Maryland Department of Natural Resources
Resource Assessment Service
MARYLAND GEOLOGICAL SURVEY
Emery T. Cleaves, Director

ADMINISTRATIVE REPORT

OPTIMIZATION OF GROUND-WATER WITHDRAWALS FROM THE LOWER PATAPSCO AND PATUXENT AQUIFERS IN THE BRYANS ROAD SERVICE AREA, CHARLES COUNTY, MARYLAND

by

David C. Andreasen

Prepared in cooperation with the
Charles County Department of Planning and Growth Management

September, 2004

Robert L. Ehrlich, Jr.
Governor

Michael S. Steele
Lieutenant Governor

C. Ronald Franks
Secretary

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CONTENTS

ILLUSTRATIONS

TABLES

OPTIMIZATION OF GROUND-WATER WITHDRAWALS FROM THE LOWER PATAPSCO AND PATUXENT AQUIFERS IN THE BRYANS ROAD SERVICE AREA, CHARLES COUNTY, MARYLAND

by

David C. Andreasen

KEY RESULTS

The main objective of the study was to minimize drawdown in the Lower Patapsco aquifer while pumping the required rate needed for both current and projected demand. Minimizing drawdown reduces well operational costs. In addition to minimizing drawdown, water levels were constrained from falling below the 80-percent management level.

Scheme 1: Optimum withdrawals in the Bryans Road well field to minimize total drawdown.

If the existing wells in the Bryans Road well field are required to pump 0.64 million gallons per day by 2020, total drawdown is minimized when only Bryans Road Well 6 (CH Bd 58), screened in the Patuxent aquifer, is pumped. By 2020 drawdown equaled 151 feet in Well 6. Withdrawals from the Lower Patapsco wells, which were significantly less than the Patuxent pumpage at the start of the simulation, were reduced to zero by 2008.

Scheme 2: Optimum withdrawals in the Bryans Road and Strawberry Hills well fields to minimize total drawdown.

If the existing wells in the Bryans Road and Strawberry Hills well fields are required to pump 0.75 million gallons per day by 2020, total drawdown is minimized when only Bryans Road Well 5 (CH Bc 78) and Well 6 (CH Bd 58), both screened in the Patuxent aquifer, are pumped. Pumpage in Wells 5 and 6 equaled 0.013 and 0.72 million gallons per day, respectively, by 2020. By 2020, total drawdown equaled 277 feet in Wells 5 and 6. Withdrawals from the Lower Patapsco aquifer, which were significantly less than the Patuxent pumpage at the start of the simulation, were reduced to zero by 2009.

Scheme 3: Maximum withdrawals from the Bryans Road and Strawberry Hills well fields constrained by the 80-percent management level (Scheme 3A) and pump intakes (Scheme 3B).

A maximum of 2.2 million gallons per day can be withdrawn from the Bryans Road and Strawberry Hills well fields by 2020 without exceeding the 80-percent management level. Approximately 1.7 million gallons per day were withdrawn from the Patuxent aquifer in the Bryans Road well field and 0.46 million gallons per day from the Lower Patapsco aquifer in the Strawberry Hills well field. Withdrawals from the Lower Patapsco aquifer at Bryans Road were reduced to zero by 2013.

A maximum of 1.8 million gallons per day can be withdrawn by 2020 before exceeding pump intakes. Approximately 1.2 million gallons per day were withdrawn from the Patuxent aquifer in the Bryans Road well field and 0.59 million gallons per day from the Lower Patapsco aquifer in the Bryans Road and Strawberry Hills well fields. Withdrawals were constrained by pump intakes in all wells except Bryans Road Well 4 (CH Bd 50) where the design pumping rate was reached before water levels fell below the pump intake. Water levels fell below the 80-percent management level in the Lower Patapsco aquifer in a relatively small area just to the northwest of Bryans Road along the Potomac River.

Scheme 4: Maximum withdrawals from existing wells in the Bryans Road and Waldorf service areas constrained by the 80-percent management level (Scheme 4A) and pump intakes (Scheme 4B).

A maximum of 7.8 million gallons per day can be withdrawn by 2020 from existing wells in the Bryans Road service area and existing wells in the Waldorf service area (plus a proposed well at White Plains Business Park) when drawdown is constrained by the 80-percent management level. Approximately 1.7 million gallons per day were withdrawn from the Patuxent aquifer in the Bryans Road well field and 6.1 million gallons per day were pumped from Lower Patapsco wells in the Waldorf service area. The Lower Patapsco wells at Bensville, Dutton's Addition, Eutaw Forest, Laurel Branch, Bryans Road, and Strawberry Hills, which are located near the outcrop area where less available drawdown occurs, were not pumped.

A maximum of 7.0 million gallons per day can be withdrawn by 2020 from existing wells in the Bryans Road service area and existing wells in the Waldorf service area (plus a proposed well at White Plains Business Park) when drawdown is constrained by pump intakes. Approximately 1.2 million gallons per day were withdrawn from the Patuxent aquifer in the Bryans Road well field and 5.8 million gallons per day were withdrawn from the Lower Patapsco aquifer (5.3 and 0.5 million gallons per day from the Waldorf and Bryans Road service areas, respectively). Water levels in the Lower Patapsco aquifer fell below the 80-percent management level in a relatively small area just to the northwest of Bryans Road along the Potomac River.

Scheme 5: Future Patuxent aquifer production wells in the Bryans Road service area optimized for minimum total drawdown under a hypothetical 2020 water demand of 3 million gallons per day.

Total drawdown is minimized when three out of six hypothetical wells were pumped along with existing wells at Bryans Road (Wells 5 and 6). Each hypothetical well pumped 0.72 million gallons per day. The optimum withdrawal rates at Bryans Road Wells 5 and 6 were 0.12 and 0.72 million gallons per day, respectively. A large cone-of-depression formed over much of the Bryans Road service area by 2020 as a result of the withdrawals. Total pumping head at the five sites equaled 2,824 feet. Available drawdown remaining by 2020 ranged from 85 feet at Bryans Road Well 5 to 272 feet at Hypothetical Well 2.

INTRODUCTION

The Maryland Geological Survey conducted a study in 2003 that determined optimum withdrawal rates for production wells operated by the Charles County Department of Public Utilities in the Waldorf service area (Andreasen, 2003a). The main objective of the study was to minimize drawdown in the Lower Patapsco aquifer while pumping the required rate needed for both current and projected demand. Minimizing drawdown reduces well operational costs. In addition to minimizing drawdown, water levels were constrained from falling below the 80-percent management level. The optimization analysis utilized output from a ground-water-flow model that simulated flow in the Patuxent and Lower Patapsco aquifers throughout Charles County and surrounding areas (Andreasen, 1999). While head conditions in the northwestern part of Charles County (Bryans Road-Indian Head area) were included in the optimization analysis, ground-water withdrawals in that area were not optimized. This study expands the area where withdrawals are optimized by including Lower Patapsco and Patuxent production wells in the Bryans Road service area operated by the Charles County Department of Public Utilities (fig. 1). The Bryans Road service area includes the Bryans Road and Strawberry Hills well fields (tab. 1). Production wells in the Bryans Road well field include: Well 3 (CH Bc 76), Well 4 (CH Bd 50), Well 5 (CH Bc 78), and Well 6 (CH Bd 58). Production wells in the Strawberry Hills well field include: Well 1 (CH Bd 33) and Well 2 (CH Bd 35). Production wells in the Waldorf service area include: Smallwood West Well 11 (CH Be 58), Westwood Drive Well 15 (CH Be 71), Billingsley Road Well 12 (CH Be 64), White Oak Well 10 (CH Bf 150), Cleveland Park Well 14 (CH Be 67), St. Paul Well 9 (CH Bf 147), Bensville Wells 1 and 2 (CH Bd 57 and 51), Dutton's Addition (CH Bd 49), Eutaw Forest Wells 1, 2, and 3 (CH Bd 44, 40, and 46), Laurel Branch Wells 1, 3, and 4 (CH Bd 39, 47, and 48), and proposed Well 16 (White Plains Business Park) (fig. 2; tab. 2).

PRODUCTION WELLS IN THE BRYANS ROAD SERVICE AREA

In 2002 an average of 0.2 million gallons per day (Mgal/d) was withdrawn by the Charles County Department of Public Utilities for public supply in the Bryans Road service area. The water was withdrawn from a total of five wells, three in the Bryans Road well field and two in the Strawberry Hills well field. In the Bryans Road well field two of the wells, Well 3 (CH Bc 76) and Well 4 (CH Bd 50), are screened in the Lower Patapsco aquifer and one well, Well 5 (CH Bc 78), is screened in the Patuxent aquifer (tab. 1). A second Patuxent well, Well 6 (CH Bd 58), was under construction in 2004. The wells at Strawberry Hills, Well 1 (CH Bd 33) and Well 2 (CH Bd 35), are both screened in the Lower Patapsco aquifer. The Lower Patapsco wells have been in production the longest (since about 1992 for the Bryans Road well field and the late 1960's for the Strawberry Hills well field). The Patuxent well (Well 5) at Bryans Road, located in the South Hampton development, has been in production since 1997.

