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OPTIMIZATION OF GROUND-WATER WITHDRAWALS IN THE LOWER PATAPSCO AQUIFER, WALDORF, MARYLAND

by

David C. Andreasen

Prepared by Maryland Geological Survey
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in cooperation with the
Charles County Department of Planning
and Growth Management
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OPTIMIZATION OF GROUND-WATER WITHDRAWALS IN THE LOWER PATAPSCO AQUIFER, WALDORF, MARYLAND

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KEY RESULTS

The north-central part of Charles County, Maryland is supplied by a network of wells screened in the Magothy and Lower Patapsco aquifers. The wells, operated by the Charles County Department of Utilities, supply water to the Waldorf area and to several communities located west of Waldorf. In 2001, averages of approximately 2.4 and 2.6 million gallons per day were pumped from the Magothy and Lower Patapsco aquifers, respectively. In response to pumping, water levels in both aquifers have declined. The greatest amount of drawdown has occurred in the Lower Patapsco aquifer with water levels as deep as 170 feet below sea level. Pumping water levels may be as deep as 550 feet below land surface, resulting in substantial pumping costs. The Lower Patapsco aquifer is a good source for municipal supply in the Waldorf area because it has relatively high transmissivity (up to 3,000 feet squared per day) and sufficient available drawdown (up to 550 feet in the eastern part of the Waldorf area in 2001). However, increased use, possibly as much as 5 million gallons per day if pumpage is shifted from the shallower Magothy aquifer, will cause additional drawdown and higher pumping costs. Additionally, increased withdrawals from the Lower Patapsco aquifer may cause water levels to fall below the 80-percent management level in the Indian Head-Bryans Road area, which is located west of the project area. To address these concerns, withdrawals from the Lower Patapsco aquifer were optimized to minimize drawdown. Optimization was performed using a three-dimensional ground-water-flow model (MODFLOW code) combined with linear programming (MODMAN and SuperLINDO codes). Optimum withdrawals were also determined given constraints that water levels not fall below management levels or pump intakes.

- **Maximizing withdrawals in the existing Lower Patapsco Waldorf well system while constraining water levels above pump intakes (Scheme 1, pgs. 18 to 20)**

  Billingsley Road Well 12, Cleveland Park Well 14, St. Paul Well 9, and Bensville Wells 1 or 2 can pump continuously at design rates without causing water levels to fall below pump intakes. Water levels at Smallwood West Well 11, Westwood Drive Well 15, White Oak Well 10, Dutton’s Addition, and Eutaw Forest reach pump intakes at rates less than the design rates. Withdrawal from Laurel Branch Well 4 (CH Bd 48) is constrained by the pump intake in the adjacent model cell containing Laurel Branch Wells 1 and 3 (CH Bd 39 and 47). The total optimized withdrawal rate equals 5.6 million gallons per day, which is approximately 3 million gallons per day more than the average annual amount withdrawn in 2001.

- **Maximizing withdrawals while constraining water levels above the top of the Lower Patapsco aquifer and the 80-percent management level in the Lower Patapsco Waldorf well system (Scheme 2, pgs. 20 to 21)**

  Withdrawals can increase up to the design rates for each well while water levels remain above the top of the aquifer and the 80-percent management level in the Lower Patapsco Waldorf well system. Pumpage at the individual well sites ranges from 0.05 to 1.01 million gallons per day. The total withdrawal rate equals 6.2 million gallons per day. Simulated water levels range from 13 to 640 feet above the top of the aquifer at the 12 well sites and 40 to 490 feet above the 80-percent management level in the surrounding model cells. The 80-percent management level is exceeded in a small area along the Potomac River shoreline northwest of Bryans Road.

- **Maximizing withdrawals in the existing Lower Patapsco Waldorf well system while constraining water levels above the 80-percent management level in the Bryans Road Area (Scheme 3, pg. 21)**

If pumpage at the Bensville site is phased out over a 2-year period, a maximum of 5.8 million gallons per day can be pumped from the remaining sites without exceeding the 80-percent management level in the Indian Head-Bryans Road area.

- **Minimizing total drawdown in the existing Lower Patapsco Waldorf well system while pumping cumulative rates of 2.6 and 5.0 million gallons per day (Scheme 4, pgs. 21 to 26)**

At a cumulative rate of 2.6 million gallons per day with all wells pumping a minimum daily rate equal to 6 hours of pumping at design rates, the minimum total drawdown equaled 885 feet (3,739 feet of total pumping head). Pumping rates in individual production wells ranged from 0.014 to 1.0 million gallons per day. When wells were allowed to shut off, total drawdown was reduced to 378 feet (1,384 feet of total pumping head). Pumping rates in individual production wells ranged from 0.24 to 1.0 million gallons per day. Optimizing withdrawals, while requiring the wells to pump a minimum amount, increased total pumping head by approximately 5 percent from the simulated 2001 amount of 3,549 feet. The amount is greater under the optimized scheme because Westwood Drive (Well 15) was not pumped in 2001. When withdrawals are optimized using the well configuration pumped in 2001 (Westwood Drive Well 15 not pumped), total pumping head is reduced to 3,429 feet, or 3.4 percent less than the simulated 2001 total pumping head. Optimizing withdrawals while allowing the wells to shut off reduced total pumping head by 61 percent from the 2001 amount.

At a cumulative rate of 5.0 million gallons per day with all wells pumping a minimum daily rate equal to 6 hours of pumping at design rates, the minimum total drawdown equaled 1,772 feet (4,626 feet of total pumping head). Pumping rates in individual production wells ranged from 0.014 to 1.0 million gallons per day. When wells were allowed to shut off, total drawdown was reduced to 1,253 feet (3,234 feet of total pumping head). Pumping rates in individual production wells ranged from 0.046 to 1.0 million gallons per day. Water levels did not fall below the 80-percent management level in the Indian Head-Bryans Road area.

- **Minimizing total drawdown in the existing Lower Patapsco Waldorf well system and in a proposed well at the White Plains Business Park (Well 16) while pumping at cumulative rates of 2.6 and 5.0 million gallons per day (Scheme 5, pgs. 26 to 30)**

At a cumulative rate of 2.6 million gallons per day with all wells pumping a minimum daily rate equal to 6 hours of pumping at design rates, the minimum total drawdown equaled 958 feet (4,066 feet of total pumping head). Pumping rates in individual production wells ranged from 0.014 to 1.0 million gallons per day. When wells were allowed to shut off, total drawdown was reduced to 362 feet (1,362 feet of total pumping head). Pumping rates in individual production wells ranged from 0.35 to 1.0 million gallons per day.

At a cumulative rate of 5.0 million gallons per day with all wells pumping a minimum daily rate equal to 6 hours of pumping at design rates, the minimum total drawdown equaled 1,892 feet (5,001 feet of total pumping head). Pumping rates in individual production wells ranged from 0.014 to 1.0 million gallons per day. When wells were allowed to shut off, total drawdown was reduced to 1,183 feet (2,949 feet of total pumping head). Pumping rates in individual production wells ranged from 0.26 to 1.0 million gallons per day.

- **Scheme 6: Selection of future well site producing the least amount of drawdown (Scheme 6, pgs. 30 to 35)**

One well site was selected out of four candidate sites located in areas with at least 450 feet of available drawdown. The selected site is located approximately 1 mile east of the White Oak well site in an area of relatively high transmissivity. The total optimized pumpage from the existing well sites, the proposed well site at White Plains Business Park (Well 16), and the hypothetical well equaled 2.6 million gallons per day. Optimized withdrawals totaled 980 feet (4,327 feet of total pumping head) with all wells pumping a minimum daily rate equal to 6 hours of pumping at design rates. Adding the White Plains Business Park well and the hypothetical well and optimizing pumpage, increased total pumping head by 22 percent from the simulated 2001 amount of 3,549 feet.

When the existing wells and proposed well at the White Plains Business Park (Well 16) were allowed to shut off, total drawdown equaled 323 feet (1,286 feet total pumping head) for a 64-percent reduction in total pumping head compared to 2001. The same site was selected for the hypothetical well as in the previous optimization.

INTRODUCTION

The north-central part of Charles County, Maryland is supplied by 24 production wells operated by the Charles County Department of Utilities. This well system, referred to in this report as the Waldorf well system, supplies water to the Waldorf area and to the communities of Bensville, Dutton's Addition, Eutaw Forest, and Laurel Branch located to the west of Waldorf (fig. 1). Fifteen of the wells are screened in the Lower Patapsco aquifer and nine are screened in the shallower Magothy aquifer. The Magothy and Lower Patapsco aquifers are the most productive aquifers underlying this part of Charles County. The Upper Patapsco aquifer is either absent or is a relatively thin layer hydraulically connected to the Magothy aquifer. The Patuxent aquifer, underlying the Lower Patapsco aquifer, consists of thin, muddy sands. Transmissivity of the Patuxent aquifer determined in a test well at the Smallwood West well field was 30 feet squared per day (ft^2/d) (Wilson and Fleck, 1990). This value may be lower than the actual transmissivity of the entire aquifer because of partial penetration and difficulty in developing the well. Additional data on the hydraulic properties of the Patuxent aquifer in this area is needed to better assess its water-supply capability. In 2001, averages of 2.6 and 2.4 million gallons per day (Mgal/d) were pumped from the Lower Patapsco and Magothy aquifers, respectively, in the Waldorf well system. This system also receives water from the Washington Suburban Sanitary Commission (WSSC). Approximately 10 million gallons were supplied by WSSC in 2001 for testing and flushing the supply interconnection (Jerome Michael, per. comm., 2002).

OBJECTIVES

The objectives of this study are to: (1) maximize Lower Patapsco aquifer withdrawals in the Waldorf well system while maintaining water levels above pump intakes and management levels in the well field and in the Indian Head-Bryans Road area; (2) minimize drawdown in the Lower Patapsco aquifer in the Waldorf well system while pumping a cumulative rate of 2.6 Mgal/d (average amount pumped in 2001); (3) minimize drawdown in the Lower Patapsco aquifer in the Waldorf well system while pumping a cumulative rate of 5 Mgal/d (average amount pumped from both the Lower Patapsco and Magothy aquifers in the Waldorf well system in 2001); and, (4) select a site for a future well in an area that would produce the least amount of drawdown in the Waldorf well system.

PURPOSE

Withdrawals from the Lower Patapsco aquifer in the Waldorf well system combined with other withdrawals in Charles and Prince George's Counties have caused water levels to decline to altitudes as deep as 173 feet (ft) below sea level at Waldorf (Curtin and others, 2002d). Pumping levels inside production wells are as much as 550 ft below land surface. Pumping water from greater depths increases energy (Anderson, 1963, p. 126) and maintenance costs[1]. The purpose of this study is to optimize withdrawals from the Lower Patapsco production wells in the Waldorf well system in a way that reduces drawdown, and in turn, pumping cost. The optimized pumping rate can be used to devise pumpage distribution schemes and locate new well sites. Additionally, withdrawals in the Waldorf area could cause water levels to fall below the 80-percent management level in the Indian Head-Bryans Road area (Andreasen, 1999). Pumping the Lower Patapsco production wells in the Waldorf well system at optimum rates which constrain water levels above the management level can lead to a more balanced use of the Lower Patapsco aquifer in northern Charles County.

ACKNOWLEDGMENTS

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[1] Cost per hour of operation = gallons per minute x total hydraulic head in feet x 0.746 x rate per kilowatt hour/ 3,960 x pump efficiency (60 to 70%) x motor efficiency (90 to 95%)

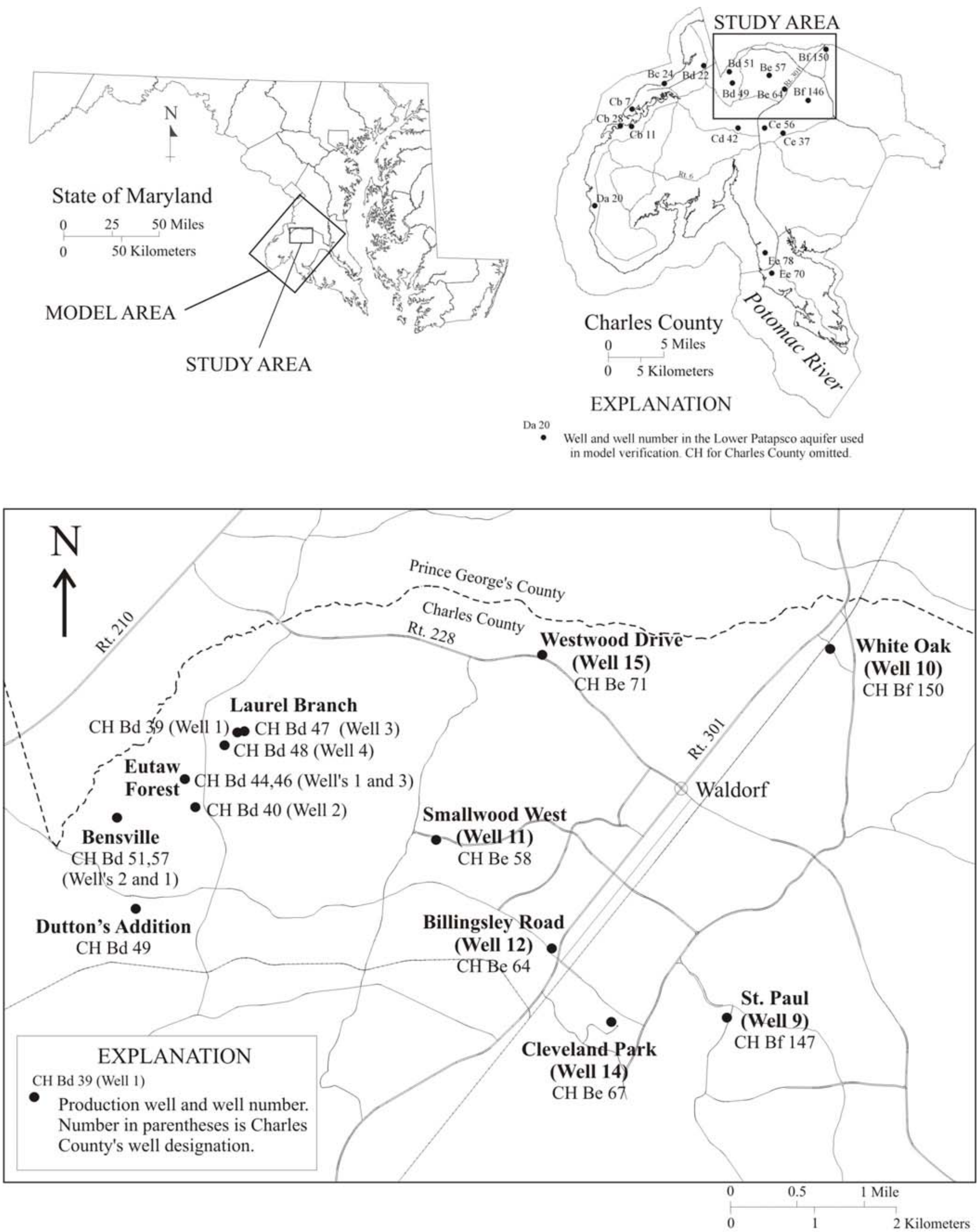


Figure 1. Location of study area, Lower Patapsco production wells in the Waldorf well system, and wells used in model verification.

Inc. (Richmond, Virginia). Michael K. Hinchy (Development and Capital Services, Charles County Department of Planning and Growth Management) provided technical assistance regarding the construction and operation of the county's well fields throughout the study. William B. Fleck, U.S. Geological Survey, provided many useful ideas pertaining to the optimization analysis. The report received technical reviews by Harry J. Hansen and David D. Drummond (Maryland Geological Survey), and Jonathan Dillow (U.S. Geological Survey). The manuscript was prepared for publication by Donajean M. Appel.

LOWER PATAPSCO AQUIFER WELLS IN THE WALDORF WELL SYSTEM

The Charles County Department of Utilities began supplying water to the Waldorf area in 1962 with the construction of two production wells screened in the Magothy aquifer (Mack and others, 1983). Additional Magothy wells were added during the 1970's to supply the growing population. Water withdrawn from the Magothy aquifer by public-supply wells increased from about 0.15 Mgal/d in 1962 (Mack and others, 1983) to 2.4 Mgal/d in 2001. Although the Magothy aquifer is capable of yielding large quantities of water to wells, it has less available drawdown than the deeper lower Patapsco aquifer. By the mid-1980s, water levels in the Magothy aquifer began to approach the 80-percent management level established by the Maryland Department of the Environment. To stabilize the declining water levels, production was shifted in part to the deeper Lower Patapsco aquifer. The Lower Patapsco aquifer has been pumped in the Waldorf area since 1984. The first production well was constructed at the St. Paul site Well 9 (CH Bf 147). By 2002, five additional production wells (Smallwood West Well 11, Billingsley Road Well 12, White Oak Well 10, Cleveland Park Well 14, and Westwood Drive Well 15) were constructed in the Lower Patapsco aquifer in the Waldorf area (tab. 1; fig. 1). These wells, together with nine Lower Patapsco wells located west of Waldorf at Bensville (two wells), Dutton's Addition (one well), Eutaw Forest (three wells), and Laurel Branch (three wells), supply water to a large portion of northern Charles County. Each site has a separate ground-water appropriation permit (tab. 1). Wells at Smallwood West, Westwood Drive, Billingsley Road, White Oak, Cleveland Park, and St. Paul are connected to a common distribution system, as are wells at Bensville, Dutton's Addition and Eutaw Forest. The wells at Laurel Branch are planned to be connected to the Bensville, Dutton's Addition, and Eutaw Forest system. Eventually, both groups of wells will be connected to form a single supply system (Michael Hinchy, Charles County Department of Planning and Growth Management, per. comm., 2001). The total average annual pumpage from all 15 Lower Patapsco wells increased from 0.096 Mgal/d in 1984 to 2.6 Mgal/d in 2001 (Judith Wheeler, per. comm., 2002).

WELL RECORDS

The 15 Lower Patapsco wells operating in the Waldorf well system range in depth from 822 to 1,417 ft below land surface (tab. 1; apps. A1-A10). Well-casing diameters range from 4 to 18 inches and well-screen diameters range from 2 to 12 inches. The water-bearing capacity of the wells was tested by the well contractor at the time of construction. During testing, pumping rates ranged from 26 to 610 gallons per minute (gal/min) (tab. 1). Specific capacity calculated from 24- to 36-hour pump tests range from 0.5 gallons per minute per foot of drawdown (gal/min/ft) in CH Bd 44 (Eutaw Forest Well 1) to 6.5 gal/min/ft in CH Bf 150 (White Oak Well 10). The larger diameter wells generally have higher specific capacities, likely because more complete well development is possible in a larger diameter casing and screen.

Well efficiency is an important factor in the design and operation of production wells. Low well efficiency increases drawdown during pumping, which in turn increases pumping costs. The efficiency of 11 of the production wells was estimated using specific capacity and transmissivity (feet squared per day) values derived from aquifer tests. Constant-rate aquifer tests were performed by the driller in 11 of the 15 wells. Calculating transmissivity using the aquifer-test data is discussed in a later section of the report. Well efficiency was calculated by comparing theoretical and actual transmissivity (computed from aquifer tests) (Driscoll, 1986, p. 577). The computation consisted

Table 1. Well data for Lower Patapsco wells in the Waldorf well system

[ft = feet; in. = inch; -- = no data or not applicable; Layne = Layne-Atlantic Co.; Schultes = A. C. Schultes of Maryland, Inc.; Shannahan = Shannahan Artesian Well Co.; Sydnor = Sydnor Hydrodynamics, Inc.]

