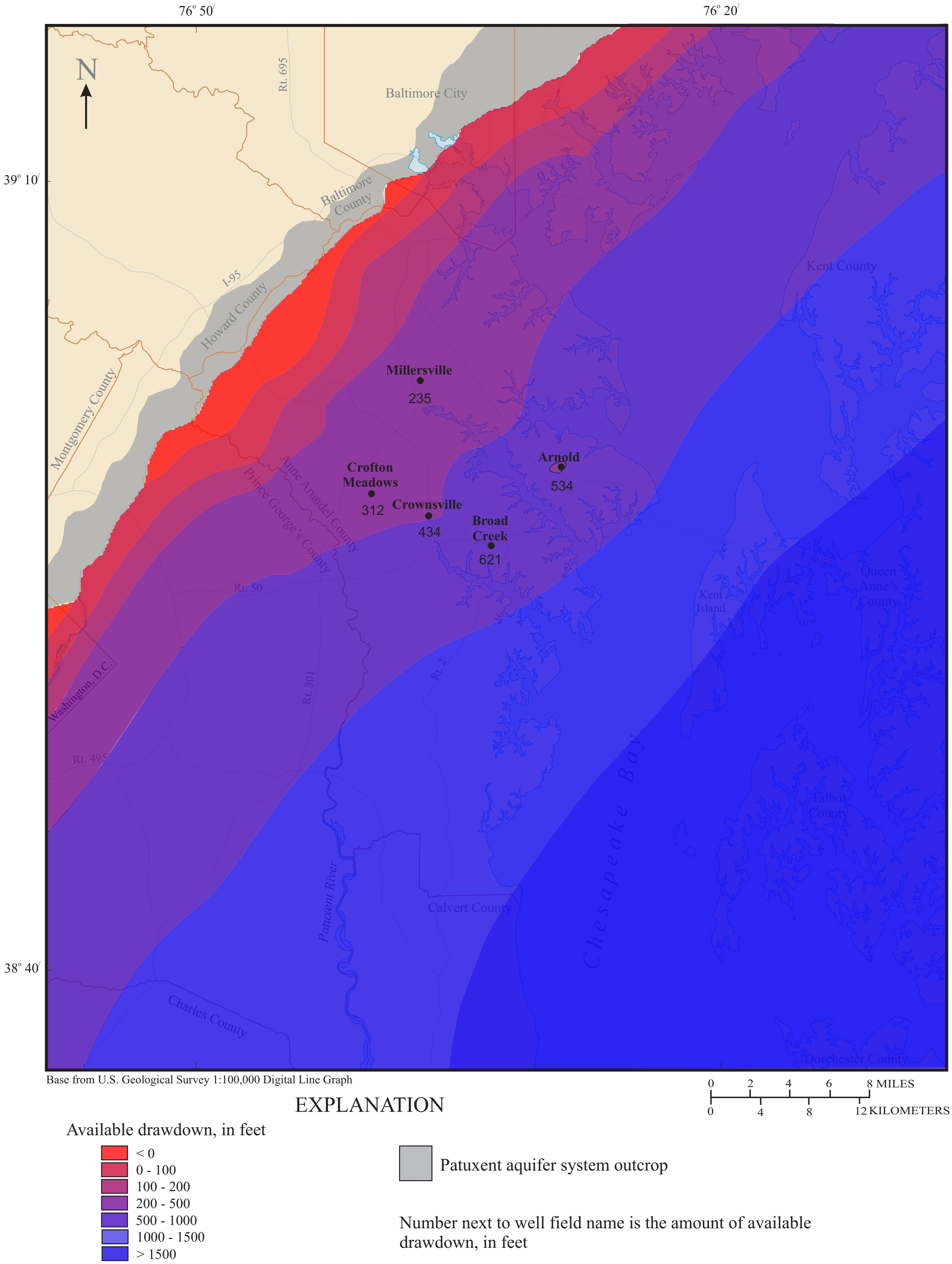


Figure 13. Simulated remaining available drawdown at maximum withdrawals (steady state) in the Patuxent aquifer system.

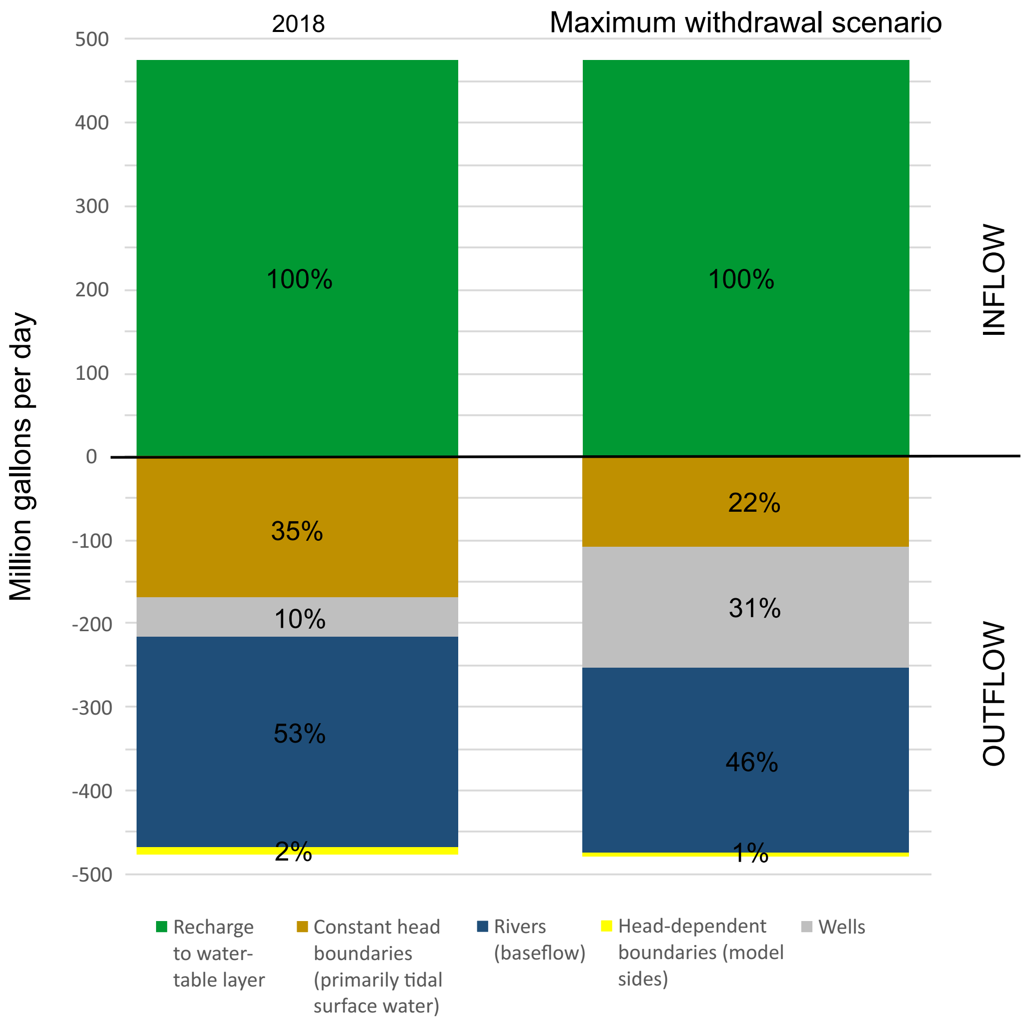


Figure 14. Net water budget for the entire model domain for 2018 and maximum withdrawal scenario.

Mgal/d)(Andreasen, 2007, p. 39). Under the maximum withdrawal scenario, net discharge to rivers decreased to approximately 30.3 x 10^6 ft^3/d (~221 Mgal/d). Therefore, the maximum withdrawals result in an approximate 14-percent reduction in net discharge to rivers from the 2018 amount.

The simulated water budget in the individual aquifer systems (Upper Patapsco, Lower Patapsco, and Patuxent) for the transient period 1900-2018, the 2086 build-out scenario, and the maximum-withdrawal scenario is shown in Figure 15. The graph illustrates how the various flow components including vertical and horizontal flow (flow between aquifers and flow across the model edge), recharge, and aquifer storage, change with time as a result of changing (increasing) withdrawals. Recharge in this graph, referred to as "deep recharge", represents the amount of water entering the outcrop areas of the confined aquifers from the unconfined water-table. Overall, the changing budget over time shows that recharge and vertical flow between aquifers (upward and downward vertical flow) increases as withdrawals increase. Of note is the relative importance of vertical flow between aquifers. As withdrawals increase the amount of water flowing between aquifers also increases. This is a result of the degree of modeled vertical leakance representing the intervening confining units discussed earlier in the report (section entitled "Limitations of Quasi-3D Representation"). While the amount of vertical flux between aquifers may run somewhat counter to common conceptions of the amount of flow between aquifer systems it is not without precedence. Drummond (2007), in his groundwater-flow model of multiple aquifer systems (including the Upper and Lower Patapsco) in Southern Maryland states that *"Under pumping conditions most water enters the confined aquifers as leakage through the overlying confining units. Although in most of these aquifers water can directly enter from the outcrop area as recharge, downward leakage is applied over a much larger area, and is the predominant component of inflow."* Similarly, Achmad (1991), in his groundwater-flow model of the Patapsco aquifer system in Anne Arundel County, also found that vertical leakance through the confining bed was an important component of the flow system. Pertaining to model calibration, he states that *"...computed water levels of the lower Patapsco aquifer were 20 to 40 ft lower than they should have been."* To attain calibration he continues *"one option was to simulate an increase in vertical leakage through the confining unit by increasing the confining-unit leakance in the model....After several trials, it was found that a confining-unit leakance ranging from 10^{-8} to 10^{-6} s^{-1} [0.0086 to 0.079 ft^{-1}] gave the best water-level and base-flow comparisons."*

Recharge entering the outcrop areas of the confined Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems (deep recharge), as a linear rate, increases from less than 1 inch per year (in/yr) during the first half of the 1900s, 1.5 in/yr in 2018, 1.8 to 2 in/yr in 2086 build-out scenario, and 2 to 3.5 in/yr in the maximum-withdrawal scenario (fig. 16). The increased deep recharge is induced from the aquifer outcrop areas as head gradients steepen as a result of the increased withdrawals. By comparison, recharge applied to the water-table aquifer ranges from 9 to 18 in/yr. Therefore, deep recharge to the confined aquifers under the high-withdrawal scenarios account for a significant portion of the total recharge entering the water-table aquifer.