Table 1 contains well data for the Bryans Road service area. Specific capacity is a measurement of the supply potential of a well. It is dependent on both the hydrologic characteristics of the aquifer (transmissivity, storage, and aquifer boundaries) and the hydraulic characteristics of the well. Wells screened in very permeable formations and that have been developed thoroughly have a relatively high specific capacity. Conversely, poorly developed wells screened in low permeability formations have a relatively low specific capacity. Specific capacity for the wells screened in the Lower Patapsco aquifer in the Bryans Road and Strawberry Hills well fields range from 1.8 gallons per minute per foot of drawdown (gpm/ft) (Bryans Road Well 4) to 7.1 gpm/ft (Strawberry Hills Well 1) (tab. 1). Bryans Road Well 5 (Patuxent aquifer) has a specific capacity of 2.6 gpm/ft. Transmissivity, a measure of the ability of an aquifer to transmit water, was calculated at two sites: Bryans Road Well 3 (Lower Patapsco aquifer) at 1,130 feet squared per day (ft^2/d) and Bryans Road Well 5 (Patuxent aquifer) at 937 ft^2/d (tab. 1). Transmissivity values were calculated by the Jacob straight-line method from 24-hour, constant-rate aquifer tests (Fetter, 1980, p. 266).

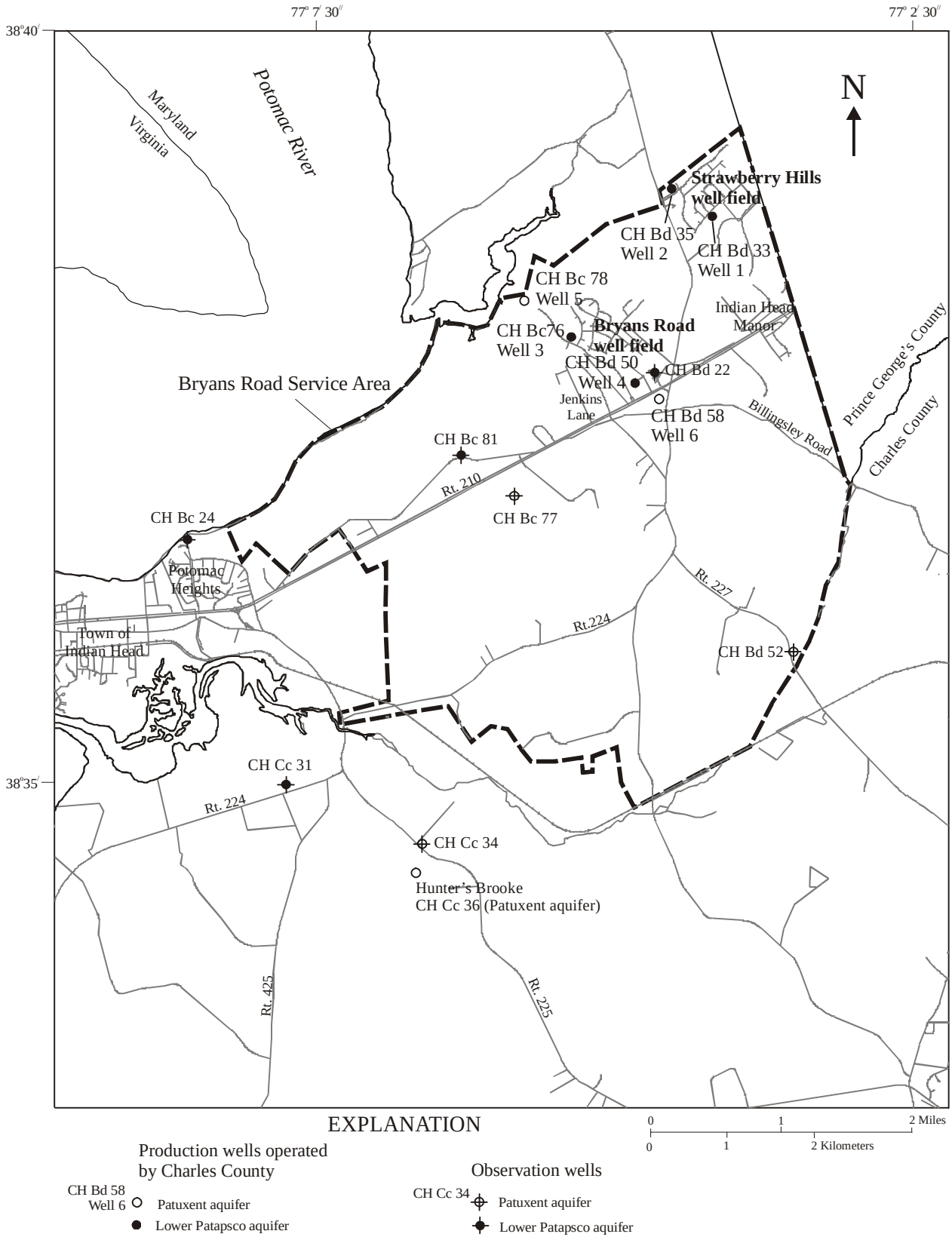

Figure 1. Location of production and observation wells in the Indian Head-Bryans Road area.

Table 1. Well data for the Lower Patapsco and Patuxent wells in the Bryans Road service area.

[ft = feet; in. = inch; gpm = gallons per minute; gpm/ft = gallons per minute per foot; ft^2/d = feet squared per day; Mgal/d = million gallons per day; Sydnor = Sydnor Hydrodynamics, Inc.; Schultes = A.C. Schultes of Maryland; Layne = Layne-Atlantic Co.; -- = data not available]

Well field	Well number (Owner's number)	State permit number	Aquifer	Ground-water appropriation permit number	Driller	Completion year	Altitude of land surface (ft)	Well depth (ft below land surface)	Diameter (in.)		Screen Position (ft below land surface)
									Casing	Screen	
Bryans Road	CH Bc 76 (Well 3)	CH-88-1638	Lower Patapsco	CH1955G003	Sydnor	1991	171	615	22, 16, 8	8	540 - 605
	CH Bd 50 (Well 4)	CH-88-2044	Lower Patapsco		Sydnor	1991	180	658	16, 8, 6	6	591 - 606; 618 - 638
	CH Bc 78 (Well 5)	CH-94-0394	Patuxent	CH1995G023	Sydnor	1995	34	800	10, 6	6	675 - 685; 710 - 790
	CH Bd 58 (Well 6)	CH-94-5552	Patuxent	CH1998G008	Schultes	2004	180	1108	12, 6	6	990 - 1,050; 1,086 - 1,098
Strawberry Hills	CH Bd 33 (Well 1)	CH-66-0079	Lower Patapsco	CH1966G005	Layne	1966	180	586	18, 10	10	536 - 556; 561 - 586
	CH Bd 35 (Well 2)	CH-72-0050	Lower Patapsco		Layne	1973	170	645	20, 10	10	595 - 645

Well field	Well number (Owner's number)	Water level (ft below land surface)		Pumping rate (gpm)	Date measured (month/year)	Specific capacity (gpm/ft) / Duration (hour)	Transmissivity (ft^2/d)	Approximate available drawdown in 2003, ft
		Static	Pumping					
Bryans Road	CH Bc 76 (Well 3)	262	351	400	6/1991	4.5 / 24	1,130	70
	CH Bd 50 (Well 4)	263	414	280	12/1991	1.8 / 24	--	110
	CH Bc 78 (Well 5)	16	310	750	9/1995	2.6 / 24	937	480
	CH Bd 58 (Well 6)	198	473	622	3/2004	2.3 / 72	1,210	550
Strawberry Hills	CH Bd 33 (Well 1)	194	250	400	8/1966	7.1 / 8	--	70
	CH Bd 35 (Well 2)	205	259	300	4/1973	5.6 / 8	--	40

Well field	Well number (Owner's number)	Design pumping rate, Mgal/d	Altitude of pump intake, ft related to sea level
Bryans Road	CH Bc 76 (Well 3)	0.65	-229
	CH Bd 50 (Well 4)	.20	-303
	CH Bc 78 (Well 5)	1.0	-376
	CH Bd 58 (Well 6)	0.72 (estimated)	400 (estimate)
Strawberry Hills	CH Bd 33 (Well 1)	.43	-177
	CH Bd 35 (Well 2)	.39	-230

