REPORT OF INVESTIGATIONS NO. 61
1995

DELINEATION OF WELLHEAD PROTECTION AREAS USING PARTICLE TRACKING ANALYSIS AND HYDROGEOLOGIC MAPPING, NORTHERN ANNE ARUNDEL COUNTY, MARYLAND

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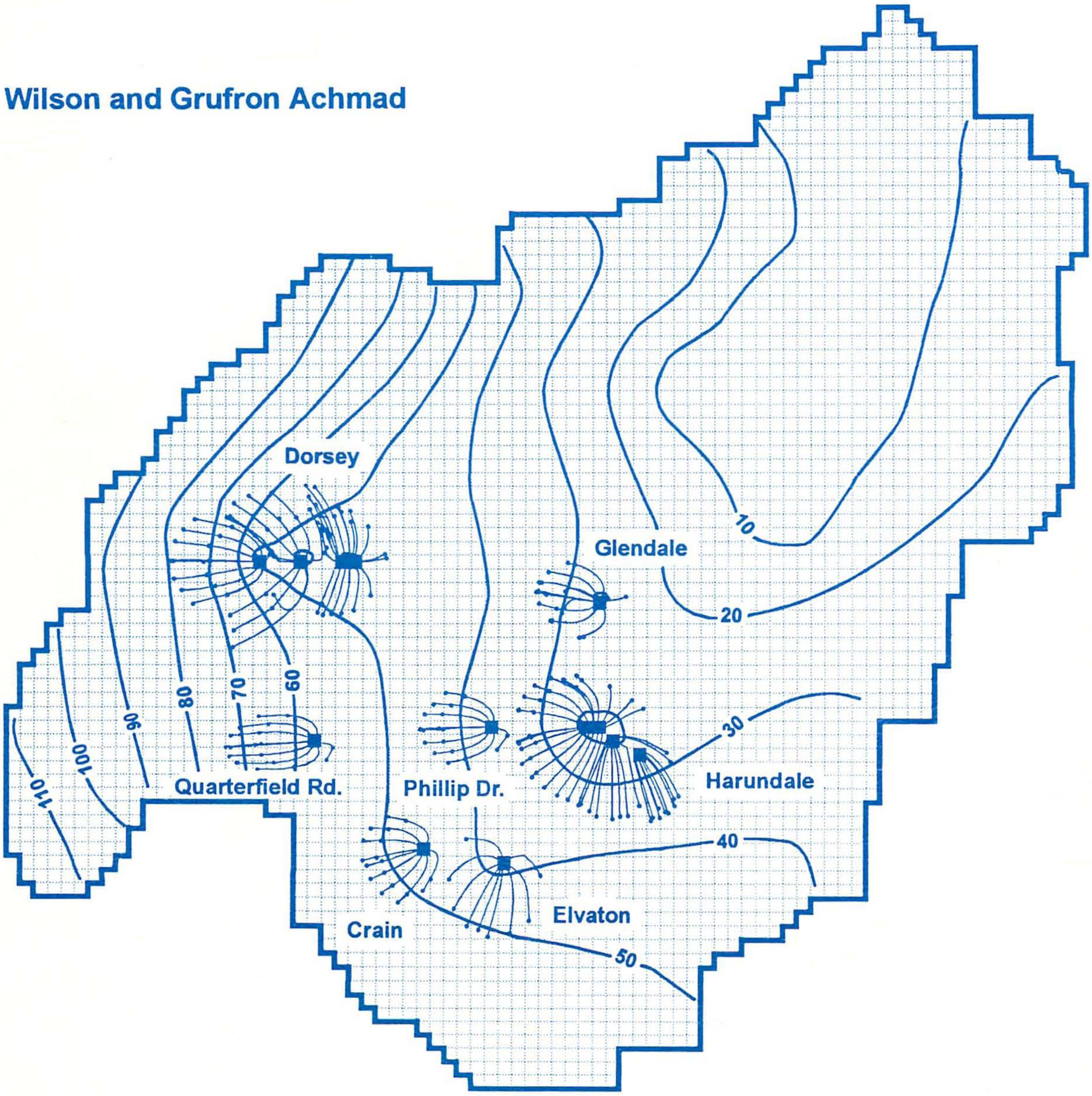
John M. Wilson and Grufron Achmad



Prepared in cooperation with the
Anne Arundel County Department of Public Works
and
The Maryland Department of the Environment

Department of Natural Resources
Maryland Geological Survey
Emery T. Cleaves, Director

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DELINEATION OF WELLHEAD PROTECTION AREAS USING PARTICLE TRACKING ANALYSIS AND HYDROGEOLOGIC MAPPING, NORTHERN ANNE ARUNDEL COUNTY, MARYLAND

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ABSTRACT

Two computer modeling techniques are used to delineate wellhead protection areas (WHPAs) for the public-supply wells of northern Anne Arundel County, Maryland and the results of the two techniques are compared. One technique is ground-water-flow modeling using the U.S. Geological Survey MODFLOW program in combination with particle tracking using the 1989 version of the U.S. Geological Survey MODPATH program. The other technique is particle tracking using the semianalytical option of the GPTRAC module of the U.S. Environmental Protection Agency WHPA code (version 2.1). The WHPAs are for wells screened in the Lower Patapsco aquifer, a semiconfined aquifer which is overlain by the Upper Patapsco aquifer, an unconfined water-table aquifer. Both aquifers consist of unconsolidated sands, gravels and discontinuous beds of clay. The ground-water-flow model used to generate head distributions is an updated and verified version of the flow model described in Achmad (1991).

Hydrogeologic mapping is used to develop an "aquifer vulnerability map" of the study area. Four qualitative degrees of aquifer vulnerability to potential contamination are mapped.

Tritium determinations indicate that most of the water produced from the Lower Patapsco aquifer in 1991 had a component of post-1945 water. Precise dates are not determined because of mixing of ground water of different ages; the estimated tritium ages are, however, consistent with ages inferred from the particle tracking analyses.

The MODPATH and GPTRAC particle tracking techniques are used to delineate ten and twenty-year zones of transport for the public-supply wells under three different pumpage scenarios; similar aquifer parameters are input to both models. The plan views of these transport zones are compared by size and shape. Using the 1990 pumpage appropriation of 9.15 million gallons per day, six of the seven ten-year zones of transport delineated by GPTRAC range from 36 to 17 percent smaller and one is 18 percent larger than the corresponding MODPATH zones; the percentage coincident area of the MODPATH and GPTRAC zones of transport ranges from 64 to 81 percent. Shapes of corresponding zones of transport are mostly similar. Increasing the simulation time to twenty years caused differences between corresponding zones of transport to increase; for two of the well fields these differences are significant.

Differences between the zones of transport described by MODPATH and GPTRAC are caused by differing capabilities of the two techniques. The zones of transport described by MODPATH are considered more realistic than those described by the semianalytical option of GPTRAC (version 2.1) because head output from MODFLOW is calibrated using field values before it is input to MODPATH. Additionally, MODFLOW can simulate heterogeneous aquifer conditions and multi-layered aquifer systems more realistically than GPTRAC. GPTRAC is limited to simulating homogeneous aquifer conditions in a single layer aquifer system and also has more limited options for treating aquifer boundary conditions than MODFLOW. In cases where the aquifer system is relatively homogeneous, however, GPTRAC may simulate zones of transport for a semiconfined aquifer that are comparable to the MODFLOW-MODPATH technique.

MODPATH is used to backtrack particles to land surface and delineate zones of contribution (recharge areas) in the water-table aquifer. Under the model scenario that used the 1990 pumpage appropriation, the recharge areas for the well fields covered about 50 percent of the area between the well fields and the upgradient ground-water divides. In this simulation, the time required for recharge to travel from the water table to the different pumping wells ranged from 10 to 60 years. MODPATH is also used to compare a time-related zone of contribution with the time-related zone of transport for one of the production wells.

Overall water quality of the Lower Patapsco aquifer is good. Contaminants, however, are present in the more vulnerable regions of the aquifer. Most of the known contaminant sites are downgradient from the production wells described herein; therefore, substances released at these sites will not enter the zones of transport under the rate of actual pumpage or the 1990 pumpage appropriation. Releases from several contaminant sites located upgradient of the production wells would without remediation pose a threat to the Glendale and Sawmill well fields; at present, both of these well fields are unused.

INTRODUCTION

PURPOSE AND SCOPE

There are three primary objectives to this report. The first objective is to compare two computer modeling techniques used to delineate wellhead protection areas. The techniques studied are the semianalytical GPTRAC module of the U.S. Environmental Protection Agency WHPA (wellhead protection area) code version 2.1, and the U.S. Geological Survey MODPATH particle tracking program applied to head distributions calculated by the U.S. Geological Survey MODFLOW ground-water-flow model. The MODFLOW model discussed in this report is an updated version of the model described in Achmad (1991). Hydrogeologic mapping is used to delineate four qualitative zones of aquifer vulnerability and also to determine the aquifer framework upon which the ground-water-flow and particle tracking models are based. Wellhead protection areas based solely on hydrogeologic mapping are not delineated. Ground-water ages based on tritium determinations are used to verify the results of the GPTRAC and MODPATH particle tracking simulations. The second objective is an assessment of the ground-water quality of the study area and the potential for contamination of the Lower Patapsco aquifer and public-supply wells from known sites of surface and shallow subsurface contamination. The third objective is to create a set of maps that show plan views of the surface and subsurface areas that supply water to the production wells screened in the Lower Patapsco aquifer during 10 and 20-year periods, and also a set of maps showing plan views of the zones of contribution (recharge areas) of the Lower Patapsco aquifer under different well field pumpage rates. These maps contribute information that can be used to develop a wellhead protection program.

DESCRIPTION OF THE STUDY AREA

The study area is in the northern part of Anne Arundel County, Maryland approximately 8 mi (miles) south of Baltimore and 6 mi west of the Chesapeake Bay (fig. 1). The study area covers 27 mi^2 (square miles) and encompasses the drainage basins of Sawmill, Furnace and Marley Creeks, and the upper reaches of Curtis Creek (fig. 2). Sawmill Creek empties into Furnace Creek, and Furnace and Marley Creeks join to form Curtis Creek, a tributary of the Patapsco River; the Patapsco River is a tributary of the Chesapeake Bay. Furnace Creek forms a sub-basin within the Sawmill-Furnace Creek drainage. The Sawmill-Furnace Creek and Marley Creek drainage basins are third-order stream basins and cover 13.7 and 13.5 mi^2 respectively. Furnace Creek and the lower reaches of Marley Creek are tidal. Sawmill, Furnace and Marley Creeks are low gradient, low discharge streams that have dissected the Coastal Plain sediments to form rolling uplands. Altitudes range from sea level in the northeastern part of the study area to 210 ft (feet) above sea level along the highest points of the drainage basin divides. Maximum local relief is 170 ft.

The climate of the study area is temperate; the annual average temperature is 55° F (degrees Fahrenheit) (Vokes and Edwards, 1974); temperature extremes range from below 0° F for short periods during the winter to over 100° F for short periods during the summer. Annual average precipitation in the study area is about 42 inches.

The study area is urbanized and includes housing developments, industrial parks, shopping centers and major highways. Most of the urbanization of the study area has occurred during the last 50 years. Land use before the 1940's was primarily agricultural with the urbanized area limited to the original town of Glen Burnie. The growth in population and change in land-use patterns has increased the demand for ground water and the threat of contamination to the ground-water resources.

WELL NUMBERING SYSTEM AND WELL LOCATION MAPS

The well numbering system used in this report is that of the Maryland Geological Survey (MGS). The Anne Arundel County Department of Public Works (AA DPW), however, uses a different system to identify its production wells. A list of the AA DPW production and test well names and their corresponding MGS well numbers are shown in table 1. The AA DPW well names represent the well field in which the well occurs, and if there is more than one well in a well field, numbers are assigned to the wells. For example, AA DPW production wells Dorsey 1 and Dorsey 14 are in the Dorsey well field. Wells in well fields that have only one production well are not numbered, but only identified by name; for example, the Elvaton and Glendale production wells. The locations of the AA DPW production wells identified by their AA DPW names are shown on figure 2.