While beyond the scope of this study, climate change may significantly impact recharge to aquifers thus affecting water availability. Climate change in Maryland, aside from higher average temperatures, is likely to alter rainfall patterns increasing the number and severity of storms and droughts (Maryland Commission on Climate Change, 2016), which in turn could affect the amount of water recharging aquifer systems.

Effect on Water Levels in the Magothy Aquifer

The maximum simulated withdrawals cause water levels in the Magothy aquifer to decline by as much as approximately 75 ft in the vicinity of the Arnold well field (fig. 17). The decline is related to a direct hydraulic connection between the Magothy and Upper Patapsco aquifers on the Broadneck Peninsula (Andreasen, 2007; Fleck and Andreasen, 1996; Mack and Andreasen, 1991). The resulting drawdown in the Magothy causes water levels to fall below the management water level in that aquifer. The decline also increases the head gradient from the subcrop of the Magothy aquifer beneath the brackish Severn and Magothy Rivers, creating the potential for saltwater intrusion. The potential of saltwater intruding the Magothy aquifer resulting in part from withdrawals in the Upper Patapsco at the Arnold well field was first raised in an earlier investigation of brackish-water intrusion in east-central Anne Arundel County (Fleck and Andreasen, 1996).

SIMULATED GROUNDWATER TRAVEL TIME

Travel times (advective flow) of groundwater flowing to production wells in AADPW's well fields were estimated under the maximum-withdrawals scenario. The steady-state predictive model was used in conjunction with the U.S. Geological Survey's MODPATH particle-tracking code (Pollock, 2016) to track particles backwards from

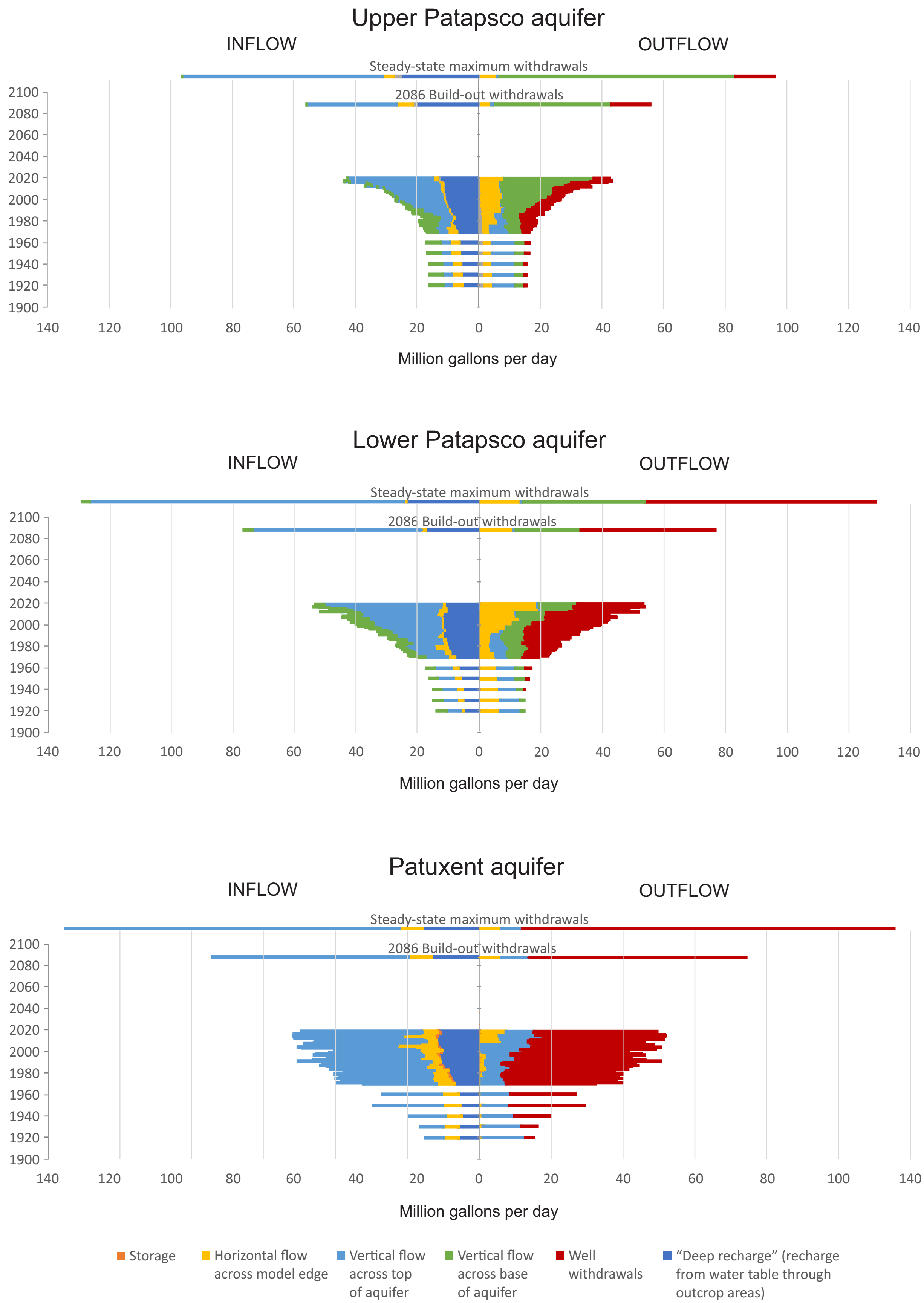


Figure 15. Variations in simulated water budget over time in the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems.

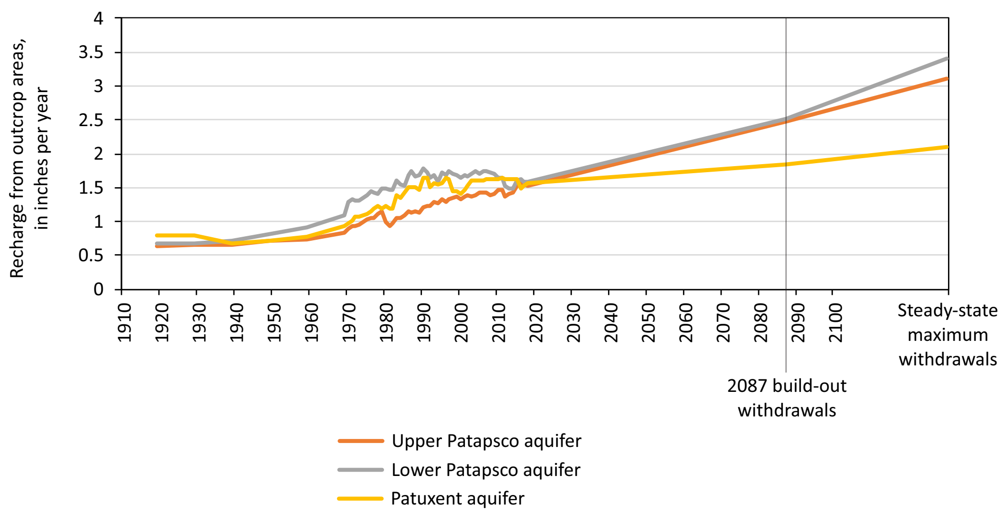


Figure 16. Simulated water budget for maximum withdrawal scenario by aquifer.