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 (Well 11)	CH Be 58	--	CH1983G112	Layne	1985	210	1,160	16, 8	8	925-964, 1,048-1,160
Westwood Drive (Well 15)	CH Be 71	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 (Well 12)	CH Be 64	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 (Well 10)	CH Bf 150	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 (Well 14)	CH Be 67	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 (Well 9)	CH Bf 147	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	CH1994G003	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 1. Well data for Lower Patapsco wells in the Waldorf well system—Continued

[ft = feet; gal/min = gallons per minute; gal/min/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 (gal/min)	Date measured (month-year)	Specific capacity (gal/min/ft)	Transmissivity (ft^2/d) Drawdown phase (Recovery phase)	Well efficiency (percent)	Available drawdown in 2001 (ft)
		Static	Pumping						
Smallwood West (Well 11)	CH Be 58	237	350	550	8-85	4.9	1,730	76	415
Westwood Drive (Well 15)	CH Be 71	319	474	610	3-02	3.9	854 (1,708)	61	375
Billingsley Road (Well 12)	CH Be 64	298	473	550	5-89	3.1	(1,070)	77	385
White Oak (Well 10)	CH Bf 150	228	313	554	7-85	6.5	3,000	58	475
Cleveland Park (Well 14)	CH Be 67	318	436	600	2-96	5.1	1,600	85	530
St. Paul (Well 9)	CH Bf 147	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

of (1) multiplying the specific capacity by 267 (to convert to ft^2/d units), (2) dividing the result by the transmissivity, and (3) multiplying by 100. Results show that well efficiency ranges from 33 percent in CH Bd 44 (Eutaw Forest Well 1) to 93 percent in CH Bd 47 (Laurel Branch well 3) (tab. 1). Generally, the larger diameter wells have greater efficiency.

The production wells are equipped with centrifugal pumps, either turbine or submersible. Pump selection (type and size) is based on the amount of total hydraulic head that develops at design pumping rates. For instance, if the design rate of a production well with a specific capacity of 5 gal/min/ft and a static water level of 100 ft below land surface is 500 gal/min, then the total hydraulic head at which the pump must operate at a system pressure of 60 pounds per square inch (140 ft head) is 240 ft. Therefore, the selected pump, at its peak efficiency, should produce, as nearly as possible, 500 gal/min at 240 ft of total hydraulic head. The design rates of the Lower Patapsco wells in the Waldorf well system range from 38 to 700 gal/min (tab. 2).

WATER LEVELS AND AVAILABLE DRAWDOWN

Water levels and pumpage in the Lower Patapsco aquifer for the period 1979 to 2002 in the Waldorf well system are shown in figure 2. Water levels were measured by the Maryland Geological Survey and the U.S. Geological Survey. Withdrawals from the Lower Patapsco aquifer started in 1984 and have increased to an average of 2.6 Mgal/d in 2001. Monthly average withdrawals periodically exceeded 3.0 Mgal/d during the period 1997-2001. The withdrawals have formed a relatively deep cone-of-depression surrounding the Waldorf area (Curtin and others, 2002d). Between 1979 and 2001, water levels declined from approximately 5 ft below sea level to as much as 175 ft below sea level. Since about the mid-1990s, the water-level trend flattened as pumpage stabilized at an average rate of about 2.6 Mgal/d. The deepest water levels occurred at Billingsley Road and Smallwood West at approximately 175 ft and 165 ft, respectively, below sea level. During the period of record, two pumping levels were recorded at Smallwood West (200 ft below sea level in 1996), and Billingsley Road (175 ft below sea level in 2002). The continuous water-level record for CH Bf 146, located approximately 50 ft from the St. Paul production well (CH Bf 147), fluctuates by as much as 40 ft in response to pumping in the production well (fig. 2).

Most of the water levels plotted in figure 2 were measured with the pumps turned off. Pumping water levels are typically significantly deeper. Absence of, or constrictions in, riser pipes prevent measuring pumping water levels in most of the Lower Patapsco wells in the Waldorf well system. Maximum pumping water levels were estimated by calculating drawdown using 24-hour specific capacity values and the design pumping rate for each well (tab. 2). The drawdown amount was subtracted from the measured or estimated static water level at each well to obtain a pumping water level.

Available drawdown is defined as the difference between the water level at any point in time and at any location, and the 80-percent management level. In 1997 available drawdown in the Lower Patapsco aquifer in the Waldorf well system ranged from approximately 200 to 550 ft (Andreasen, 1999). The available drawdown in 2001 ranged from 140 ft at Bensville to 550 ft at St. Paul (tab. 1; apps. A1-A10). The greatest available drawdown occurs in the eastern part of Waldorf where the aquifer is at a greater depth.

TRANSMISSIVITY

Transmissivity of the Lower Patapsco aquifer was calculated from aquifer tests in 11 of the 15 production wells in the Waldorf well system. The aquifer tests were conducted by the well-drilling contractor at the time of well construction. During the tests, the wells were pumped at constant rates for periods ranging from 24 to 36 hours, followed by recovery periods of at least 12 hours. Pumping rates ranged from 26 to 610 gal/min (tab. 1). Water levels were recorded in the pumped wells during both pumping and recovery phases of the tests. The pumping and recovery water-level data were plotted with respect to time since the pumping began and stopped, respectively. The water-level data were analyzed by the Jacob straight-line method as described in Fetter (1980, p. 266). Transmissivities calculated by this method range from 400 ft^2/d at Eutaw Forest to 3,000 ft^2/d at White Oak (tab. 1).

Table 2. Estimated pumping levels at design rates for Lower Patapsco production wells in the Waldorf well system, 2001

[gal/min/ft = gallons per minute per foot; gal/min = gallons per minute; Mgal/d = million gallons per day; m = measured; e = estimated]

Well field	Well number (Owner's number)	Specific capacity (gal/min/ft)	Design rate (gal/min)	Calculated drawdown at design yield (ft)	Static water level in 2001 (ft related to sea level) (model-cell value)	Estimated pumping level in 2001 (ft related to sea level)
Smallwood West (Well 11)	CH Be 58	4.9	500	102	-166m (-151)	-268
Westwood Drive (Well 15)	CH Be 71	3.9	650	167	-99m (-94)	-266
Billingsley Road (Well 12)	CH Be 64	3.1	497	160	-173m (149)	-333
White Oak (Well 10)	CH Bf 150	6.5	700	107	-100m (-92)	-207
Cleveland Park (Well 14)	CH Be 67	5.1	575	113	-113m (-128)	-226
St. Paul (Well 9)	CH Bf 147	4.6	360	78	-145e (-142)	-223
Bensville	CH Bd 51 (Well 2)	3.4	250	74	-152m (-136)	-226
	CH Bd 57 (Well 1)	2.4	270	112	-152e (-136)	-264
Dutton's Addition	CH Bd 49	2.5	150	60	-122m (120)	-182
Eutaw Forest	CH Bd 44 (Well 1)	0.5	70	140	-120e (-130)	-260
	CH Bd 40 (Well 2)	.7	38	54	-120e (-130)	-174
	CH Bd 46 (Well 3)	1.6	90	56	-120e (-130)	-176
Laurel Branch	CH Bd 39 (Well 1)	2.1	130	62	-120e (-130)	-182
	CH Bd 47 (Well 3)	1.9	135	71	-120e (-130)	-191
	CH Bd 48 (Well 4)	4.2	300	71	-120e (-130)	-191
			Total = 6.8 Mgal/d			

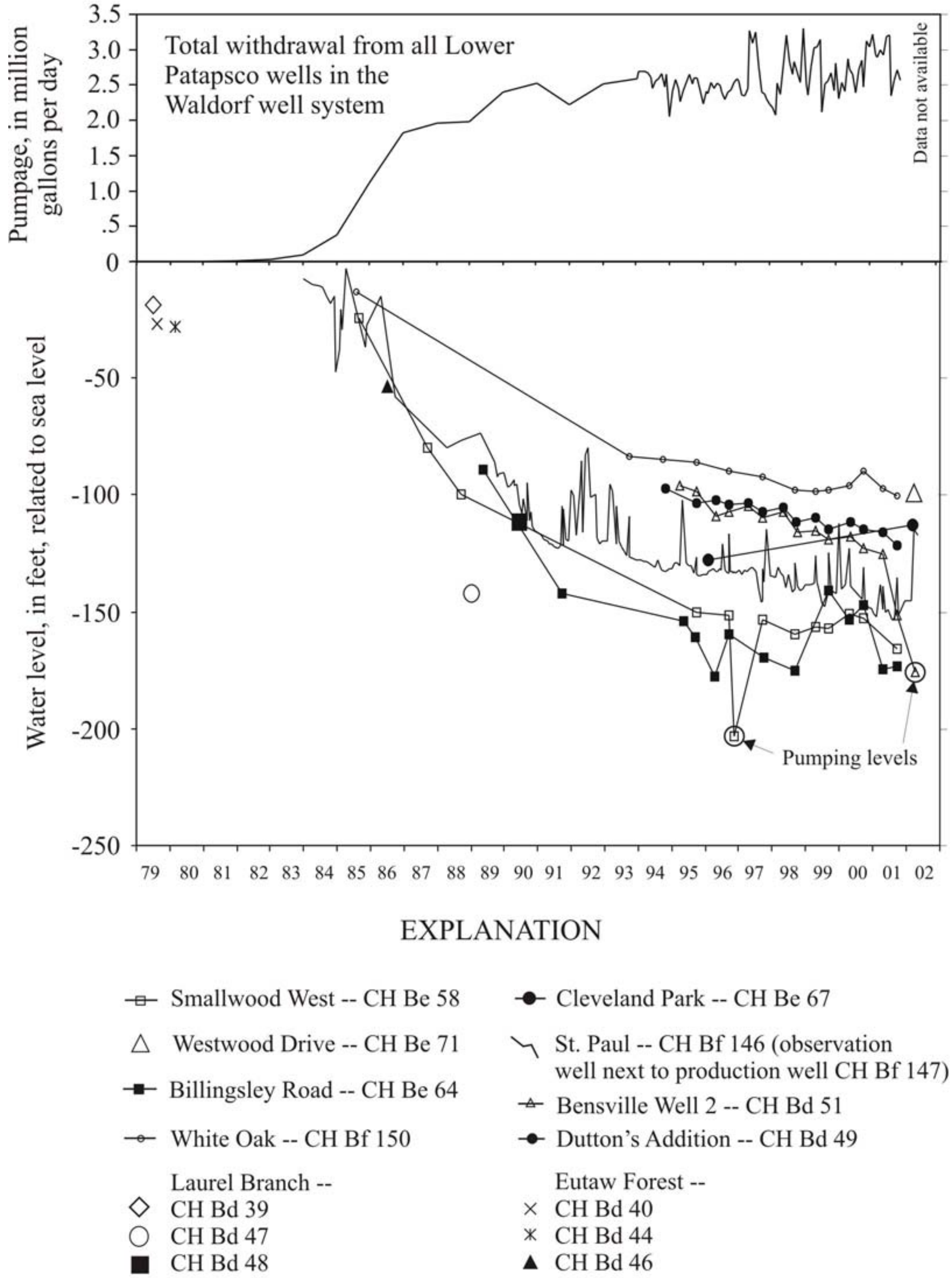


Figure 2. Water levels and pumpage in the Lower Patapsco aquifer in the Waldorf well system, 1979-2002.

SIMULATION OF GROUND-WATER FLOW

Development of optimum pumping schemes requires a numerical ground-water-flow model. A flow model developed in a previous study (Andreasen, 1999) to assess future withdrawals from the Lower Patapsco and Patuxent aquifers in the Indian Head-Bryans Road area, was revised and used for this study. The model simulates flow using the three-dimensional, finite-difference ground-water-flow model MODFLOW (McDonald and Harbaugh, 1988). The model consists of four layers, representing from top to bottom, the Upper Patapsco aquifer (layer 1), the Lower Patapsco aquifer (layer 2), the upper Patuxent aquifer (layer 3), and the lower Patuxent aquifer (layer 4). Model layer 1 was assigned a specified-head boundary with heads specified for selected stress periods. Lateral boundaries include no-flow and general-head boundaries. For a detailed description of the model, the reader is referred to Andreasen (1999).

Revisions to the ground-water-flow model consisted of: (1) reducing cell size in the Waldorf area, (2) expanding the simulation period from 1900-1997 to 1900-2001, and (3) updating pumpage arrays, specified-head and general-head boundaries, and the transmissivity arrays for the Lower Patapsco aquifer (layer 2). Model calibration was verified after the revisions were made by comparing simulated and observed water levels.

Model-cell size was reduced from as much as 7,600 ft x 7,600 ft in the Waldorf area in the original model to 1,000 ft x 1,000 ft in the revised model (fig. 3). The smaller cell size increases precision of simulated water levels because water levels are averaged over smaller areas.

The transient simulation period was extended to 2001 by adding 48 stress periods, each 1 month in duration. Pumpage data for the Lower Patapsco production wells in the Waldorf well system were input to the model for each additional stress period. Semi-annual pumpage data were input to the model for the remainder of the Lower Patapsco wells in the model area withdrawing more than 10,000 gallons per day (gal/d) and for the Patuxent aquifer production well at South Hampton. The specified-head boundary in layer 1, and the general-head boundaries in layers 2, 3, and 4 were revised using 2000 head data. Head data for these boundaries were obtained from potentiometric surface maps for the Upper and Lower Patapsco aquifers prepared by Curtin and others (2002a and 2002b) and from an observation-well network maintained in Charles County (Andreasen and Fewster, 2002).

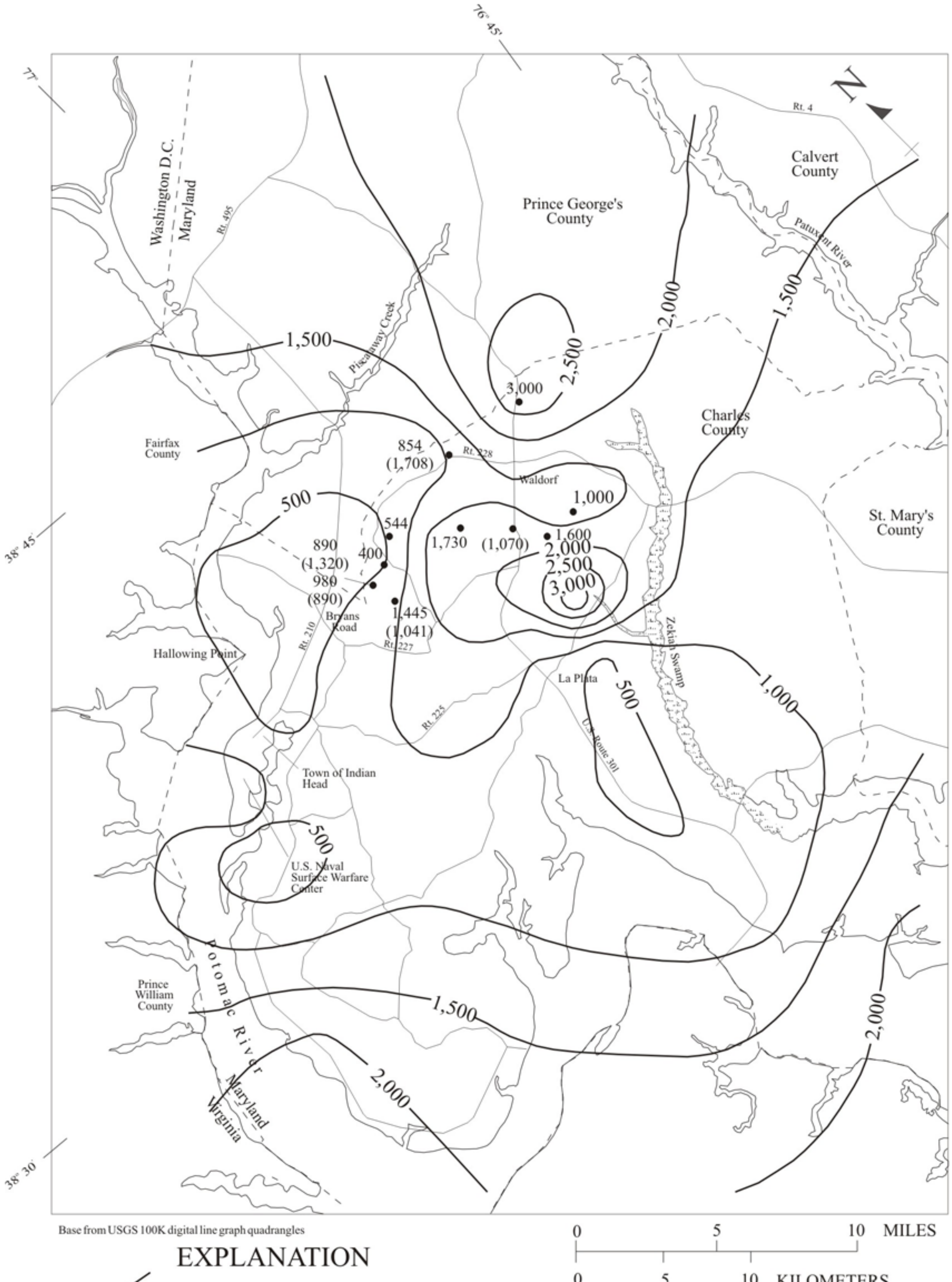
The transmissivity array for model layer 2 (Lower Patapsco aquifer) presented in Andreasen (1999; pgs. 24-25) was revised using values given in table 1. Areas of relatively high transmissivity occur northeast of Waldorf at the Charles County–Prince George's County boundary, and northeast of La Plata (fig. 4). Transmissivity in those areas is greater than 2,500 ft^2/d. Areas of relatively low transmissivity (less than 500 ft^2/d) occur south of La Plata, in the Bryans Road area, and south of Indian Head.

Performance of the revised model was verified by comparing simulated and observed heads at the end of the simulation period 1900-2001 in 15 wells screened in the Lower Patapsco aquifer (fig. 1). Three wells (PG Ed 34, PG Fc 17, and PG Hf 31) located in southern Prince George's County were also compared (Andreasen, 1999). The root-mean-square error calculated by comparing simulated and observed heads was 10.5 ft. This is a slight improvement over the root-mean square error of 14.2 ft obtained from the original model using a different set of wells (Andreasen, 1999, p. 51). The differences between simulated and observed heads at the end of the 1900-2001 simulation period at St. Paul, Smallwood West, Billingsley Road, White Oak, Bensville, and Dutton's Addition range from 3 to 26 ft (fig. 5). Differences between simulated and observed heads may be caused, in part, by local pumping conditions in or near the well sites at the time of measurement.

OPTIMIZED WITHDRAWALS FROM THE LOWER PATAPSCO WELLS IN THE WALDORF WELL SYSTEM

Withdrawals from the Lower Patapsco aquifer in the Waldorf well system were optimized over a 2-year period (2002-2003). The simulation time was divided into 24 stress periods, each 1 month in duration. Withdrawals from the Lower Patapsco aquifer outside the Waldorf area were increased over the 2-year period based on projected population growth (Andreasen, 1999, tab. 7, p. 62). Withdrawal

Figure 3. Revised ground-water-flow model grid.



EXPLANATION

2,000 — Line of equal transmissivity, in feet squared per day. Contour interval is 500 feet squared per day.