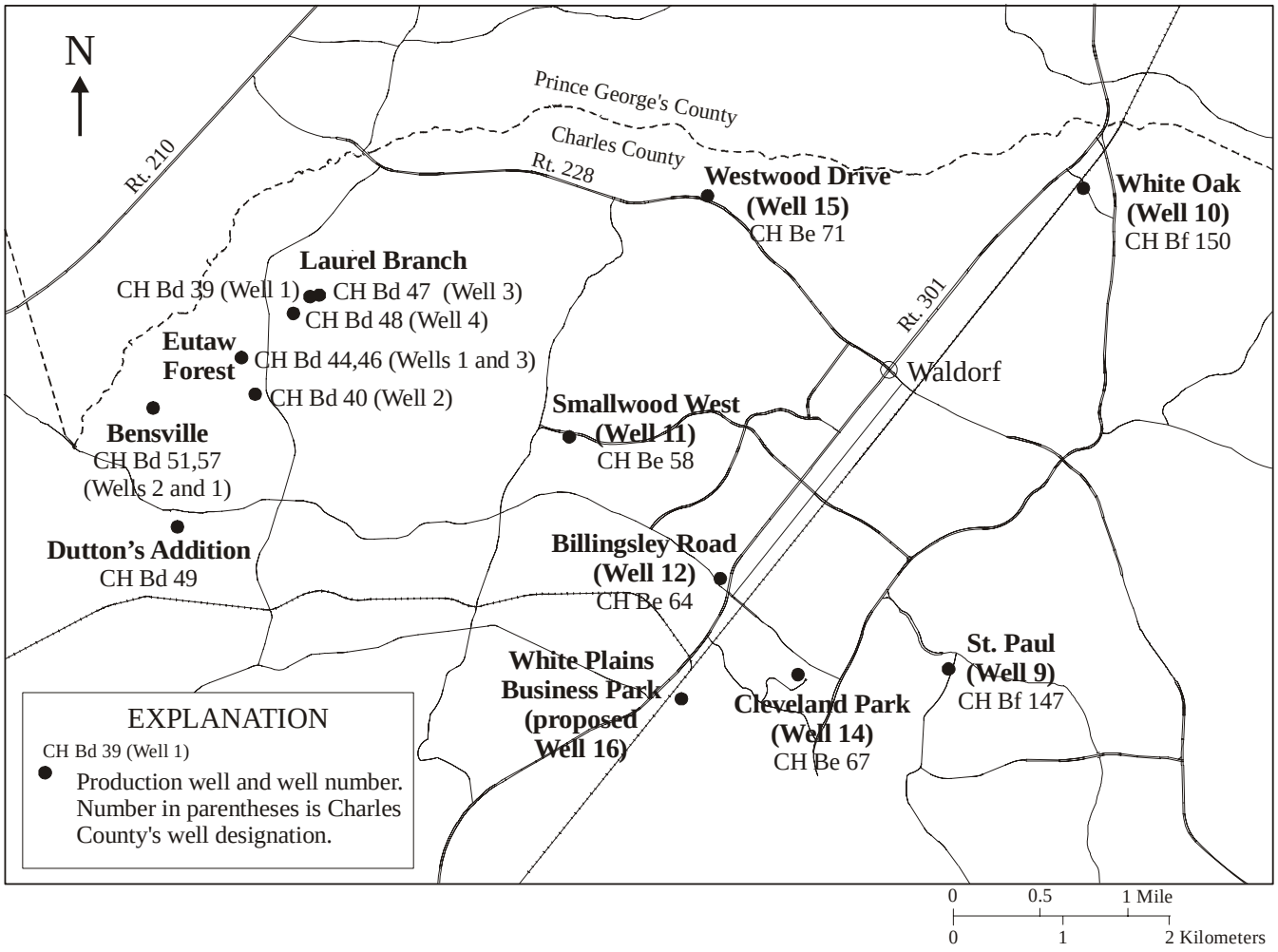

Figure 2. Location of Lower Patapsco production wells in the Waldorf service area.

WATER LEVELS AND AVAILABLE DRAWDOWN

Water levels in the Lower Patapsco aquifer measured in four wells in the Bryans Road-Indian Head area have declined between 4 and 14 feet (ft) since about 1996 (fig. 3). The decline in water levels prior to that period was significantly greater. The reduction in the rate of drawdown is attributed to a decrease in the rate of water withdrawn from the Lower Patapsco aquifer in the Bryans Road-Indian Head area (fig. 3). Withdrawals averaged 2.1 Mgal/d from 1986 to 1995 and 1.6 Mgal/d from 1996 to 2002 (Judith Wheeler, U.S. Geological Survey, personal communication, 2003). Lower Patapsco pumpage in the Bryans Road-Indian Head area shown in figure 3 includes withdrawals only from sites appropriated for an average amount of 10,000 gallons per day (gal/d) or more. Those sites include the Bryans Road well field, the Strawberry Hills well field, Indian Head Manor, Potomac Heights, Town of Indian Head, Jenkins Lane, and the U.S. Naval Surface Warfare Center (NSWC). Individual, residential withdrawals, estimated to be approximately 0.16 Mgal/d in the larger area of northwestern Charles County, are not included (Andreasen, 1999, p. 37). In part, the reduction in pumpage from the Lower Patapsco aquifer is a result of shifting pumpage in the Bryans Road well field to the deeper Patuxent aquifer.

Water levels in the Patuxent aquifer measured in an observation well (CH Bc 77) in the Bryans Road-Indian Head area were relatively stable prior to 1997 (fig. 3). As water was pumped from Bryans Road Well 5 water levels in the aquifer declined. Bryans Road Well 5 and a

Table 2. Well data for the Lower Patapsco wells in the Waldorf service area.

[ft = feet; in. = inch; -- = no data; Layne = Layne-Atlantic Co.; Schultes = A.C. Schultes of Maryland; Sydnor = Sydnor Hydrodynamics, Inc.; Shannahan = Shannahan Artesian Well Co.]

Well field	Well number (Owner's number)	State permit number	Ground-water appropriation permit number	Driller	Completion year	Altitude of land surface (ft)	Well depth (ft below land surface)	Diameter (in.)		Screen Position (ft below land surface)
								Casing	Screen	
Smallwood West	CH Be 58 (Well 11)	--	CH1983G112	Layne	1985	210	1,160	16, 8	8	925-964, 1,048-1,160
Westwood Drive	CH Be 71 (Well 15)	CH-94-3965	CH1983G512	Schultes	2001	220	1,225	18, 8	8	855-890, 1,035-1,055, 1,125-1,155, 1,205-1,220
Billingsley Road	CH Be 64 (Well 12)	CH-88-0341	CH1983G312	Sydnor	1989	210	1,173	18, 8	8	895-900, 915-925, 948-958, 1,077-1,102, 1,118-1,163
White Oak	CH Bf 150 (Well 10)	CH-81-1195	CH1983G212	Sydnor	1985	215	1,341	16, 8	8	797-800, 890-898, 938-970, 1,154-1,176, 1,204-1,240, 1,276-1,285, 1,306-1,336
Cleveland Park	CH Be 67 (Well 14)	CH-94-0464	CH1983G412	Schultes	1996	215	1,405	16, 8	8	970-975, 985-990, 1,014-1,022, 1,033-1,043, 1,072-1,084, 1,102-1,120, 1,148-1,158, 1,166-1,202, 1,218-1,238, 1,260-1,276, 1,286-1,298, 1,346-1,358, 1,372-1,400
St. Paul	CH Bf 147 (Well 9)	CH-81-0738	CH1983G012	Sydnor	1983	193	1,417	12	12	1,059-1,069, 1,073-1,083, 1,161-1,166, 1,170-1,180, 1,184-1,189, 1,195-1,205, 1,244-1,249, 1,252-1,262, 1,298-1,328, 1,342-1,417
Bensville	CH Bd 51 (Well 2)	CH-94-0037	CH1989G032	Sydnor	1995	185	1,040	8, 6	6	897-912, 934-944, 972-987, 1,010-1,035
	CH Bd 57 (Well 1)	CH-94-0724		Sydnor	1996	185	1,040	8, 6	6	920-940, 960-980, 984-999, 1,005-1,030
Dutton's Addition	CH Bd 49	CH-93-0385	CG1994G003	Sydnor	1994	183	1,045	8, 6	6	820-860, 995-1,040
Eutaw Forest	CH Bd 44 (Well 1)	CH-73-2500	CH1978G015	Sydnor	1980	180	822	6, 4	4	799-822
	CH Bd 40 (Well 2)	CH-73-2417		Sydnor	1979	185	904	4, 2	3	736-741, 825-846
	CH Bd 46 (Well 3)	CH-81-1714		Sydnor	1986	180	830	6, 4	4	700-730, 805-820
Laurel Branch	CH Bd 39 (Well 1)	CH-73-2377	CH1977G036	Shannahan	1979	200	900	6, 4	4	738-756, 769-774, 825-846, 866-886
	CH Bd 47 (Well 3)	CH-88-0124		Sydnor	1989	160	868	8, 6	6	734-779, 843-858
	CH Bd 48 (Well 4)	CH-88-0765		Sydnor	1990	130	825	8, 6	6	648-688, 747-762, 805-815

Table 2. Well data for the Lower Patapsco wells in the Waldorf service area—Continued.