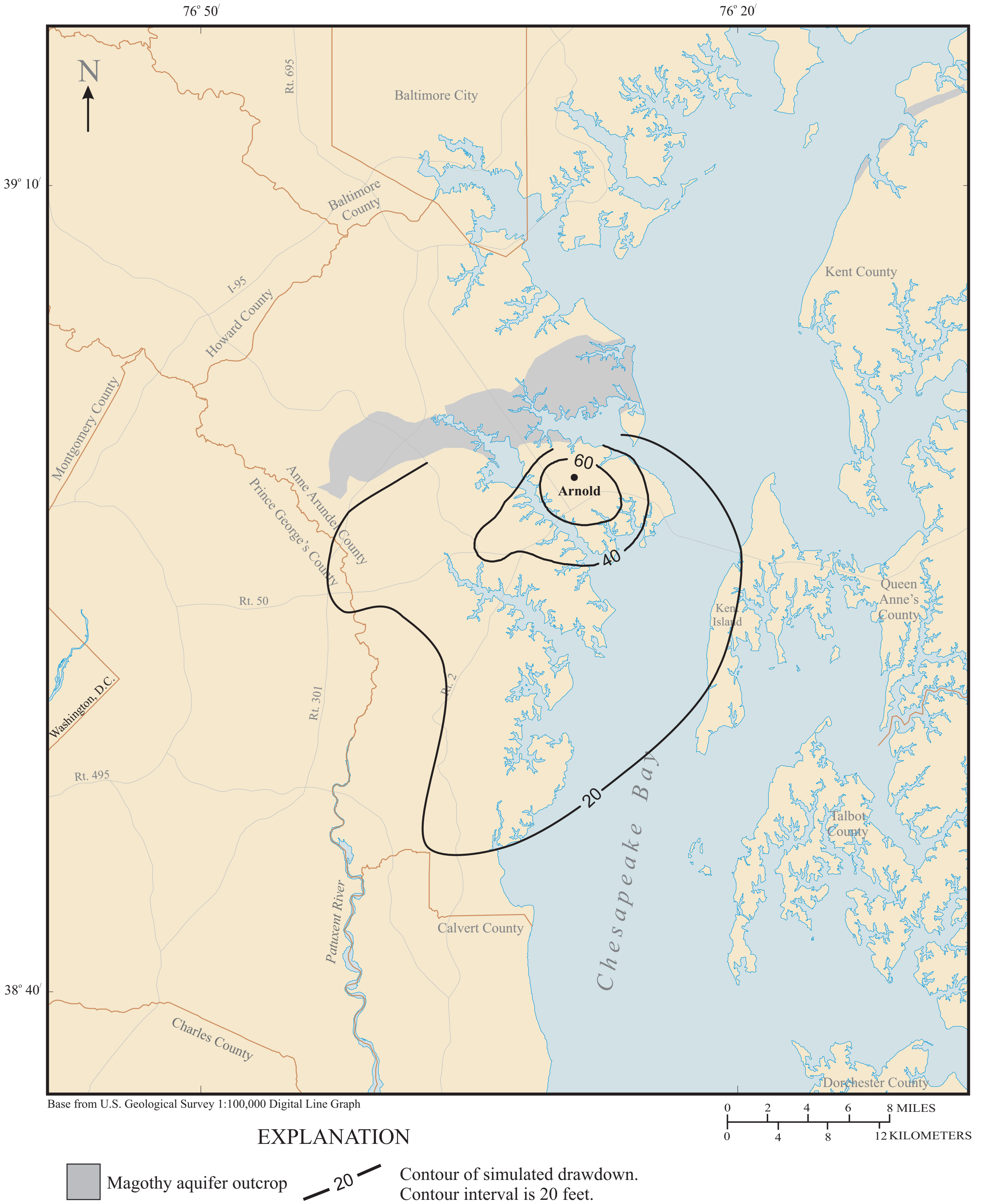


Figure 17. Simulated drawdown in the Magothy aquifer from 2018 resulting from maximum withdrawals (steady state) in the Upper and Lower Patapsco and Patuxent aquifer systems.

model cells representing the production wells until they terminate at the water-table aquifer (recharge area) or constant-head (brackish tidal surface water) boundaries. An array of 2x2 particles were placed on the bottom and center plane of the model pumping cells containing the AADPW withdrawals and were tracked backwards until they terminated at boundaries. The number and configuration of particles (see inset on Figures 18-20) was selected so that the flow-path lines could be clearly visualized without overcrowding. To further help in visualization, flow-path lines for particles placed on the center and bottom planes of the model cells are shown in separate figures (figs. 18-20). The particle path lines are marked with arrows indicating 100-year travel time intervals. A summary of travel times is given in Table 5 for the maximum-withdrawal scenario, and for comparison, simulated 2018 and 2086 (build-out) conditions.

In the Upper Patapsco aquifer system well fields, the minimum travel time to model boundaries (water table and tidal surface water) is 75 years for Arnold and 277 years for Broad Creek (figs. 18a and 18b.). Particles tracked backwards from the Severndale well field (Upper Patapsco wells not pumped in the maximum withdrawal scenario) reach the water table in as little as 30 years. Particles tracking northward from the Arnold well field pass upwards to the Magothy aquifer and intercept the tidal Magothy River, indicating the potential for saltwater intrusion in the Magothy aquifer. The median travel time to the Arnold and Broad Creek well fields is approximately 116 and 408 years, respectively.

In the Lower Patapsco aquifer system well fields, the minimum travel times to model boundaries is 135 years for Arnold, 277 years for Broad Creek, 94 years for Crofton Meadows, 144 years for Crownsville, 70 years for Millersville, and 97 years for Severndale (figs. 19a and 19b.). The median travel time 377 years for Arnold, 408 years for Broad Creek, 161 years for Crofton Meadows, 275 years for Crownsville, 105 years for Millersville, and 112 years for Severndale.

In the Patuxent aquifer system well fields, the minimum travel times to model boundaries is 459 years for Arnold, 375 for Broad Creek, 244 for Crofton Meadows, 234 for Crownsville, and 193 years for Millersville (figs. 20a and 20b.). The median travel time is 632 years for Arnold, 1,626 years for Broad Creek, 332 years for Crofton Meadows, 272 years for Crownsville, and 238 years for Millersville.

The shortest travel times (less than 100 years) to the water-table aquifer (recharge area) and constant-head (brackish tidal surface water) boundaries include the Upper Patapsco well fields at Arnold (75 years to brackish Magothy River) and Severndale (30 years to recharge area), and the Lower Patapsco aquifer wells fields at Crofton Meadows, Millersville, and Severndale (94, 70, and 97 years to recharge area, respectively).

Travel times from well fields to model boundaries under the maximum-withdrawal scenario range from approximately 1.4- to 16-times less than under 2018 pumping conditions and 1.1- to 9.9-times less than under 2086 build-out pumping conditions (tab. 5). Increasing withdrawals results in faster travel times as head gradients steepen.

SUMMARY

Anne Arundel County public water supply relies on groundwater pumped from the Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems. The six major well fields (Arnold, Broad Creek, Crofton Meadows, Dorsey Road, and Severndale) operated by AADPW pumped approximately 33.5 Mgal/d in 2018. Remaining available drawdown in 2018 in the Upper Patapsco aquifer system at the Arnold, Broad Creek, and Severndale well fields was approximately 140, 183, and 24 ft, respectively. Remaining available drawdown in the Lower Patapsco aquifer system at the Arnold, Broad Creek, Crofton Meadows, and Severndale well fields was approximately 470, 500, 190, and 150 ft, respectively. Remaining available drawdown in the Patuxent aquifer system at the Arnold, Broad Creek, and Crofton Meadows well fields was approximately 820, 960, and 500 ft, respectively. In all three aquifer systems, there is a relatively narrow band parallel to the aquifer outcrops where water levels are below management levels.

A previously developed groundwater-flow model was revised and used to estimate maximum withdrawal rates in the existing AADPW well fields (Arnold, Broad Creek, Crofton Meadows, and Severndale) and future well fields (Crownsville and Millersville) before water levels reach management levels. The model time period was extended from 1900-2015 to 1900-2018, pumpage amounts were updated, and boundary heads were revised. Calibration of the model was verified by comparing the statistical match between simulated and observed heads at the end of the simulation period and by a visual examination of trends over the simulation period.

Using the transient (1900-2018) flow model, modified to operate in steady-state mode, a simulation was run to estimate maximum withdrawals. Withdrawals from the major AADPW well fields (existing and future) were increased until water levels reached management levels. The