1,445 (1,041) • Transmissivity, in feet squared per day, calculated from drawdown and recovery (in parentheses) portions of aquifer tests (see tab. 1).

Figure 4. Transmissivity of the Lower Patapsco aquifer used in the ground-water-flow model.

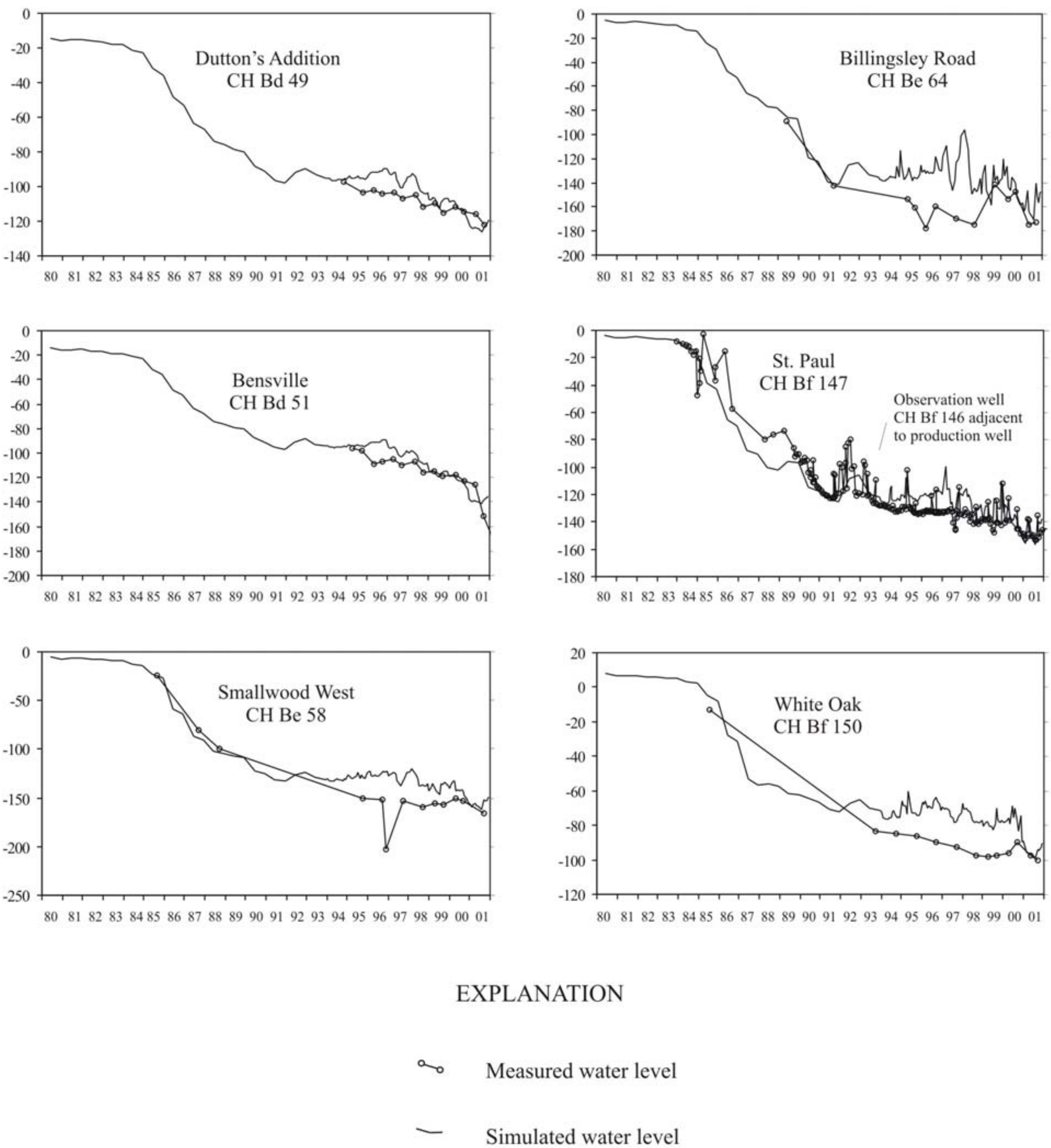


Figure 5. Hydrographs of measured and simulated water levels in the Lower Patapsco aquifer in the Waldorf well system, 1980-2001.

from the Patuxent aquifer at South Hampton was held constant at the December 2001 rate of 0.238 Mgal/d. Heads along the perimeter of model layers 2, 3, and 4 (represented by a general-head boundary) and in model layer 1 (Upper Patapsco aquifer represented using specified heads) were assigned using measured water levels from 2001 (Andreasen and Fewster, 2002; Curtin and others, 2002c).

OPTIMIZATION METHOD

Traditionally, ground-water management problems involving a numerical ground-water-flow model were solved by the trial-and-error method. For example, to determine the maximum pumping rate of a production well without exceeding a specified drawdown, the modeler would make repeated model runs varying pumping rates and checking simulated drawdown until the specified drawdown was reached. For complex problems involving many wells, this method is laborious and may or may not produce an optimal solution. In this study, the ground-water management problem was solved by a linear-programming technique using the MODMAN code (Greenwald, 1998). This method removes the subjectivity of the trial-and-error method and increases the likelihood of obtaining an optimal solution.

The first step in the optimization process is to define the ground-water management problem in terms of an objective function, decision variables, and constraints (fig. 6). The objective function is subject to one or more constraints, which are also defined by decision variables. In ground-water management problems, decision variables are typically pumpage, water levels, or drawdown. In the example of maximizing withdrawal from a production well without exceeding a specified drawdown, the decision variable is the pumping rate in the production well (managed well) and the constraint is the specified drawdown.

The next step in the process is to create a response matrix that relates pumping rate to drawdown at each managed well. MODMAN accomplishes this by running the ground-water-flow model MODFLOW multiple times to determine the drawdown response for each managed well. The objective function is then transformed into a linear program by MODMAN using the response matrix. The linear program can then be solved to maximize or minimize the decision variables. The linear program was solved using the linear program solver SuperLINDO (2002). The ground-water management problem can be solved using linear programming because the drawdown response caused by pumping in a fully saturated, confined aquifer is linear. The principle of linear superposition states that drawdown at a location influenced by multiple pumping wells is equal to the sum of the drawdowns caused by each well individually (Todd, 1980, p. 148).

In the final steps, a check is performed to determine if the problem is feasible and optimal. The solution is feasible if the calculated decision variables satisfy all constraints. If the solution is not feasible, then the objective function must be re-formulated. The solution is optimal if it maximizes or minimizes the objective function.

Objective functions used in this study maximize withdrawals given specified head constraints or minimize total drawdown given a specified cumulative withdrawal rate from the Lower Patapsco aquifer in the Waldorf well system. These objective functions written as mathematical expressions are:

Maximize Total Withdrawal Given Specified Head And Capacity Constraints

$$\text{Maximize } \sum_{i=1}^{n} Qi$$

such that,

Constraint 1 $\quad \overset{n}{\underset{i=1}{Q_i}} <$ design pumping rate of managed well i

Constraint 2 $\quad H_C \geq 80$ - percent management level

Constraint 3 $\quad H_A \geq$ top of Lower Patapsco aquifer or pump intake

where,

Q_i = pumpage at managed well i,

H_C = head in model cells surrounding managed well (ft)

H_A = head in model cell containing managed well (ft).

Minimize Total Drawdown Given a Specified Cumulative Withdrawal Rate

$$\text{Minimize } \sum_{i=1}^{n} \Delta Si$$

such that,

Constraint 1 $\sum_{i=1}^{n} Q_i = Q_D$

Constraint 2 $\overset{n}{\underset{i=1}{Q}}$ < design pumping rate of managed well i

Constraint 3 $\overset{n}{\underset{i=1}{Q}}$ > specified minimum pumping rate

where,

Δs_i = drawdown at managed well i

Q_i = pumpage at managed well i

Q_D = cumulative withdrawal rate from managed wells.

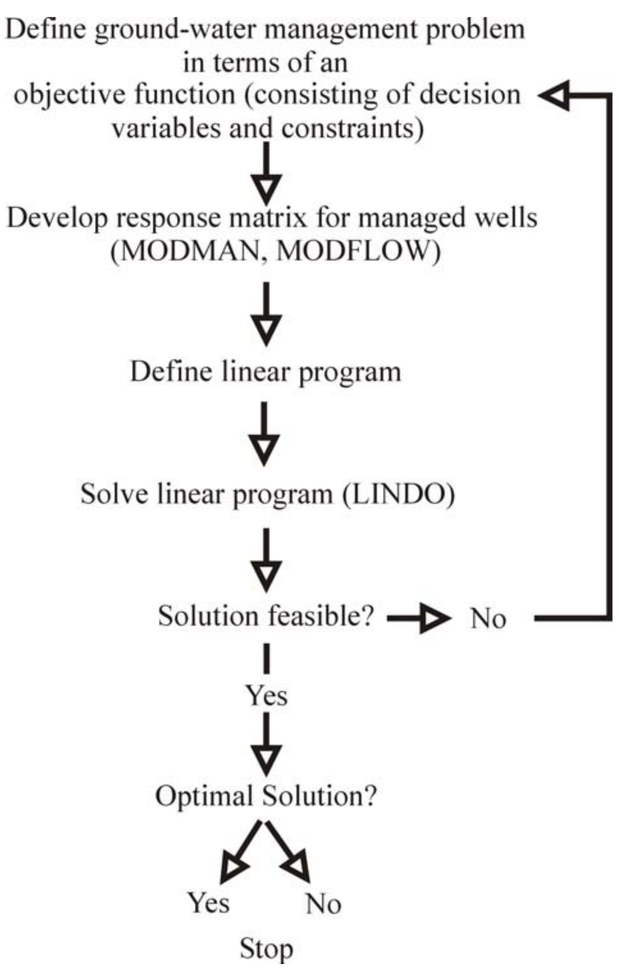


Figure 6. Steps involved in the optimization process.

Pumpage in model cells representing the Lower Patapsco production wells were optimized for selected wells using simulated heads calculated immediately outside the production wells. For cells with square dimensions, the MODMAN program converted model-cell head to head immediately outside a pumping well using the Thiem equation (Greenwald, 1998). These include the Westwood Drive, White Oak, Bensville, Dutton's Addition, and Eutaw Forest well sites. The remaining well sites are located in rectangular cells. Optimized heads for these production wells were based on model-cell values. Model-cell heads represent average heads over model-cell areas and are, therefore, shallower than heads immediately outside pumping wells. At well sites with multiple wells, the model assumes that only one well is pumping. In those cases, the highest design pumping rate and shallowest pump intake altitude are used during optimization.

Since optimization utilizes output from the ground-water-flow model (either model-cell heads or model-cell heads converted by the Thiem equation), well efficiency is not factored into the analysis. Optimization assumes that all wells pumping in model cells are 100-percent efficient.

OPTIMIZATION SCHEMES

Scheme 1: Maximizing Withdrawals in the Existing Lower Patapsco Waldorf Well System While Constraining Water Levels Above Pump Intakes

In this scheme, pumpage from the existing Lower Patapsco wells was maximized over a 2-year period (2002-2003) with the constraints that water levels not fall below pump intakes, and pumping rates for the individual wells not exceed rates equal to continuous 24-hour discharge at design pumping rates. All of the wells pumped simultaneously. Design pumping rates are listed in tables 2 and 3. Pumpage from the Lower Patapsco wells was optimized for each month-long stress period. Optimized withdrawal rates, pump intake altitudes, and design pumping rates are given in table 3.

Results indicate that Billingsley Road Well 12, Cleveland Park Well 14, St. Paul Well 9, and Bensville Well 1 or 2 can pump continuously at design rates without causing water levels to fall below pump intakes. Water levels at Smallwood West Well 11, Westwood Drive Well 15, White Oak Well 10, Dutton's Addition, and Eutaw Forest reach pump intakes at rates less than the design rates (tab.

Table 3. Optimized withdrawal rates for the Lower Patapsco well sites constrained by pump intakes (Scheme 1)

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

Well site	Well number (Owner's number)	Design pumping rate (Mgal/d)	Altitude of pump intake (ft related to sea level)	Optimized withdrawal in stress period 24 (Mgal/d)	Simulated head in stress period 24 (ft related to sea level)	Average annual withdrawal for 2001 (Mgal/d)
Smallwood West (Well 11)	CH Be 58	0.72	-240	0.71	-240[1]	0.58
Westwood Drive (Well 15)	CH Be 71	.94	-340	.81	-340[2]	0
Billingsley Road (Well 12)	CH Be 64	.72	-490	.72	-242[1]	.47
White Oak (Well 10)	CH Bf 150	1.0	-200	.91	-200[2]	.49
Cleveland Park (Well 14)	CH Be 67	.83	-268	.83	-240[1]	.30
St. Paul (Well 9)	CH Bf 147	.52	-257	.52	-215[1]	.50
Bensville	CH Bd 51 (Well 2)	.36	-374	.39	-344[2]	.10
	CH Bd 57 (Well 1)	.39	-382			
Dutton's Addition	CH Bd 49	.22	-237	.17	-237[2]	.01
Eutaw Forest	CH Bd 44 (Well 1)	.10	-261	.09	-261[2]	.06
	CH Bd 46 (Well 3)	.13	-303			
	CH Bd 40 (Well 2)	.06	-235	.04	-235[2]	
Laurel Branch	CH Bd 48 (Well 4)	.43	-325	.37	-249[1]	.10
	CH Bd 39 (Well 1)	.19	-215	0	-215[1]	
	CH Bd 47 (Well 3)	.19	-353			
		Total[3] = 6.2 Mgal/d		Total = 5.6 Mgal/d		Total = 2.6 Mgal/d

[1] Model-cell head.
[2] Head calculated immediately outside pumping well.
[3] The highest design pumping rate at sites with multiple wells was used in total.

3). Withdrawal from Laurel Branch Well 4 (CH Bd 48) is constrained by the pump intake in the adjacent model cell containing Laurel Branch Wells 1 and 3 (CH Bd 39 and 47). Since the water level has reached the pump intake in the model cell containing Laurel Branch Wells 1 and 3, no water can be pumped from this site. The optimized withdrawals for the period 2002-2003 are shown in figure 7 and listed in Appendix B. Total withdrawals decrease from 6.2 to 5.6 Mgal/d over the 2-year period. The total optimized withdrawal rates are approximately 3 Mgal/d more than the average withdrawal rate in 2001.

During the simulation period, water levels decline in response to the increased withdrawals. When the water level reaches the pump intake of the well, the withdrawal rate is decreased. Water levels at Westwood Drive Well 15 (CH Be 71) and Laurel Branch Well 1 (CH Bd 39) reach pump intakes after 5 months of pumping, followed by Eutaw Forest Wells 1 and 3 (CH Bd 44 and 46) after 6 months, White Oak Well 10 (CH Bf 150), Eutaw Forest Well 2 (CH Bd 40), and Dutton's Addition (CH Bd 49) after 8 months, and Smallwood West Well 11 (CH Be 58) after 17 months. Figure 7 shows the optimized pumpage amounts for the individual withdrawal sites over the 2-year simulation period.

The ground-water-flow model was re-run using the optimized withdrawals. Model-cell water levels at the end of the 2-year simulation in the Waldorf area range between approximately 120 ft to 250 ft below sea level, compared to measured water levels ranging from 100 to 173 ft below sea level in 2001 (Curtin and others, 2002d). The optimized pumpage array does not cause water levels to fall below the 80-percent management level along the Potomac River shoreline northwest of Bryans Road.

Scheme 2: Maximizing Withdrawals While Constraining Water Levels Above the Top of the Lower Patapsco Aquifer and the 80-Percent Management Level in the Lower Patapsco Waldorf Well System

In this scheme, pumpage from the production wells was maximized with the constraints that heads not fall below the top of the aquifer in the model cells representing the Lower Patapsco production wells in the Waldorf well system, and pumping rates for the individual wells not exceed rates equal to continuous 24-hour discharge at design pumping rates. In addition, water levels are constrained from falling below the 80-percent management level in

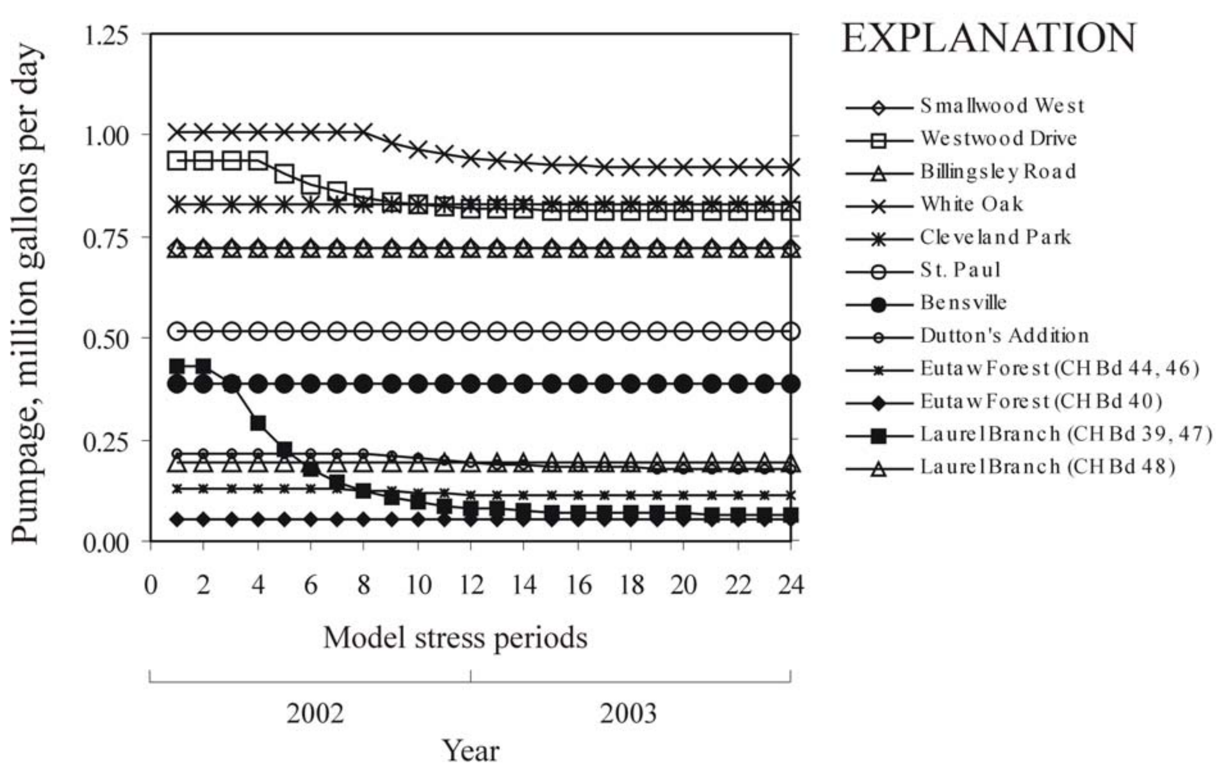


Figure 7. Optimized withdrawals for the period 2002-2003 (Scheme 1).

the model cells immediately surrounding the pumping wells. The sum of pumpage from the Lower Patapsco wells is optimized for each month-long stress period over the 2-year simulation period (2002-2003).