[ft = feet; gpm = gallons per minute; gpm/ft = gallons per minute per foot; ft^2/d = feet squared per day; -- = no data or not applicable]

Well field	Well number (Owner's number)	Water level (ft below land surface)		Pumping rate (gpm)	Date measured (month-year)	Specific capacity (gpm/ft)	Transmissivity (ft^2/d) Drawdown phase (Recovery phase)	Well efficiency (percent)	Available drawdown in 2001, ft
		Static	Pumping						
Smallwood West	CH Be 58 (Well 11)	237	350	550	8-85	4.9	1,730	76	415
Westwood Drive	CH Be 71 (Well 15)	319	474	610	3-02	3.9	854 (1,708)	61	375
Billingsley Road	CH Be 64 (Well 12)	298	473	550	5-89	3.1	(1,070)	77	385
White Oak	CH Bf 150 (Well 10)	228	313	554	7-85	6.5	3,000	58	475
Cleveland Park	CH Be 67 (Well 14)	318	436	600	2-96	5.1	1,600	85	530
St. Paul	CH Bf 147 (Well 19)	207	317	510	2-84	4.6	1,000	65	550
Bensville	CH Bd 51 (Well 2)	280	362	275	3-95	3.4	890 (1,320)	69	140
	CH Bd 57 (Well 1)	309	425	280	6-96	2.4	980 (890)	62	140
Dutton's Addition	CH Bd 49	280	370	223	10-94	2.5	1,445 (1,041)	46	320
Eutaw Forest	CH Bd 44 (Well 1)	208	402	91	2-80	0.5	400	33	200
	CH Bd 40 (Well 2)	212	249	26	8-79	0.7	--	--	200
	CH Bd 46 (Well 3)	233	288	90	6-86	1.6	--	--	200
Laurel Branch	CH Bd 39 (Well 1)	219	260	88	6-79	2.1	--	--	240
	CH Bd 47 (Well 3)	305	377	140	1-89	1.9	544	93	240
	CH Bd 48 (Well 4)	243	290	200	5-90	4.2	--	--	240

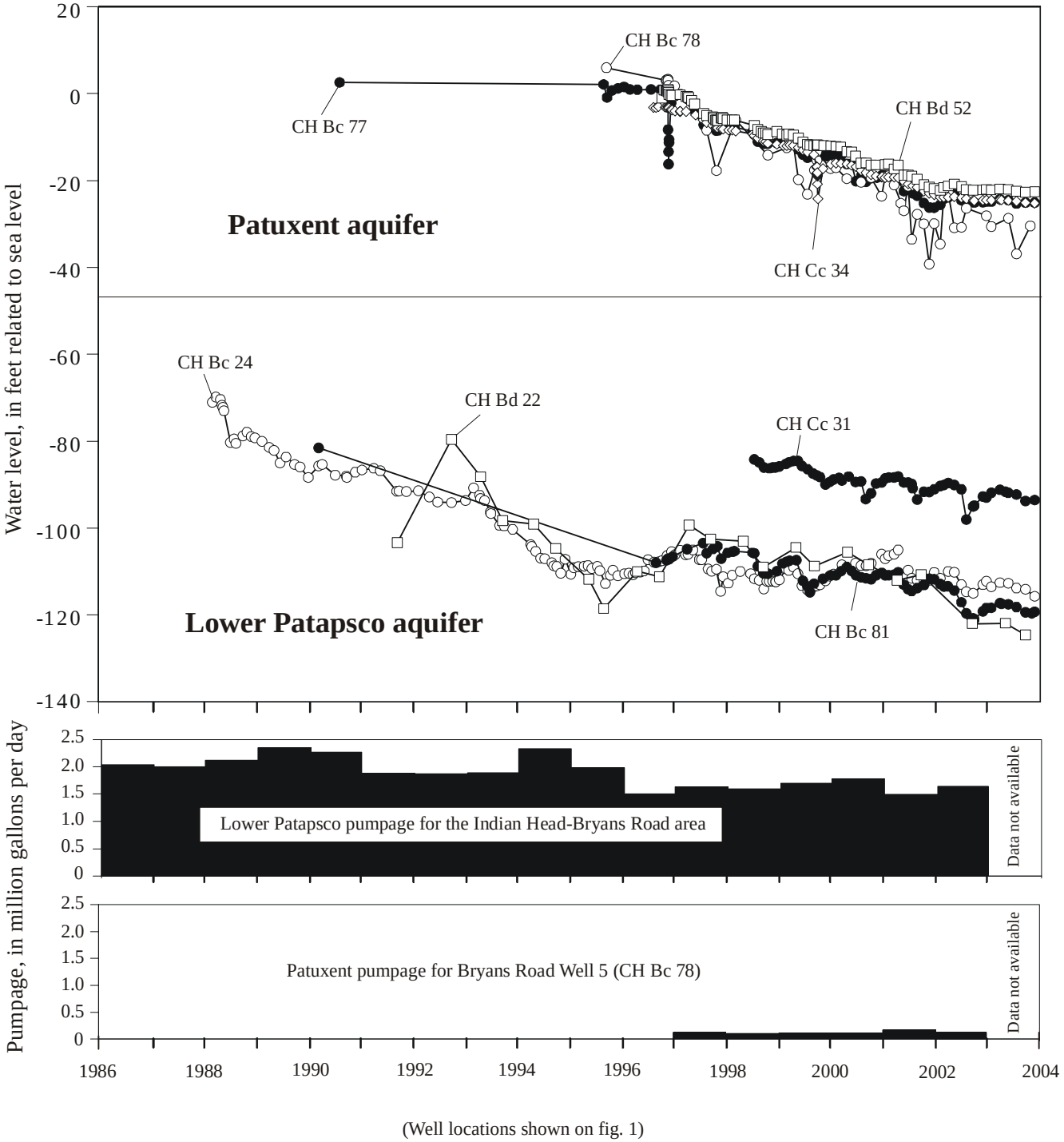

Figure 3. Water-level and pumpage trends in the Lower Patapsco and Patuxent aquifers in the Bryans Road-Indian Head area.

production well at the NSWC at Indian Head are the only wells withdrawing water from the Patuxent aquifer in Charles County. Withdrawals from Well 5 averaged 0.12 Mgal/d from the start of pumping in 1997 to 2002. Since about 2001 water-level decline in the Patuxent aquifer has begun to stabilize.

Available drawdown is defined in this report as the difference between the present potentiometric surface and the management level. The management level is defined as 80 percent of the difference between the estimated pre-pumping potentiometric surface and the top of the aquifer (Code of Maryland Regulations, 1997). In the Bryans Road well field available drawdown in the Lower Patapsco aquifer ranged from approximately 70 to 110 ft in Fall 2003. In the Strawberry Hills well field available drawdown ranged from approximately 40 to 70 ft in 2003. Available drawdown in the Patuxent aquifer is significantly greater, ranging from approximately 480 to 550 ft in 2003 at the Bryans Road well field.

OPTIMIZED WITHDRAWALS FROM THE LOWER PATAPSCO AND PATUXENT AQUIFERS

Possible options for supplying water to the Bryans Road service area include connecting the Bryans Road and Strawberry Hills well fields, connecting the Bryans Road and Waldorf service areas, and constructing additional production wells. Optimization modeling was used to test several water-supply options (Greenwald, 1998). Objective functions based on constraint criteria for each option were transformed into mathematical expressions used to solve the optimization problem. The ground-water- management model used in optimization is discussed in detail in Andreasen (2003a). The ground-water-flow model area includes all of Charles County, parts of Calvert, Prince George's, and St. Mary's Counties, and adjacent parts of the Virginia Coastal Plain (Andreasen, 2003a, p. 14). Optimization was conducted over an 18-year simulation period (2003 to 2020) using one-year stress periods. Withdrawals from individual managed wells were not allowed to exceed rates equal to continuous 24-hour discharge at design pumping rates. In optimization modeling head constraints may be applied to cells with managed well sites. For model cells with square dimensions simulated head can be converted to head occurring immediately outside the pumping well using the Thiem equation (Greenwald, 1998). Such well sites include Westwood Drive, White Oak, Bensville, Dutton's Addition, Eutaw Forest, Bryans Road, and Strawberry Hills. Over the simulation period heads assigned to the general-head boundaries in model layers representing the Lower Patapsco and Patuxent aquifers declined at a rate of 0.5 feet per year (ft/yr). This downward trend is a continuation of the regional head decline observed in the Lower Patapsco and Patuxent aquifers since about the mid-1980s (Curtin and Dine, 1995). Withdrawals from users appropriated for more than 10,000 gal/d from the Lower Patapsco aquifer outside the Waldorf and Bryans Road service areas were adjusted over the simulation period based on projected 2020 water demand (Andreasen, 1999, tab. 7, p. 62). Total pumpage from those users increased from 2.7 to 3.2 Mgal/d over the simulation period. The greatest increase in pumpage was simulated at La Plata where the 2020 withdrawals totaled 1.2 Mgal/d. Because withdrawals at the NSWC at Indian Head are not expected to increase significantly, the rate was held constant during the simulation period at 2002 levels (Kathy Frey, NSWC, personal communication, 2003).