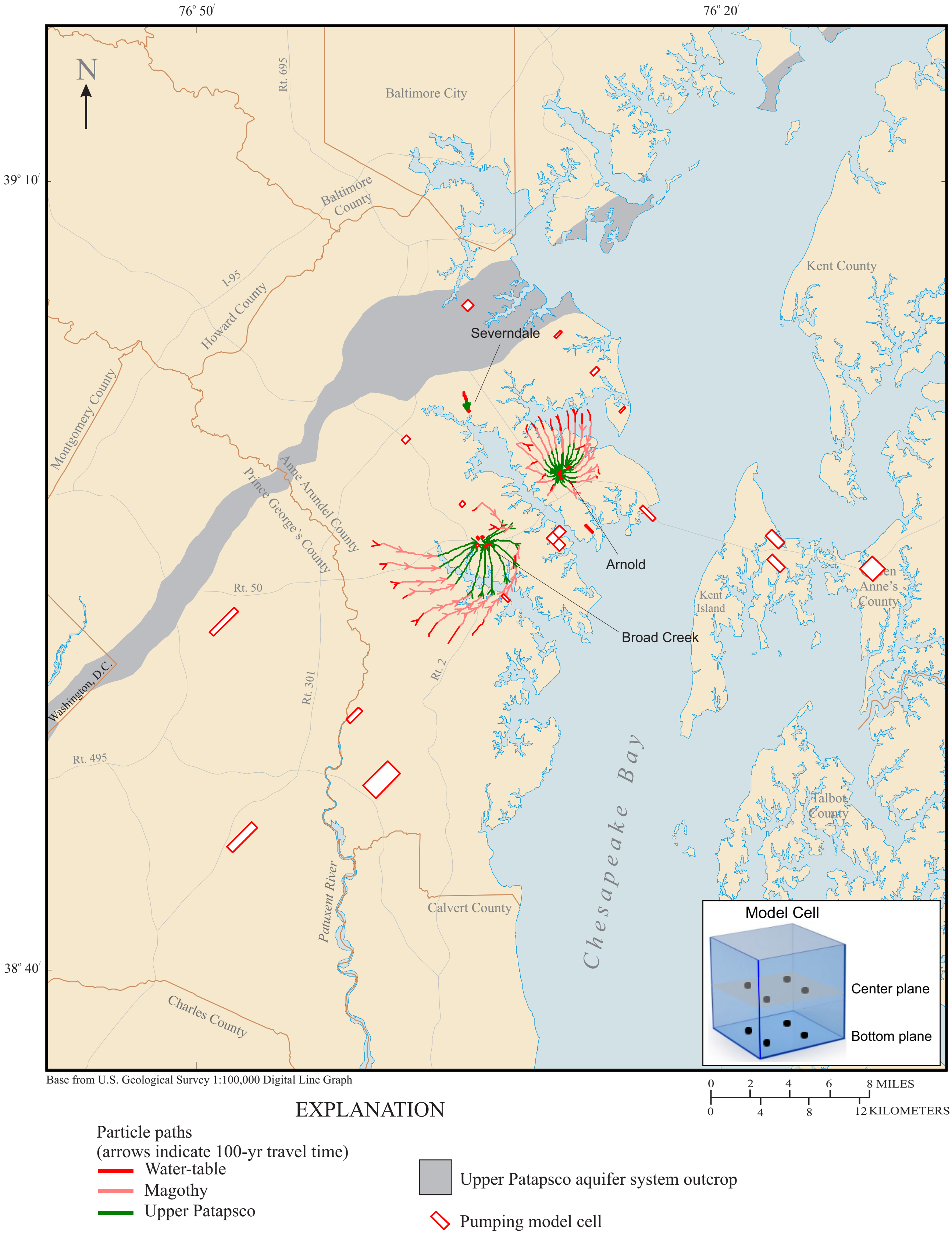


Figure 18a. Particle paths in the Upper Patapsco aquifer system at simulated maximum withdrawals with a 2x2 array of particles placed on a plane in the center of the model cell.

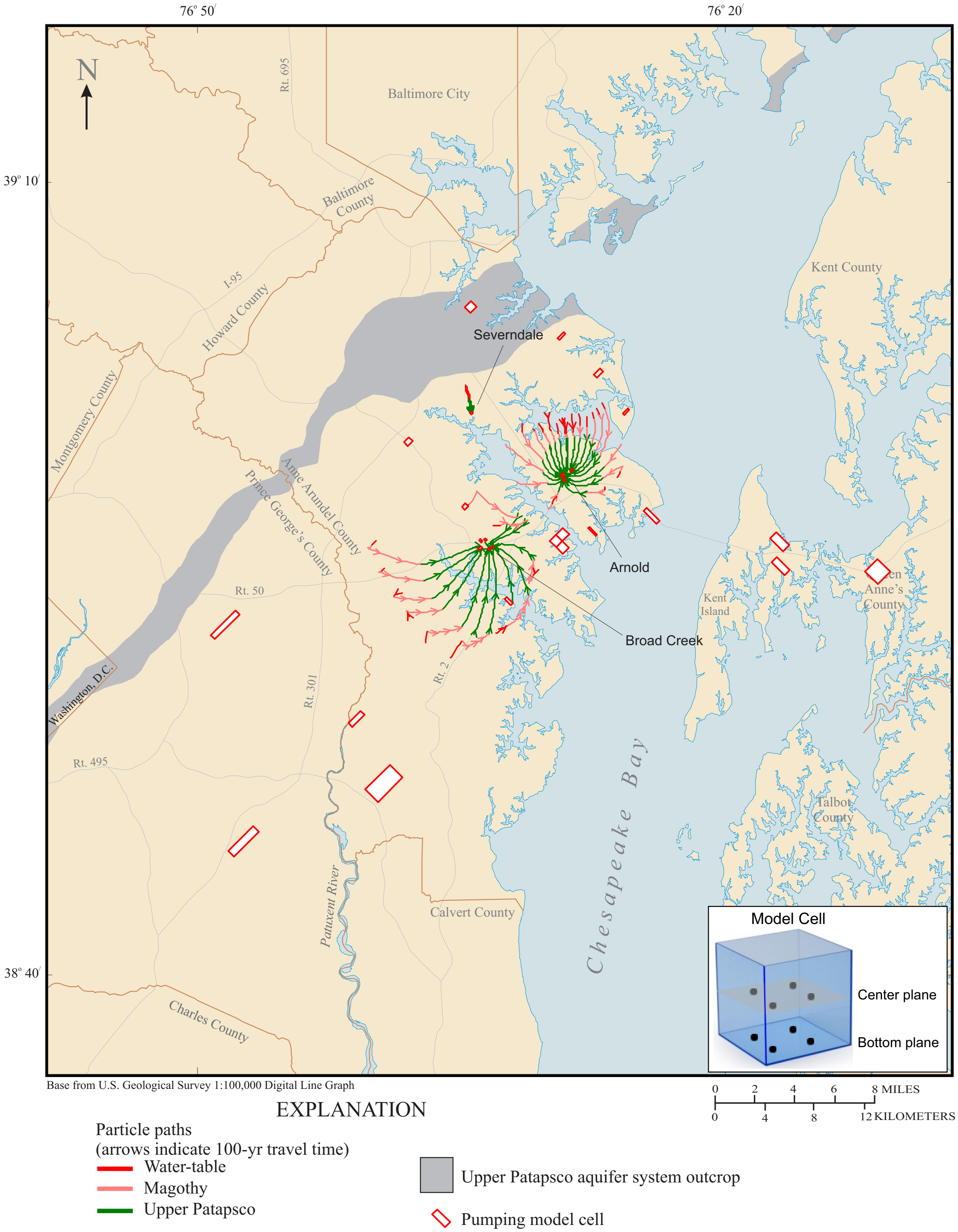


Figure 18b. Particle paths in the Upper Patapsco aquifer system at simulated maximum withdrawals with a 2x2 array of particles placed on the bottom face of the model cell.