Results indicate that the head constraints do not limit the amount that can be pumped from the Lower Patapsco wells. All of the wells can be pumped at design rates without causing water levels to fall below the top of the aquifer at the managed wells or the 80-percent management level in model cells immediately surrounding the managed wells. Pumpage at the individual well sites range from .05 to 1.0 Mgal/d. The total withdrawal equals 6.2 Mgal/d by the end of the simulation period (stress period 24). Simulated heads (model-cell head or head calculated immediately outside the pumping well) in the pumped model cells range from 13 to 640 ft above the top of the aquifer at the 12 well sites (tab. 4). Model-cell heads in cells immediately surrounding the pumping wells range from 40 to 490 ft above the 80-percent management level. The least amount of available drawdown occurs around the Bensville site. More available drawdown occurs at the well sites located further to the southwest where the top of the aquifer is deeper. Simulated heads are 80 to 283 ft deeper than measured static heads in 2001. The lowest water level is 382 ft below sea level at Westwood Drive Well 15. The 80-percent management level is exceeded in a small area along the Potomac River shoreline northwest of Bryans Road.

Scheme 3: Maximizing Withdrawals in the Existing Lower Patapsco Waldorf Well System While Constraining Water Levels Above the 80-Percent Management Level in the Indian Head-Bryans Road Area

In this scheme, withdrawals from the Lower Patapsco wells were maximized with the constraints that water levels not fall below the 80-percent management level in the Indian Head-Bryans Road area, and pumping rates for the individual wells not exceed rates equal to continuous 24-hour discharge at design pumping rate. There is less available drawdown in the Indian Head-Bryans Road area than in the Waldorf area because the Lower Patapsco aquifer is shallower. Therefore, there is a greater risk of depleting the available drawdown in this area from declining regional water levels. The head constraints were assigned to model cells along the Potomac River shoreline (fig. 8). Pumpage from the Lower Patapsco wells is optimized for each month-long stress period.

Results indicate that to maximize total Lower Patapsco aquifer withdrawals without causing water levels to fall below management levels in the Indian Head-Bryans Road area, pumpage at the Bensville site should be phased out (fig. 9). If pumpage at the Bensville site is phased out over a 2-year period, a maximum of 5.8 Mgal/d can be pumped from the remaining sites. Optimized withdrawal rates for the individual well sites are given in Appendix C. Under this optimized pumping scheme, available drawdown above the 80-percent management level ranges from 0 to 100 ft in the Indian Head-Bryans Road area.

Scheme 4: Minimizing Total Drawdown in the Existing Lower Patapsco Waldorf Well System

In this scheme, total drawdown in the Lower Patapsco well system was minimized over a 24-month period by optimizing pumpage with the constraint that pumping rates in the individual wells not exceed their designed pumping rates (tab. 5). Two approaches were used to determine minimum total drawdown. In the first approach (designated as Scheme 4A), the 12 well sites were required to pump a minimum daily rate equal to 6 hours of pumping at design rates. In the second approach (designated as Scheme 4B), the wells were allowed to shut off during optimization.

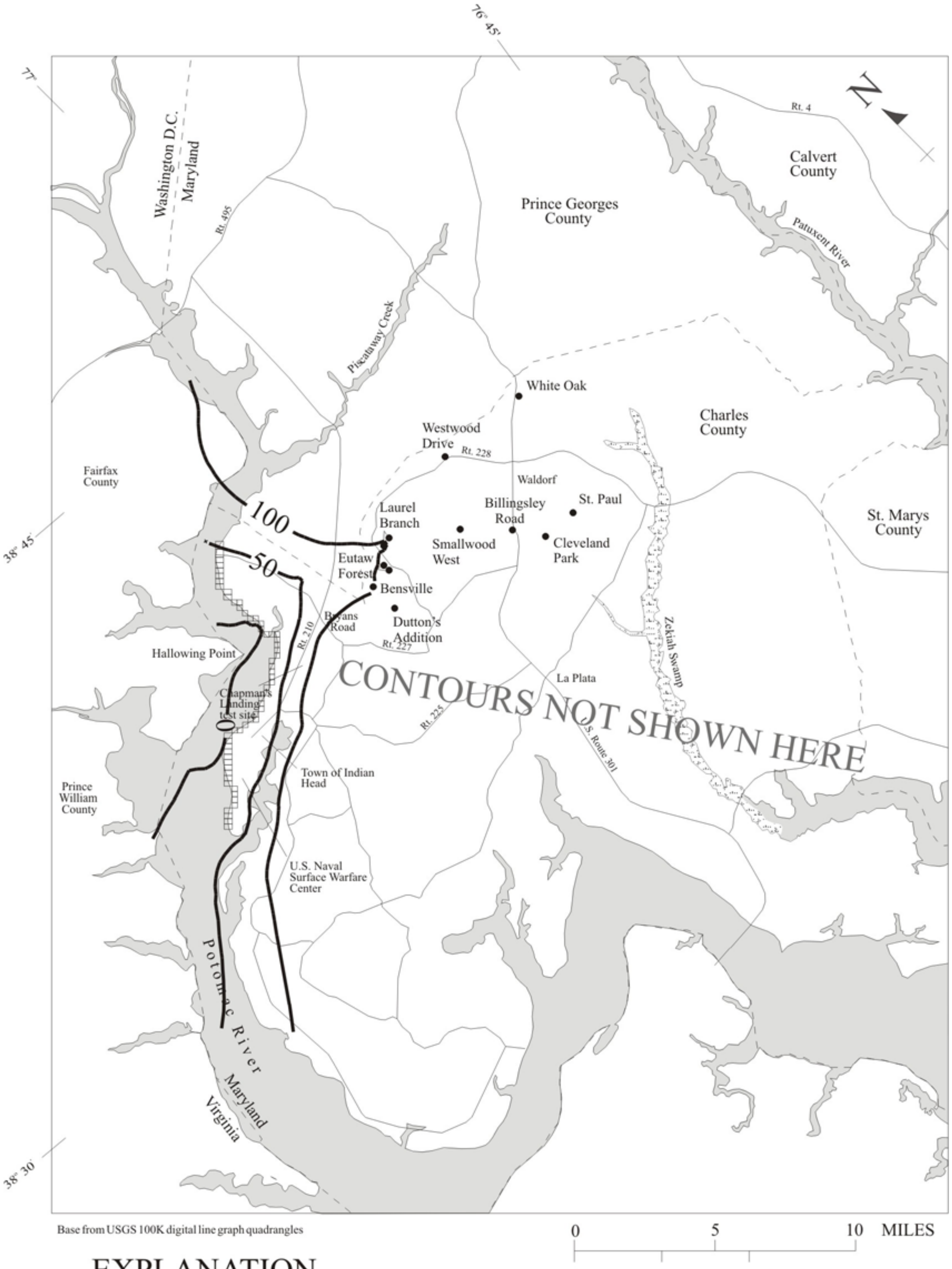
In both approaches (Schemes 4A and 4B), total drawdown was minimized using two different cumulative pumpage amounts: 2.6 Mgal/d (average amount pumped in 2001), and 5.0 Mgal/d (average amount pumped from both the Lower Patapsco and Magothy aquifers in the Waldorf well system in 2001). Water levels in the Magothy aquifer, similar to water levels in the Lower Patapsco aquifer, have declined because of pumping. Because the Magothy aquifer has less available drawdown owing to its shallower depth, it is beneficial to reduce drawdown in this aquifer by shifting pumpage to the deeper Lower Patapsco aquifer. Reduction in pumpage, or limits on future increases, in the Magothy aquifer may be necessary in the future to prevent water levels from exceeding the 80-percent management level. The ability of the Lower Patapsco aquifer to compensate for a reduction in pumpage from the Magothy aquifer was tested based on the assumption that all Magothy pumpage (2.4 Mgal/d in 2001) would be shifted to the Lower Patapsco aquifer. In

Table 4. Optimized withdrawal rates for the Lower Patapsco well sites constrained by top of aquifer and 80-percent management level (Scheme 2)

[Mgal/d = million gallons per day; ft = feet; m = measured; e = estimated]

Well site	Well number (Owner's number)	Design pumping rate (Mgal/d)	Altitude of the top of the Lower Patapsco aquifer (ft related to sea level)	Optimized withdrawal in stress period 24 (Mgal/d)	Simulated head in stress period 24 (ft related to sea level)	Static water level in 2001 (ft related to sea level)
Smallwood West (Well 11)	CH Be 58	0.72	-718	0.72	-258[1]	-166 m
Westwood Drive (Well 15)	CH Be 71	.94	-618	.94	-382[2]	-99 m
Billingsley Road (Well 12)	CH Be 64	.72	-738	.72	-256[1]	-173 m
White Oak (Well 10)	CH Bf 150	1.0	-722	1.0	-218[2]	-100 m
Cleveland Park (Well 14)	CH Be 67	.83	-785	.83	-252[1]	-113 m
St. Paul (Well 9)	CH Bf 147	.52	-865	.52	-225[1]	-145 e
Bensville	CH Bd 51 (Well 2)	.36	-379	.39	-366[2]	-152 m
	CH Bd 57 (Well 1)	.39				
Dutton's Addition	CH Bd 49	.22	-529	.22	-266[2]	-122 m
Eutaw Forest	CH Bd 44 (Well 1)	.10	-403	.13	-303[2]	-130
	CH Bd 46 (Well 3)	.13				
	CH Bd 40 (Well 2)	.06	-430	.06	-267[2]	-130
Laurel Branch	CH Bd 48 (Well 4)	.43	-444	.43	-262[1]	-130
	CH Bd 39 (Well 1)	.19	-475	.19	-289[1]	-130
	CH Bd 47 (Well 3)	.19				
		Total[3] = 6.2 Mgal/d		Total = 6.2 Mgal/d		

[1] Model-cell head.
[2] Head calculated immediately outside pumping well.
[3] The highest design pumping rate at sites with multiple wells was used in total.



EXPLANATION

—100— Line of equal available drawdown above the 80-percent management level, in feet.

• Well site

□ Model cell where head was constrained at the 80-percent management level.

Figure 8. Available drawdown based on maximized withdrawals from the Lower Patapsco wells in the Waldorf well system (Scheme 3).

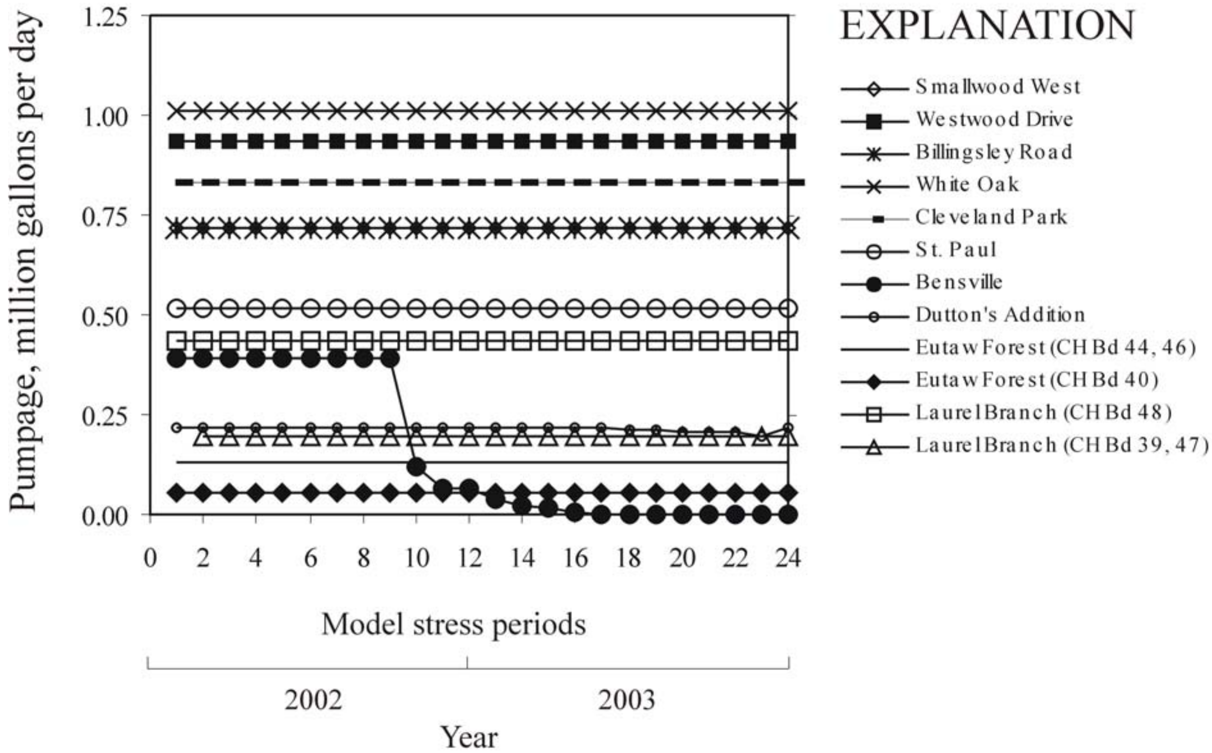


Figure 9. Optimized withdrawals for the period 2002-2003 (Scheme 3).

practice, however, Magothy pumpage would not be reduced to zero, but only to a level that stabilizes water levels above the 80-percent management level.

During optimization, total drawdown at the production wells was minimized by varying pumpage in the model cells representing the production wells. Drawdown was calculated as the difference between heads without pumpage from the Waldorf Lower Patapsco production wells, and heads with pumpage from the Waldorf Lower Patapsco production wells.

In Scheme 4A, when pumped at a cumulative rate of 2.6 Mgal/d in each stress period (1-month periods), the minimum total drawdown for the 12 Lower Patapsco well sites equaled 885 ft. Drawdown ranged from 60 to 85 ft by the end of the 2-year simulation period (stress period 24) (tab. 5). The withdrawal rates ranged from 0.014 to 1.0 Mgal/d. The withdrawal rate at White Oak Well 10 is the greatest at 1.0 Mgal/d, followed by St. Paul Well 9 at 0.44 Mgal/d. Smallwood West Well 11, Westwood Drive Well 15, Billingsley Road Well 12, and Cleveland Park Well 14 each pumped between 0.18 and 0.23 Mgal/d. The well systems to the west of Waldorf, Bensville, Dutton's Addition, Eutaw Forest, and Laurel Branch, each pumped less then 0.11 Mgal/d. The optimized withdrawals resulted in simulated model-cell water levels ranging from 109 to 132 ft below sea level at the well sites. Water levels ranged from 250 to 340 ft below land surface under the optimized pumping scheme compared to simulated 2001 pumping levels from 260 to 362 ft below land surface (tab. 5). The total pumping head (total depth of water level below land surface) at all sites equaled 3,739 ft under the optimized pumping scheme, compared to 3,549 ft under the simulated 2001 pumping conditions. Total pumping head is greater under the optimized pumping scheme because Westwood Drive (Well 15) was not pumped in 2001. Under optimized withdrawals, water levels did not fall below the 80-percent management level in the Indian Head-Bryans Road area. When withdrawals are optimized using the well configuration pumped in 2001 (Westwood Drive Well 15 not pumped), total pumping head is reduced to 3,429 ft, or 3.4 percent less than the simulated 2001 total pumping head.

In Scheme 4A, when pumped at a cumulative rate of 5.0 Mgal/d in each stress period (1-month periods), the minimum total drawdown for 12 Lower Patapsco well sites equaled 1,772 ft. Drawdown ranged from 115 to 193 ft in stress period 24 (tab. 5).

Table 5. Optimized withdrawal rates producing the minimum amount of total drawdown (Scheme 4A)

[Mgal/d = million gallons per day; ft = feet; -- = no data or not applicable]

Well site	Well number (Owner's number)	Upper and lower pumping constraints (Mgal/d[1])	Optimized withdrawal rate (Mgal/d)	Draw-down[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)	Optimized withdrawal rate (Mgal/d)	Draw-down[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)	Simulated 2001 pumping level (ft below land surface)
			2.6 Mgal/d				5 Mgal/d				2.6 Mgal/d
Smallwood West (Well 11)	CH Be 58	0.18 / 0.72	0.18	-45.3-(-118.9)=74	-119	329	0.63	-45.3-(-216.6)=171	-216	426	362
Westwood Drive (Well 15)	CH Be 71	.23 / .94	.23	-31.7-(-109.1)=77	-109	329	.94[3]	-31.7-(-224.9)=193	-225	446	--[4]
Billingsley Road (Well 12)	CH Be 64	.18 / .72	.18	-47.5-(-122.6)=75	-123	333	.72[3]	-47.5-(-226.3)=179	-226	435	360
White Oak (Well 10)	CH Bf 150	.25 / 1.0	1.0[3]	-28.0-(-110.2)=82	-110	325	1.0[3]	-28.0-(-154.5)=126	-154	369	309
Cleveland Park (Well 14)	CH Be 67	.21 / .83	.21	-50.3-(-125.1)=75	-125	340	.83[3]	-50.3-(-226.3)=176	-226	441	344
St. Paul (Well 9)	CH Bf 147	.13 / .52	.44	-46.7-(-132.0)=85	-132	325	.52[3]	-46.7-(-203.7)=157	-204	397	336
Bensville	CH Bd 51 (Well 2) CH Bd 57 (Well 1)	.097 / .39	.097	-49.4-(-119.0)=70	-119	304	.097	-49.4-(-172.4)=123	-172	357	321
Dutton's Addition	CH Bd 49	.054 / .22	.054	-52.0-(-112.2)=60	-112	295	.054	-52.0-(-167.4)=115	-167	350	305
Eutaw Forest	CH Bd 44 (Well 1) CH Bd 46 (Well 3)	.032 / .13	.032	-46.5-(-116.4)=70	-116	301	.032	-46.5-(-176.0)=130	-176	361	315
	CH Bd 40 (Well 2)	.014 / .06	.014	-47.7-(-114.7)=67	-115	295	.014	-47.7-(-175.2)=128	-175	355	310
Laurel Branch	CH Bd 48 (Well 4)	.11 / .43	.11	-42.4-(-120.3)=78	-120	250	.11	-42.4-(-181.7)=139	-182	312	260
	CH Bd 39 (Well 1) CH Bd 47 (Well 3)	.049 / .19	.049	-41.4-(-113.3)=72	-113	313	.049	-41.4-(-176.7)=135	-177	377	327
			Total = 2.6 Mgal/d	Total = 885 ft		Total = 3,739 ft	Total = 5.0 Mgal/d	Total = 1,772 ft		Total = 4,626 ft	Total = 3,549 ft

[1] Smaller number is equal to pumping 6 hours at the design rate and larger number is the design rate.
[2] Drawdown is the difference between heads at the end of the simulation period (stress period 24) with and without the managed wells.
[3] Optimized rate equals design rate.
[4] Not pumped in 2001.

The withdrawal rates ranged from 0.014 to 1.0 Mgal/d. The optimized withdrawals resulted in simulated model-cell water levels ranging from 154 to 226 ft below sea level and 312 to 445 ft below land surface at the well sites. The total pumping head equaled 4,626 ft under the optimized pumping scheme, compared to 3,549 in 2001 when the aquifer was pumped at 2.6 Mgal/d. Therefore, pumping an additional 2.1 Mgal/d increases total pumping head by approximately 30 percent. Under optimized withdrawals, water levels did not fall below the 80-percent management level in the Indian Head-Bryans Road area.