Scheme 1: Optimum withdrawals in the Bryans Road well field to minimize total drawdown

In Scheme 1 withdrawals in the Bryans Road well field were optimized to minimize total drawdown in the production wells. Total drawdown is the summation of drawdown occurring in the production wells over the simulation period 2003 to 2020. During optimization the water demand for the Bryans Road well field was increased incrementally from 0.13 Mgal/d in 2003 to 0.64 Mgal/d in 2020. The 2020 water demand was calculated by multiplying the projected 2020 population for the Bryans Road Transportation Analysis Zone (TAZ) by a per capita water-use rate of 80 gal/d (Jason Groth, Charles County Department of Planning and Growth Management, personal communication, 2003). Withdrawals from the Strawberry Hills

well field were increased from a yearly average rate of 0.097 Mgal/d in 2002 to 0.11 Mgal/d in 2020 to reflect projected growth (Jason Groth, Charles County Department of Planning and Growth Management, personal communication, 2004). Lower Patapsco aquifer withdrawals from wells supplying water to the Waldorf service area totaled 6.5 Mgal/d by 2020 from one existing well (White Oak) and eight hypothetical wells located east of the Waldorf Development District (Scheme 7C in Addendum to Maryland Geological Survey Open-File Report No. 2003-02-17) (Andreasen, 2003a and 2003b) (fig. 4). Withdrawals from these wells were increased incrementally over the simulation period from 2.6 Mgal/d to 6.5 Mgal/d. A well screened in the Patuxent aquifer at Hunter's Brooke (CH Cc 36) (fig. 1) pumped 0.116 Mgal/d during the simulation. Water levels in the Lower Patapsco and Patuxent aquifers were not allowed to fall below the 80-percent management level.

Results of the optimization indicate that total drawdown was minimized when only Bryans Road Well 6 (CH Bd 58) screened in the Patuxent aquifer was pumped. By 2020 drawdown equaled 151 ft in Well 6. Withdrawals from the Lower Patapsco wells, significantly less than the Patuxent pumpage at the start of the simulation, were reduced to zero by 2008 (tab. 3). The simulated water level in 2020 for the model cell representing Well 6 was 169 ft below sea level compared to approximately 20 ft below sea level in 2002.

Scheme 2: Optimum withdrawals in the Bryans Road and Strawberry Hills well fields to minimize total drawdown

In Scheme 2 withdrawals in the Bryans Road and Strawberry Hills well fields were optimized to minimize total drawdown in the production wells. The Bryans Road and Strawberry Hills well fields were assumed connected. During optimization the water demand for the Bryans Road and Strawberry Hills well fields was increased incrementally from 0.22 Mgal/d in 2003 to 0.75 Mgal/d in 2020. The 2020 withdrawal rate is equal to the projected demand of 0.64 Mgal/d for the Bryans Road well field and 0.11 Mgal/d for the Strawberry Hills well field. Lower Patapsco aquifer withdrawals from wells supplying water to the Waldorf service area totaled 6.5 Mgal/d by 2020 from one existing well (White Oak) and eight hypothetical wells located east of the Waldorf Development District (Scheme 7C in Addendum to Maryland Geological Survey Open-File Report No. 2003-02-17) (Andreasen, 2003a and 2003b) (fig. 4). Withdrawals from these wells were increased incrementally over the simulation period from 2.6 Mgal/d to 6.5 Mgal/d. The Patuxent well at Hunter's Brooke pumped 0.116 Mgal/d during the simulation.

Results of the optimization indicate that total drawdown in the Bryans Road and Strawberry Hills well fields was minimized when only Bryans Road Well 5 (CH Bc 78) and Well 6 (CH Bd 58), both screened in the Patuxent aquifer, were pumped. Pumpage in Wells 5 and 6 equaled 0.03 and 0.72 Mgal/d, respectively, by 2020 (tab. 4). Pumpage from Well 5 was simulated in 2020 because Well 6 had reached its design rate. By 2020, total drawdown equaled 277 ft in Wells 5 and 6. The deepest simulated water level occurred at Well 6 at 191 ft below sea level. The water level in 2003 was approximately 25 ft below sea level at that site. Withdrawals from the Lower Patapsco wells, significantly less than the Patuxent pumpage at the start of the simulation, were reduced to zero by 2009 (tab. 4).

Scheme 3: Maximum withdrawals from the Bryans Road and Strawberry Hills well fields constrained by the 80-percent management level (Scheme 3A) and pump intakes (Scheme 3B)

In Scheme 3A withdrawals from the Bryans Road and Strawberry Hills well fields were maximized in each one-year stress period over the simulation period 2002-2020. Water levels were not allowed to fall below the 80-percent management level in either Charles County or southern Prince George's County. Water levels were not constrained immediately surrounding the managed wells. As in the previous schemes, Lower Patapsco aquifer withdrawals from wells supplying water to the Waldorf service area totaled 6.5 Mgal/d by 2020 from one existing well (White Oak) and eight hypothetical wells located east of the Waldorf Development District (Scheme 7C in Addendum to Maryland Geological Survey Open-File Report No. 2003-02-17) (Andreasen, 2003a and 2003b) (fig. 4). Withdrawals from these wells were increased incrementally over the simulation period from 2.6 Mgal/d to 6.5 Mgal/d. The Patuxent well at Hunter's Brooke pumped 0.116 Mgal/d during the simulation.

Results indicate that a total of 2.2 Mgal/d can be withdrawn from the Bryans Road and