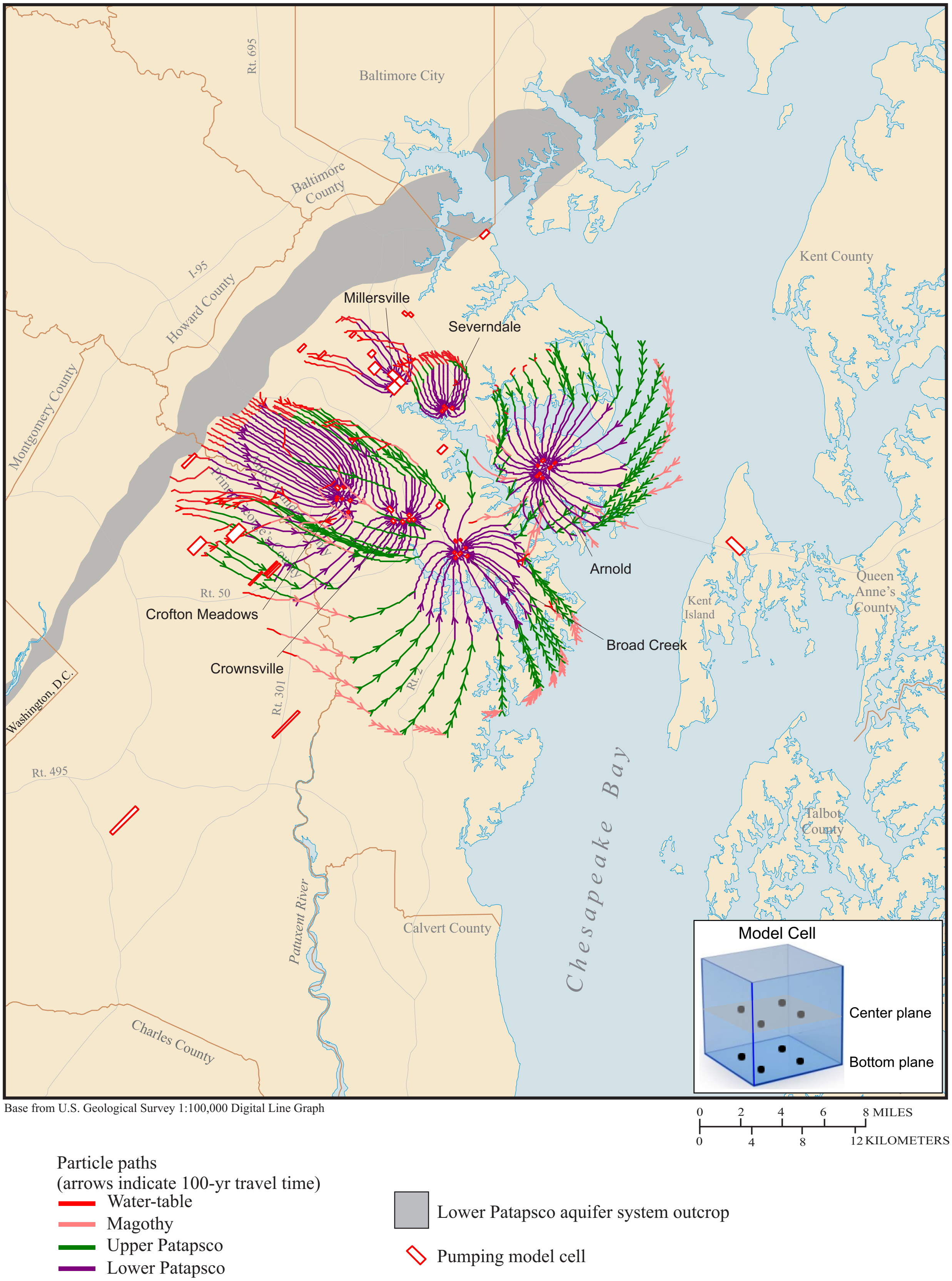
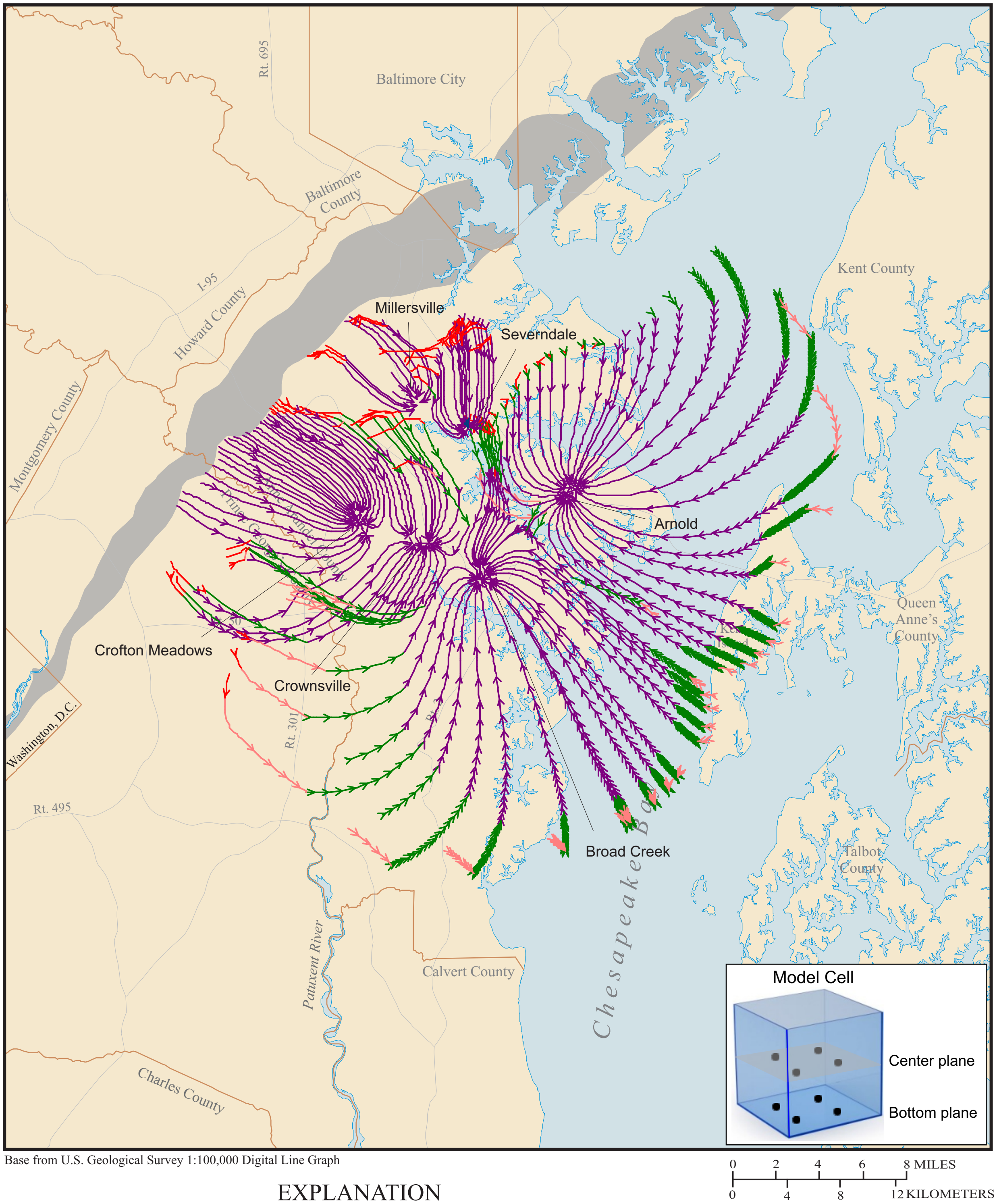


Figure 19a. Particle paths in the Lower Patapsco aquifer system at simulated maximum withdrawals with a 2x2 array of particles placed on a plane in the center of the model cell.



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

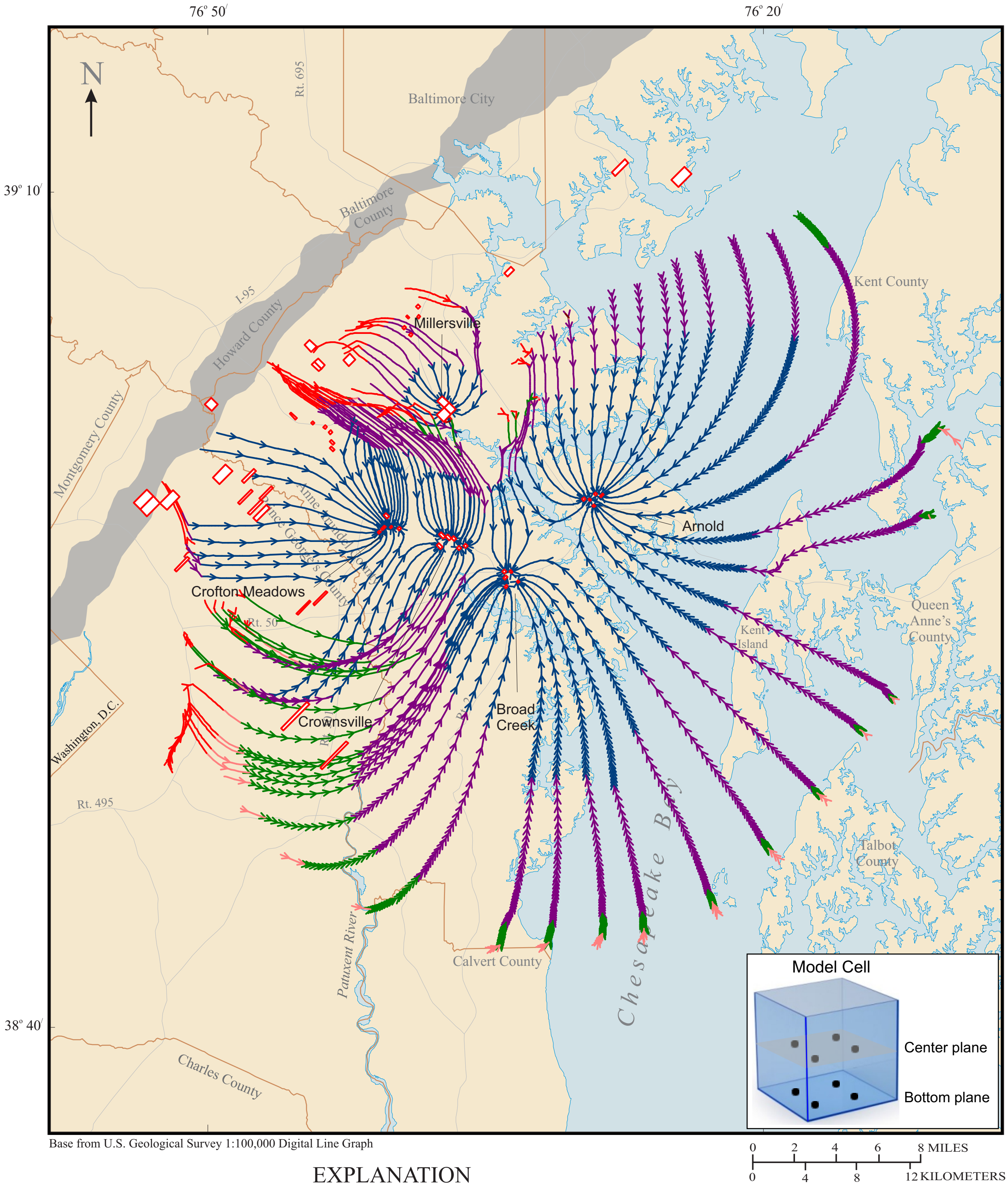
EXPLANATION

Particle paths
(arrows indicate 100-yr travel time)
- Water-table
- Magothy
- Upper Patapsco
- Lower Patapsco

Lower Patapsco aquifer system outcrop

Pumping model cell

Figure 19b. Particle paths in the Lower Patapsco aquifer system at simulated maximum withdrawals with a 2x2 array of particles placed on the bottom face of the model cell.