In Scheme 4B, the production wells were allowed to shut off during optimization. The minimum total drawdown for the Lower Patapsco well system when pumped at a cumulative rate of 2.6 Mgal/d in each stress period (1-month periods) equaled 378 ft. Drawdown ranged from 82 to 110 ft in stress period 24 (tab. 6). The withdrawal rates ranged from 0.24 to 1.0 Mgal/d. Three of the 12 well sites were pumped. The optimized withdrawals resulted in simulated model-cell water levels ranging from 110 to 161 ft below sea level and 325 to 376 ft below land surface at the well sites. By comparison, simulated pumping water levels in 2001 ranged from 260 to 362 ft below land surface (tab. 6). The total pumping head equaled 1,384 ft under the optimized pumping scheme, compared to 3,549 ft in 2001. Therefore, the optimized withdrawals reduced total pumping head by approximately 61 percent. Water levels did not fall below the 80-percent management level in the Indian Head-Bryans Road area.

In Scheme 4B, when pumped at a cumulative rate of 5.0 Mgal/d in each stress period (1-month periods), the minimum total drawdown for the Lower Patapsco well system equaled 1,253 ft. Drawdown ranged from 116 to 193 ft in stress period 24 (tab .6). The withdrawal rates ranged from 0.046 to 1.0 Mgal/d. Eight of the 12 well sites were pumped. The optimized withdrawals resulted in simulated model-cell water levels ranging from 155 to 227 ft below sea level and 350 to 445 ft below land surface at the well sites (tab. 6). The total pumping head equaled 3,234 ft under the optimized pumping scheme, compared to 3,549 ft in 2001 when the aquifer was pumped at 2.6 Mgal/d. Therefore, under optimized pumping conditions, an additional 2.1 Mgal/d can be pumped with approximately 9 percent less total pumping head than in 2001. Water levels did not fall below the 80-percent management level in the Indian Head-Bryans Road area.

Scheme 5: Minimizing Total Drawdown in the Existing Lower Patapsco Waldorf Well System and in a Proposed Well at the White Plains Business Park (Well 16)

In this scheme, total drawdown in the Lower Patapsco well system and at a proposed well site at the White Plains Business Park (Well 16) was minimized over a 24-month period by optimizing pumpage at the individual wells. Pumpage in the individual wells was constrained by the design pumping rates. The site for proposed Well 16 is located approximately ¼ mile (mi) east of the intersection of Routes 301 and 227 (fig. 10). Two approaches were used to determine minimum total drawdown. In the first approach (designated as Scheme 5A), the 12 well sites were required to pump a minimum daily rate equal to 6 hours of pumping at design rates. In the second approach (designated as Scheme 5B), the wells were allowed to shut off during optimization. In both approaches (Schemes 5A and 5B), total drawdown was minimized using two different cumulative pumpage amounts: 2.6 Mgal/d (average amount pumped from the Lower Patapsco aquifer in 2001), and 5.0 Mgal/d (average amount pumped by both the Lower Patapsco and Magothy production wells in the Waldorf well system in 2001).

In Scheme 5A, when pumped at a cumulative rate of 2.6 Mgal/d, the minimum total drawdown for the 12 existing Lower Patapsco well sites and for Well 16 equaled 958 ft. Drawdown ranged from 62 to 82 ft in stress period 24 (tab. 7). The optimized withdrawal rates ranged from 0.014 to 1.0 Mgal/d. The optimized withdrawals resulted in water levels ranging from 109 to 126 ft below sea level and 251 to 341 ft below land surface (tab. 7). The total pumping head was 4,066 ft compared to 3,549 ft in 2001.

In Scheme 5A, when pumped at a cumulative rate of 5.0 Mgal/d in each stress period, the minimum total drawdown for the 12 existing Lower Patapsco well sites and for Well 16 equaled 1,892 ft. Drawdown ranged from 114 to 189 ft in stress period 24 (tab. 7). The total pumping head was 5,001 ft. The optimized withdrawal rates ranged from 0.014 to 1.0 Mgal/d. The optimized withdrawals resulted in water levels ranging from 153 to 232 ft below sea level and 307 to 447 ft below land surface. Water levels did not fall below the 80-percent management level in the Indian Head-Bryans Road area.

Table 6. Optimized withdrawal rates producing the minimum amount of total drawdown (Scheme 4B)

[Mgal/d = million gallons per day; ft = feet; -- no data or not applicable]

Well site	Well number (Owner's number)	Upper and lower pumping constraints (Mgal/d[1])	Optimized withdrawal rate (Mgal/d)	Draw-down[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)	Optimized withdrawal rate (Mgal/d)	Draw-down[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)	Simulated 2001 pumping level (ft below land surface)
			2.6 Mgal/d				5 Mgal/d				2.6 Mgal/d
Smallwood West (Well 11)	CH Be 58	0 / 0.72	0	--	--	--	0.72[3]	-45.3-(-219.6)=174	-220	430	362
Westwood Drive (Well 15)	CH Be 71	0 / .94	0	--	--	--	.94[3]	-31.7-(-224.7)=193	-225	445	--[4]
Billingsley Road (Well 12)	CH Be 64	0 / .72	0.24	-47.5-(-132.1)=85	-132	342	.72[3]	-47.5-(-227.2)=180	-227	437	360
White Oak (Well 10)	CH Bf 150	0 / 1.0	1.0[3]	-28.0-(-110.4)=82	-110	325	1.0[3]	-28.0-(-154.6)=127	-155	370	309
Cleveland Park (Well 14)	CH Be 67	0 / .83	.83[3]	-50.3-(-160.7)=110	-161	376	.83[3]	-50.3-(-227.0)=177	-227	442	344
St. Paul (Well 9)	CH Bf 147	0 / .52	.52[3]	-46.7-(-147.8)=101	-148	341	.52[3]	-46.7-(-204.2)=158	-204	397	336
Bensville	CH Bd 51 (Well 2) CH Bd 57 (Well 1)	0 / .39	0	--	--	--	.046	-49.4-(-164.9)=116	-165	350	321
Dutton's Addition	CH Bd 49	0 / .22	0	--	--	--	.22[3]	-52.0-(-179.7)=128	-180	363	305
Eutaw Forest	CH Bd 44 (Well 1) CH Bd 46 (Well 3)	0 / .13	0	--	--	--	0	--	--	--	315
	CH Bd 40 (Well 2)	0 / .06	0	--	--	--	0	--	--	--	310
Laurel Branch	CH Bd 48 (Well 4)	0 / .43	0	--	--	--	0	--	--	--	260
	CH Bd 39 (Well 1) CH Bd 47 (Well 3)	0 / .19	0	--	--	--	0	--	--	--	327
			Total = 2.6 Mgal/d	Total = 378 ft		Total = 1,384 ft	Total = 5.0 Mgal/d	Total = 1,253 ft		Total = 3,234 ft	Total = 3,549 ft

[1] Upper pumping constraint is the design rate.
[2] Drawdown is the difference between heads at the end of the simulation period (stress period 24) with and without the managed wells.
[3] Optimized rate equals design rate.
[4] Not pumped in 2001.

EXPLANATION

-50 Simulated potentiometric surface at 2.6 million gallons per day in feet related to sea level.

-50 Simulated potentiometric surface at 5 million gallons per day in feet related to sea level.

• Lower Patapsco production well

Figure 10. Simulated potentiometric surface of the Lower Patapsco aquifer when pumped at optimized rates of 2.6 and 5.0 million gallons per day in the Waldorf well system (Scheme 5A).

Table 7. Optimized withdrawal rates producing the minimum amount of total drawdown (Scheme 5A)

[Mgal/d = million gallons per day; ft = feet; -- no data or not applicable]

Well site	Well number (Owner's number)	Upper and lower pumping constraints (Mgal/d[1])	Optimized withdrawal rate (Mgal/d)	Draw-down[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)	Optimized withdrawal rate (Mgal/d)	Draw-down[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)	Simulated 2001 pumping level (ft below land surface)
			2.6 Mgal/d				5 Mgal/d				2.6 Mgal/d
Smallwood West (Well 11)	CH Be 58	0.18 / 0.72	0.18	-45.3-(-120.3)=75	-120	330	0.18	-45.3-(-191.6)=146	-192	402	362
Westwood Drive (Well 15)	CH Be 71	.23 / .94	.23	-31.7-(-109.4)=78	-109	329	.94[3]	-31.7-(-220.7)=189	-221	441	--[4]
Billingsley Road (Well 12)	CH Be 64	.18 / .72	.18	-47.5-(-124.2)=77	-124	334	.45	-47.5-(-216.9)=169	-217	427	360
White Oak (Well 10)	CH Bf 150	.25 / 1.0	1.0[3]	-28.0-(-109.8)=82	-110	325	1.0[3]	-28.0-(-153.3)=125	-153	368	309
Cleveland Park (Well 14)	CH Be 67	.21 / .83	.21	-50.3-(-125.7)=75	-126	341	.83[3]	-50.3-(-232.2)=182	-232	447	344
St. Paul (Well 9)	CH Bf 147	.13 / .52	.26	-46.7-(-121.6)=75	-122	315	.52[3]	-46.7-(-206.6)=160	-207	400	336
Bensville	CH Bd 51 (Well 2) CH Bd 57 (Well 1)	.097 / .39	.097	-49.4-(-120.2)=71	-120	305	.097	-49.4-(-169.8)=120	-170	355	321
Dutton's Addition	CH Bd 49	.054 / .22	.054	-52.0-(-113.5)=62	-114	297	.054	-52.0-(-165.6)=114	-166	349	305
Eutaw Forest	CH Bd 44 (Well 1) CH Bd 46 (Well 3)	.032 / .13	.032	-46.5-(-117.6)=71	-118	303	.032	-46.5-(-172.1)=126	-172	357	315
	CH Bd 40 (Well 2)	.014 / .06	.014	-47.7-(-116.0)=68	-116	296	.014	-47.7-(-171.4)=124	-171	351	310
Laurel Branch	CH Bd 48 (Well 4)	.11 / .43	.11	-42.4-(-121.4)=79	-121	251	.11	-42.4-(-176.8)=134	-177	307	260
	CH Bd 39 (Well 1) CH Bd 47 (Well 3)	.049 / .19	.049	-41.4-(-114.3)=73	-114	314	.049	-41.4-(-171.3)=130	-171	371	327
Proposed well at White Plains Business Park (Well 16)		.18 / .72	.18	-53.0-(-125.7)=72	-126	326[5]	.72[3]	-53.0-(-225.9)=173	-226	426[5]	--
			Total = 2.6 Mgal/d	Total = 958 ft		Total = 4,066 ft	Total = 5.0 Mgal/d	Total = 1,892 ft		Total = 5,001 ft	Total = 3,549 ft

[1] Smaller number is equal to pumping 6 hours at the design rate and larger number is the design rate.
[2] Drawdown is the difference between heads at the end of the simulation period (stress period 24) with and without the managed wells.
[3] Optimized rate equals design rate.
[4] Not pumped in 2001.
[5] Assumes a land-surface altitude of 200 ft.

The simulated potentiometric surface of the Lower Patapsco aquifer, resulting from pumpage at the cumulative rate of 2.6 Mgal/d (Scheme 5A), produced a cone-of-depression greater than 75 ft below sea level in the Waldorf area (fig. 10). Water levels were as much as 25 ft higher than the potentiometric surface in 2001 (Curtin and others, 2002d). When pumped at the cumulative rate of 5.0 Mgal/d (Scheme 5A), the potentiometric surface deepened to more than 125 feet below sea level.

In Scheme 5B, the production wells were allowed to shut off during optimization. The minimum total drawdown for the Lower Patapsco well system and for Well 16 when pumped at a cumulative rate of 2.6 Mgal/d equaled 362 ft. Drawdown ranged from 83 to 95 ft in stress period 24 (tab. 8). The optimized withdrawal rates ranged from 0.35 to 1.0 Mgal/d. Four of the 12 well sites were pumped. The optimized withdrawals resulted in water levels ranging from 111 to 148 ft below sea level and 326 to 354 ft below land surface (tab. 8). The total pumping head was 1,362 ft compared to 3,549 ft in 2001. Water levels did not fall below the 80-percent management level in the Indian Head-Bryans Road area.

In Scheme 5B, when pumped at a cumulative pumping rate of 5.0 Mgal/d, the minimum total drawdown for the 12 existing Lower Patapsco well sites and for Well 16 equaled 1,183 ft. Drawdown ranged from 127 to 190 ft in stress period 24 (tab. 8). The optimized withdrawal rates ranged from 0.26 to 1.0 Mgal/d. Seven of the 12 well sites were pumped. The optimized withdrawals resulted in water levels ranging from 155 to 238 ft below sea level and 370 to 453 ft below land surface. The total pumping head was 2,949 ft. Water levels did not fall below the 80-percent management level in the Indian Head-Bryans Road area.

Scheme 6: Selection of Future Well Site Producing the Least Amount Of Drawdown

The optimization process was used to locate a site for a future well that would produce the least amount of total drawdown in the Lower Patapsco Waldorf well system. To accomplish this, a decision variable, referred to as a binary integer variable, is added to the objective function for minimizing drawdown. The formulation of this decision variable is discussed in detail in Ahlfeld and Mulligan (2000; p. 123-135). The optimization algorithm selected one out of four candidate well sites located east of Rt. 301 (fig. 11). The potential well sites were located in areas with at least 450 ft of available drawdown in 2001. Two approaches were used to determine minimum total drawdown. In the first approach (designated as Scheme 6A), the 12 existing well sites, plus the proposed Well 16 at White Plains Business Park, were required to pump a minimum daily rate equal to 6 hours of pumping at design rates. In the second approach (designated as Scheme 6B), the existing wells, plus Well 16, were allowed to shut off during optimization. The hypothetical well selected by the optimization algorithm was required to pump 0.5 Mgal/d in both approaches. Total discharge from the combined set of wells (existing wells, proposed Well 16, and the hypothetical well) was required to total 2.6 Mgal/d over the 2-year simulation period.

In simulation 6A, optimized pumping rates ranged from 0.014 Mgal/d at Eutaw Forest Well 2 (CH Bd 40) to 0.64 Mgal/d at White Oak Well 10 (tab. 9). The hypothetical well site selected from the candidate sites is located approximately 1 mi east of the White Oak well site in an area of relatively high transmissivity (figs. 4 and 11). Drawdown in the existing wells, proposed Well 16, and the hypothetical well over the 2-year simulation period ranged from 60 to 77 ft. Total drawdown equaled 980 ft. Drawdown in the hypothetical well was 65 ft. Simulated water levels ranged from 92 ft below sea level at the hypothetical well site to 123 ft below sea level at the proposed White Plains Business Park site (Well 16) (tab. 9). The total pumping head was 4,327 ft compared to 3,549 ft under simulated 2001 pumping conditions (2.6 Mgal/d). Therefore, by adding the White Plains Business Park well and the hypothetical well, and optimizing pumpage, total pumping head increased by 22 percent.

The simulated potentiometric surface of the Lower Patapsco aquifer, resulting from pumpage at the cumulative rate of 2.6 Mgal/d (Scheme 6A), produced a cone-of-depression greater than 80 ft below sea level in the Waldorf area (fig. 11).

In simulation 6B, optimized pumping rates ranged from 0.38 Mgal/d at St. Paul Well 9 to 1.0 Mgal/d at White Oak Well 10 (tab. 10). The same site was selected for the hypothetical well as in the previous scheme. Drawdown in the existing wells, proposed Well 16, and the hypothetical well over the 2-year simulation period ranged from 70 to 87 ft. Total drawdown equaled 323 ft. Drawdown in the hypothetical well was 70 ft. Simulated water levels ranged from 97 ft below sea level at the hypothetical well site to 140 ft below sea level at the proposed White Plains Business Park site (Well 16) (tab. 10). The total pumping head was 1,286 ft compared to

Table 8. Optimized withdrawal rates producing the minimum amount of total drawdown (Scheme 5B)

[Mgal/d = million gallons per day; ft = feet; -- no data or not applicable]

Well site	Well number (Owner's number)	Upper and lower pumping constraints (Mgal/d[1])	Optimized withdrawal rate (Mgal/d)	Draw-down[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)	Optimized withdrawal rate (Mgal/d)	Draw-down[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)	Simulated 2001 pumping level (ft below land surface)
			2.6 Mgal/d				5 Mgal/d				2.6 Mgal/d
Smallwood West (Well 11)	CH Be 58	0 / 0.72	0	--	--	--	0.26	-45.3-(-196.6)=151	-197	407	362
Westwood Drive (Well 15)	CH Be 71	0 / .94	0	--	--	--	.94[3]	-31.7-(-222.0)=190	-222	442	--[4]
Billingsley Road (Well 12)	CH Be 64	0 / .72	0	--	--	--	.72[3]	-47.5-(-233.1)=186	-233	443	360
White Oak (Well 10)	CH Bf 150	0 / 1.0	1.0[3]	-28.0-(-110.8)=83	-111	326	1.0[3]	-28.0-(-155.0)=127	-155	370	309
Cleveland Park (Well 14)	CH Be 67	0 / .83	.35	-50.3-(-138.9)=89	-139	354	.83[3]	-50.3-(-237.5)=187	-238	453	344
St. Paul (Well 9)	CH Bf 147	0 / .52	.52[3]	-46.7-(-141.3)=95	-141	334	.52[3]	-46.7-(-210.5)=164	-210	403	336
Bensville	CH Bd 51 (Well 2); CH Bd 57 (Well 1)	0 / .39	0	--	--	--	0	--	--	--	321
Dutton's Addition	CH Bd 49	0 / .22	0	--	--	--	0	--	--	--	305
Eutaw Forest	CH Bd 44 (Well 1); CH Bd 46 (Well 3)	0 / .13	0	--	--	--	0	--	--	--	315
	CH Bd 40 (Well 2)	0 / .06	0	--	--	--	0	--	--	--	310
Laurel Branch	CH Bd 48 (Well 4)	0 / .43	0	--	--	--	0	--	--	--	260
	CH Bd 39 (Well 1); CH Bd 47 (Well 3)	0 / .19	0	--	--	--	0	--	--	--	327
Proposed well at White Plains Business Park (Well 16)		0 / .72	.72[3]	-53.0-(-148.3)=95	-148	348[4]	.72[3]	-53.0-(-230.8)=178	-231	431[5]	--
			Total = 2.6 Mgal/d	Total = 362 ft		Total = 1,362 ft	Total = 5.0 Mgal/d	Total = 1,183 ft		Total = 2,949 ft	Total = 3,549 ft

[1] Upper pumping constraint is the design rate.
[2] Drawdown is the difference between heads at the end of the simulation period (stress period 24) with and without the managed wells.
[3] Optimized rate equals design rate.
[4] Not pumped in 2001.
[5] Assumes a land-surface altitude of 200 ft.