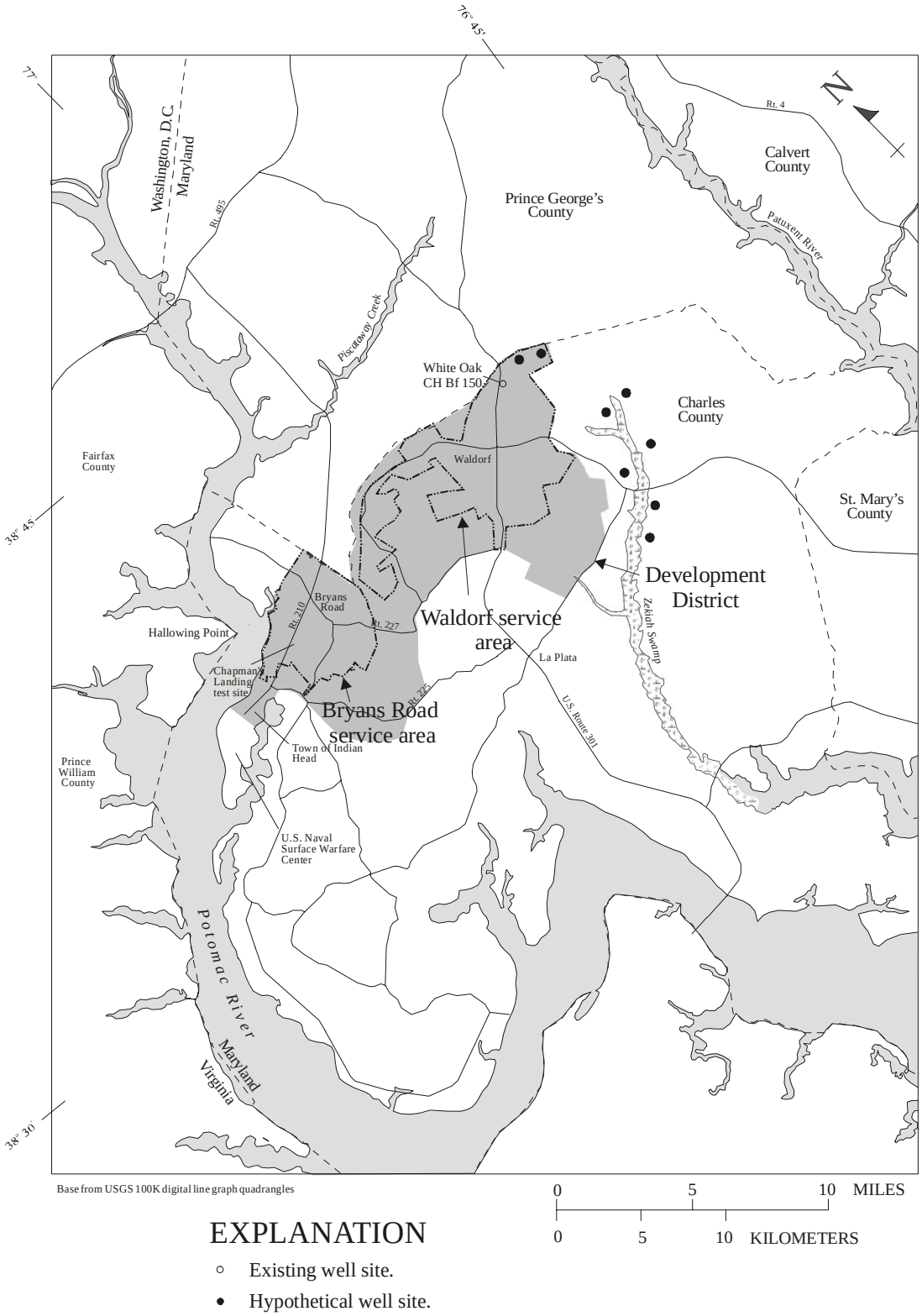

Figure 4. Location of wells supplying water to the Waldorf service area used in optimization schemes 1, 2, 3, and 5.

Table 3. Scheme 1: Optimized withdrawals from the Bryans Road well field producing the least amount of total drawdown.

[Mgal/d = million gallons per day]

Year (Stress period)	Optimized withdrawals from Bryans Road Well Field, Mgal/d			
	Lower Patapsco aquifer		Patuxent aquifer	
	CH Bc 76 Well 3	CH Bd 50 Well 4	CH Bc 78 Well 5	CH Bd 58 Well 6
2003 (1)	0.002	0.002	0	0.13
2004 (2)	.001	.001	0	.16
2005 (3)	.001	.001	0	.19
2006 (4)	.001	.001	0	.22
2007 (5)	.001	0	0	.25
2008 (6)	0	0	0	.28
2009 (7)	0	0	0	.31
2010 (8)	0	0	0	.34
2011 (9)	0	0	0	.37
2012 (10)	0	0	0	.40
2013 (11)	0	0	0	.43
2014 (12)	0	0	0	.46
2015 (13)	0	0	0	.49
2016 (14)	0	0	0	.52
2017 (15)	0	0	0	.55
2018 (16)	0	0	0	.58
2019 (17)	0	0	0	.61
2020 (18)	0	0	0	.64

Strawberry Hills well fields by 2020 without exceeding the 80-percent management level (tab. 5). Approximately 1.7 Mgal/d was withdrawn from the Patuxent aquifer in the Bryans Road well field and 0.46 Mgal/d was withdrawn from the Lower Patapsco aquifer in the Strawberry Hills well field. Withdrawals from the Lower Patapsco aquifer at Bryans Road were reduced to zero by 2013. Design pumping rates were reached in Bryans Road Well 5 (CH Bc 78) and Well 6 (CH Bd 58), and Strawberry Hills Well 1 (CH Bd 33). By 2020, water levels in the Lower Patapsco aquifer ranged from 116 ft below sea level in Bryans Road Well 3 (CH Bc 76) to 224 ft below sea level in Strawberry Hills Well 1 (CH Bd 33). Water levels are above the 80-percent management level in all areas except for the area immediately surrounding Strawberry Hills Well 1. At that location water levels were approximately 40 ft below the management level. Water levels in the Patuxent aquifer by 2020 were 398 and 340 ft below sea level at Bryans Road Well 5 (CH Bc 78) and Well 6 (CH Bd 58), respectively. Available drawdown remaining at Bryans Road Well 5 and Well 6 by 2020 equaled 110 and 240 ft, respectively.

In Scheme 3B withdrawals were maximized with the constraint that water levels not fall below pump intakes in the managed wells. The unmanaged wells were pumped at the same rates as in Scheme 3A. Results indicate that a total of 1.8 Mgal/d can be withdrawn by 2020 before water levels fall below pump intakes (tab. 6). Approximately 1.2 Mgal/d was withdrawn from the Patuxent aquifer in the Bryans Road well field and 0.59 Mgal/d was withdrawn from Lower Patapsco aquifer in the Bryans Road and Strawberry Hills well fields. By 2020, water levels in the Lower Patapsco aquifer ranged from 177 ft below sea level at Strawberry Hills Well 1 (CH Bd 33) to 260 ft below sea level at Bryans Road Well 4 (CH Bd 50). Water levels fell below the 80-percent management level in the Lower Patapsco aquifer in a relatively small area just to the northwest of Bryans Road along the Potomac River. By 2020 water levels in the Patuxent

Table 4. Scheme 2: Optimized withdrawals from the Bryans Road and Strawberry Hills well fields producing the least amount of total drawdown.

[Mgal/d = million gallons per day]

Year (Stress period)	Optimized withdrawals, Mgal/d[1]					
	Lower Patapsco aquifer		Patuxent aquifer		Lower Patapsco aquifer	
	Bryans Road well field				Strawberry Hills well field	
	CH Bc 76 Well 3	CH Bd 50 Well 4	CH Bc 78 Well 5	CH Bd 58 Well 6	CH Bd 33 Well 1	CH Bd 35 Well 2
2003 (1)	0.001	0.001	0	0.22	0.001	0.001
2004 (2)	.001	.0004	0	.26	.001	.001
2005 (3)	.0002	0	0	.28	.0009	.0009
2006 (4)	0	0	0	.32	.0006	.0007
2007 (5)	0	0	0	.35	.0004	.0004
2008 (6)	0	0	0	.38	.0001	.0003
2009 (7)	0	0	0	.41	0	0
2010 (8)	0	0	0	.44	0	0
2011 (9)	0	0	0	.47	0	0
2012 (10)	0	0	0	.50	0	0
2013 (11)	0	0	0	.53	0	0
2014 (12)	0	0	0	.56	0	0
2015 (13)	0	0	0	.59	0	0
2016 (14)	0	0	0	.62	0	0
2017 (15)	0	0	0	.65	0	0
2018 (16)	0	0	0	.68	0	0
2019 (17)	0	0	0	.71	0	0
2020 (18)	0	0	0.03	.72*	0	0

* Design pumping rate.

[1] Assumes that the Bryans Road and Strawberry Hills well fields will be connected by 2008.

aquifer were 376 and 400 ft below sea level at Bryans Road Well 5 (CH Bc 78) and Well 6 (CH Bd 58), respectively. Withdrawals were constrained by pump intakes in all wells except Bryans Road Well 4 (CH Bd 50) where the design pumping rate was reached before water levels fell below the pump intake.

Scheme 4: Maximum withdrawals from existing wells in the Bryans Road and Waldorf service areas constrained by the 80-percent management level (Scheme 4A) and pump intakes (Scheme 4B)

In Scheme 4A withdrawals from existing wells in the Bryans Road (Bryans Road and Strawberry Hills well fields) and Waldorf (including proposed Well 16 at White Plains Business Park) service areas were maximized in each one-year stress period over the simulation period 2003-2020. Locations of the Bryans Road and Waldorf service area wells are shown in figures 1 and 2. Water levels were not allowed to fall below the 80-percent management level in either Charles or southern Prince George's Counties. Water levels were not constrained immediately surrounding the managed wells. During optimization withdrawals from individual managed wells were also constrained to design pumping rates (tab. 7). The Patuxent well at Hunter's Brooke pumped 0.116 Mgal/d during the simulation.

Results indicate that a total of 7.8 Mgal/d can be withdrawn without exceeding the 80-percent management level in every stress period over the 18-year simulation period (tab. 7). Approximately 1.7 Mgal/d was withdrawn from the Patuxent aquifer in the Bryans Road well field and 6.1

Table 5. Scheme 3A: Maximum optimized withdrawals from the Bryans Road and Strawberry Hills well fields constrained by the 80-percent management level.