The Maryland Geological Survey well numbering system divides each Maryland County into 5-minute quadrangles of latitude and longitude and numbers each well within a quadrangle in the order in which the well was inventoried. Using well AA Bd 156 as an example, the first two letters "AA" stand for Anne Arundel County, the second two letters "Bd" represent the 5-minute quadrangle, and the "156" means that this well was the 156th well inventoried in the Bd quadrangle. Inventoried wells that become part of the MGS data base generally have useful hydrogeologic data associated with them. The location of key wells used for hydrogeologic control, identified by their MGS well numbers, are shown in figure 3. The lines of the hydrogeologic cross-sections (pls. 1-4) are also shown on figure 3. All wells mentioned in this report are documented in Appendix A, "Records of Selected Wells and Test Holes". The locations of the wells and test

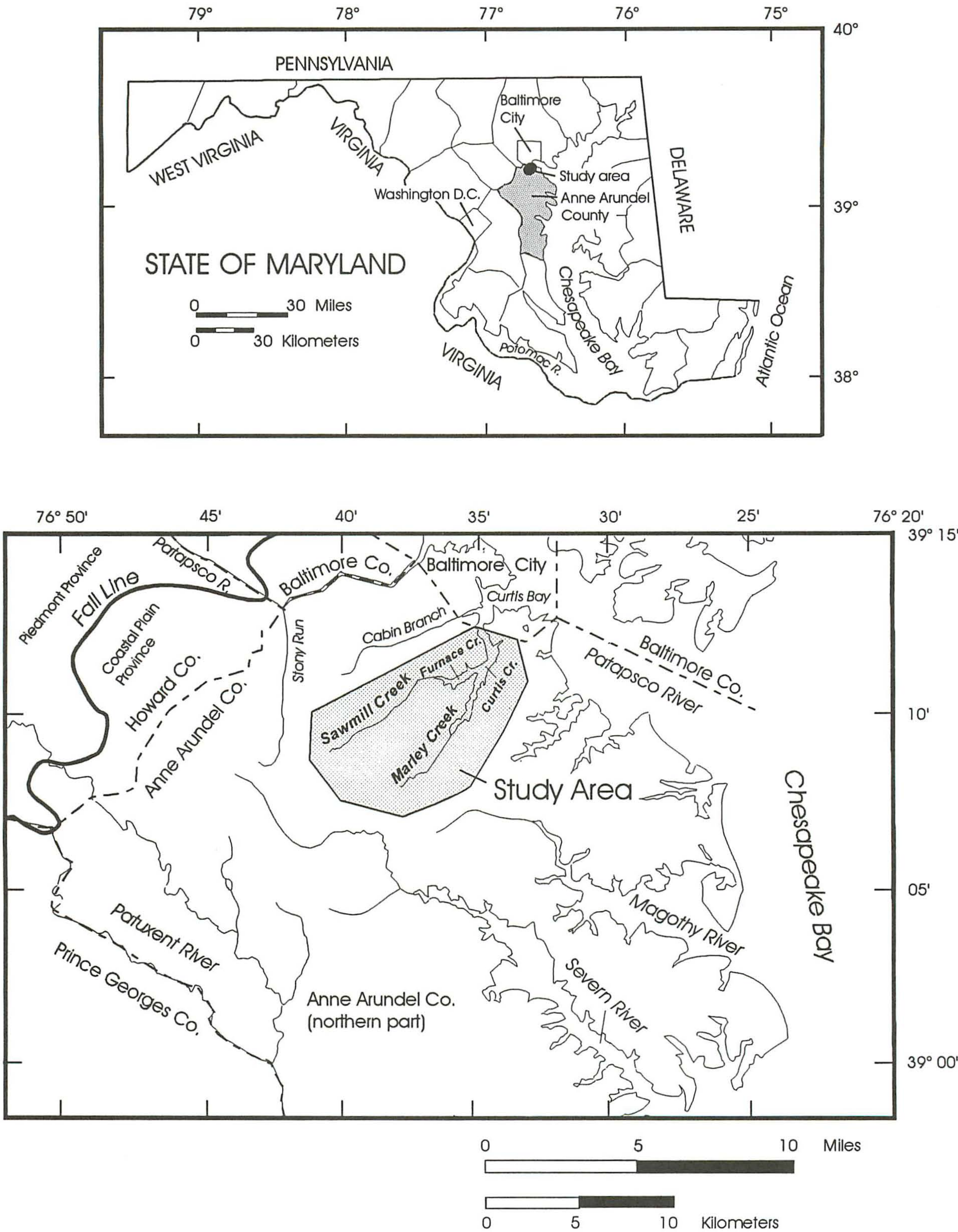


Figure 1. — Location of study area.

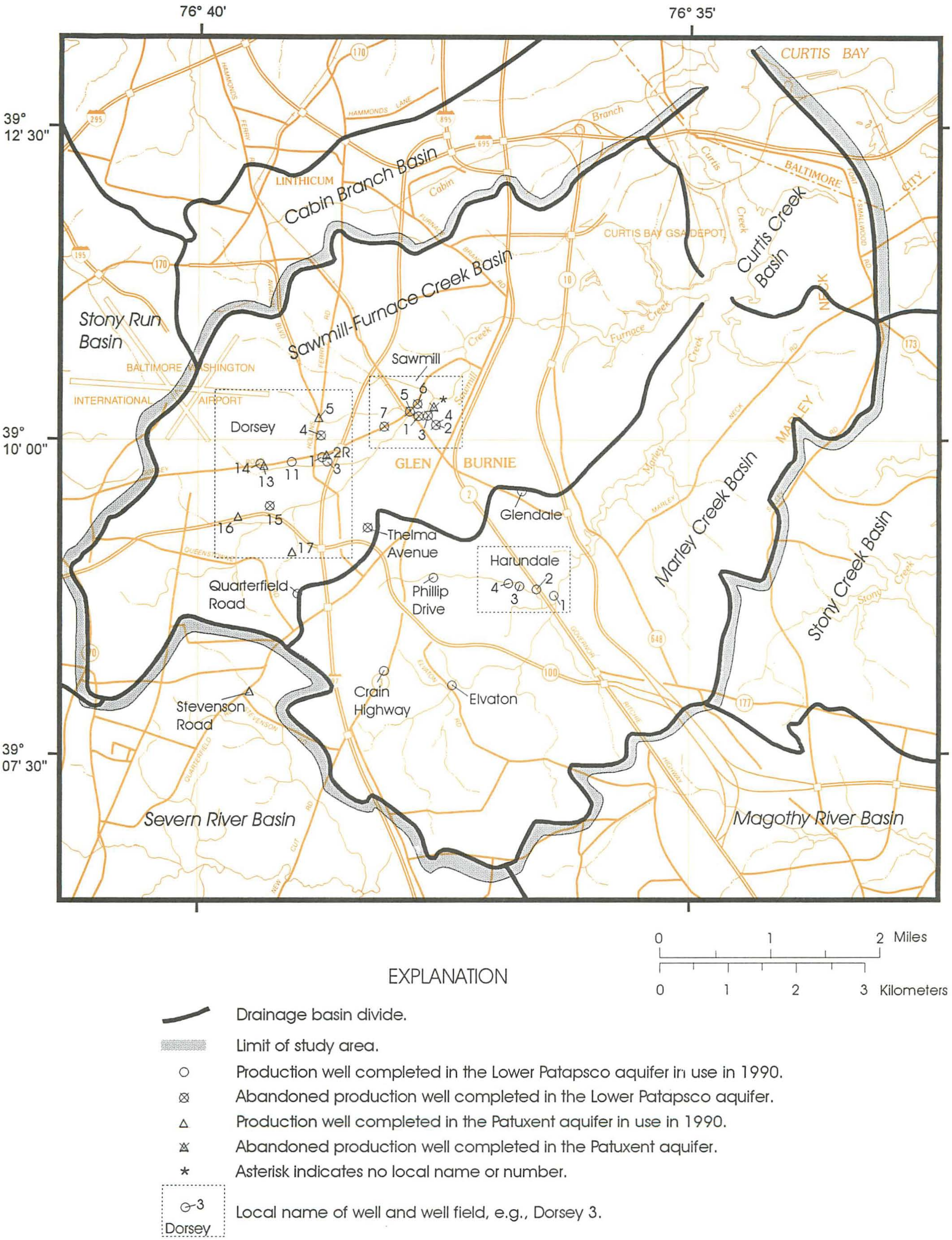


Figure 2. — Study area, drainage basin divides and locations of production wells.

Table 1.—Correlation of well and test hole names used by the Anne Arundel County Department of Public Works with well numbers used by the Maryland Geological Survey

Anne Arundel County Department of Public Works well name	Maryland Geological Survey well number	Aquifer	Status of well in 1993
Dorsey 1	AA Bd 55	Lower Patapsco	In use
Dorsey 2	AA Bd 57	Patuxent	Abandoned
Dorsey 2R	AA Bd 161	Patuxent	In use
Dorsey 3	AA Bd 56	Lower Patapsco	In use
Dorsey 4	AA Ad 74	Lower Patapsco	Abandoned
Dorsey 5	AA Ad 76	Patuxent	In use
Dorsey 11	AA Bd 64	Lower Patapsco	In use
Dorsey 13	AA Bd 66	Patuxent	In use
Dorsey 14	AA Bd 92	Lower Patapsco	In use
Dorsey 15	AA Bd 95	Lower Patapsco	Abandoned
Dorsey 16	AA Bd 97	Patuxent	In use
Dorsey 17	AA Bd 98	Patuxent	In use
Dorsey 1 test well	AA Bd 45	Patuxent	Abandoned
Dorsey 2 test well	AA Bd 67	Lower Patapsco	Abandoned
Dorsey 4 test well	AA Ad 73	Lower Patapsco	Abandoned
Dorsey 5 test well	AA Ad 75	Patuxent	Abandoned
Dorsey 13 test well	AA Bd 65	Patuxent	Abandoned
Dorsey 15 test well	AA Bd 94	Lower Patapsco	Abandoned
Dorsey 16 test well	AA Bd 96	Patuxent	Abandoned
Harundale 1	AA Bd 36	Lower Patapsco	In use
Harundale 2	AA Bd 37	Lower Patapsco	In use
Harundale 3	AA Bd 63	Lower Patapsco	In use
Harundale 4	AA Bd 61	Lower Patapsco	Abandoned
Harundale 4R	AA Bd 160	Lower Patapsco	In use
Harundale 4 test well	AA Bd 60	Lower Patapsco	Abandoned
Harundale test well - East	AA Bd 23	Patuxent	Abandoned
Sawmill 1	AA Ad 1	Lower Patapsco	Unused
Sawmill 2	AA Ad 2	Lower Patapsco	Unused
Sawmill 3	AA Ad 23	Lower Patapsco	Unused
Sawmill 4	AA Ad 40	Lower Patapsco	Unused
Sawmill 5	AA Ad 41	Lower Patapsco	Unused
Sawmill 6	AA Ad 67	Lower Patapsco	Unused
Sawmill 7	AA Ad 68	Lower Patapsco	Unused
Sawmill[1]	AA Ad 29	Patuxent	Abandoned
Phillip Drive well	AA Bd 101	Lower Patapsco	In use
Glendale test well	AA Bd 102	Lower Patapsco	Abandoned
Glendale well	AA Bd 103	Lower Patapsco	Unused
Crain Highway test well	AA Bd 104	Lower Patapsco	Abandoned
Crain Highway well	AA Bd 105	Lower Patapsco	In use
Elvaton test well	AA Bd 106	Lower Patapsco	Abandoned
Elvaton well	AA Bd 107	Lower Patapsco	In use
Thelma Ave. well	AA Bd 108	Lower Patapsco	Abandoned
Quarterfield Rd. well	AA Bd 109	Lower Patapsco	In use
Stevenson Rd. test well	AA Bd 121	Patuxent	Abandoned
Stevenson Rd. well	AA Bd 122	Patuxent	In use
Telegraph Rd. test well	AA Bc 210	Patuxent	Observation
Telegraph Rd. well	AA Bc 209	Patuxent	In use

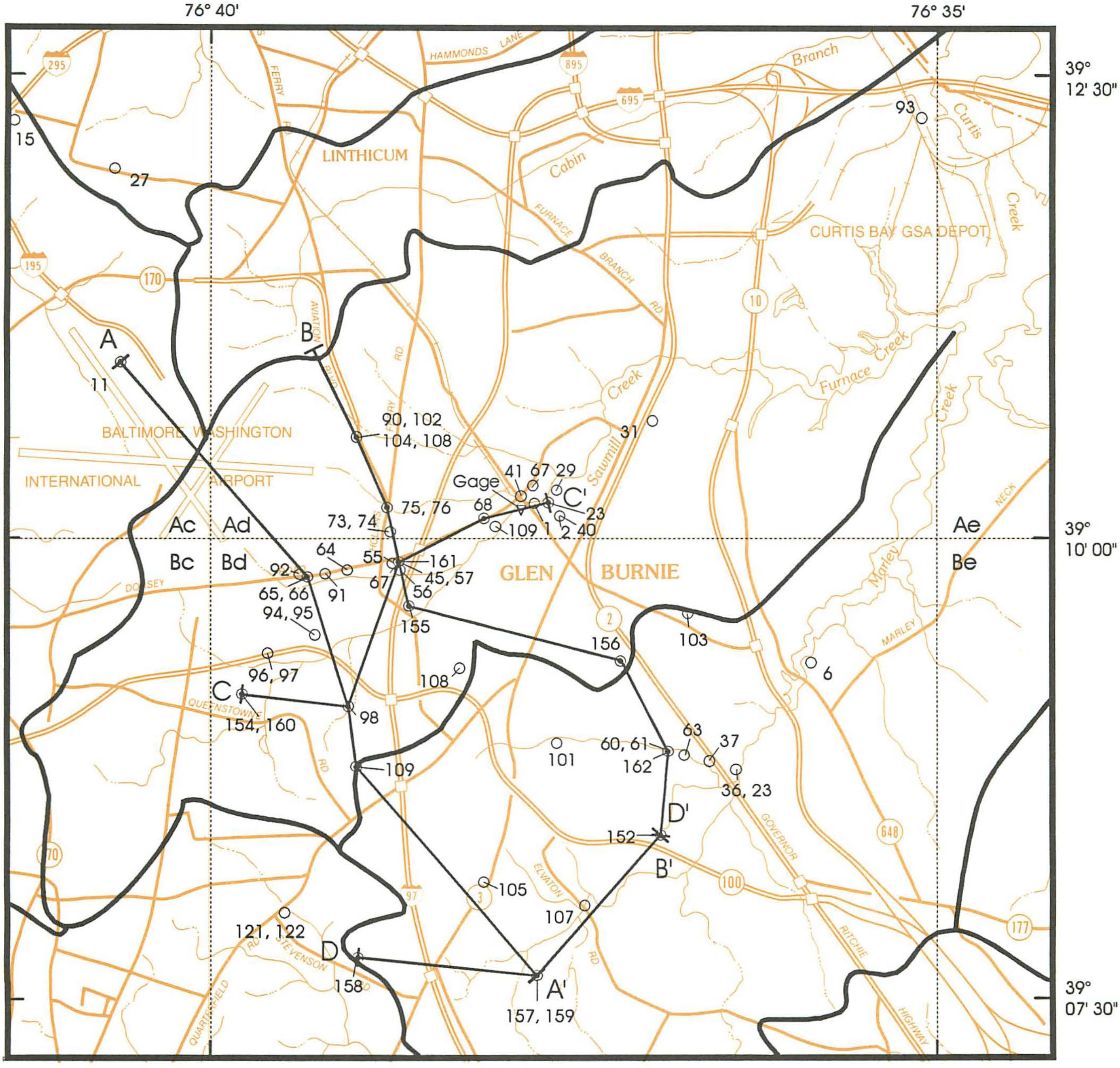
[1]No Anne Arundel County Department of Public Works name for well

holes in Appendix A are plotted on a series of topographic base maps (figs. 59-65) that follow the appendices.