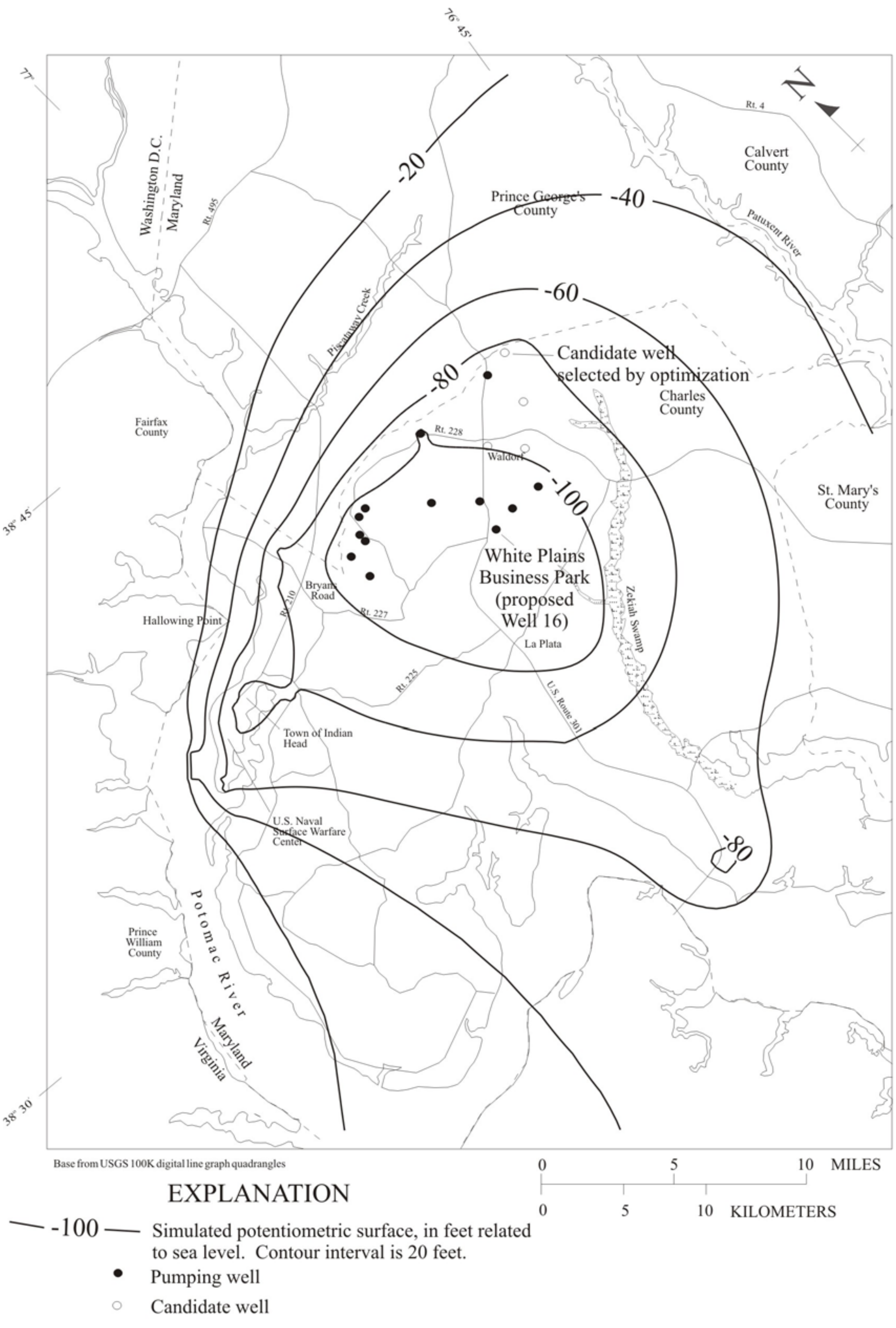


Figure 11. Simulated potentiometric surface of the Lower Patapsco aquifer (Scheme 6A).

Table 9. Optimized withdrawal rates producing the minimum amount of total drawdown (Scheme 6A)

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

Well site	Well number (Owner's number)	Upper and lower pumping constraints (Mgal/d[1])	Optimized withdrawal rate in stress period 24 (Mgal/d)	Drawdown[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface)
Smallwood West (Well 11)	CH Be 58	0.18 / .72	0.18	-45.3-(-118.0)=73	-118	328
Westwood Drive (Well 15)	CH Be 71	.23 / .94	.24	-31.7-(-107.5)=76	-108	328
Billingsley Road (Well 12)	CH Be 64	.18 / .72	.18	-47.5-(-121.3)=74	-121	331
White Oak (Well 10)	CH Bf 150	.25 / 1.0	.64	-28.0-(-100.9)=73	-111	326
Cleveland Park (Well 14)	CH Be 67	.21 / .83	.21	-50.3-(-121.9)=72	-122	337
St. Paul (Well 9)	CH Bf 147	.13 / .52	.13	-46.7-(-111.7)=65	-112	305
Bensville	CH Bd 51 (Well 2)	.097 / .39	.097	-49.4-(-118.6)=69	-119	304
	CH Bd 57 (Well 1)					
Dutton's Addition	CH Bd 49	.054 / .22	.054	-52.0-(-111.8)=60	-112	295
Eutaw Forest	CH Bd 44 (Well 1)	.032 / .13	.032	-46.5-(-115.8)=69	-116	301
	CH Bd 46 (Well 3)					
	CH Bd 40 (Well 2)	.014 / .06	.014	-47.7-(-114.2)=66	-114	294
Laurel Branch	CH Bd 48 (Well 4)	.11 / .43	.11	-42.4-(-119.7)=77	-120	250
	CH Bd 39 (Well 1)	.049 / .19	.049	-41.4-(-112.6)=71	-113	313
	CH Bd 47 (Well 3)					
Proposed well at White Plains Business Park (Well 16)		.17 / .72	.17	-53.0-(-122.7)=70	-123	323[4]
Hypothetical well		.5 / .5	.5[3]	-27.4-(-92.4)=65	-92	292[4]
			Total = 2.6 Mgal/d	Total = 980 ft		Total = 4,327 ft

[1] Smaller number is equal to pumping 6 hours at the design rate and larger number is the design rate.
[2] Drawdown is the difference between heads at the end of the simulation period (stress period 24) with and without the managed wells.
[3] Optimized rate equals design rate.
[4] Assumes a land-surface altitude of 200 ft.

Table 10. Optimized withdrawal rates producing the minimum amount of total drawdown (Scheme 6B)

[Mgal/d = million gallons per day; ft = feet; -- = no data or not applicable]

Well site	Well number (Owner's number)	Upper and lower pumping constraints (Mgal/d[1])	Optimized withdrawal rate in stress period 24 (Mgal/d)	Drawdown[2] (ft)	Simulated pumping level (ft related to sea level)	Simulated pumping level (ft below land surface
Smallwood West (Well 11)	CH Be 58	0 / .72	0	--	--	--
Westwood Drive (Well 15)	CH Be 71	0 / .94	0	--	--	--
Billingsley Road (Well 12)	CH Be 64	0 / .72	0	--	--	--
White Oak (Well 10)	CH Bf 150	0 / 1.0	1.0[3]	-28.0-(-114.2)=86	-114	329
Cleveland Park (Well 14)	CH Be 67	0 / .83	0	--	--	--
St. Paul (Well 9)	CH Bf 147	0 / .52	.38	-46.7-(-126.9)=80	-127	320
Bensville	CH Bd 51 (Well 2)	0 / .39	0	--	--	--
	CH Bd 57 (Well 1)					
Dutton's Addition	CH Bd 49	0 / .22	0	--	--	--
Eutaw Forest	CH Bd 44 (Well 1)	0 / .13	0	--	--	--
	CH Bd 46 (Well 3)					
	CH Bd 40 (Well 2)	0 / .06	0	--	--	--
Laurel Branch	CH Bd 48 (Well 4)	0 / .43	0	--	--	--
	CH Bd 39 (Well 1)	0 / .19	0	--	--	--
	CH Bd 47 (Well 3)					
Proposed well at White Plains Business Park (Well 16)		0 / .72	.72[3]	-53.0-(-140.4)=87	-140	340[4]
Hypothetical well		.5 / .5	.5[3]	-27.4-(-97.3)=70	-97	297[4]
			Total = 2.6 Mgal/d	Total = 323 ft		Total = 1,286 ft

[1] Upper pumping constraint is the design rate.
[2] Drawdown is the difference between heads at the end of the simulation period (stress period 24) with and without the managed wells.
[3] Optimized rate equals design rate.
[4] Assumes a land-surface altitude of 200 ft.

3,549 ft under simulated 2001 pumping conditions (2.6 Mgal/d). Therefore, by adding the White Plains Business Park well and the hypothetical well, and optimizing pumpage, total pumping head can be reduced by 64 percent.

SUMMARY

The annual average pumpage from the Lower Patapsco aquifer by the Waldorf well system increased from 0.096 Mgal/d in 1984 to 2.6 Mgal/d in 2001. The withdrawals have caused the formation of a relatively deep cone-of-depression surrounding the Waldorf area. Between 1979 and 2001, water levels declined from a high of approximately 5 ft below sea level to as much as 175 ft below sea level. Since the mid-1990s, the water-level trend flattened as pumpage stabilized at an average rate of about 2.6 Mgal/d. The deepest water levels occurred at Billingsley Road and Smallwood West at approximately 175 ft and 165 ft below sea level. While shallower aquifers, principally the Magothy aquifer, are available, the Lower Patapsco aquifer has the greatest potential for water supply because of its relatively high transmissivity (as much as 3,000 ft^2/d) and available drawdown (as much as 550 ft). However, increasing pumpage can result in excessive drawdown, which will increase pumping cost and possibly cause water levels to fall below pump intakes and the 80-percent management level. To reduce the likelihood of extreme conditions developing, withdrawals from the Lower Patapsco wells in the Waldorf well system were optimized to minimize drawdown. Pumping rates were also maximized with the constraint that water levels not fall below the top of the aquifer and the 80-percent management level in the Lower Patapsco Waldorf well system, or in the Indian Head-Bryans Road area. In addition, a future well site was selected from a group of candidate sites that would minimize cumulative drawdown in the Lower Patapsco Waldorf well system.

A four-layer finite-difference ground-water-flow model previously developed for the Lower Patapsco and Patuxent aquifers in Charles County was revised for use in optimization. Revisions to the model consisted of reducing cell size in the Waldorf area, extending the simulation period by four years, and updating pumpage, time-specified heads, and transmissivity input arrays. Performance of the model was verified by comparing simulated and observed heads at the end of the simulation period 1900-2001 in 20 wells screened in the Lower Patapsco aquifer. For the optimization process, the simulation time of the revised model was changed to 2 years (2002-2003). The ground-water management code MODMAN was used to develop objective functions written as a linear program, which was then solved by the linear program solver SuperLINDO. Objective functions used in this study either maximized withdrawals given specified head constraints or minimized drawdown given a cumulative withdrawal rate for the entire Lower Patapsco Waldorf well system.

In the first optimization scheme, withdrawals from the existing Lower Patapsco wells were maximized while constraining water levels above pump intakes. Results indicate that Billingsley Road Well 12, Cleveland Park Well 14, St. Paul Well 9, and Bensville Well 1 or 2 can pump continuously at their design rates without causing water levels to fall below pump intakes. Water levels at Smallwood West Well 11, Westwood Drive Well 15, White Oak Well 10, Dutton's Addition, and Eutaw Forest reached pump intakes at rates less than their design rates. Withdrawal from Laurel Branch Well 4 (CH Bd 48) is constrained by the pump intake in the adjacent model cell containing Laurel Branch Wells 1 and 3 (CH Bd 39 and 47). The total optimized withdrawals equaled 5.6 Mgal/d.

In the second optimization scheme, withdrawals from the existing Lower Patapsco wells were maximized while constraining water levels above the top of the Lower Patapsco aquifer in the production wells and the 80-percent management level in model cells surrounding the production wells. Withdrawals increased up to the design rate at each well without causing water levels to fall below the top of the aquifer or the 80-percent management level in model cells immediately surrounding the pumping wells. The total optimized withdrawals equal 6.2 Mgal/d.

In the third optimization scheme, withdrawals from the existing Lower Patapsco Waldorf well system were maximized with the constraint that water levels not fall below the 80-percent management level in the Indian Head-Bryans Road area. This analysis was performed because there is a greater risk of depleting the available drawdown in this area from declining regional water levels

compared to the Waldorf area. Results indicate that pumpage at the Bensville site should be phased out in order to maximize total Lower Patapsco aquifer withdrawals, without causing water levels to fall below the 80-percent management level in the Indian Head-Bryans Road area. If pumpage at the Bensville site is phased out over a 2-year period, a maximum of 5.8 Mgal/d can be pumped from the remaining sites.

In the fourth optimization scheme, total drawdown in the existing Lower Patapsco Waldorf well system was minimized. Optimization was performed with the wells pumping a minimum daily rate equal to 6 hours of pumping at design rates (Scheme 4A), and with wells allowed to shut off during optimization (Scheme 4B). Cumulative withdrawal rates of 2.6 Mgal/d (average annual withdrawal in 2001), and 5.0 Mgal/d (average withdrawal from both the Lower Patapsco and Magothy aquifers in the Waldorf well system in 2001) were in Schemes 4A and 4B. The 5.0 Mgal/d rate assumes that all Magothy pumpage is shifted to the Lower Patapsco aquifer. Drawdown in Scheme 4A for the 12 Lower Patapsco well sites, when pumped at a cumulative rate of 2.6 Mgal/d, ranged from 60 to 85 ft. The withdrawal rates ranged from 0.014 to 1.0 Mgal/d. The minimum drawdown in Scheme 4A for 12 Lower Patapsco well sites, when pumped at a cumulative rate of 5.0 Mgal/d ranged from 115 to 193 ft. The withdrawal rates ranged from 0.014 to 1.0 Mgal/d. In Scheme 4B, when wells are allowed to shut off, drawdown ranged from 82 to 110 ft at a cumulative pumping rate of 2.6 Mgal/d. The withdrawal rates ranged from 0.24 to 1.0 Mgal/d. In Scheme 4B, when wells are allowed to shut off, drawdown ranged from 116 to 193 when pumped at a cumulative rate of 5.0 Mgal/d. The withdrawal rates ranged from 0.046 to 1.0 Mgal/d.

In the fifth optimization scheme, total drawdown in the existing Lower Patapsco Waldorf well system and in a proposed well at the White Plains Business Park (Well 16) was minimized. Optimization was performed with the wells pumping a minimum daily rate equal to 6 hours of pumping at design rates (Scheme 5A), and with wells allowed to shut off during optimization (Scheme 5B). Cumulative withdrawal rates of 2.6 and 5.0 Mgal/d were in Schemes 5A and 5B. Drawdown in Scheme 5A for the 12 Lower Patapsco well sites, when pumped at a cumulative rate of 2.6 Mgal/d, ranged from 62 to 82 ft. The withdrawal rates ranged from 0.014 to 1.0 Mgal/d. Drawdown in Scheme 5A for 12 Lower Patapsco well sites, when pumped at a cumulative rate of 5.0 Mgal/d, ranged from 114 to 189 ft. The withdrawal rates ranged from 0.014 to 1.0 Mgal/d. In Scheme 5B, when wells are allowed to shut off, drawdown ranged from 83 to 95 ft at a cumulative pumping rate of 2.6 Mgal/d. The withdrawal rates ranged from 0.35 to 1.0 Mgal/d. In Scheme 5B, when wells are allowed to shut off, drawdown ranged from 127 to 190 ft when pumped at a cumulative rate of 5.0 Mgal/d. The withdrawal rates ranged from 0.26 to 1.0 Mgal/d.

In the final optimization scheme, a hypothetical well site was selected out of four candidate sites located in areas with at least 450 ft of available drawdown such that total drawdown was minimized in the existing production wells, proposed wells, and the hypothetical well. The selected site is approximately 1 mi east of the White Oak well site in an area of relatively high transmissivity. The site was selected by optimizing pumpage first with the constraint that the existing wells and Well 16 pump a minimum daily rate equal to 6 hours of pumping at design rates (Scheme 6A), and second by allowing those same wells to shut off (Scheme 6B). The hypothetical well selected during optimization was required to pump 0.5 Mgal/d in both schemes, and the cumulative withdrawal rate from all wells (existing wells, proposed Well 16, and the hypothetical well) was required to total 2.6 Mgal/d. Drawdown in Scheme 6A for all of the Lower Patapsco well sites ranged from 60 to 77 ft. The withdrawal rates ranged from 0.014 to 0.64 Mgal/d. In Scheme 6B, when wells are allowed to shut off, drawdown ranged from 70 to 87 ft. The withdrawal rates ranged from 0.38 to 1.0 Mgal/d.

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APPENDIXES

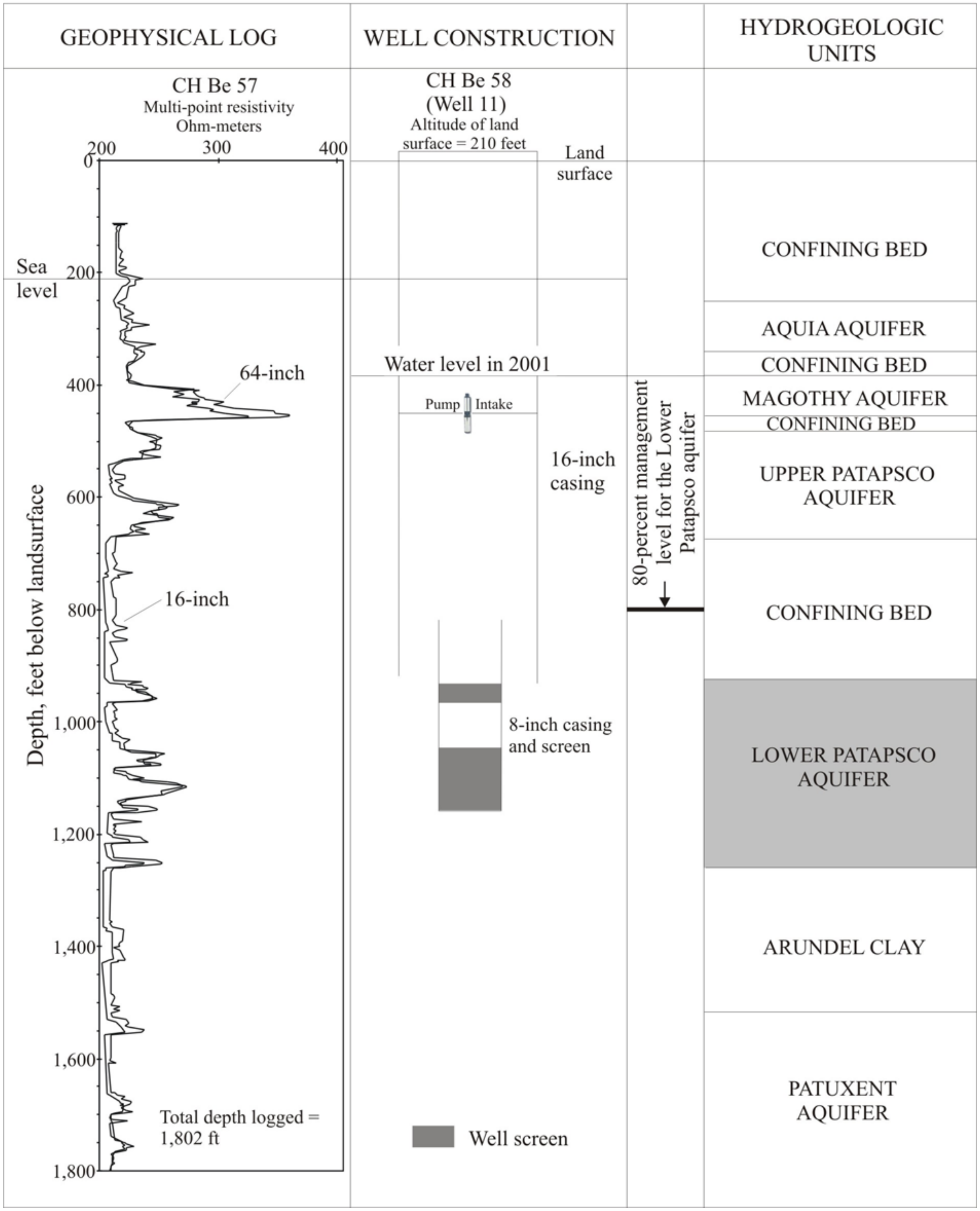
A1-A10. Geophysical logs, well-construction, and hydrogeologic data for Lower Patapsco wells in the Waldorf well system:

A1 Smallwood West (Well 11)
A2 Westwood Drive (Well 15)
A3 Billingsley Road (Well 12)
A4 White Oak (Well 10)
A5 Cleveland Park (Well 14)
A6 St. Paul (Well 9)
A7 Bensville
A8 Dutton’s Addition
A9 Eutaw Forest
A10 Laurel Branch

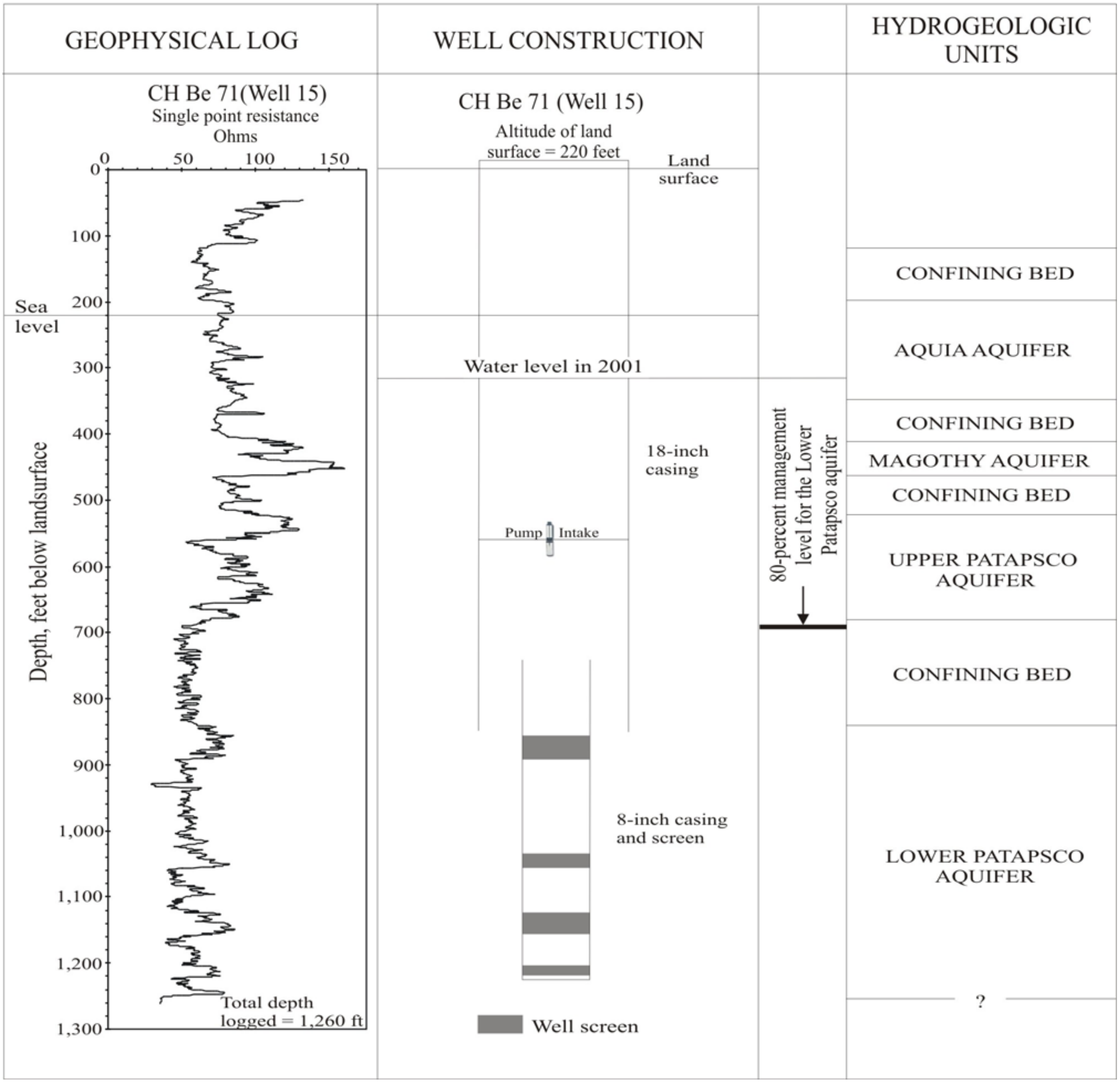
B. Maximum pumping rates constrained by pump intakes (Scheme 1)

C. Maximum pumping rates constrained by the 80-percent management level in the Indian Head-Bryans Road area (Scheme 3)

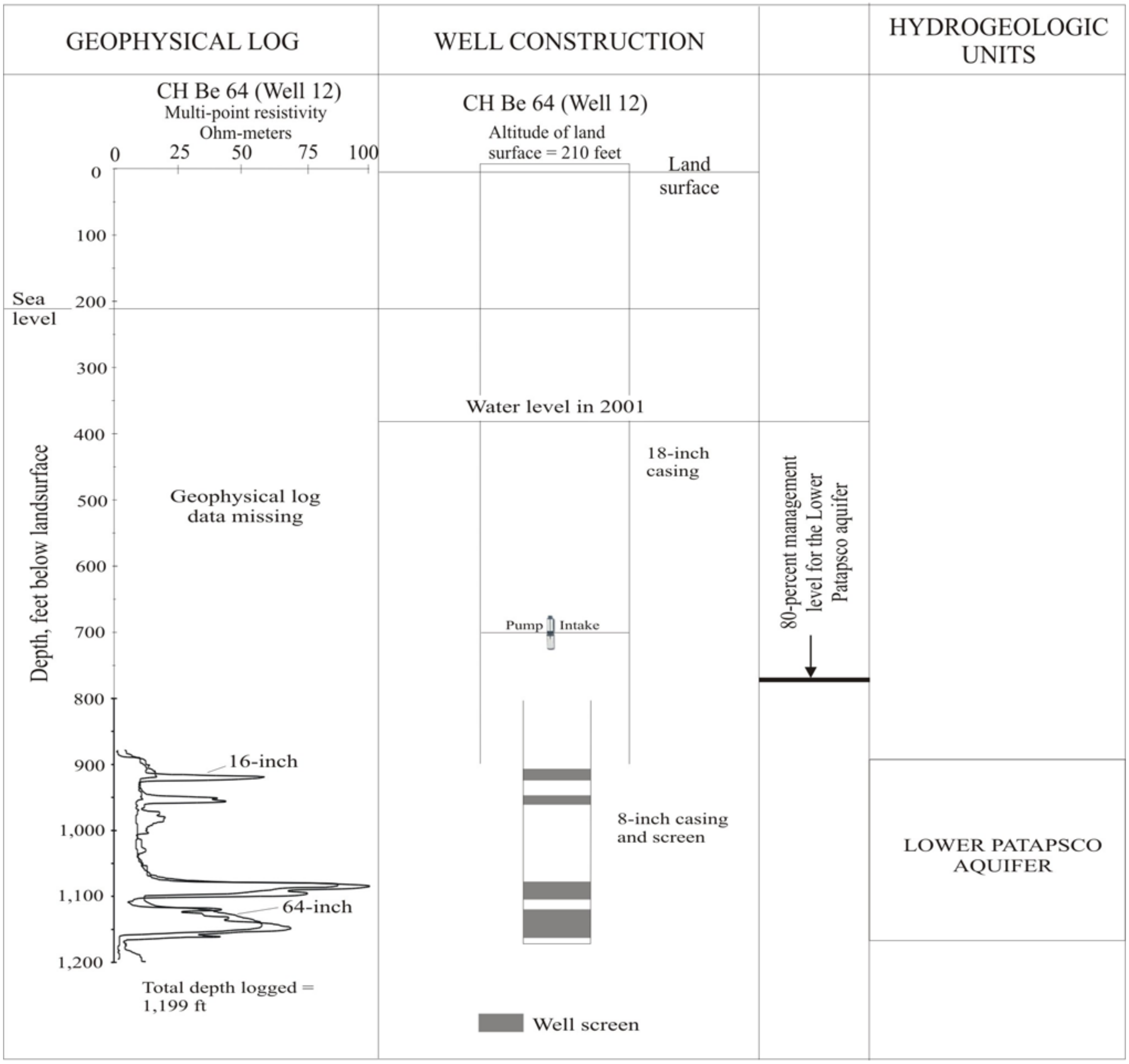
Appendix A1 Smallwood West (Well 11)



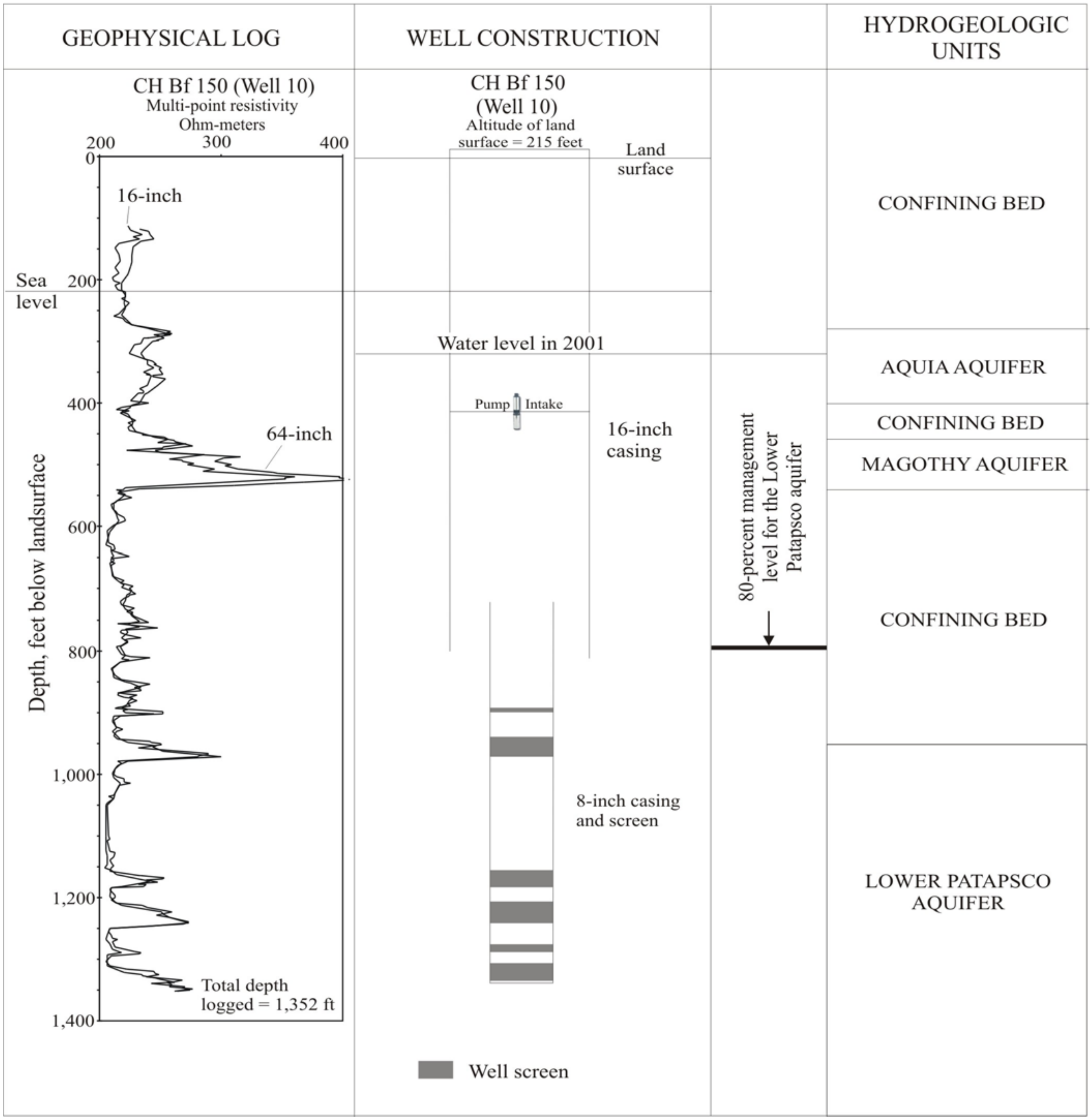
Appendix A2 Westwood Drive (Well 15)



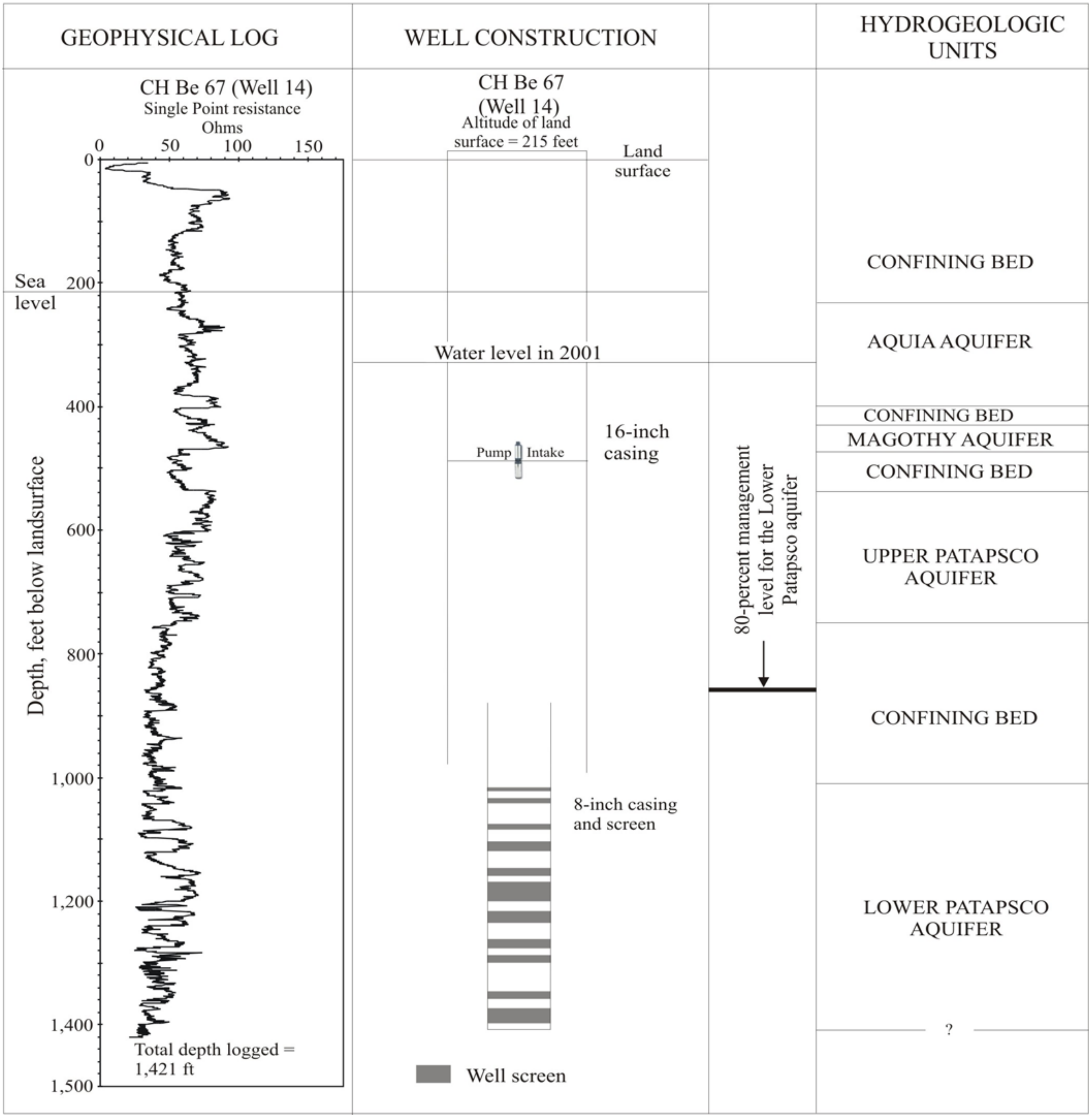
Appendix A3   Billingsley Road (Well 12)



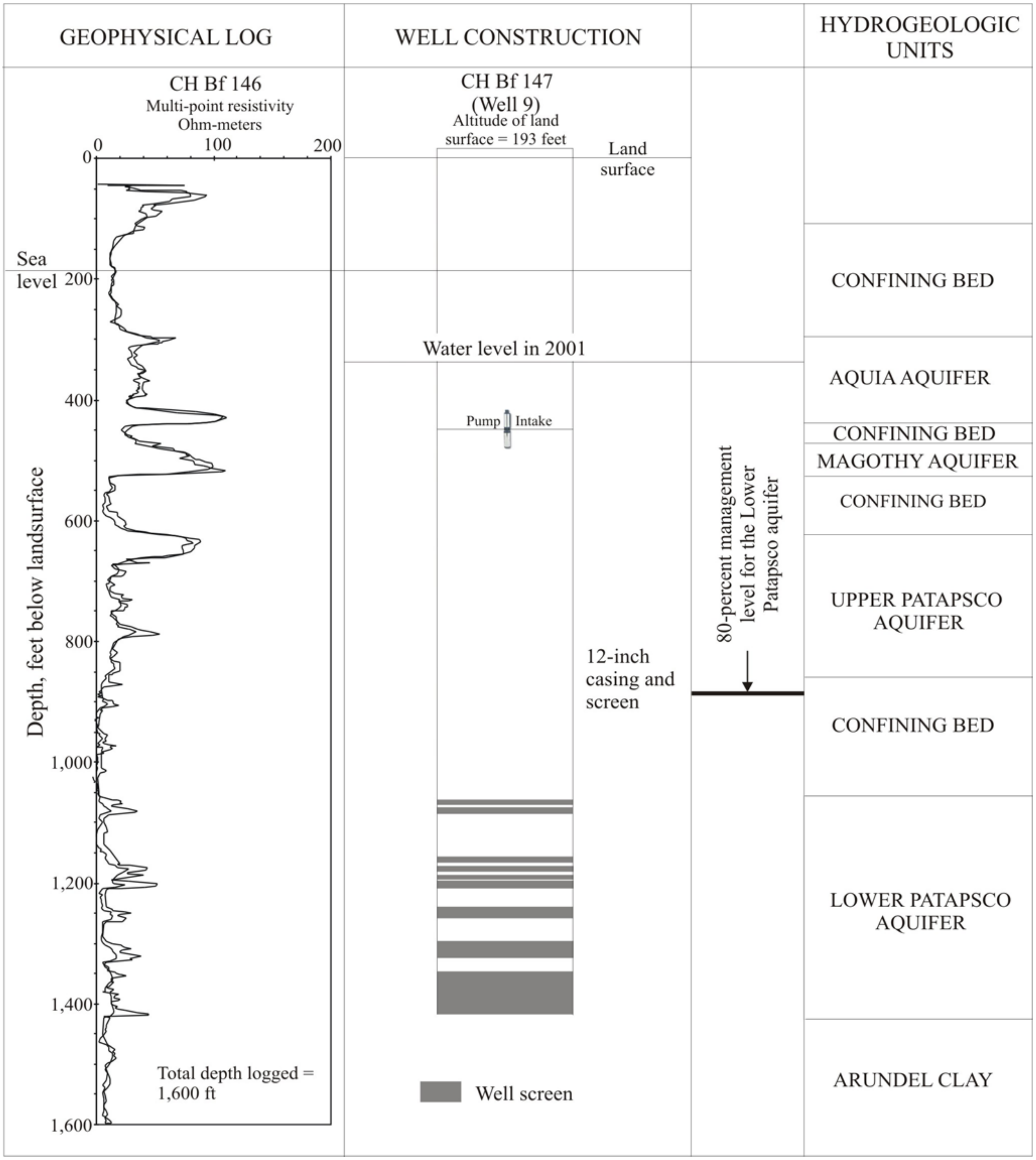
Appendix A4 White Oak (Well 10)