[Mgal/d = million gallons per day]

Year (Stress period)	Optimized withdrawals, Mgal/d					
	Lower Patapsco aquifer		Patuxent aquifer		Lower Patapsco aquifer	
	Bryans Road well field				Strawberry Hills well field	
	CH Bc 76 Well 3	CH Bd 50 Well 4	CH Bc 78 Well 5	CH Bd 58 Well 6	CH Bd 33 Well 1	CH Bd 35 Well 2
2003 (1)	0	0.20	1.0*	0.72*	0.43*	0.28
2004 (2)	0	.20	1.0*	.72*	.43*	.21
2005 (3)	0	.18	1.0*	.72*	.43*	.20
2006 (4)	0	.15	1.0*	.72*	.43*	.21
2007 (5)	0	.13	1.0*	.72*	.43*	.21
2008 (6)	0	.10	1.0*	.72*	.43*	.21
2009 (7)	0	.078	1.0*	.72*	.43*	.21
2010 (8)	0	.054	1.0*	.72*	.43*	.21
2011 (9)	0	.031	1.0*	.72*	.43*	.21
2012 (10)	0	.010	1.0*	.72*	.43*	.21
2013 (11)	0	0	1.0*	.72*	.43*	.20
2014 (12)	0	0	1.0*	.72*	.43*	.19
2015 (13)	0	0	1.0*	.72*	.43*	.16
2016 (14)	0	0	1.0*	.72*	.43*	.13
2017 (15)	0	0	1.0*	.72*	.43*	.11
2018 (16)	0	0	1.0*	.72*	.43*	.09
2019 (17)	0	0	1.0*	.72*	.43*	.07
2020 (18)	0	0	1.0*	.72*	.43*	.03

* Design pumping rate.

Mgal/d was withdrawn from the Lower Patapsco wells in the Waldorf service area. Individual pumping rates ranged from 0.19 to 1.0 Mgal/d (tab. 7). The Lower Patapsco wells at Bensville, Dutton's Addition, Eutaw Forest, Laurel Branch, Bryans Road, and Strawberry Hills, located near the outcrop area where available drawdown is less, were not pumped. By 2020, water levels in the Lower Patapsco aquifer ranged from 106 ft below sea level at Strawberry Hills Well 2 (CH Bd 35) to 284 ft below sea level at Cleveland Park (CH Be 67) (tab. 7). By 2020 water levels in the Patuxent aquifer were 403 and 345 ft below sea level at Bryans Road Wells 5 (CH Bc 78) and 6 (CH Bd 58), respectively.

In Scheme 4B withdrawals from wells in the Bryans Road and Waldorf service areas were maximized with the constraint that water levels not fall below pump intakes nor exceed the design pumping rates in the managed wells. Results indicate that a total of 7.0 Mgal/d can be withdrawn by 2020 (tab. 8). Approximately 1.2 Mgal/d were withdrawn from the Patuxent aquifer in the Bryans Road well field and 5.8 Mgal/d were withdrawn from the Lower Patapsco aquifer (5.3 and 0.5 Mgal/d from the Waldorf and Bryans Road service areas, respectively). Individual pumping rates ranged from 0.019 to 0.78 Mgal/d (tab. 8). By 2020, water levels in the Lower Patapsco aquifer ranged from 177 ft below sea level at Strawberry Hills Well 1 (CH Bd 33) to 356 ft below sea level at Bensville (CH Bd 51 and 57) (tab. 8). Water levels in the Patuxent aquifer by 2020 were 376 and 400 ft below sea level at Bryans Road Wells 5 (CH Bc 78) and 6 (CH Bd 58), respectively. At the time of optimization Well 16 at White Plains Business Park and Well 6 at Bryans Road had not been completed; therefore, estimated pump settings of 300 and 400 ft below sea level, respectively, were used. This pumping

Table 6. Scheme 3B: Maximum optimized withdrawals from the Bryans Road and Strawberry Hills well fields constrained by pump intakes.

[Mgal/d = million gallons per day]

Year (Stress period)	Optimized withdrawals, Mgal/d					
	Lower Patapsco aquifer		Patuxent aquifer		Lower Patapsco aquifer	
	Bryans Road well field				Strawberry Hills well field	
	CH Bc 76 Well 3	CH Bd 50 Well 4	CH Bc 78 Well 5	CH Bd 58 Well 6	CH Bd 33 Well 1	CH Bd 35 Well 2
2003 (1)	0.188	0.20*	0.69	0.72*	0.10	0.20
2004 (2)	.19	.20*	.60	.72*	.10	.20
2005 (3)	.18	.20*	.60	.72*	.098	.19
2006 (4)	.18	.20*	.53	.72*	.095	.19
2007 (5)	.19	.20*	.52	.72*	.093	.19
2008 (6)	.17	.20*	.51	.72*	.091	.19
2009 (7)	.17	.20*	.50	.72*	.089	.19
2010 (8)	.17	.20*	.50	.71	.087	.18
2011 (9)	.17	.20*	.50	.71	.085	.18
2012 (10)	.16	.20*	.50	.71	.083	.18
2013 (11)	.16	.20*	.45	.70	.081	.18
2014 (12)	.16	.20*	.49	.70	.079	.18
2015 (13)	.16	.20*	.49	.70	.077	.17
2016 (14)	.16	.20*	.49	.70	.075	.17
2017 (15)	.15	.20*	.49	.70	.073	.17
2018 (16)	.15	.20*	.49	.70	.071	.17
2019 (17)	.15	.20*	.49	.70	.069	.17
2020 (18)	.15	.20*	.49	.70	.066	.17

* Design pumping rate.

scheme caused water levels in the Lower Patapsco aquifer to fall below the 80-percent management level in a relatively small area just to the northwest of Bryans Road along the Potomac River.

Scheme 5: Future Patuxent aquifer production wells in the Bryans Road service area optimized for minimum total drawdown under a hypothetical 2020 water demand of 3 million gallons per day

In this scheme, three Patuxent aquifer production well sites were selected out of six candidate sites in the Bryans Road service area (fig. 5). Each well was required to pump 0.72 Mgal/d. The two existing production wells in the Bryans Road well field (Well 5—CH Bc 78 and Well 6—CH Bd 58) (fig. 5) were also allowed to pump up to their design rates. The hypothetical wells and the existing wells were required to pump a total of 3 Mgal/d over the simulation period (2003-2020). During optimization total drawdown was minimized at all existing and candidate well sites. Once a hypothetical well was selected as active by the optimization algorithm, it remained active for the duration of the simulation period. Withdrawals from existing Lower Patapsco wells in the Strawberry Hills and Bryans Road well fields were fixed at the rates determined in optimization Scheme 3A, in which withdrawals were maximized without exceeding the 80-percent management level. By 2020 the amount pumped from the Strawberry Hills well field had decreased to 0.46 Mgal/d. The Lower Patapsco wells in the Bryans Road well field were phased out by 2013. Lower Patapsco aquifer withdrawals from wells supplying water to the Waldorf service area totaled 6.5 Mgal/d by 2020 from one existing well (White Oak) and eight hypothetical wells located east of the Waldorf

Table 7. Scheme 4A: Maximum optimized withdrawals from the Lower Patapsco and Patuxent aquifers in the Bryans Road and Waldorf service areas constrained by the 80-percent management level.

[Mgal/d = million gallons per day; ft = feet]

Well site	Well number (Owner's number)	Design pumping rate, Mgal/d	Optimized withdrawals, Mgal/d	Simulated model-cell head in stress period 18 (2020), ft related to sea level
Smallwood West	CH Be 58	0.72	0.72	-274
Westwood Drive	CH Be 71	.94	.94	-264
Billingsley Road	CH Be 64	.72	.72	-282
White Oak	CH Bf 150	1.0	1.0	-184
Cleveland Park	CH Be 67	.83	.83	-284
St. Paul	CH Bf 147	.52	.52	-252
Bensville	CH Bd 51 (Well 2)	.36	0	-202
	CH Bd 57 (Well 1)	.39		
Dutton's Addition	CH Bd 49	.22	0	-207
Eutaw Forest	CH Bd 44 (Well 1)	.10	0	-226
	CH Bd 46 (Well 3)	.13		
	CH Bd 40 (Well 2)	.06	0	-224
Laurel Branch	CH Bd 48 (Well 4)	.43	.43	-257
	CH Bd 39 (Well 1)	.19		
	CH Bd 47 (Well 3)	.19	.19	-278
Proposed well at White Plains	Well 16	.72	.72[2]	-282
Bryans Road	CH Bc 76 (Well 3)	.65	0	-119
	CH Bd 50 (Well 4)	.2	0	-131
	CH Bc 78[1] (Well 5)	1.0	1.0	-403
	CH Bd 58[1] (Well 6)	.72	.72[2]	-345
Strawberry Hills	CH Bd 33 (Well 1)	.43	0	-120
	CH Bd 35 (Well 2)	.39	0	-106
			Total = 7.8 Mgal/d	

[1] Well screened in the Patuxent aquifer. All other wells in table are screened in the Lower Patapsco aquifer.