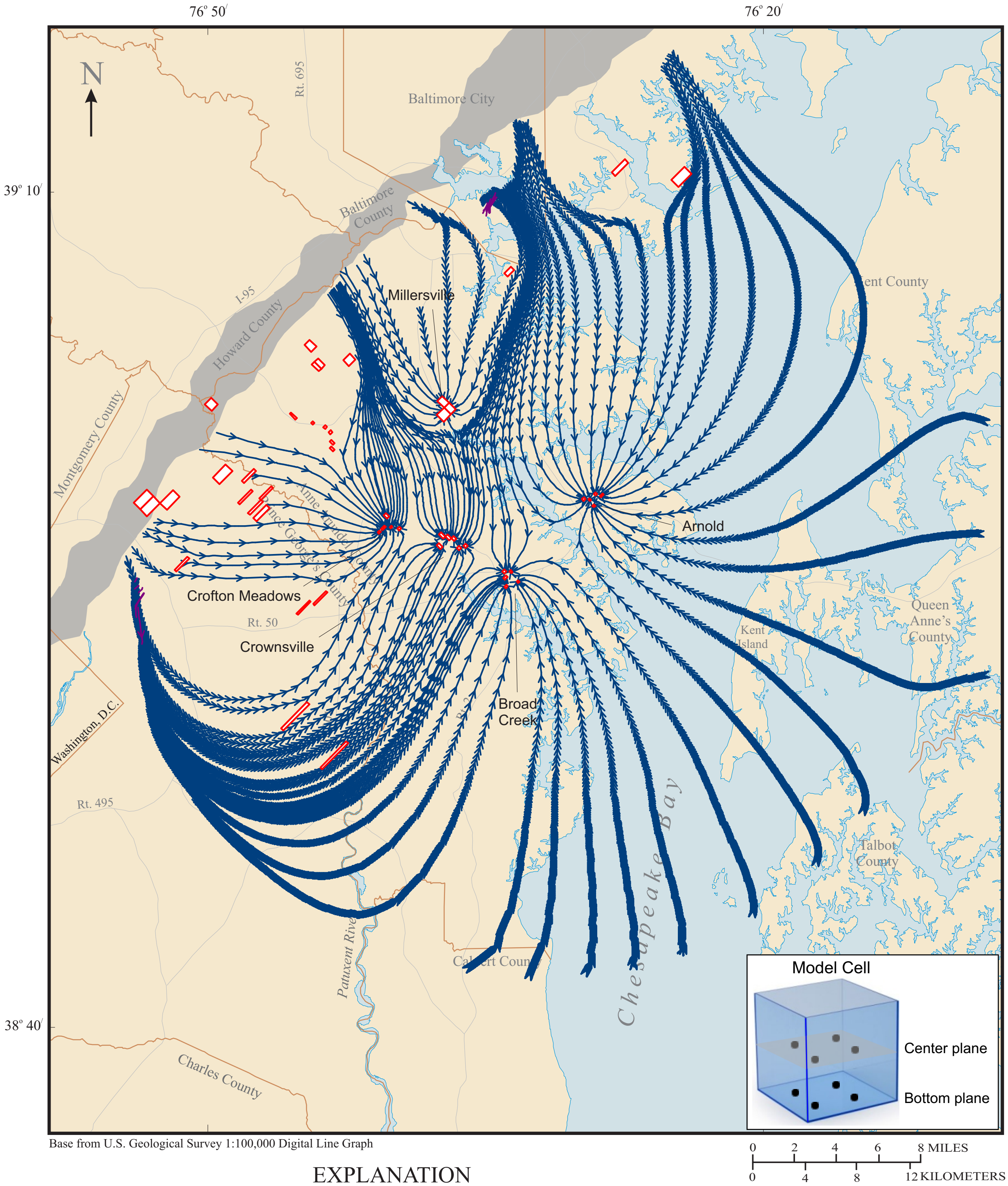
EXPLANATION

Particle paths
(arrows indicate 100-yr travel time)
- Water-table
- Magothy
- Upper Patapsco
- Lower Patapsco
- Patuxent

Patuxent aquifer system outcrop

Pumping model cell

Figure 20a. Particle paths in the Patuxent aquifer system at simulated maximum withdrawals with a 2x2 array of particles placed on a plane in the center of the model cell.



EXPLANATION

Particle paths
(arrows indicate 100-yr travel time)
Lower Patapsco
Patuxent

Patuxent aquifer system outcrop

Pumping model cell

Figure 20b. Particle paths in the Patuxent aquifer system at simulated maximum withdrawals with a 2x2 array of particles placed on the bottom face of the model cell.

Table 5. Particle travel times from AADPW well fields to the water-table aquifer or tidal surface water.

Well field	Simulated 2018 conditions		Simulated 2086 Build-out scenario		Maximum withdrawal scenario	
	Minimum, years	Median, years	Minimum, years	Median, years	Minimum, years	Median, years
Upper Patapsco aquifer system						
Arnold	235	441	113	142	75	116
Broad Creek	511	1,073	395	609	277	408
Severndale	59	84	37	39	30	33
Lower Patapsco aquifer system						
Arnold	627	1,187	299	488	135	377
Broad Creek	931	1,837	447	496	277	408
Crofton Meadows	129	358	110	206	94	161
Crownsville	519	749	237	467	144	275
Millersville	176	211	79	117	70	105
Severndale	164	245	135	181	97	112
Patuxent aquifer system						
Arnold	2,632	4,661	894	1,073	459	632
Broad Creek	6,119	11,320	3,727	6,060	375	1,626
Crofton Meadows	479	788	271	728	244	332
Crownsville	1,174	1,356	528	573	234	272
Millersville	564	632	228	261	193	238

management constraints which control the maximum allowable withdrawal rates were defined as the 80-percent management level measured at a distance of approximately one-quarter mile updip (to the northwest) of each AADPW well field. Results of the modeling show that a total of 114.4 million gallons per day can be withdrawn from the well fields before water levels reach management levels. This amount is approximately 1.7 times greater than the 2086 build-out value of 66.5 million gallons per day and approximately 3.4 times greater than the amount pumped in 2018. Simulated water levels are as deep as 155, 295, and 480 feet below sea level in the Upper Patapsco, Lower Patapsco, and Patuxent aquifers, respectively. As a result of the simulated leakage between aquifers, the amount that can be withdrawn from deeper aquifers is controlled, in part, by the available drawdown in shallower aquifers. This magnitude of drawdown has the potential to cause land subsidence in addition to well interference with other groundwater users. Saltwater intrusion may also be an issue in the Magothy aquifer on the Broadneck Peninsula related to the Upper Patapsco withdrawals.

The simulated net water budget for the maximum-withdrawal scenario indicates that recharge applied to the water-table aquifer (100 percent of net inflow to the model) is balanced by net outflow of approximately 46 percent to rivers (baseflow), 31 percent to wells, 22 percent to constant heads, and 1 pecent to head dependent boundaries. The maximum withdrawals result in an approximate 14-percent reduction in river discharge over the 2018 amount.

Groundwater travel times from AADPW well fields pumped in the maximum withdrawal scenario were calculated using the groundwater-flow model and the particle-tracking code MODPATH. In the Upper Patapsco aquifer system well fields, the minimum travel time from model boundaries (water table and brackish tidal surface water) is 75 years for Arnold, 277 years for Broad Creek, and 30 years for Severndale. In the Lower Patapsco aquifer system well fields, the minimum travel times from model boundaries is 135 years for Arnold, 277 years for Broad Creek, 94 years for Crofton Meadows, 144 years for Crownsville, 97 years for Severndale, and 70 years for Millersville. In the Patuxent aquifer system well fields, the minimum travel times from model boundaries is 459 years for Arnold, 375 for Broad Creek, 244 for Crofton Meadows, 234 for Crownsville, and 193 years for Millersville. The well fields with the shortest travel times (less than 100 years) to the water-table aquifer (recharge area) and brackish tidal surface water include the Upper Patapsco well field at Arnold (75-year travel time to brackish Magothy River) and Severndale (30 years to recharge area), and the Lower Patapsco aquifer at Crofton Meadows, Severndale, and Millersville (94-, 96-, and 12-year travel time to recharge area).

ACKNOWLEDGEMENTS

This study was funded through a cooperative agreement between the Anne Arundel County Department of Public Works and the Maryland Geological Survey. Sharon Cole (AADPW) aided in the development of the study plan and in overall management of the study. Information regarding production wells operated by Anne Arundel County was provided by John P. Stokes (Earth Data, Inc.). Andrew Staley and Heather Quinn (MGS) provided technical and editorial review as well as assistance in preparation of illustrations.

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Appendix A. Appropriated withdrawals in the Magothy, and Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems in the model area, 2016-2018.

List of abbreviations

AA DPW – Anne Arundel County Department of Public Works
GAP – Groundwater Appropriation Permit
Kmg – Magothy aquifer
Ukpt – Upper Patapsco aquifer system
Lkpt – Lower Patapsco aquifer system
Kpx – Patuxent aquifer system
(e) – estimated pumpage
CA Co. – Calvert County
QA Co. – Queen Anne's County
GC – golf course

Appendix A. Appropriated withdrawals in the Magothy, and Upper Patapsco, Lower Patapsco, and Patuxent aquifer systems in the study area, 2016-2018.