PREVIOUS STUDIES

The first modern studies of the surface and ground-water resources of Anne Arundel County are by Bennion (1949) and Brookhart (1949), respectively. Mack (1962) describes the ground-water resources of Anne Arundel County and includes a section on the Glen Burnie area. Lucas (1976) presents a compilation of basic ground-water and water-quality data for Anne Arundel County. Mack and Achmad (1986) describe the hydrogeology of Anne Arundel County and assess the ground-water production capabilities of the Patuxent, Lower Patapsco, Upper Patapsco, and Magothy aquifers with a ground-water-flow model. Chapelle (1985) includes some water-quality data from northern Anne Arundel County in an assessment of the ground-water resources of the industrial area of Baltimore, Maryland. Achmad (1991) uses a ground-water-flow model to describe the ground-water-resource potential of the Lower and Upper Patapsco aquifers in northern Anne Arundel County.

Glaser (1969) describes the stratigraphy, petrology, and origins of the sediments of the Potomac Group and Magothy Formation. Hansen (1969) uses geophysical logs to infer the depositional environments and determine the sand distribution trends of the subsurface Potomac Group in Maryland. Glaser's (1976) geologic map of Anne Arundel County shows the outcrop distribution of the geologic units in the county. Glaser (1976) does not subdivide the Potomac Group into formations, but instead maps the surficial sand and clay facies of the Potomac Group because the lithologic similarity of the Patuxent and Patapsco Formations in outcrop makes the subdivision of the Potomac Group in parts of Anne Arundel County problematic (Glaser, oral commun., 1994). In the subsurface of northern Anne Arundel County, however, division of the Potomac Group into formations is possible (Hansen, 1969).



0 1 2 Miles

0 1 2 3 Kilometers

EXPLANATION

Drainage basin divide.

66 ○ Well or test hole used for hydrogeologic control and well number.

▽ Sawmill Creek stream gage (USGS station number 01589512).

A⊢⊣A' Lines of hydrogeologic section shown on plates 1-4.

Ac ¦ Ad / Bc ¦ Bd 5-minute quadrangle designations for well numbering system. Dashed lines denote quadrangles.

Figure 3. — Wells, test holes and stream gages used for hydrogeologic control, and lines of hydrogeologic sections.

ACKNOWLEDGMENTS

This report was prepared as part of a joint funding agreement between the Anne Arundel County Department of Public Works, Maryland Department of the Environment, and Maryland Geological Survey. Additional funding was provided by the U.S. Environmental Protection Agency under Section 106 of the Federal Clean Water Act. The authors wish to express their thanks to the following individuals who contributed to the completion of this study: Harry Hansen of the Maryland Geological Survey, John Grace and Norman Lazarus of the Maryland Department of the Environment, and Philip Berger and Douglas Heath of the U.S. Environmental Protection Agency provided helpful reviews of the manuscript. Alex McNamee and Norman Lazarus of the Maryland Department of the Environment compiled and located the ground-water contaminant sites in the study area. Robert L. Michel, U.S. Geological Survey, provided the tritium determination in precipitation data for Washington, D.C. The personnel of the Anne Arundel County Department of Public Works, especially Seymour Bayuk (retired) and Fazle Ali, were very supportive of the study; they provided important data regarding the water-supply system and access to the county production wells for water-quality sampling. Additionally, Fazle Ali provided helpful comments on the draft of the report. Donajean Appel, Maryland Geological Survey, provided word processing assistance during the preparation of the report.

GEOLOGIC UNITS

The study area lies near the western edge of the Coastal Plain Province (fig. 1). Sediments of the Coastal Plain are mostly unconsolidated sands, gravels, silts and clays. The stratigraphic column (tab. 2) shows the geologic units present in the study area. Plates 1 to 4 are hydrogeologic cross-sections through the project area (fig. 3). The surficial geology from Glaser (1976) is shown on figure 4.

Undifferentiated Pre-Cambrian to lower Paleozoic (?) crystalline rocks form the basal geologic unit in the study area. The altitude of the crystalline basement ranges from 400 to 600 ft below sea level in the study area (Hansen and Edwards, 1986).

Sediments of the Lower Cretaceous Potomac Group unconformably overlie the crystalline basement and its saprolitic cover. Hansen's (1969) division of the subsurface Potomac Group in the Baltimore-Washington area into three formations is applicable to the study area. From the stratigraphically lowest to highest unit, they are: the Patuxent Formation, the Arundel Clay, and the Patapsco Formation (tab. 2). Total thickness of the Potomac Group in the study area ranges from 125 to 800 ft. The regional strike of the Potomac Group is about N 45° E and the regional dip is between 50 and 80 ft/mi (feet per mile) to the southeast.

The Patuxent Formation is a light gray to orange-brown, medium to coarse-grained sand or pebbly sand and gravel interbedded with pale-gray to maroon clay and clayey silt (Weaver and others, 1968; Glaser, 1969). In the study area, the Patuxent Formation ranges from 130 to 350 ft thick and is more than 45 percent sand and gravel (Hansen,1969). The sediments of the Patuxent Formation in Maryland were deposited by a braided river system (Glaser, 1969; Hansen, 1969).

The Arundel Clay conformably overlies the Patuxent Formation. The Arundel Clay is a tough, dark gray to maroon, massive, lignitic clay and silty clay that contains abundant siderite concretions (Weaver and others, 1968; Glaser, 1969). The massive clay-silt facies of the Arundel Clay is in places interstratified with 10 to 20 ft thick beds of fine to medium, muddy sand. In the study area, the Arundel Clay ranges from 125-250 ft thick (pls. 1-3). The top of the Arundel Clay dips southeastward in the study area at about 50 ft/mi (fig. 5).

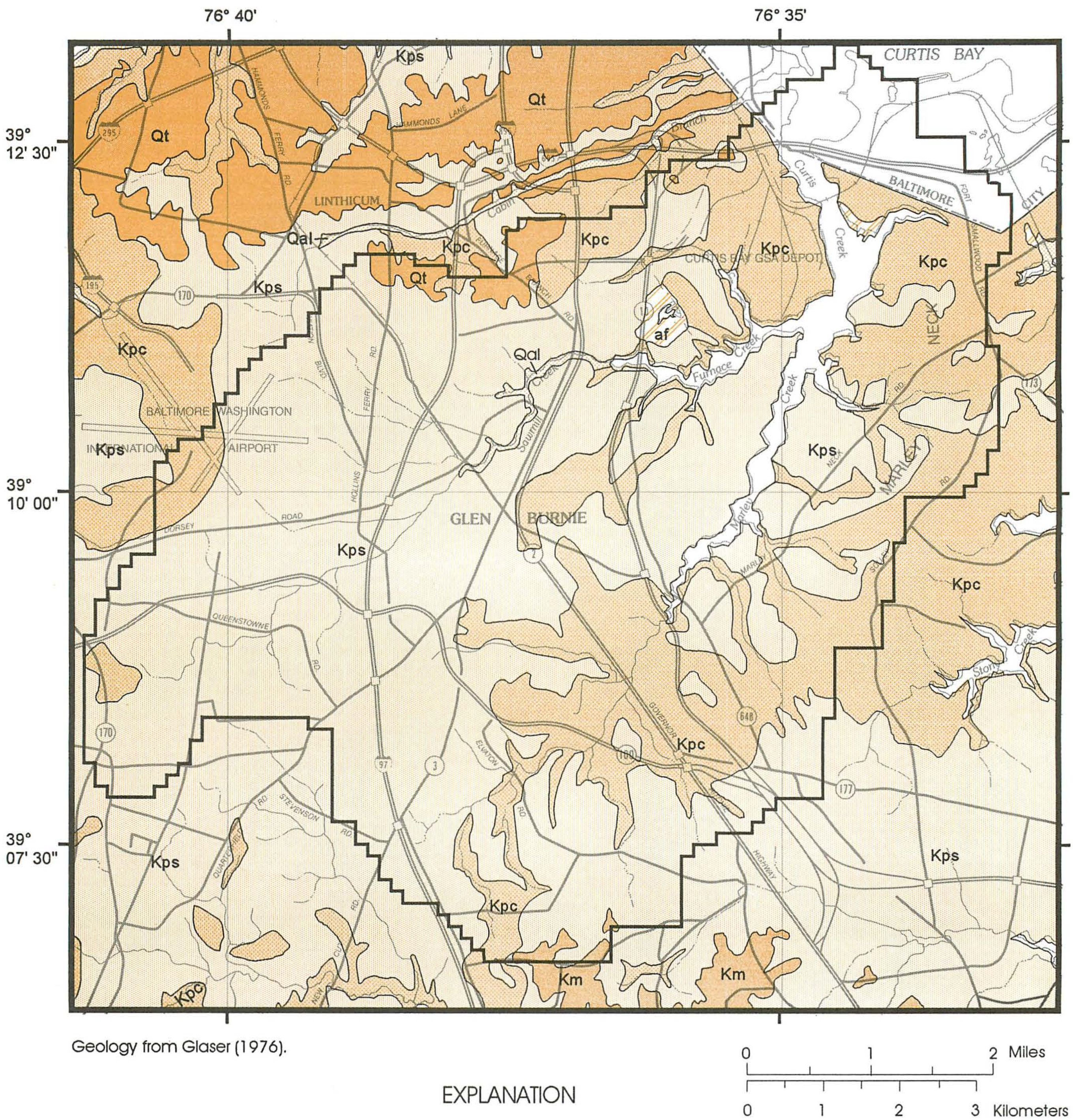
The Patapsco Formation unconformably overlies the Arundel Clay. The erosional unconformity between the Arundel Clay and Patapsco Formation is a mappable horizon in the subsurface of the study area and defines the lower boundary of the Lower Patapsco aquifer (fig. 5). The Patapsco Formation is a buff to brown, fine to medium grained, argillaceous sand and gravel that is interbedded with variegated (gray, red, and brown) silt and clay (Weaver and others, 1968). In the study area, the Patapsco ranges from 125 to 400 ft thick. Sand and gravel comprise more than 45 percent of the Patapsco Formation in northern Anne Arundel County (Hansen, 1969). A braided river system, similar to the river system that deposited the Patuxent sediments, deposited the sediments of the Patapsco Formation in the northern part of Anne Arundel County (Glaser, 1969; Hansen, 1969). Figure 4, the northern part of the geologic map of Anne Arundel County (Glaser, 1976), shows the outcropping sand and clay-silt facies of the Potomac Group, but not formation divisions. For the purposes of this report, sediments mapped as Potomac Group on figure 4 that lie within the Sawmill-Furnace Creek and Marley Creek drainage basins are assigned to the Patapsco Formation.

Outcrops of the Upper Cretaceous Magothy Formation unconformably overlie the Patapsco Formation in the extreme southern portion of the study area (fig. 4). In this region, the Magothy forms a thin cover (3-20 ft thick) along the drainage divide between Marley Creek drainage basin and the drainage basins of the Severn and Magothy Rivers. The Magothy Formation is a white to pale gray, fine to coarse grained, well sorted, quartz sand interstratified with silt-clay and subordinate pebbly sand or gravel (Glaser, 1976).

Table 2.—Stratigraphy and hydrologic characteristics of the geologic formations in the Sawmill-Furnace Creek and Marley Creek basins, Anne Arundel County, Maryland

SYSTEM	SERIES	GROUP	FORMATION OR INFORMAL UNIT	THICKNESS (FEET)	GENERAL LITHOLOGY*	HYDROLOGIC CHARACTERISTICS
QUATERNARY	HOLOCENE		Artificial fill	0 - 50	Heterogeneous, unstratified materials; may include sand, gravel, clay, slag, dredge spoil, and construction debris.	May be a source of ground-water contaminants.
			Alluvium	0 - 35	Interbedded sand, silt, clay, and subordinate gravel; organic matter common. Color is generally tan, brown, or gray.	Confining bed in most places, poor aquifer in some places; assigned to the Upper Patapsco aquifer.
	PLEISTOCENE		Terrace Deposits	0 - 45	Interbedded sand, gravel, and silt-clay. Color is tan, buff, gray, or reddish brown.	Aquifer or leaky confining unit in a region located in the northern part of the study area; assigned to the Upper Patapsco aquifer.
CRETACEOUS	UPPER CRETACEOUS		Magothy Formation	0 - $\approx$20	Fine to coarse grained sand, interstratified with silt-clay and subordinate pebbly sand or gravel. Color is white to pale gray.	Aquifer or leaky confining unit in a small region located in the southern part of the study area; assigned to the Upper Patapsco aquifer.
	LOWER CRETACEOUS	POTOMAC	Patapsco Formation	125 - 400	Fine to coarse grained quartz sand, pebbly sand and gravel, and subordinate silt-clay. Color generally buff to reddish brown; Clay-silt, often massive, with subordinate fine to medium grained muddy sand; color is red, tan, gray, buff, or mottled.	Upper Patapsco aquifer
						Confining unit
						Lower Patapsco aquifer
			Arundel Clay	125 - 250	Clay-silt, massive, with subordinate fine to medium muddy sand; color is red, tan, gray, buff, or mottled.	Confining unit
			Patuxent Formation	130 - 350	Fine to coarse grained quartz sand, pebbly sand and gravel, and subordinate silt-clay; color is generally buff to reddish brown; Clay-silt, often massive, with subordinate fine to medium grained muddy sand; color is red, tan, gray, buff, or mottled.	Patuxent aquifer and confining units
LOWER PALEOZOIC(?) TO PRECAMBRIAN(?)			Undifferentiated crystalline basement	Unknown	May be gneiss, schist, quartz diorite, pyroxenite, or gabbro. Usually with saprolite cover.	Confining unit

* Color exhibited in outcrop and core samples; color may differ in drill cuttings.
Column constructed from Glaser (1976), Mack and Achmad (1986), and this report.