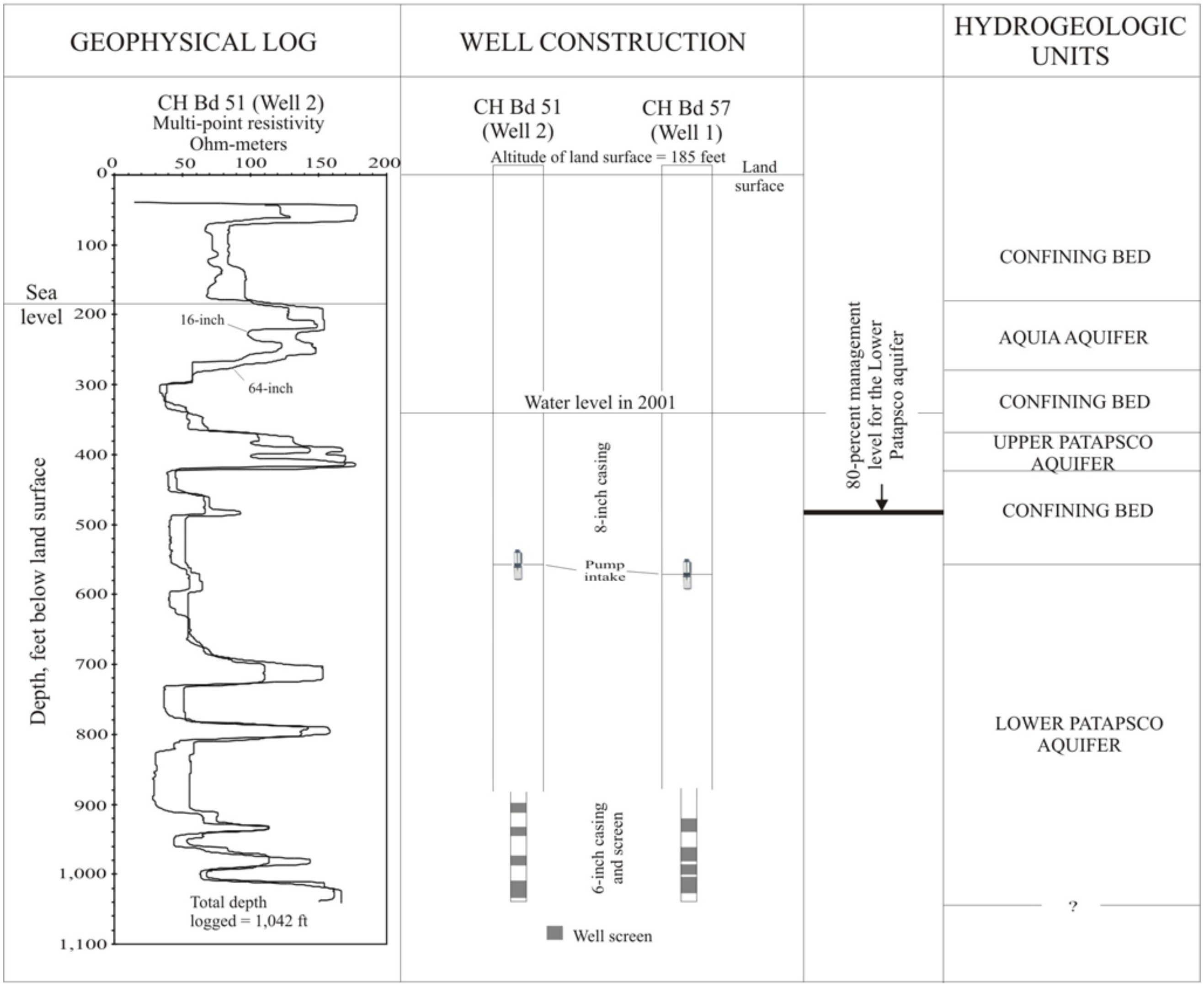
Appendix A5 Cleveland Park (Well 14)



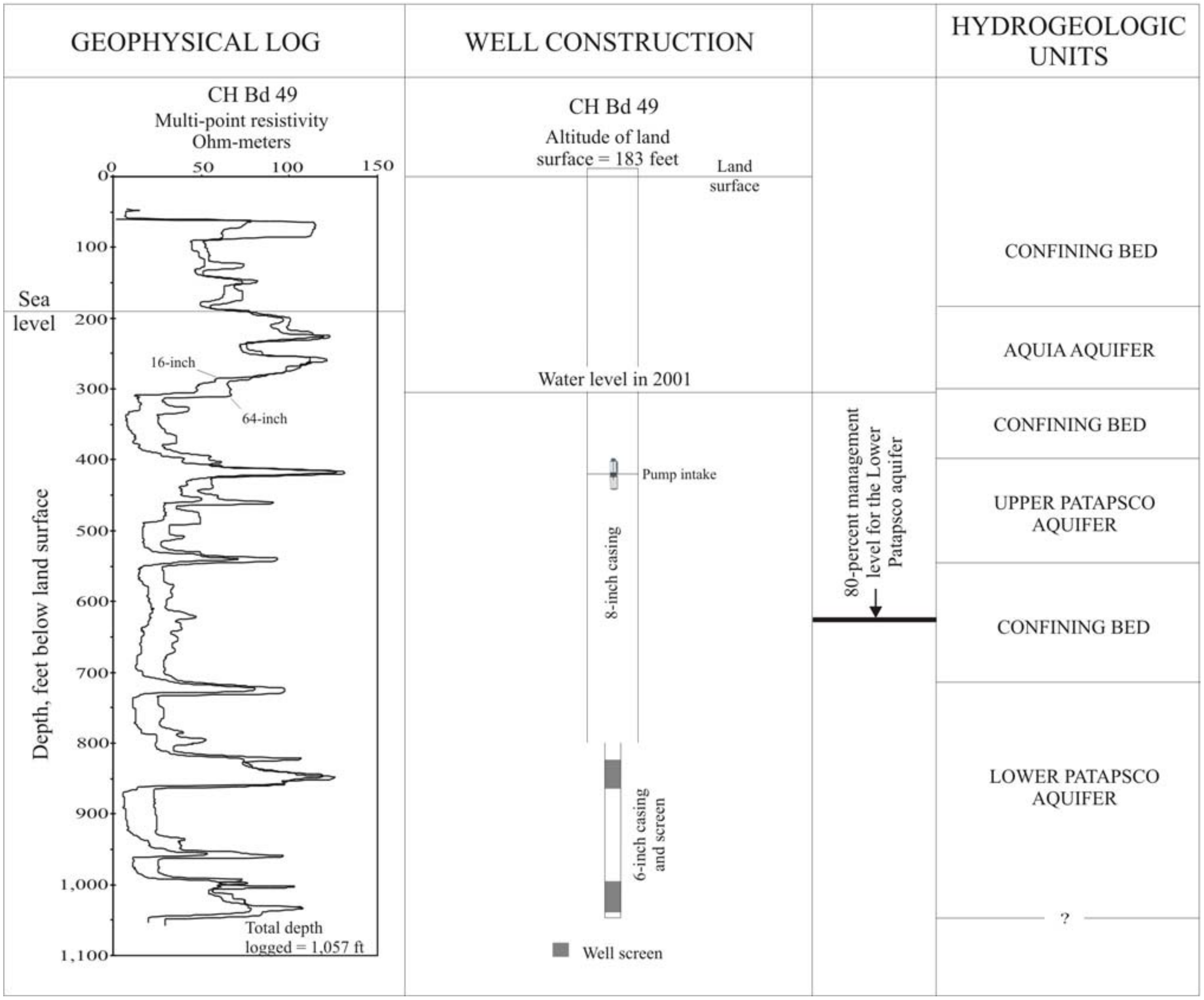
Appendix A6 St. Paul (Well 9)



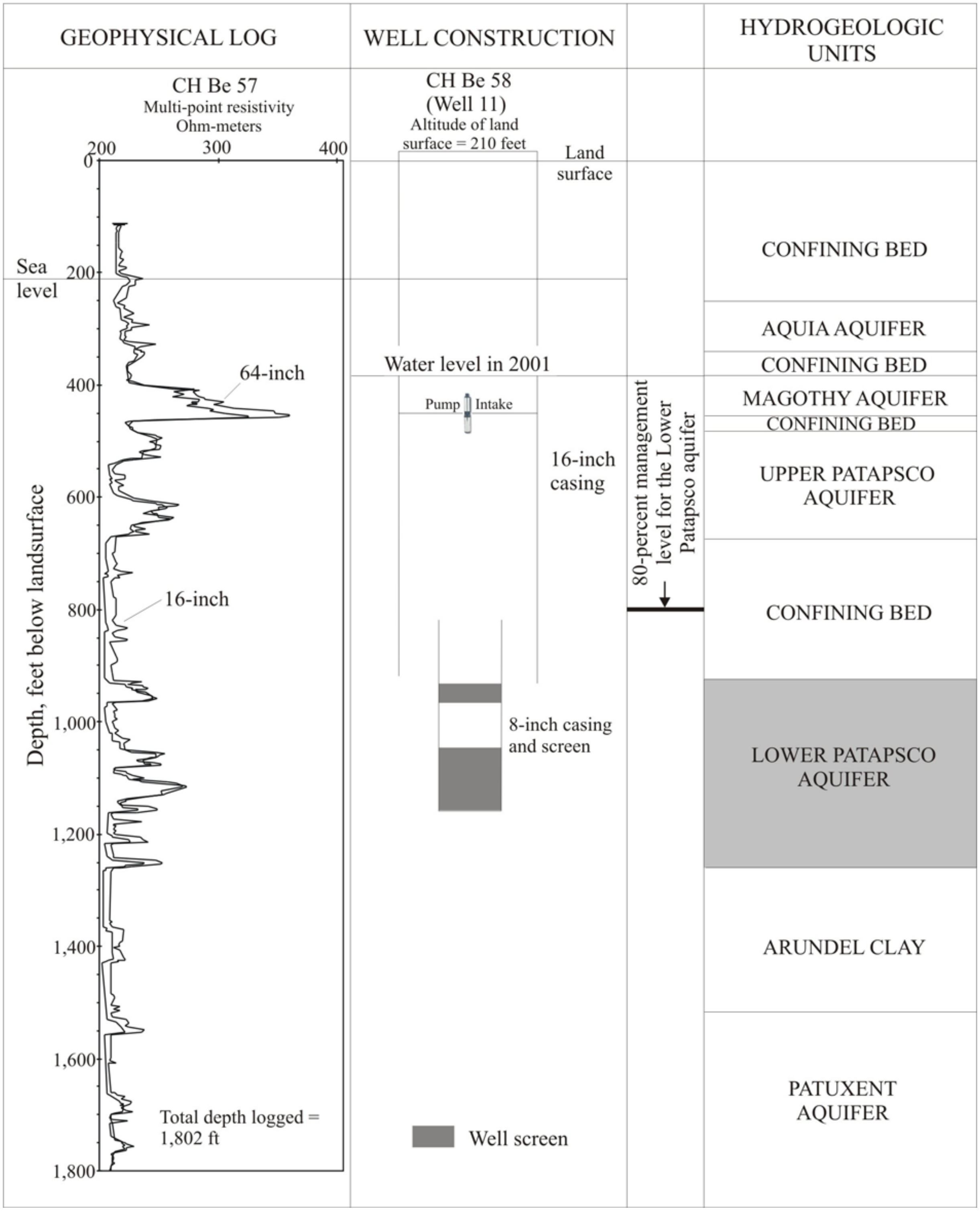
Appendix A7 Bensville



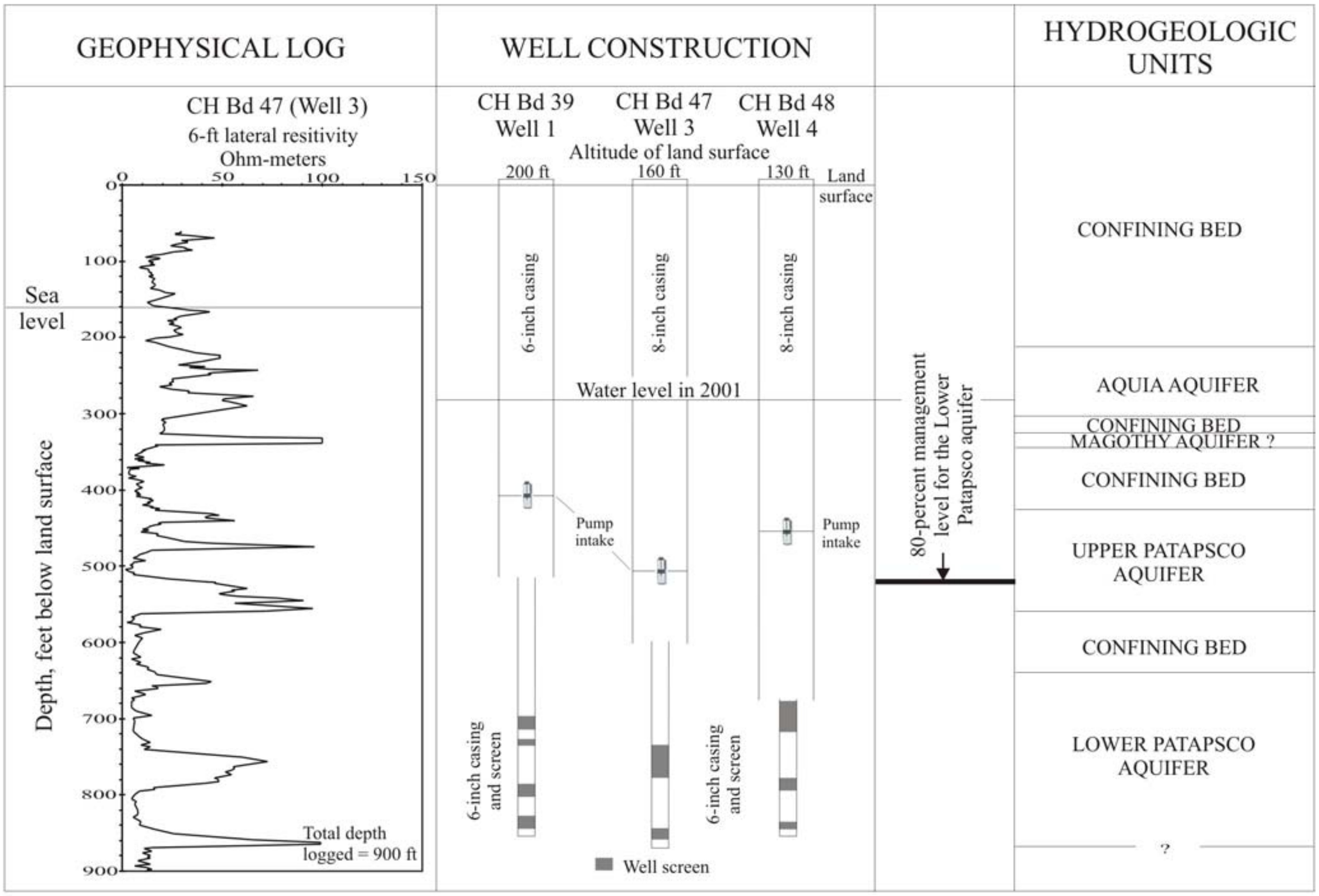
Appendix A8 Dutton's Addition



Appendix A1 Smallwood West (Well 11)



Appendix A10 Laurel Branch



Casing and screen depths for wells CH Bd 39 and CH Bd 48 are adjusted to altitude at well CH Bd 47.

Appendix B. Maximum pumping rates constrained by pump intakes (Scheme 1).

Well Site	Well(s)	Pumpage, million gallons per day																							
		2002												2003											
		Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Smallwood West (Well 11)	CH Be 58	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.72	0.71	0.71	0.71	0.71
Westwood Drive (Well 15)	CH Be 71	.94	.94	.94	.94	.90	.87	.85	.84	.83	.82	.82	.81	.81	.81	.81	.81	.81	.81	.81	.81	.81	.81	.81	.81
Billingsley Road (Well 12)	CH Be 64	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72
White Oak (Well 10)	CH Bf 150	1.01	1.01	1.01	1.01	1.01	1.01	1.01	.99	.97	.95	.94	.93	.93	.92	.92	.92	.92	.91	.91	.91	.91	.91	.91	.91
Cleveland Park (Well 14)	CH Be 67	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83
St. Paul (Well 9)	CH Bf 147	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52
Bensville	CH Bd 51 CH Bd 57	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Dutton's Addition	CH Bd 49	.22	.22	.22	.22	.22	.22	.22	0.21	0.20	0.19	0.18	0.18	0.18	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Eutaw Forest	CH Bd 44 CH Bd 46	.13	.13	.13	.13	.13	.12	.11	.10	.10	.10	.10	.10	.10	.10	.09	.09	.09	.09	.09	.09	.09	.09	.09	.09
	CH Bd 40	.05	.05	.05	.05	.05	.05	.05	.05	.05	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04
Laurel Branch	CH Bd 48	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	0.41	0.40	0.39	0.38	0.38	0.38	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37
	CH Bd 39 CH Bd 47	.19	.19	.19	.19	.14	.09	.05	.03	.01	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00	.00
Total		6.2	6.2	6.2	6.2	6.1	6.0	5.9	5.8	5.8	5.7	5.7	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6	5.6

Appendix C. Maximum pumping rates constrained by the 80-percent management level in the Indian Head-Bryans Road area (Scheme 3).

Well Site	Well(s)	Pumpage, million gallons per day																							
		2002												2003											
		Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	April	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Smallwood West (Well 11)	CH Be 58	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72
Westwood Drive (Well 15)	CH Be 71	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94	.94
Billingsley Road (Well 12)	CH Be 64	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72	.72
White Oak (Well 10)	CH Bf 150	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Cleveland Park (Well 14)	CH Be 67	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83	.83
St. Paul (Well 9)	CH Bf 147	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52	.52
Bensville	CH Bd 51 CH Bd 57	.39	.39	.39	.39	.39	.39	.39	.39	.39	.12	.06	.07	.04	.02	.02	.00	.00	.00	.00	.00	.00	.00	.00	.00
Dutton's Addition	CH Bd 49	.22	.22	.22	.22	.22	.22	.22	.22	.22	.22	.22	.22	.22	.22	.22	.22	.22	.21	.21	.21	.21	.20	.19	.22
Eutaw Forest	CH Bd 44 CH Bd 46	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13	.13
	CH Bd 40	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05	.05
Laurel Branch	CH Bd 48	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43	.43
	CH Bd 39 CH Bd 47	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19	.19
Total		6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	6.2	5.9	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.8	5.7	5.8