GAP	Owner	Aquifer	Average annual appropriation, gallons per day	Production wells	Model cell (row, col,layer)	2016	2017	2018
AA1932G003	U.S. Naval Academy	Ukpt	1,750,000	AA Df 12, 13	54,92,4	289,884	325,809	127,396
				AA Df 80,83,160	54,91,4	434,870	488,762	181,114
				AA Df 101	53,91,4	144,899	162,855	63,679
					Total	869,740	977,523	382,227
AA1947G003	Laurel Racing Association	Kpx	43,000	AA Bb 22	92,6,6	23,260	23,488	22,036
AA1949G004	Sandy Point State Park	Kmg	29,000	AA Cg 6, 8	24,94,3	29,339	24,716	25,471
AA1953G008	AA DPW, Severndale	Lkpt	7,000,000	AA Ce 131, 7R	48,50,5	2,310,284	2,609,964	2,701,813
				AA Ce 121	50,50,5	1,155,142	1,304,982	1,350,906
				AA Ce 122	48,49,5	1,155,142	1,304,982	1,350,906
				AA Ce 139	46,52,5	1,155,142	1,304,982	1,350,906
					Total	5,775,709	6,524,910	6,754,532
AA1953G108	AA DPW, Severndale	Ukpt	450,000	3R	48,50,4	0	0	145,211
AA1953G208	AA DPW, Severndale	Kpx	1,600,000	AA Ce 149	46,52,6	0	0	0
AA1954G001	Crownsville State Hospital	Kmg	215,000	AA Cd 11	60,60,3	14,083	28,166	14,083
				AA Cd 43, 72	62,60,3	13,762	27,525	13,762
				AA Cd 50	61,60,3	20,370	40,739	20,370
					Total	56,332	55,049	81,479
AA1960G021	Landsman Mobile Home Park	Kmg	20,000	AA Cd 93	63,67,3	15,170	14,998	15,770(e)
AA1962G030	Chemetals Corporation	Kpx	122,000	AA Ae 35, 36	18,29,6	9,563	4,387	333
AA1963G008	Holiday Mobile Estates	Kpx	125,000	AA Bc 177	58,9,6	91,732	81,518	79,025
AA1963G029	Sherwood Forest Water Co.	Kmg	100,000	AA Ce 98	55,71,3	58,968	57,946	47,429
AA1965G032	Maryland Manor Mobile Estates	Kmg	74,000	AA Ec 6, 7, 8	100,89,3	68,765	69,036	65,327
AA1966G027	Northrop Grumman Corp.	Ukpt	40,000	AA Cg 18, 19	27,95,4	13,414	12,946	10,649
AA1966G028	Epping Forest	Kmg	42,000	AA Ce 99, 119	54,75,3	32,453	38,130	41,858
AA1966G048	Crofton Country Club	Kmg	60,000	AA Cc 62	89,39,3	4,041	19,178	12,219
AA1968G006	AA DPW, Broad Creek	Ukpt	1,400,000	AA De 96	62,81,4	235,063	286,254	167,875
				AA De 97	64,80,4	235,063	286,254	167,875
				AA De 136	66,77,4	235,063	286,254	167,875
					Total	705,260	858,847	503,674
AA1968G011	Southern High School	Kmg	25,000	AA Ed 39, 41	96,93,3	10,134	12,751	9,381
AA1969G016	Pioneer City	Lkpt	480,000	AA Bc 169, 195	57,15,5	327,683	318,381	315,159
AA1969G019	AA DPW, Dorsey Road	Kpx	4,800,000	AA Ad 111	34,15,6	253,738	383,631	486,578
				AA Bd 161	36,18,6	253,738	383,631	486,578
				AA Bd 177, 178, 179	40,15,6	761,036	1,150,624	1,459,392
				AA Bd 188	44,17,6	253,738	383,631	486,578
				AA Bd 189	43,20,6	253,738	383,631	486,578
					Total	1,775,631	2,684,611	3,405,022

Appendix A. Continued.

GAP	Owner	Aquifer	Average annual appropriation, gallons per day	Production wells	Model cell (row, col,layer)	2016	2017	2018
AA1969G021	U.S. Army, Ft. Meade	Kpx	3,300,000	AA Bb 68	79,13,6	322,121	322,999	324,372
				AA Bc 164	75,18,6	322,121	322,999	324,372
				AA Bc 234	73,23,6	322,121	322,999	324,372
				AA Cc 144	75,28,6	322,121	322,999	324,372
				AA Cc 120	73,26,6	322,121	322,999	324,372
				AA Cc 123	77,29,6	322,121	322,999	324,372
					Total	1,933,497	1,938,767	1,947,014
AA1970G013	Chesapeake School Complex	Ukpt	41,000	AA Bf 50, 51	18,67,4	23,883	14,795	18,012
AA1970G041	U.S. Naval Academy Golf Course	Ukpt	85,000	AA Df 89	47,93,4	31,994	25,331	8,731
AA1970G046	Provinces Water Co.	Kpx	415,000	AA Bc 192, 193, 241	59,11,6	253,096	244,557	260,003
AA1971G034	AA DPW, Gibson Island	Ukpt	120,000	AA Cf 123, 172	19,80,4	72,874	80,134	83,044
AA1972G005	AA DPW, Crofton Meadows	Kpx	8,000,000	AA Cc 103	86,43,6	939,681	979,954	824,517
				AA Cc 105	85,43,6	939,681	979,954	824,517
				AA Cc 107	88,43,6	939,681	979,954	824,517
				AA Cc 138	83,46,6	939,681	979,954	824,517
				AA Cc 151	81,41,6	939,681	979,954	824,517
				AA Cd 107	81,49,6	939,681	979,954	824,517
					Total	5,640,344	5,882,077	4,949,079
AA1972G009	City of Annapolis	Kmg	2,000,000	AA De 2	64,75,3	329,630	352,829	391,536
				AA De 45	62,75,3	329,630	352,829	391,536
				AA De 46, 88	62,76,3	659,259	705,567	783,071
					Total	1,318,519	1,411,315	1,566,142
AA1972G105	AA DPW, Crofton Meadows	Lkpt	6,800,000	AA Cc 128	84,43,5	1,280,663	1,143,302	1,054,300
				AA Cc 129	85,44,5	1,280,663	1,143,302	1,054,300
				AA Cc 140	83,46,5	1,280,663	1,143,302	1,054,300
				AA Cd 106	81,49,5	1,280,663	1,143,302	1,054,300
				AA Cc 152	81,41,5	1,280,663	1,143,302	1,054,300
					Total	6,403,314	5,716,510	5,217,501
AA1972G209	City of Annapolis	Lkpt	1,650,000	AA De 94	62,76,5	440,712	423,655	412,138
				AA De 139	64,75,5	440,712	423,655	412,138
					Total	881,425	847,310	824,276
AA1972G309	City of Annapolis	Ukpt	1,850,000	AA De 219	62,76,4	654,895	586,019	506,467
				AA De 220	64,75,4	654,895	586,019	506,467
					Total	1,309,791	1,172,038	1,012,934
AA1973G013	Patuxent Mobile Estates	Kmg	40,000	AA-74-1853, AA-94-0921	102,92,3	16,414	17,482	18,737
AA1973G025	Lake Village Apartments	Kpx	160,000	AA Bc 201, 202	56,13,6	46,628	57,685	58,301
AA1981G025	AA DPW, Stevenson Road	Lkpt	830,000	AA Bd 121	52,26,5	699,993	250,855	224,603
AA1981G026	AA DPW, Telegraph Road	Lkpt	1,000,000	AA Bc 215	56,23,5	402,577	172,151	0
AA1982G031	AA DPW, Herald Harbor	Lkpt	160,000	AA Ce 123, 124	54,58,5	134,757	125,058	125,249

Appendix A. Continued.