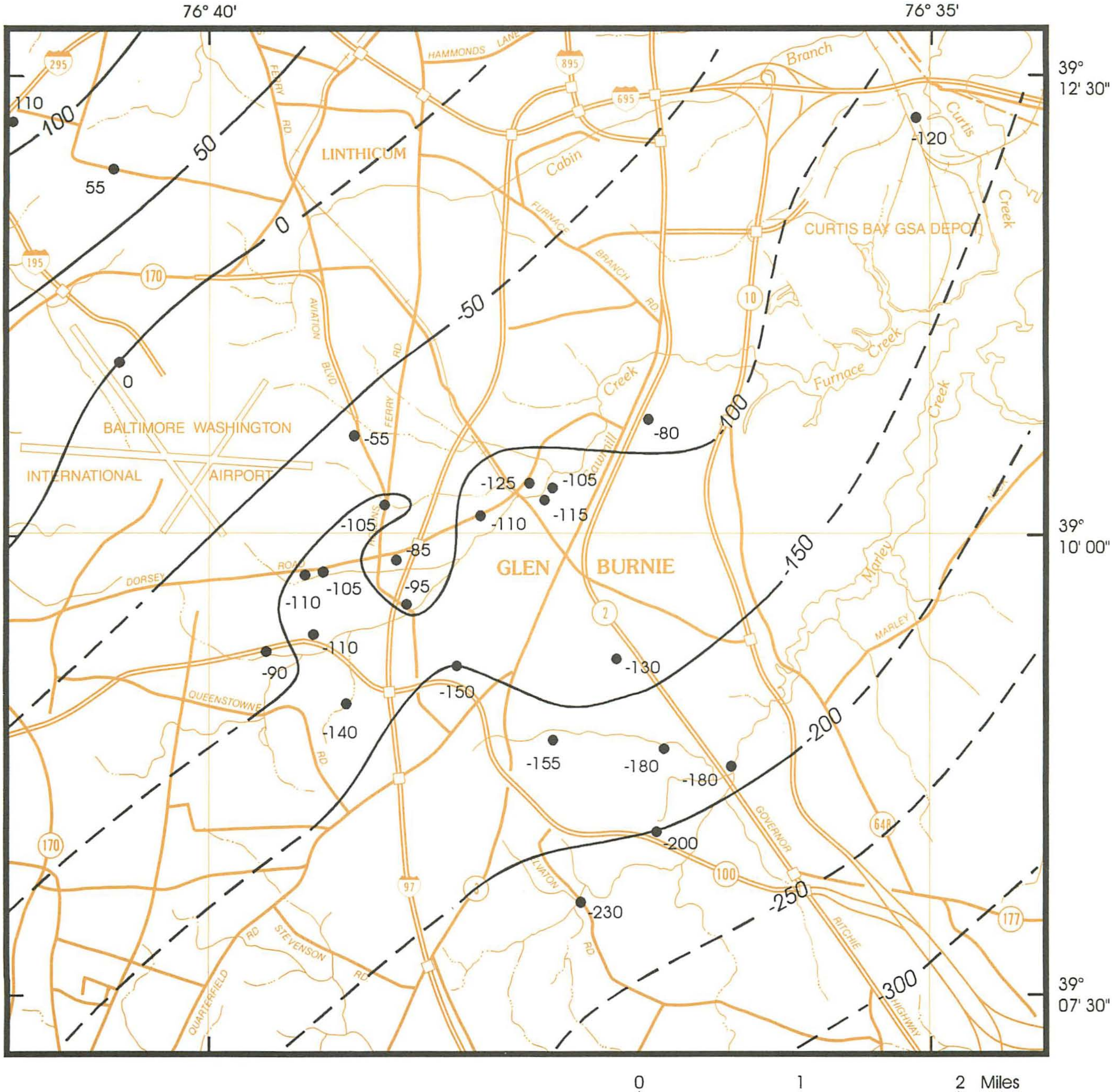


EXPLANATION

af	Artificial fill	Km	Magothy Formation		Boundary of ground-water flow model.
Qal	Quaternary alluvium		Potomac Group		
Qt	Terrace deposits	Kpc	clay-silt facies	Kps	sand facies

See text for description of units

Figure 4. — Geologic map of northern Anne Arundel County.



EXPLANATION

-180 ● Data point and altitude above or below (-) sea level in feet.

—— -200 —— Line of equal altitude, dashed where uncertain. Contour interval is 50 feet. Datum is sea level.

Figure 5. — Altitude of the top of the Arundel Clay and base of the Lower Patapsco aquifer.

Pleistocene terrace deposits (fig. 4), 3 to 40 ft thick, unconformably overlie the Patapsco Formation along parts of the basin divide between the Sawmill-Furnace Creek and Cabin Creek drainage basins. The terrace deposits within the study area are mostly tan to reddish brown, coarse-grained pebbly sands and gravels; isolated boulders of quartzose or mafic rock occur in the section. These deposits are ancient river deposits (probably of the Patapsco River) that were deposited at a high sea-level stand during the Pleistocene (Glaser, 1976).

Quaternary alluvium (fig. 4) unconformably overlies the Patapsco Formation along the floodplains of Sawmill and Furnace Creeks. The alluvium is interbedded sand, silt-clay, and subordinate gravel; poorly sorted muddy sand and silt is the predominant lithology. These sediments range from 3 to 15 ft thick and most were deposited within the last 10,000 years (Glaser, 1976).

Artificial fill (fig. 4) is emplaced into the Patapsco Formation at landfills and other sites in the study area. Artificial fill includes heterogeneous, unstratified materials and may include sand, gravel, silt, clay, slag, dredge spoil and construction debris (Glaser, 1976). In the study area, one major area of artificial fill is the Anne Arundel County landfill located just north of Furnace Creek.

HYDROGEOLOGY

HYDROGEOLOGIC UNITS AND AQUIFER PROPERTIES

Patuxent Aquifer

Sands of the Patuxent Formation form the Patuxent aquifer, the basal aquifer in the study area. The Patuxent aquifer is a confined aquifer bounded below by the crystalline basement and its saprolite cover and above by the Arundel Clay (pls. 1-3). Predominantly sandy intervals, 20 to 65 ft thick, form the aquifer's productive zones and predominantly clay-silt intervals, 30-55 ft thick, form laterally discontinuous confining units within the aquifer. The transmissivity of the Patuxent aquifer in the study area is about 2,000 ft^2/d (Hansen, 1972; Mack and Achmad, 1986). Seven AA DPW public-supply wells currently tap the Patuxent aquifer in the northern part of Anne Arundel County; five of these wells are in the Dorsey well field (fig. 2; tab. 1). In 1992, annual average pumpage from the Patuxent aquifer in northern Anne Arundel County was about 3.0 Mgal/d (million gallons per day).

Arundel Clay

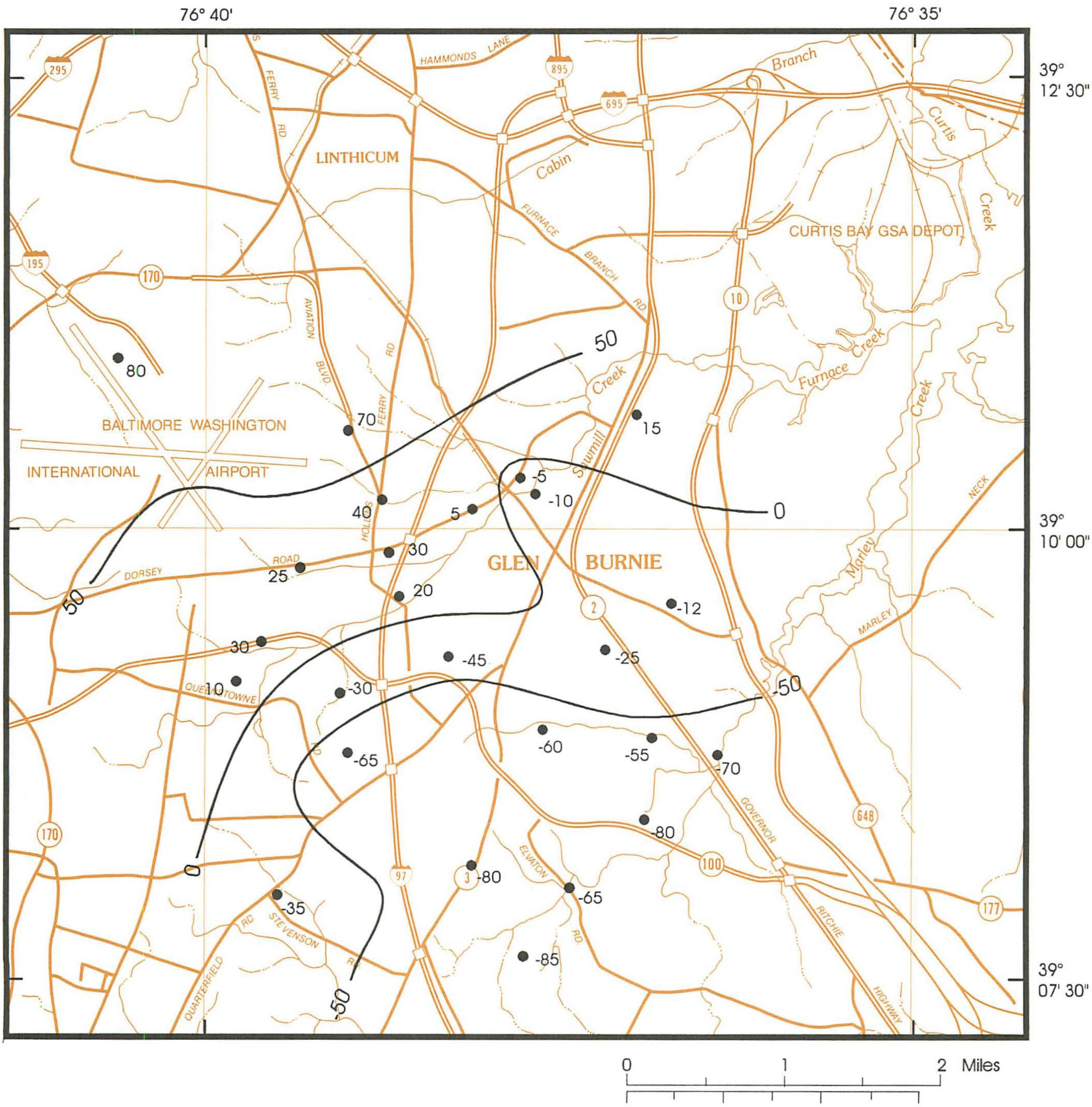
The Arundel Clay is an effective, 125 to 250 ft thick, confining unit that separates the Patuxent aquifer from the overlying Lower Patapsco aquifer (pls. 1-3). From their model calibration, Mack and Achmad (1986) obtained a vertical hydraulic conductivity for the Arundel Clay equal to 5.9×10^{-7} ft/d. The Arundel Clay is modeled as a no-flow boundary in the ground-water-flow model of Achmad (1991) because leakage between the Patuxent and Lower Patapsco aquifer is volumetrically inconsequential; a simulated 20-ft head difference across the 150-ft Arundel Clay yields about 82 gal/d of leakage in a 5-mi^2 area near the Dorsey well field (Achmad, 1991).

Lower Patapsco Aquifer

The Lower Patapsco aquifer overlies the confining unit formed by the Arundel Clay (pls. 1-4). The Lower Patapsco aquifer is a semiconfined aquifer consisting of sands of the Patapsco Formation (tab. 2). The altitude of the base of the Lower Patapsco aquifer ranges from 50 ft below sea level in the northwestern part of Sawmill Creek basin to 300 ft below sea level in the southeastern part of Marley Creek basin (fig. 5). The altitude of the top of the aquifer is shown in figure 6. The average thickness of the Lower Patapsco aquifer in the study area is 125 ft. The aquifer thickens from less than 100 ft thick in the northwestern part of Sawmill Creek basin to more than 150 ft in the southeastern part of Marley Creek basin (fig. 7). Sand counts using gamma and lithologic logs show that the percentage of sand in the Lower Patapsco aquifer ranges from 50 to 97 percent (fig. 8).

Transmissivity values of the Lower Patapsco aquifer range from 1,000 to 6,400 ft^2/d (Mack and Achmad, 1986; Achmad, 1991). Aquifer transmissivity increases from the northern part of the study area to the southern part because the aquifer thickens and becomes more sandy. In the ground-water-flow model, the Lower Patapsco aquifer is represented by three transmissivity zones; the three zones are: 1,500 ft^2/d in the northern and western parts of the study area; 4,500 ft^2/d in the central part; and 6,000 ft^2/d in the southern part of the study area (fig. 9). A uniform storage coefficient of 0.2×10^{-5} (dimensionless) was assigned to the Lower Patapsco aquifer in the flow model based on aquifer test results reported by Brookhart (1949), Mack (1962), and Mack and Achmad (1986). Effective porosity of the Lower Patapsco aquifer is estimated at 30 percent based on measured values for sands of similar texture reported in Freeze and Cherry (1979, p. 37) and Chapelle (1985, p. 30).