[2] No pump installed. Design rate was selected for use in optimization analysis.

Table 8. Scheme 4B: Maximum optimized withdrawals from the Lower Patapsco and Patuxent aquifers in the Bryans Road and Waldorf service areas constrained by pump intakes.

[Mgal/d = million gallons per day; ft = feet]

Well site	Well number (Owner's number)	Design pumping rate, Mgal/d	Pump intake, ft related to sea level	Optimized withdrawal in stress period 18 (2020), Mgal/d	Simulated head in stress period 18 (2020), ft related to sea level
Smallwood West	CH Be 58	0.72	-240	0.35	-240[3]
Westwood Drive	CH Be 71	.94	-340	.76	-340[4]
Billingsley Road	CH Be 64	.72	-490	.72	-267[3]
White Oak	CH Bf 150	1.0	-200	.78	-200[4]
Cleveland Park	CH Be 67	.83	-268	.77	-268[3]
St. Paul	CH Bf 147	.52	-257	.52	-238[3]
Bensville	CH Bd 51 (Well 2)	.36	-374	.39	-356[4]
	CH Bd 57 (Well 1)	.39	-382		
Dutton's Addition	CH Bd 49	.22	-237	.093	-237[4]
Eutaw Forest	CH Bd 44 (Well 1)	.10	-261	.088	-261[4]
	CH Bd 46 (Well 3)	.13	-303		
	CH Bd 40 (Well 2)	.06	-235	.019	-235[4]
Laurel Branch	CH Bd 48 (Well 4)	.43	-215	0	-215[3]
	CH Bd 39 (Well 1)	.19	-353		
	CH Bd 47 (Well 3)	.19	-325	.15	-221[3]
Proposed well at White Plains	Well 16	.72	-300[2]	.72	-268[3]
Bryans Road	CH Bc 76 (Well 3)	.65	-229	.11	-229[4]
	CH Bd 50 (Well 4)	.2	-303	.2	-286[4]
	CH Bc 78[1] (Well 5)	1.0	-376	.48	-376[4]
	CH Bd 58[1] (Well 6)	.72	-400[2]	.69	-400[4]
Strawberry Hills	CH Bd 33 (Well 1)	.43	-177	.029	-177[4]
	CH Bd 35 (Well 2)	.39	-230	.14	-230[4]
				Total = 7.0 Mgal/d	

[1] Well screened in the Patuxent aquifer. All other wells in table are screened in the Lower Patapsco aquifer.
[2] No pump installed. Depth was selected for use in optimization analysis.
[3] Model-cell head.
[4] Head calculated immediately outside pumping well.

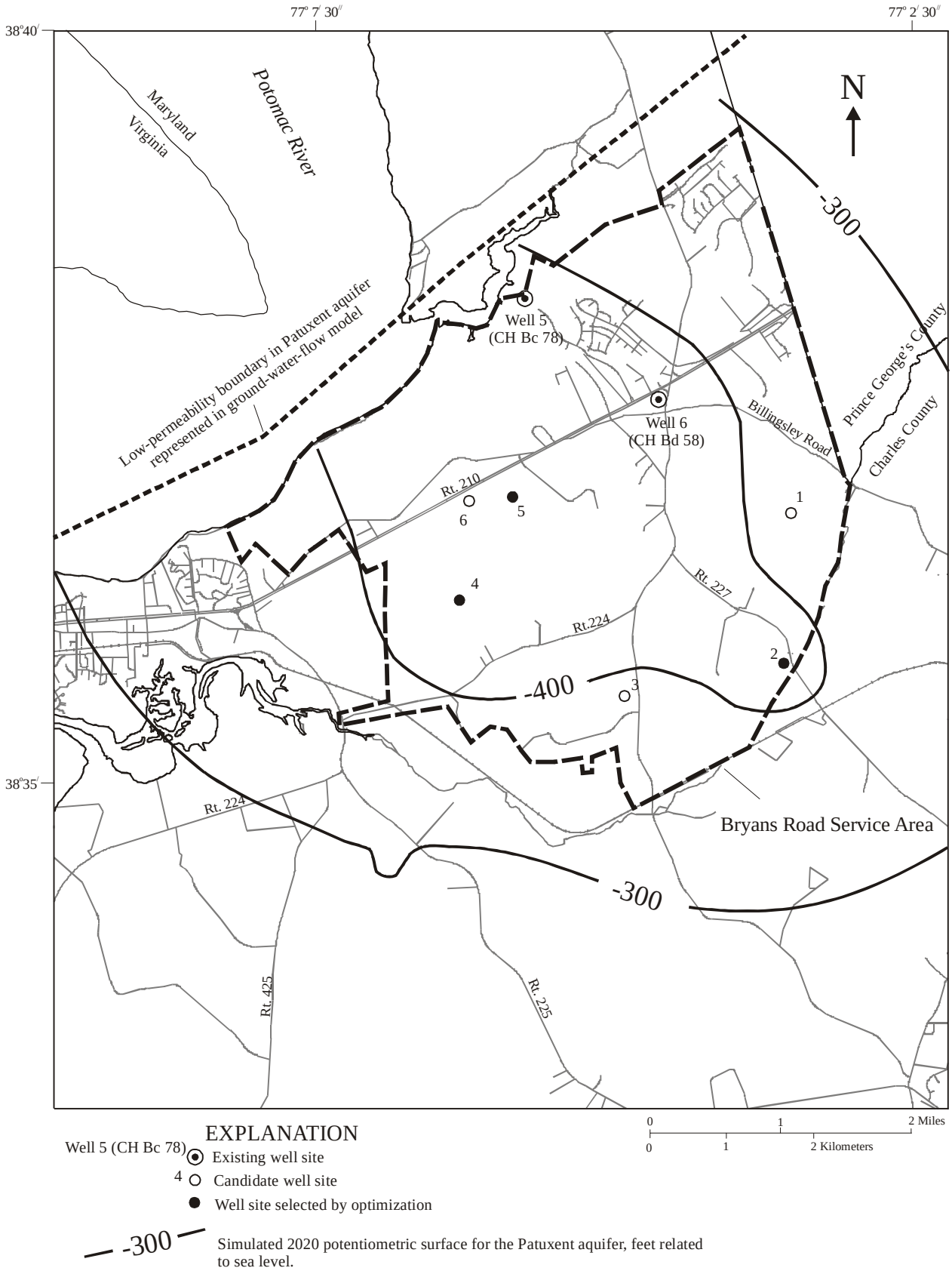

Figure 5. Location of Patuxent aquifer production well sites selected by optimization in the Bryans Road service area (Scheme 5).

Development District (Scheme 7C in Addendum to Maryland Geological Survey Open-File Report No. 2003-02-17) (Andreasen, 2003a and 2003b) (fig. 4). Withdrawals from these wells were increased incrementally over the simulation period from 2.6 Mgal/d to 6.5 Mgal/d. The Patuxent well at Hunter's Brooke pumped 0.116 Mgal/d during the simulation.

Results of optimization indicate that total drawdown is minimized when Hypothetical Wells 2, 4, and 5 were pumped. The optimum withdrawal rates at Bryans Road Wells 5 and 6 were 0.12 and 0.72 Mgal/d, respectively (tab. 9). A large cone-of-depression formed over much of the Bryans Road service area by 2020 as a result of the withdrawals (fig. 5). By 2020 simulated water levels at the withdrawal sites ranged from 423 to 495 ft below sea level (tab. 9). Total pumping head at the five sites equaled 2,824 ft. Available drawdown remaining by 2020 ranged from 85 ft at Bryans Road Well 5 to 272 ft at Hypothetical Well 2.

Table 9. Scheme 5: Optimized withdrawal rates producing the minimum amount of total drawdown in the Patuxent aquifer.

[Mgal/d = million gallons per day; ft = feet]

Well site	Well number (Owner's number)	Optimized withdrawal rate in stress period 18 (2020), Mgal/d	Drawdown[1], ft	Simulated pumping level, ft related to sea level	Simulated pumping level, ft below land surface
Bryans Road well field	CH Bc 78 (Well 5)	0.12	-423-(-20) = 403	-423	457
	CH Bd 58 (Well 6)	.72[2]	-480-(-20) =460	-480	660
Hypothetical Well 2		.72	-495-(-21) =474	-495	595[3]
Hypothetical Well 4		.72	-454-(-22) =432	-454	554[3]
Hypothetical Well 5		.72	-458-(-21) =437	-458	558[3]
					Total = 2,824

[1] Drawdown is the difference between heads at the end of the simulation period (2020) with and without the managed wells.
[2] Design pumping rate.
[3] Assumes a land surface altitude of 100 ft

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