GAP	Owner	Aquifer	Average annual appropriation, gallons per day	Production wells	Model cell (row, col,layer)	2016	2017	2018
AA1982G036	AA DPW, Arnold	Ukpt	3,500,000	AA Cf 118	39,80,4	523,222	421,569	574,746
				AA Cf 119	40,80,4	523,222	421,569	574,746
				AA Cf 120	40,81,4	523,222	421,569	574,746
				AA Cf 155	41,83,4	523,222	421,569	574,746
				AA Cf 170	35,82,4	523,222	421,569	574,746
					Total	2,616,108	2,107,847	2,873,729
AA1982G037	AA DPW, Harundale	Lkpt	2,200,000	AA Bd 36, 37	32,32,5	0	0	124,810
				AA Bd 63, 162	33,31,5	0	0	124,810
					Total	0	0	249,619
AA1984G070	Millennium Inorganic Chemicals, Inc.	Lkpt	14,500		15,31,5	17,576	10,760	11,785
AA1986G070	AA DPW, Broad Creek	Lkpt	3,600,000	AA De 177	63,80,5	1,201,182	1,148,471	1,347,796
				AA De 208	65,84,5	1,201,182	1,148,471	1,347,796
					Total	2,402,363	2,296,942	2,695,592
AA1987G051	Central Sod Farm	Kmg	40,000	AA-81-9201	36,93,3	5,544	6,656	3,643
AA1987G069	AA DPW, Arnold	Lkpt	8,000,000	AA Cf 142	40,80,5	1,712,874	1,183,448	1,483,788
				AA Cf 150	41,83,5	1,712,874	1,183,448	1,483,788
				AA Cf 168	35,82,5	1,712,874	1,183,448	1,483,788
					Total	5,139,134	3,550,699	4,451,808
AA1987G070	Eisenhower Golf Course	Ukpt/ Lkpt	15,000	AA Ce 136(Ukpt)	59,67,4	0	4,171	4,171
				AA Ce 137(Lkpt)	59,67,5	0	4,904	4,904
					Total	0	8,343	9,808
AA1988G058	Shady Oaks Sod Farm	Kmg	200,000	AA Fe 55	96,98,3	3,186	0	0
AA1989G041	Old South County Golf Course	Ukpt	68,000	AA Fd 50, 51	101,95,4	62,760	55,796	45,009
AA1989G059	James Schillinger	Lkpt	32,000	AA Bd 175, 176	52,32,5	12,093	2,753	6,696
AA1989G094	Solley Road landfill	Lkpt	50,000		24,34,5	22,834	24,249	27,429
AA1990G045	South River Colony Golf Course	Kmg	70,000	AA De 217	90,92,3	42,780	18,548	13,562
AA1992G022	Lyons Creek Mobile Home Park	Kmg	66,000	AA Fc 23	102,97,3	44,911	35,355	38,373
AA1992G031	Pumphrey farm	Lkpt	24,000	AA-81-2936	53,34,5	7,869	6,510	263
AA1997G030	Crofton Athletic Complex	Kmg	16,200	AA Dc 22, 23	91,56,3	7,290	5,316	5,443(e)
AA1999G041	Maryland Manor Mobile Estates	Ukpt	16,000	AA Ec 12	100,89,4	0	0	4,767
AA2002G017	Compass Point Golf Course	Ukpt	108,500	AA-94-8264	18,54,4	28,715	9,772	5,781
AA2003G005	Turner Pit--groundwater remediation	Kmg	288,000		80,39,3	177,231	174,270	311,371
AA2004G016	Groundwater cleanup	Lkpt	113,000		54,11,5	0	0	91,614
AA2005G015	Anne Arundel Manor Golf Course	Kmg	150,000		99,91,3	114,160	128,031	129,875(e)

Appendix A. Continued.

GAP	Owner	Aquifer	Average annual appropriation, gallons per day	Production wells	Model cell (row, col,layer)	2016	2017	2018
AA2005G020	AA DPW, Arnold	Kpx	4,500,000	AA Cf 169	35,82,6	1,187,484	1,377,793	1,206,244
				AA Cf 171	41,83,6	1,187,484	1,377,793	1,206,244
					Total	2,374,969	2,755,586	2,412,488
BA1969G020	American Yeast Corporation	Kpx	3,200,000	BA Ff 85, 90, 91	8,30,6	2,605,141	2,031,645	1,920,763(e)
BA1970G006	Rocky Point Golf Course	Kpx	65,000	BA Fg 176	6,37,6	57,992	47,016	34,310
BA1975G012	Marshy Point Nursery	Lkpt	65,000	BA Eg 260	2,31,5	2,459	21,575	0
CA1970G004	CA Co., Cavalier Country	Kmg	36,000	CA Bb 23, 24	102,99,3	18,968	18,259	18,620
CA1972G001	Northern High School	Kmg	18,000	CA Bb 25	104,102,3	11,397	11,539	11,851
CA1972G002	CA Co., Shores of Calvert	Kmg	35,000	CA Bc 7, 8	103,98,3	23,221	21,672	20,370
CA2002G010	Dunkirk Business Park	Kmg	32,000	CA-94-4579; CA-95-0067	103,100,3	12,467	13,138	14,539
KE1971G004	Town of Rock Hall	Kmg	230,000	KE Db 35, 55, 56, 57	5,95,3	97,449	167,104	178,055
PG1956G007	Boy's Village of Maryland	Kmg	65,000	PG Fd 5, 55, 67	107,89,3	24,048	13,004	18,754
PG1957G003	Glendale Golf Course	Kpt	50,000	PG-92-0625	98,34,5	15,656(e)	16,706	11,630
PG1958G003	Patuxent Wildlife Research Center	Kpx	300,000	PG Be 8	95,12,6	14,125	17,215	7,304
				PG Be 23	94,25,6	14,125	17,215	7,304
				PG Be 24	95,26,6	14,125	17,215	7,304
				PG Be 28	95,20,6	14,125	17,215	7,304
				PG Be 29	94,15,6	14,125	17,215	7,304
				PG Be 30	95,28,6	14,125	17,215	7,304
					Total	84,783	103,329	43,841(e)
PG1958G103	Patuxent Wildlife Research Center	Lkpt	200,000	PG Be 22	95,15,5	169,791	188,846	163,719(e)
PG1961G008	City of Bowie	Kmg	200,000	PG Cf 33	96,47,3	46,588	5,183	86,902
				PG Cf 34	96,40,3	46,588	5,183	86,902
					Total	93,176	10,366	173,804
PG1961G108	City of Bowie	Lkpt	1,500,000	PG Cf 32, 76	96,47,5	400,907	437,059	8,507
				PG Cf 35, 77	96,45,5	400,907	437,059	8,507
				PG Cf 80	97,43,5	200,453	218,530	4,254
					Total	1,002,267	1,092,648	21,268

Appendix A. Continued.

GAP	Owner	Aquifer	Average annual appropriation, gallons per day	Production wells	Model cell (row, col,layer)	2016	20117	2018
PG1961G208	City of Bowie	Kpx	1,800,000	PG Cf 64	96,46,6	198,383	199,596	676,705
				PG Cf 66	97,43,6	198,383	199,596	676,705
					Total	396,765	399,192	1,353,411
PG1977G008	Bowie Golf and Country Club	Lkpt	20,000	PG Ce 44, 45	96,36,5	14,872	12,704	9,942
PG1979G002	Andrews Air Force Base	Kmg	70,000	PG Ed 50	106,67,3	34,964	8,363	15,432
PG1987G003	Enterprise Golf Course	Ukpt	30,000	PG Ce 46	101,40,4	0	22,114	3,083
PG1990G012	Beltsville Agriculture Research Center	Kpx	750,000	PG Bd 17	99,9,6	193,848,	176,569	150,203
				PG Bd 61	99,8,6	193,848,	176,569	150,203
				PG Bd 62	98,10,6	193,848,	176,569	150,203
					Total	581,602	529,761	450,655
PG1994G006	U.S. Food and Drug Admin.	Kpx	30,000	PG-92-0681	97,8,6	6,415	7,726	10,710
PG1995G019	Marlton Golf Course	Kmg	40,000	PG Ee 57	105,90,3	6,639	1,479	0
PG1996G105	Andrews Air Force Base	Ukpt	110,000		106,67,4	75,489	22,370	0
PG1998G006	Beechtree GC	Lkpt	95,000	PG Df 42	101,79,5	1,130	10,838	7,451
		Kpx		PG Df 42	101,79,6	1,130	10,838	7,451
					Total	2,260	21,675	14,902
PG1998G023	NASA	Kpx	257,000	PG-94-1408	100,21,6	239,262	223,227	188,474
PG2002G009	Oak Creek Golf Club	Kpx	200,000		101,65,6	98,596	73,030	85,173
QA1984G016	QA Co., Bridgepointe	Ukpt	100,000	QA Eb 169, 170	19,102,4	12,898	27,249	51,830
QA1985G009	QA Co., Blue Heron Golf Course	Kmg	45,000	QA Fa 77	46,102,3	25,836	27,485	0
QA1985G024	QA Co., Bayside Marina	Ukpt	144,000	QA Eb 162, 171	17,101,4	125,548	10,288	205,100
QA1994G007	QA Co., Grasonville	Ukpt	100,000	QA Ec 91, 92	13,106,4	73,881	73,062	76,140
QA1997G050	QA Co., Stevensville	Lkpt	750,000	QA Eb 184	20,100,5	639,881	530,417	352,671
QA2010G007	QA Co., Stevensville	Ukpt	210,000	QA-11-0201	21,101,5	17,607	213,148	262,478

Larry Hogan
Governor

Jeannie Haddaway-Riccio
Secretary

Boyd K. Rutherford
Lt. Governor

Charles Glass
Deputy Secretary

A message to Maryland's citizens

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

MARYLAND DEPARTMENT OF NATURAL RESOURCES
Resource Assessment Service
Tawes State Office Building
580 Taylor Avenue
Annapolis, Maryland 21401
Toll free in Maryland: 877-620-8DNR
Out of State call: 410-260-8021
TTY users: Call via the Maryland Relay
[Internet Address: dnr.Maryland.gov](dnr.Maryland.gov)

MARYLAND GEOLOGICAL SURVEY
2300 St. Paul Street
Baltimore, Maryland 21218
Telephone Contact Information: 410-554-5500
[Internet Address: mgs.md.gov](mgs.md.gov)

DNR Publication No. 12-020620-208