The 1965 potentiometric surface of the Lower Patapsco aquifer reported from Achmad (1991) approximates the pre-pumping surface because development of the aquifer was not

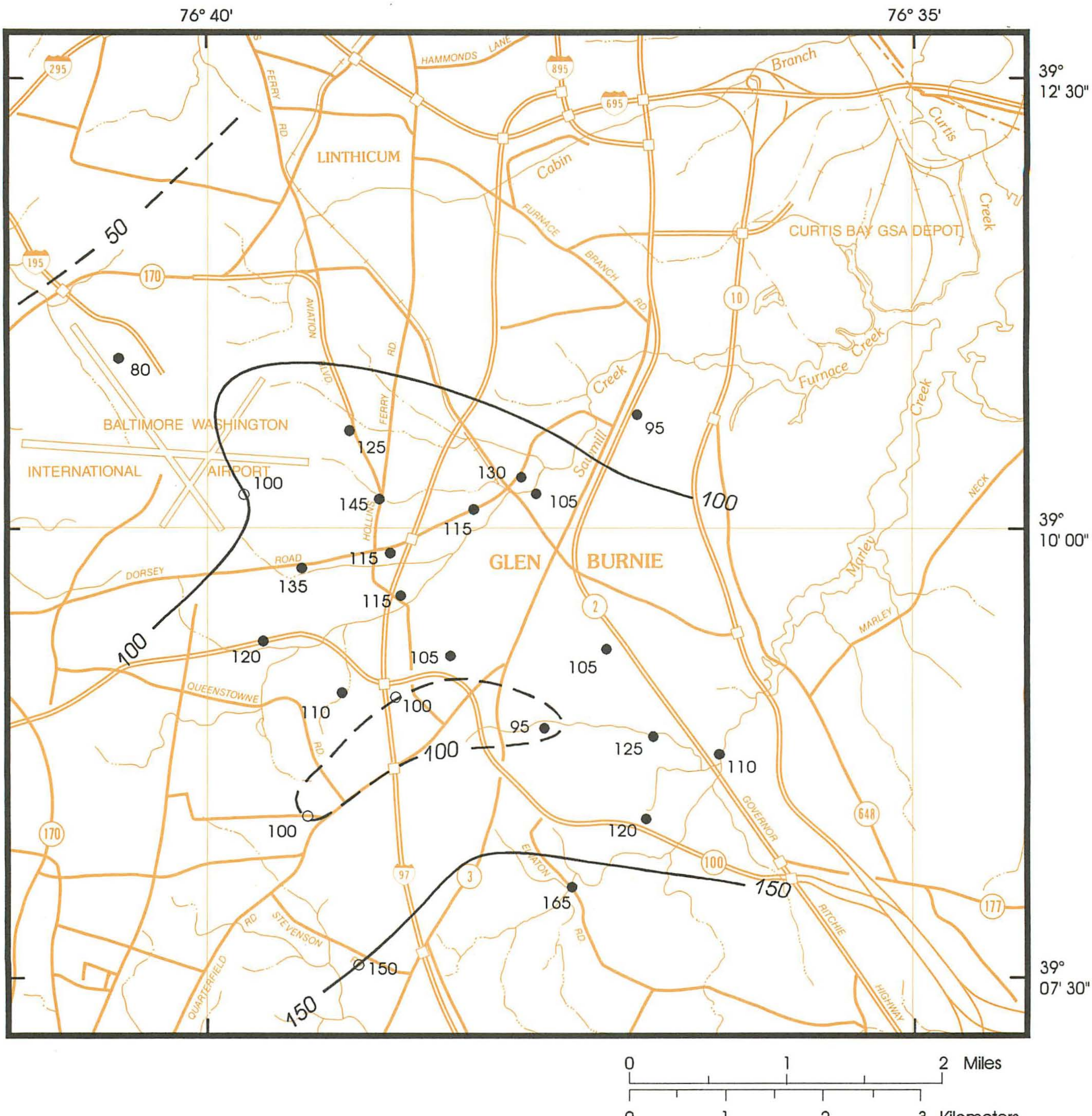


EXPLANATION

55 ● Data point and altitude above or below (-) sea level in feet.

—50— Line of equal altitude, dashed where uncertain. Contour interval is 50 feet. Datum is sea level.

Figure 6. — Altitude of the top of the Lower Patapsco aquifer.



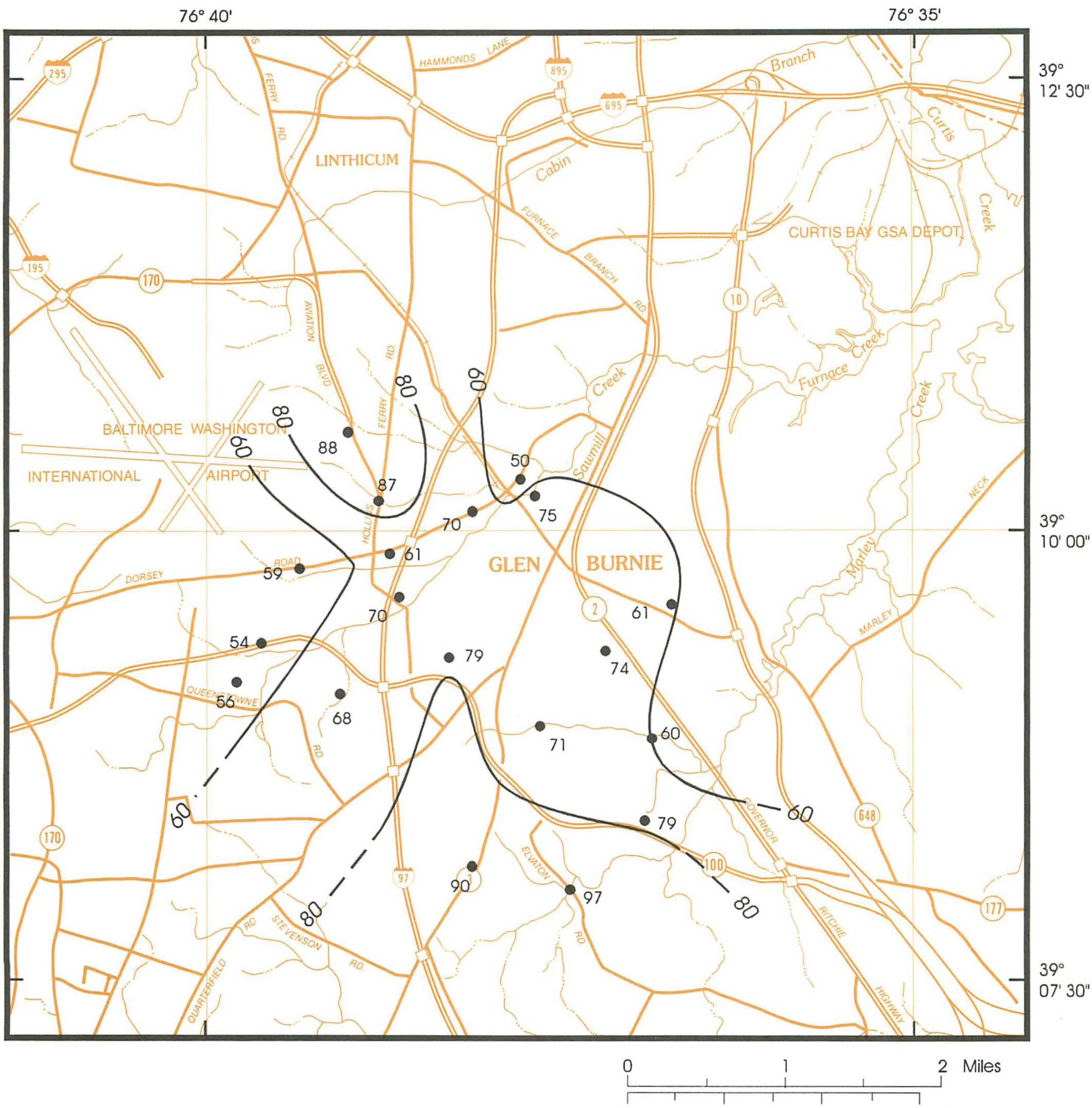
EXPLANATION

● 155 Data point and thickness in feet.

○ 100 Data point and thickness derived from overlaying the maps of the tops of the Arundel Clay and Lower Patapsco aquifer.

— 50 — Line of equal thickness, dashed where uncertain. Contour interval is 50 feet.

Figure 7. — Thickness of the Lower Patapsco aquifer.

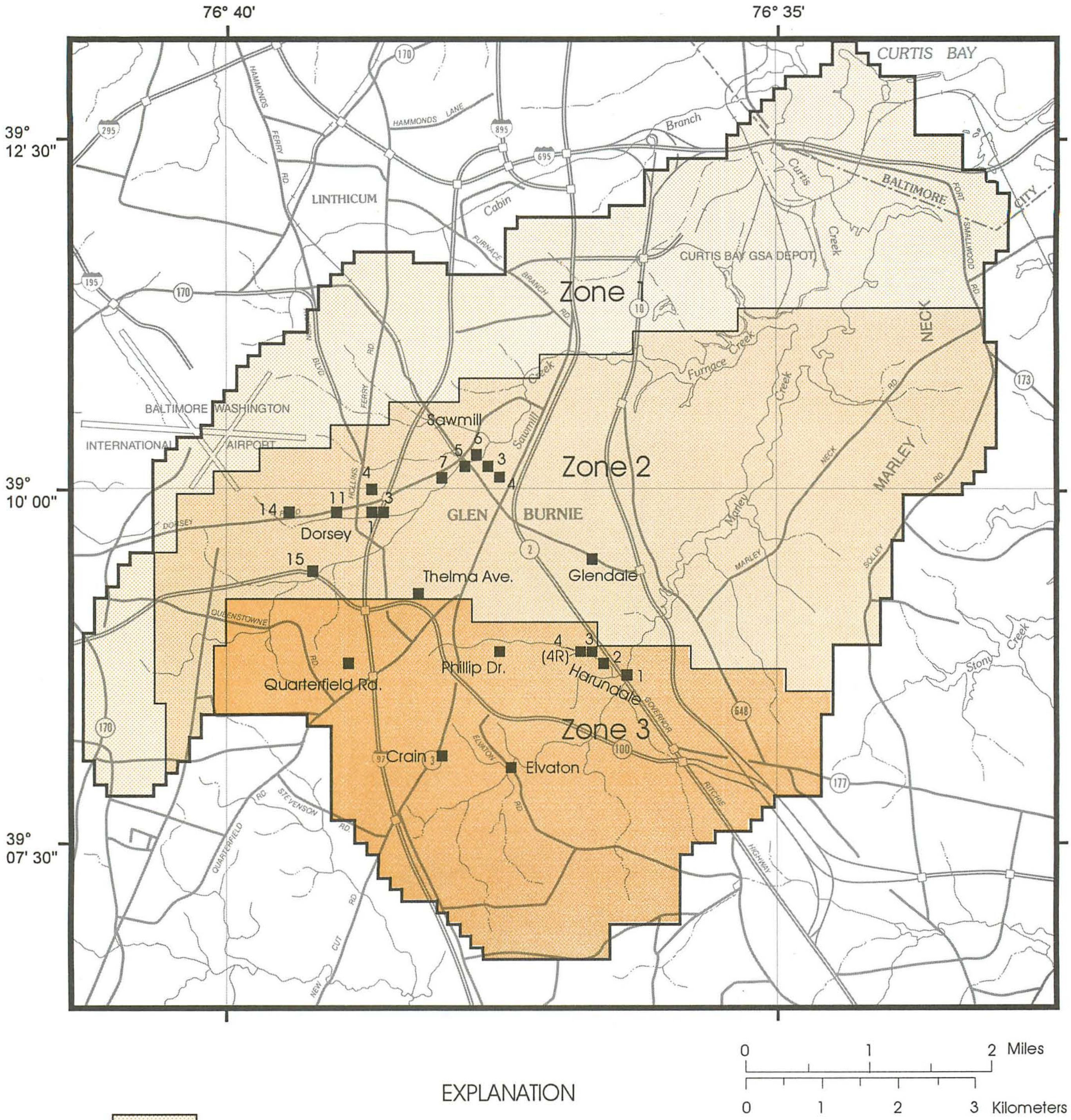


EXPLANATION

79 ● Data point and sand percentage.

— *80* — Line of equal sand percentage, dashed where uncertain. Contour interval is 20 percent.

Figure 8. — Sand percentage of the Lower Patapsco aquifer.



EXPLANATION

Zone 1	Transmissivity zone 1 equals 1,500 ft²/d (feet squared per day).
Zone 2	Transmissivity zone 2 equals 4,500 ft²/d.
Zone 3	Transmissivity zone 3 equals 6,400 ft²/d.
3 ■ Dorsey	Pumping cell in model layer two. Local name of well represented by pumping cell, e.g., Dorsey 3.
┘‾	Boundary of the ground-water-flow model.

Figure 9. — Transmissivity of the Lower Patapsco aquifer.

extensive in 1965 (fig. 10). The match of the simulated 1965 potentiometric surface with pre-1965 measured water levels is generally within 10 ft. The 1965 water levels range from 110 ft above sea level in the western part of the study area to 10 feet above sea level in the northeastern part of the study area. The general direction of ground-water flow is east-northeast. Hydraulic gradients of the Lower Patapsco aquifer range from 0.004 in the western part of the study area to about 0.0025 in the eastern part. Aquifer properties of the Lower Patapsco aquifer are summarized in table 3.

Table 3.—Properties of the Lower Patapsco aquifer

[ft = feet; ft/ft = feet per feet; ft^2/d = feet squared per day]

Aquifer type	Semiconfined
Transmissivity	Range: 1,000 to 6,400 ft^2/d Modeled in 3 zones Zone 1: 1,500 ft^2/d Zone 2: 4,500 ft^2/d Zone 3: 6,000 ft^2/d
Thickness	Range: <100 to >150 ft
Storage coefficient	0.2×10^{-5}
Effective porosity	30% (estimated)
General direction of ground-water flow	East-northeast
Hydraulic gradient (approximate pre-pumping)	Range: 0.0025 - 0.004 ft/ft

(Sources: Mack and Achmad, 1986; Achmad, 1991; this report)

Confining Unit Between the Lower and Upper Patapsco Aquifers

A leaky confining unit overlies the Lower Patapsco aquifer and separates the Lower Patapsco aquifer from the Upper Patapsco aquifer. The confining unit consists of beds of silty, fine sandy clay that occupy about the same stratigraphic level throughout the study area. Unlike the thick, massive and relatively continuous Arundel Clay, this confining unit is laterally discontinuous and heterogeneous. The average thickness of the confining unit is about 35 ft, but it ranges from zero to 60 ft thick (fig. 11). The confining unit is thinnest in the north central and south central regions of the study area and thickens in the western and eastern regions of the study area. In the northeastern region of the study area and in the vicinity of the Sawmill Creek and Dorsey well fields, the confining unit is generally more sandy than elsewhere. The hydrogeologic sections (pls. 1-4) illustrate the variable thickness and texture of the confining unit.

The vertical hydraulic conductivity of the confining unit, based on the best-fit model calibration, ranges from 3.0×10^{-2} ft/d to 3.0 ft/d. The hydraulic conductivity of the confining unit at any given site depends on the texture of the sediments. Textural (grain size, sorting) differences in the confining unit are the cause of the variation in vertical hydraulic conductivity. In the northeastern region of the study area, the confining unit is assigned a vertical hydraulic conductivity of 3.0 ft/d. In the vicinity of the Sawmill Creek and Dorsey well fields, this study uses a vertical hydraulic conductivity of 3.9×10^{-2} ft/d which is 30 percent higher than the conductivity used for those regions in an earlier version of the ground-water-flow model (Achmad, 1991) because additional geophysical log data showed that the confining unit in this area is more sandy than previously thought. In the remainder of the study area, the confining unit is assigned a vertical hydraulic conductivity of 3.0×10^{-2} ft/d. Hydraulic properties of the confining units that underlie and overlie the Lower Patapsco aquifer are summarized in table 4.

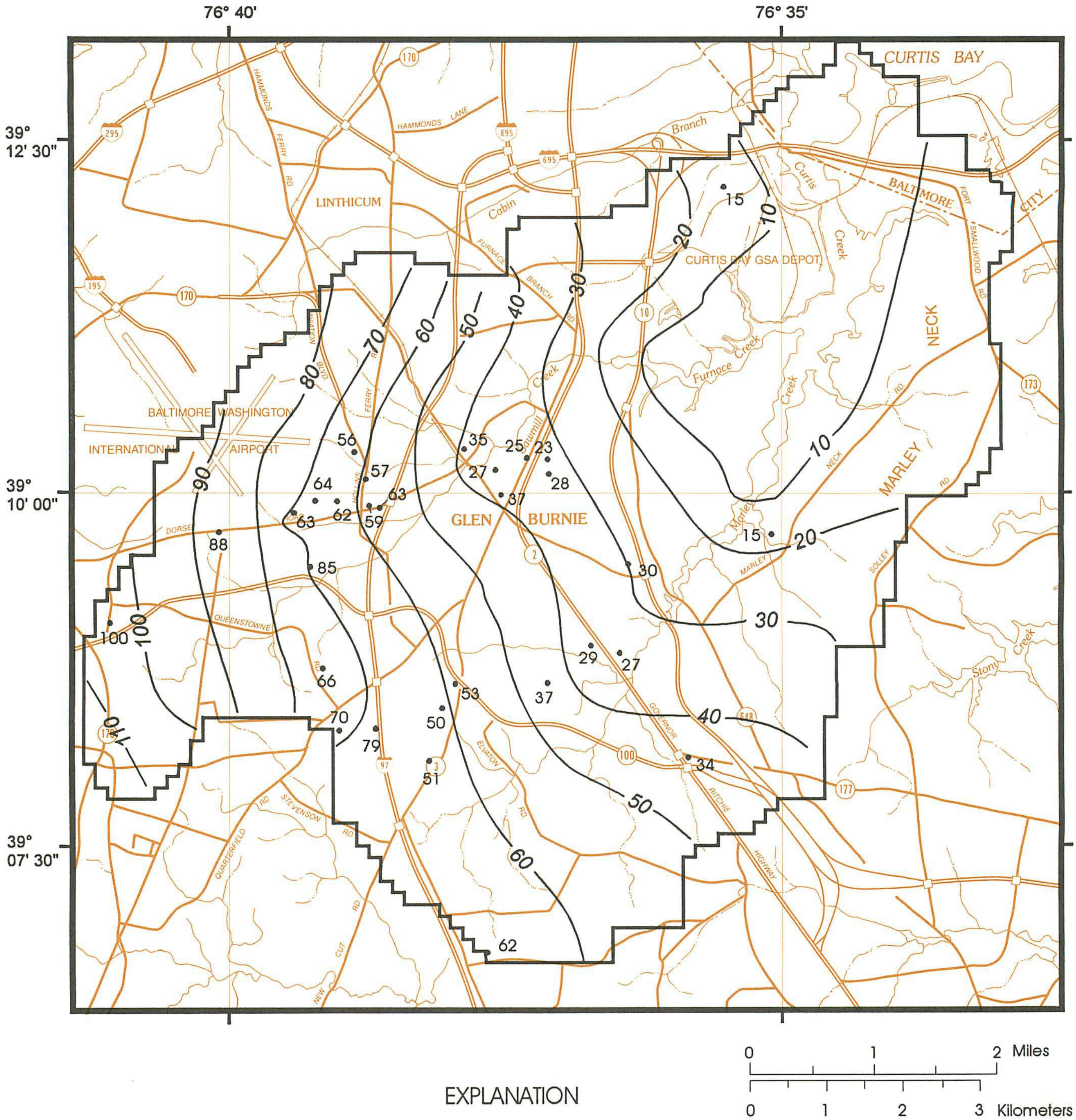
Upper Patapsco Aquifer

The unconfined to semiconfined Upper Patapsco aquifer overlies the Lower Patapsco aquifer (pls. 1-4). The bulk of the Upper Patapsco aquifer consists of sands, silts and gravels of the Patapsco Formation. Sands and gravels of the terrace deposits (fig. 4) form part, usually the unsaturated zone, of

Table 4.—Hydraulic properties of the confining units that underlie and overlie the Lower Patapsco aquifer

[ft = feet; ft/d = feet per day]

Unit	Thickness (ft)	Vertical hydraulic conductivity (ft/day)
Overlying confining unit	0 to 60 (35 average)	Range: 3.0×10^{-2} to 3.0 ft/d (model derived)
		3.0 ft/d in the northeastern region of the study area.
		3.9×10^{-2} ft/d in the vicinity of Sawmill Creek and Dorsey well fields.
		3.0×10^{-2} ft/d in the central and southern regions of the study area. This includes all well fields except Sawmill Creek and Dorsey.
Underlying confining unit (Arundel Clay)	125 to 250	5.9×10^{-7} ft/d (model derived; Mack and Achmad, 1986)



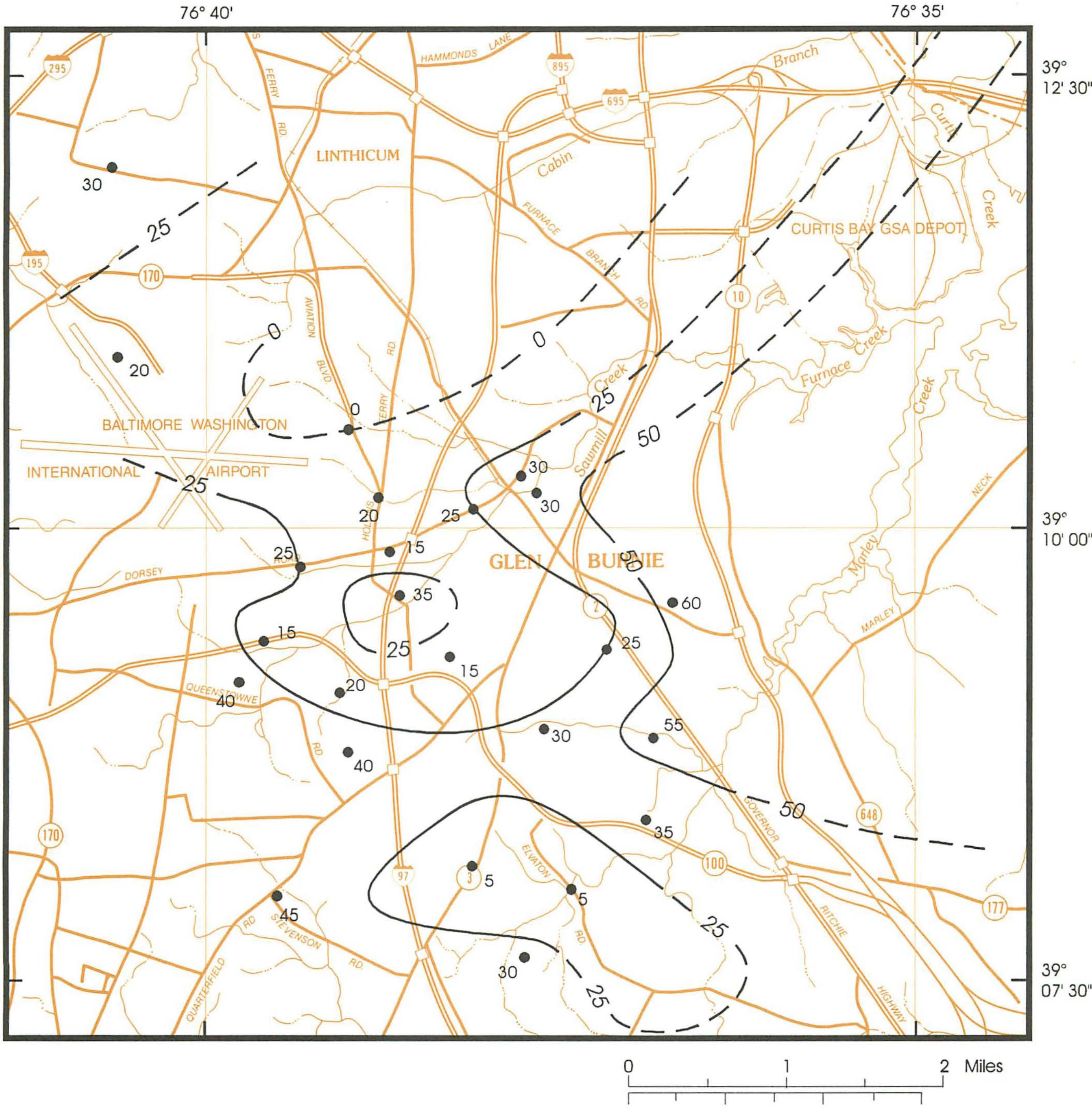
EXPLANATION

— 50 — Simulated line of equal water level, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

28 • Observation well in the Lower Patapsco aquifer and pre-1965 water-level, in feet above sea level. (Wells and water-level data documented in Achmad (1991), p. 28 and 30).

Boundary of the ground-water-flow model.

Figure 10. — Comparison of the simulated 1965 potentiometric surface and pre-1965 measured water levels for the Lower Patapsco aquifer.



EXPLANATION

30 ● Data point and thickness in feet.

— 25 — Line of equal thickness, dashed where uncertain. Contour interval is 25 feet.

Figure 11. — Thickness of the confining unit overlying the Lower Patapsco aquifer.

the aquifer along the drainage basin divide between Sawmill-Furnace Creek and Cabin Creek basins. Sands of the Magothy Formation form part of the unsaturated zone along a small section of the drainage basin divide between the Marley Creek drainage basin and the drainage basins of the Magothy and Severn Rivers (fig. 4). The sediments of the Quaternary alluvium, terrace deposits and Magothy Formation that lie in the study area are assigned to the Upper Patapsco aquifer in this report because they function as part of the water-table aquifer.

The total thickness (saturated plus unsaturated zone) of the Upper Patapsco aquifer ranges from 10 to 210 ft thick. Land surface forms the top of the aquifer; the altitude of land surface differs in the study area because of local topographic relief. The altitude of the base of the aquifer (fig. 12) is defined by the stratigraphic position and lateral continuity of the confining unit underlying the aquifer (pls. 1-4). Plate 1 shows how local topographic relief and the southeastward dip of the confining unit combine to produce a thin (only 30 ft thick) Upper Patapsco aquifer at well Bd 66 and a very thick (210 ft thick) aquifer at well Bd 109. The site of well Bd 109 is a topographic high along the drainage basin divide between Sawmill and Marley Creeks. In the central part of the Sawmill Creek basin, the Upper Patapsco aquifer ranges from 20 to 60 ft thick (pl. 3). In the central part of the Marley Creek basin, southeastward and down dip of the Sawmill Creek basin, the Upper Patapsco aquifer ranges from 90 to 110 ft thick (pl. 4). The base of the Upper Patapsco aquifer dips to the southeast (fig. 12).

Saturated thickness of the Upper Patapsco aquifer ranges from 70 to 100 percent of the total aquifer thickness; saturated thickness in the discharge areas, the creeks and their tributaries, is 100 percent of the total aquifer thickness. At topographic highs (e.g., Bd 109), saturated thickness may be as low as 70 percent of the total aquifer thickness.

Leaky confining units occur within and, in some areas, at the top of the Upper Patapsco aquifer. Clay-silt beds occur at land surface over much of the Marley Creek drainage basin and the eastern parts of the Sawmill-Furnace Creek drainage basin (Glaser, 1976; fig. 4). In those areas, the Upper Patapsco aquifer is unconfined to semiconfined. Figure 13 shows the combined sand percent of the Upper Patapsco aquifer and underlying confining unit. In the east-central part of the Marley Creek basin near the Harundale well field, clay-silt beds in this region make up more than 75 percent of the section overlying the Lower Patapsco aquifer. Regions of more than 75 percent sand and gravel occur in the north-central and south-central parts of Sawmill Creek basin and the west-central part of Marley Creek basin. Variability in the distribution of sand and clayey beds within the Upper Patapsco aquifer is also illustrated by the hydrogeologic sections (pls. 1-4).

Achmad (1991, p. 15-17) reported that in the study area hydraulic conductivities for the Upper Patapsco aquifer calculated using a steady-state flow model range from 8 to 145 ft/d with an average value of 33 ft/d. Transmissivity values derived from these data range from 330 to 4,800 ft^2/d. A specific yield of 11 percent was estimated by Achmad (1991, p. 17).

The simulated 1965 potentiometric surface of the Upper Patapsco aquifer (fig. 14) approximates pre-pumping conditions and indicates that the general direction of ground-water flow in the Upper Patapsco aquifer is east-northeast (fig. 14). Hydraulic gradients range from a low of 0.0014 along the crest of the divide between Sawmill-Furnace and Marley Creek basins to a high of 0.009 along the steeper parts of the two basins. Aquifer properties of the Upper Patapsco aquifer are summarized in table 5.

Table 5.—Properties of the Upper Patapsco aquifer

[ft^2/d = feet squared per day; ft/d = feet per day; ft/ft = feet per feet]

Aquifer type	Unconfined to semiconfined
Transmissivity	Range: 330 to 4,800 ft^2/d
Saturated thickness	Range: ≈10 to 150 ft
Hydraulic conductivity	Average: 33 ft/d Range: 8 to 145 ft/d
Specific yield	11% (estimated)
Porosity	30% (estimated)
General direction of ground-water flow	East-northeast
Hydraulic gradient (approximate pre-pumping)	Range: 0.0014 to 0.009 ft/ft

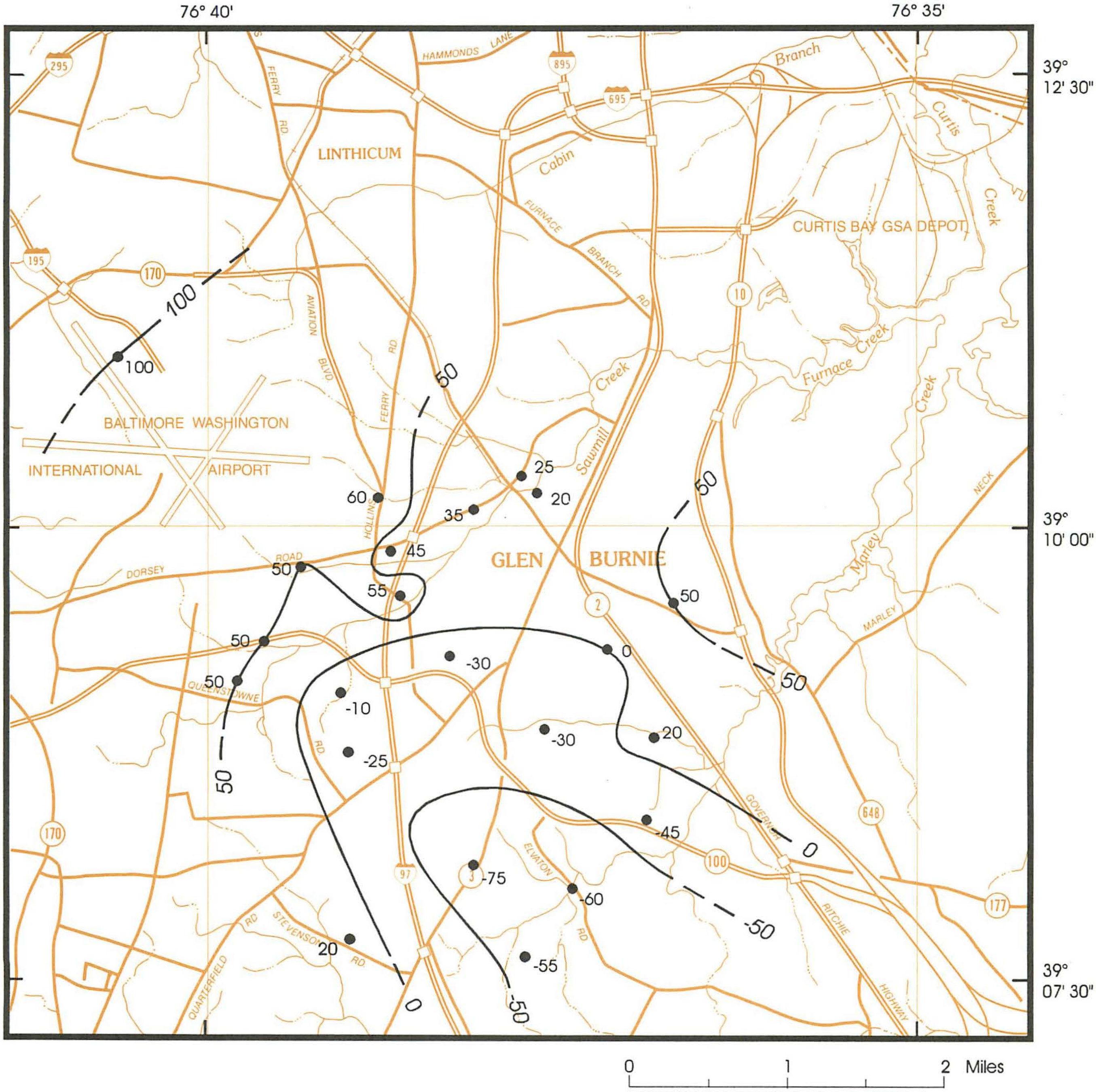
(Sources: Mack and Achmad, 1986; Achmad, 1991; this report)

GROUND-WATER QUALITY

Water-Chemistry Data

Overall, the quality of water from the Lower Patapsco aquifer is good. In most wells, the concentration of total dissolved solids is low, generally less than 50 mg/L; the water is soft with most hardness values less than 10 mg/L as $CaCO_3$; the pH ranges from 4.5 to 6.8 and indicates the water is slightly acidic.

Water chemistry data were obtained from the U.S. Geological Survey's QWDATA data base, published reports, and samples collected as part of this study. Most of the water samples were analyzed by the U.S. Geological Survey Water

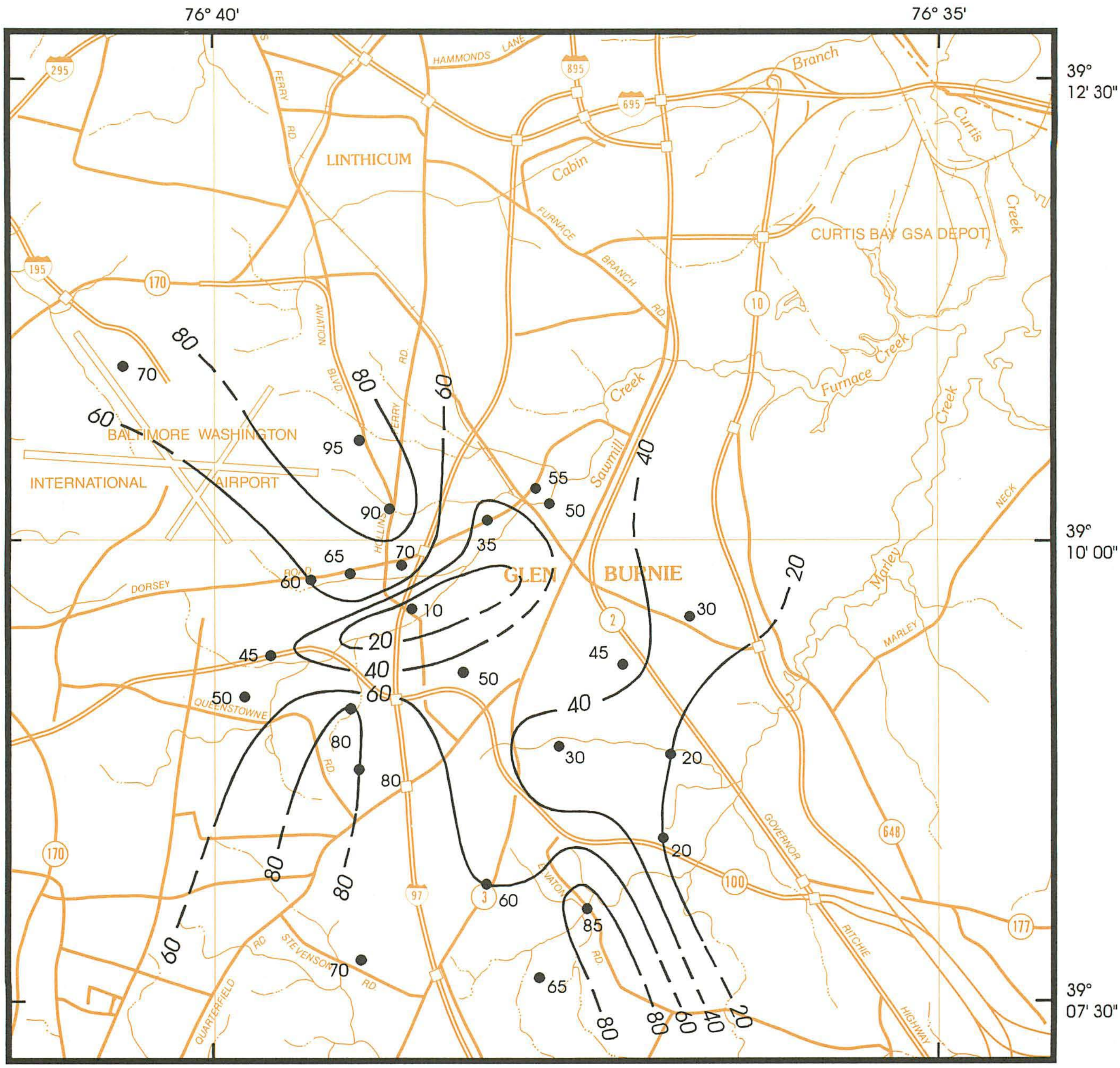


EXPLANATION

● 30 Data point and altitude above or below (-) sea level in feet.

— 25 — Line of equal altitude, dashed where uncertain. Contour interval is 50 feet. Datum is sea level.

Figure 12. — Altitude of the base of the Upper Patapsco aquifer.



EXPLANATION

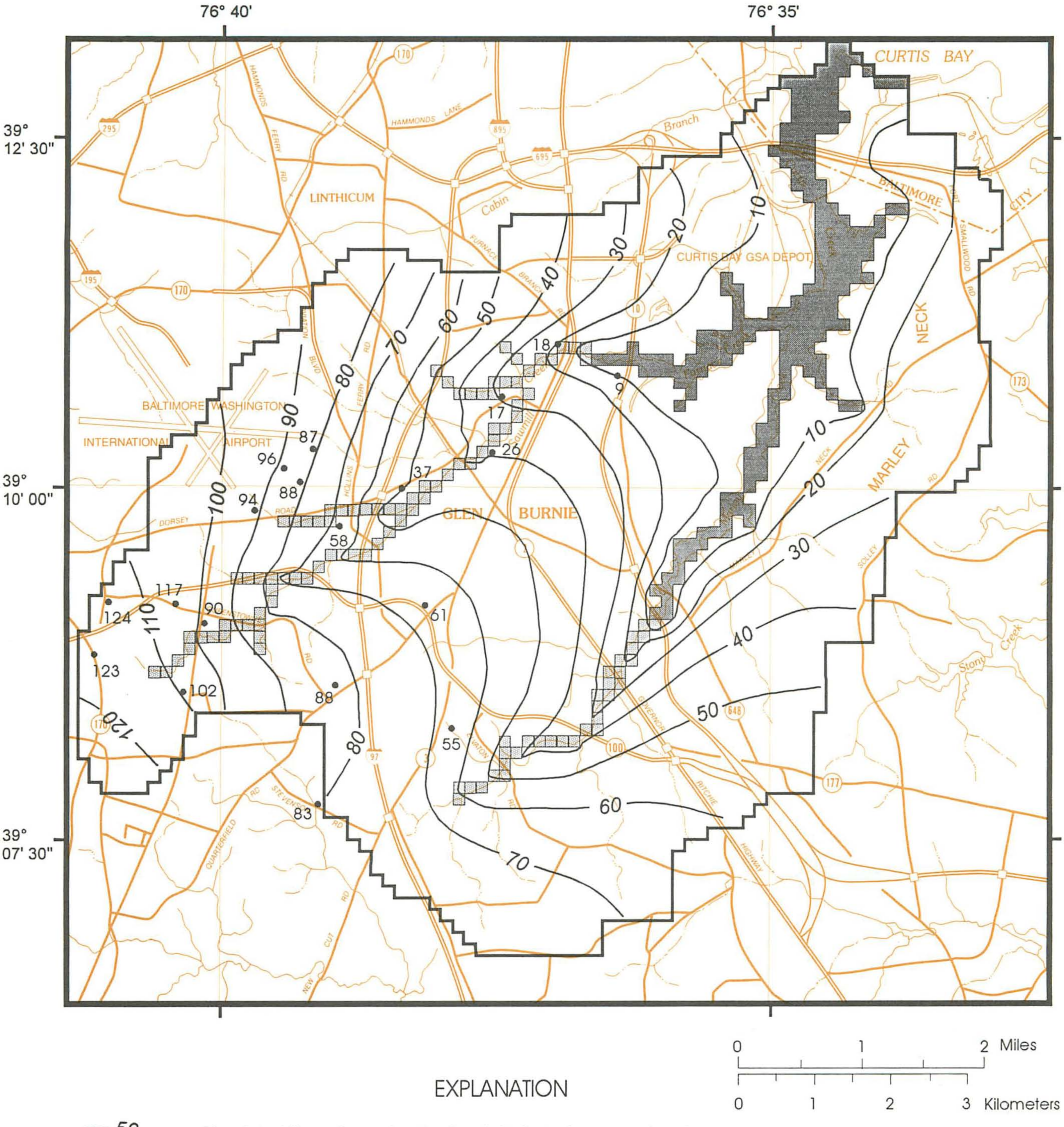
55 ● Data point and sand percentage.

—20— Line of equal sand percentage, dashed where uncertain. Contour interval is 20 percent.

0 1 2 Miles

0 1 2 3 Kilometers

Figure 13. — Combined sand percentage of the Upper Patapsco aquifer and underlying confining unit.



EXPLANATION

— 50 — Simulated line of equal water level, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

37 • Observation well in the Upper Patapsco aquifer and pre-1965 water-level, in feet above sea level. (Wells and water-level data documented in Achmad, 1991, p. 28 - 29).

Stream cells in model layer one (the Upper Patapsco aquifer).

Constant-head cells in model layer one (the Upper Patapsco aquifer). Water level in constant-head cells is sea level.

Boundary of the ground-water-flow model.

Figure 14.— Comparison of the model-simulated 1965 potentiometric surface and pre-1965 measured water levels for the Upper Patapsco aquifer.

Quality Laboratory, Arvada, Colorado. Tritium determinations were made on 36 samples by the Environmental Isotope Laboratory of the University of Waterloo (Ontario, Canada). Water chemistry data are listed in Appendices B, C and D.

Trilinear water-analysis diagrams show differences in the water composition of an aquifer and can help identify any changes in water composition that may have occurred over time. The diagrams shown here are slightly modified from the standard Piper diagrams (figs. 15 and 16). The modified diagrams plot nitrate and sulfate on the same axis; the diameter of the symbol in the anion field indicates the approximate percentage of sulfate in the sample. In the central hydrochemical facies field of the diagram, however, the diameter of the symbol indicates the approximate concentration of dissolved solids in the water sample. The chloride axis includes any minor amounts of fluoride measured in the sample. The sample data for figures 15 and 16 are shown in tables 6 and 7; the locations of the wells are on figure 17.

The percentage ionic composition of two water samples from the Lower Patapsco aquifer analyzed in 1945 and 1946 are shown on figure 15 and the percentage ionic composition of five water samples from the Lower Patapsco and one from the Upper Patapsco aquifer collected in 1991 are shown on figure 16. Most of the samples have no dominant cation and therefore lie in the central part of the cation field. Only Bd 6 (sampled in 1945) and Bd 156 (sampled in 1991) show a slight predominance of sodium over the other major cations. With respect to the anions, the water composition of the samples is more variable. For the samples from the Lower Patapsco aquifer collected in 1945-6, Bd 6 shows sulfate as the most common and chloride the second most common anion; Ad 1 shows nitrate as the most common and chloride the second most common anion. Because the concentration of total dissolved solids in these two samples is very low, 22 and 18 mg/L, small differences in the concentration of one ion with respect to another can cause relatively large percentage

Table 6. — Concentration and percentage ionic composition of water samples from the Lower Patapsco aquifer collected in 1945 and 1946

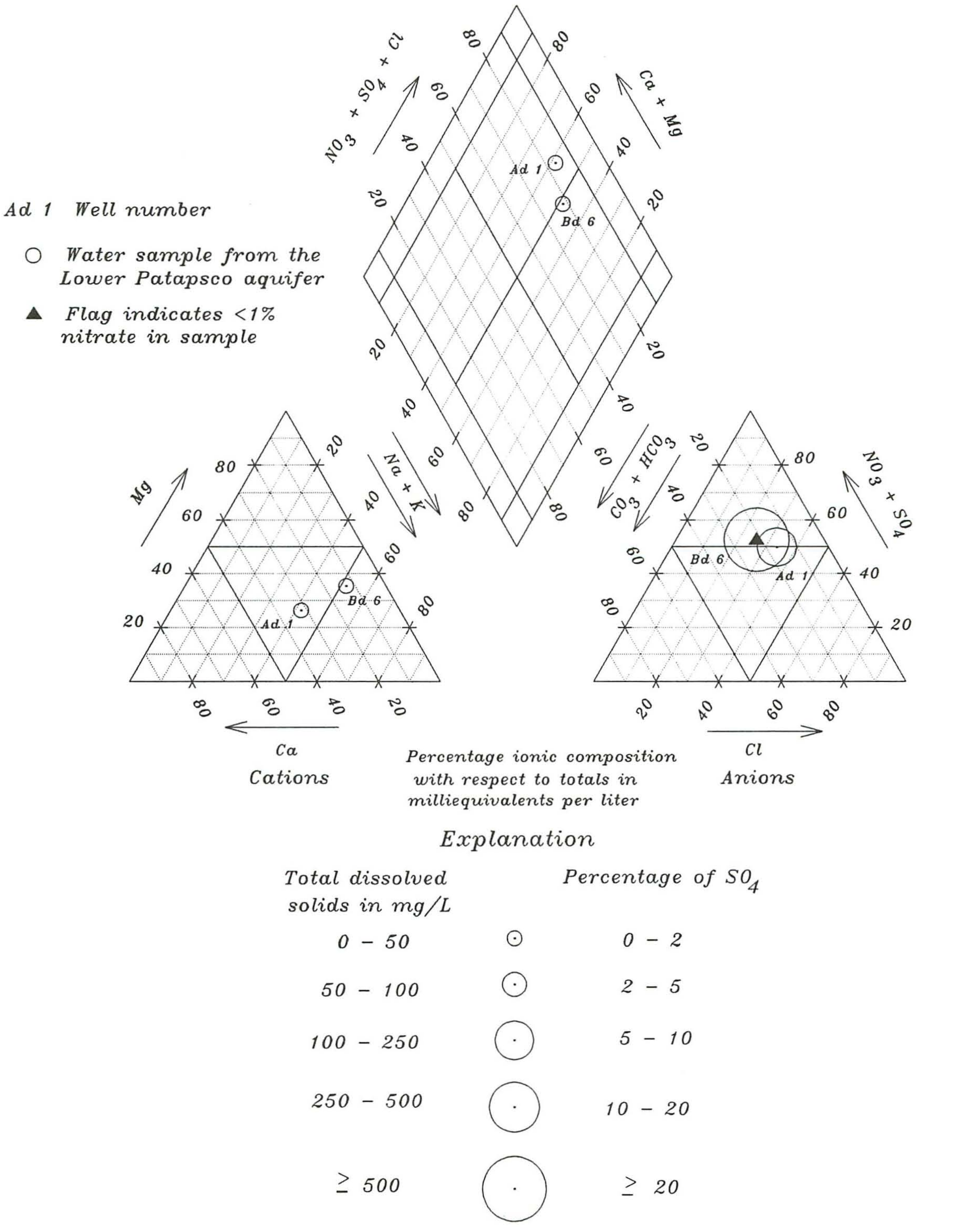
[mg/L = milligrams per liter; meq/L = milliequivalents per liter]

Well number	Date sampled	Concentration (in mg/L)					Percentage cationic composition (with respect to totals in meq/L)		
		Total dissolved solids	Na^+	K^+	Ca^{2+}	Mg^{2+}	Na^+ plus K^+	Ca^{2+}	Mg^{2+}
Lower Patapsco aquifer wells									
Ad 1	04-01-46	22	2.1	0.5	1.6	0.8	41.7	32.0	26.3
Bd 6	03-28-45	18	1.2	0.3	0.3	0.5	51.6	12.9	35.5

Well number	Date sampled	Concentration (in mg/L)						Percentage anionic composition (with respect to totals in meq/L)			
		Cl^-	F^-	SO_4^{2-}	CO_3^{2-}	HCO_3^-	NO_2^{2-} plus NO_3^- as N	Cl^+ plus F^+	SO_4^{2-}	CO_3^{2-} plus HCO_3^-	NO_3^-
Lower Patapsco aquifer wells											
Ad 1	04-01-46	2.9	--	1	0	0.04	1.4	33.7	8.6	16.5	41
Bd 6	03-28-45	1.5	--	4.6	0	0.04	0.2	25.8	51.9	21.6	0.8

Explanation of abbreviations used in table:

Na^+ = sodium; Cl^- = chloride; HCO_3^- = bicarbonate
K^+ = potassium; F^- = fluoride; NO_2^{2-} = nitrite
Ca^{2+} = calcium; SO_4^{2-} = sulfate; NO_3^- = nitrate
Mg^{2+} = magnesium; CO_3^{2-} = carbonate; N = nitrogen



The diameter of the circle within the central hydrochemical facies field is proportional to the concentration of dissolved solids and the diameter of the circle within the anion field is proportional to the percentage of sulfate.

Figure 15. — Percentage ionic composition of water samples from the Lower Patapsco aquifer collected in 1945 and 1946.

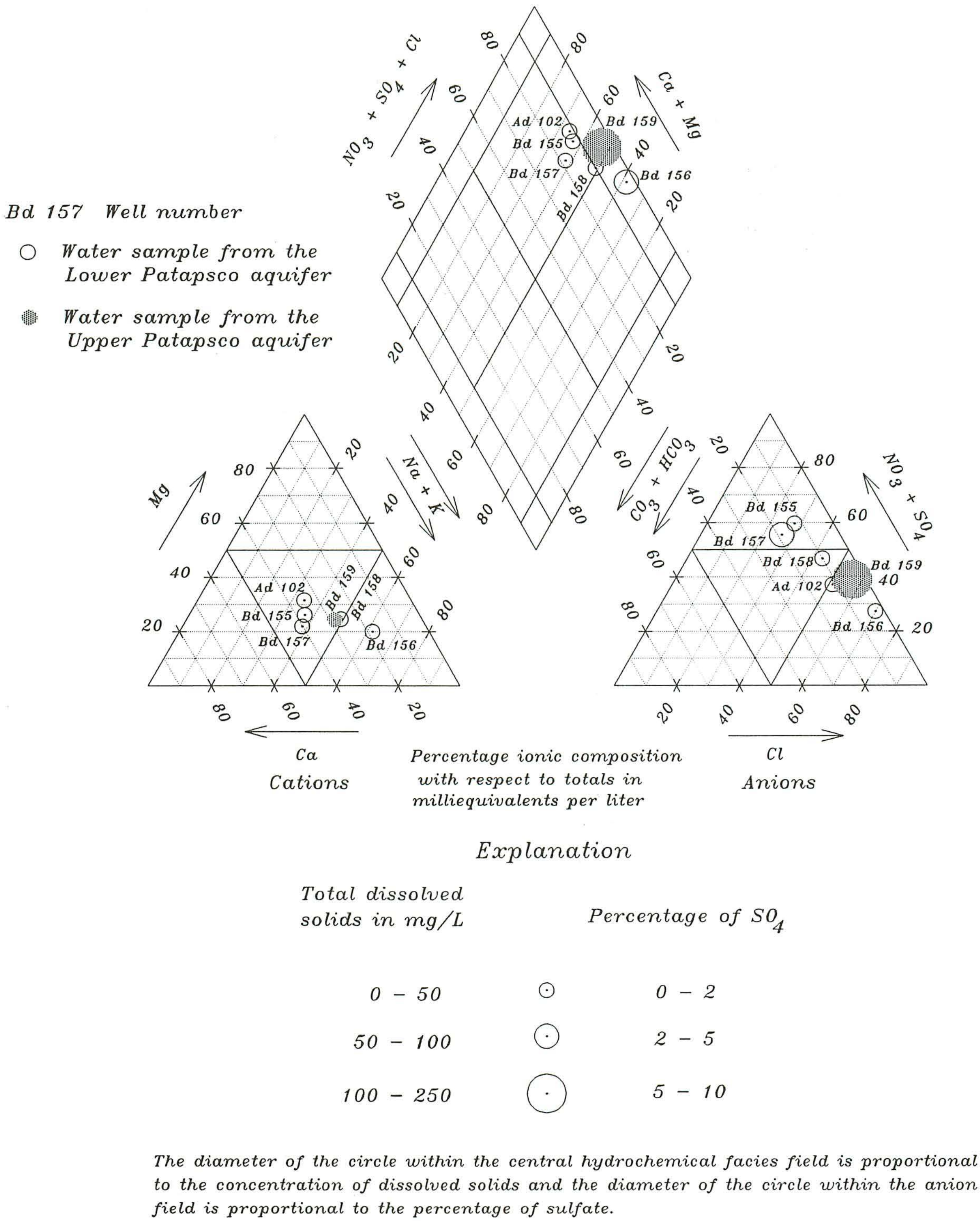


Figure 16. — Percentage ionic composition of water samples from the Upper and Lower Patapsco aquifers collected in 1991.

Table 7. — Concentration and percentage ionic composition of water samples from the Lower and Upper Patapsco aquifers collected in 1991

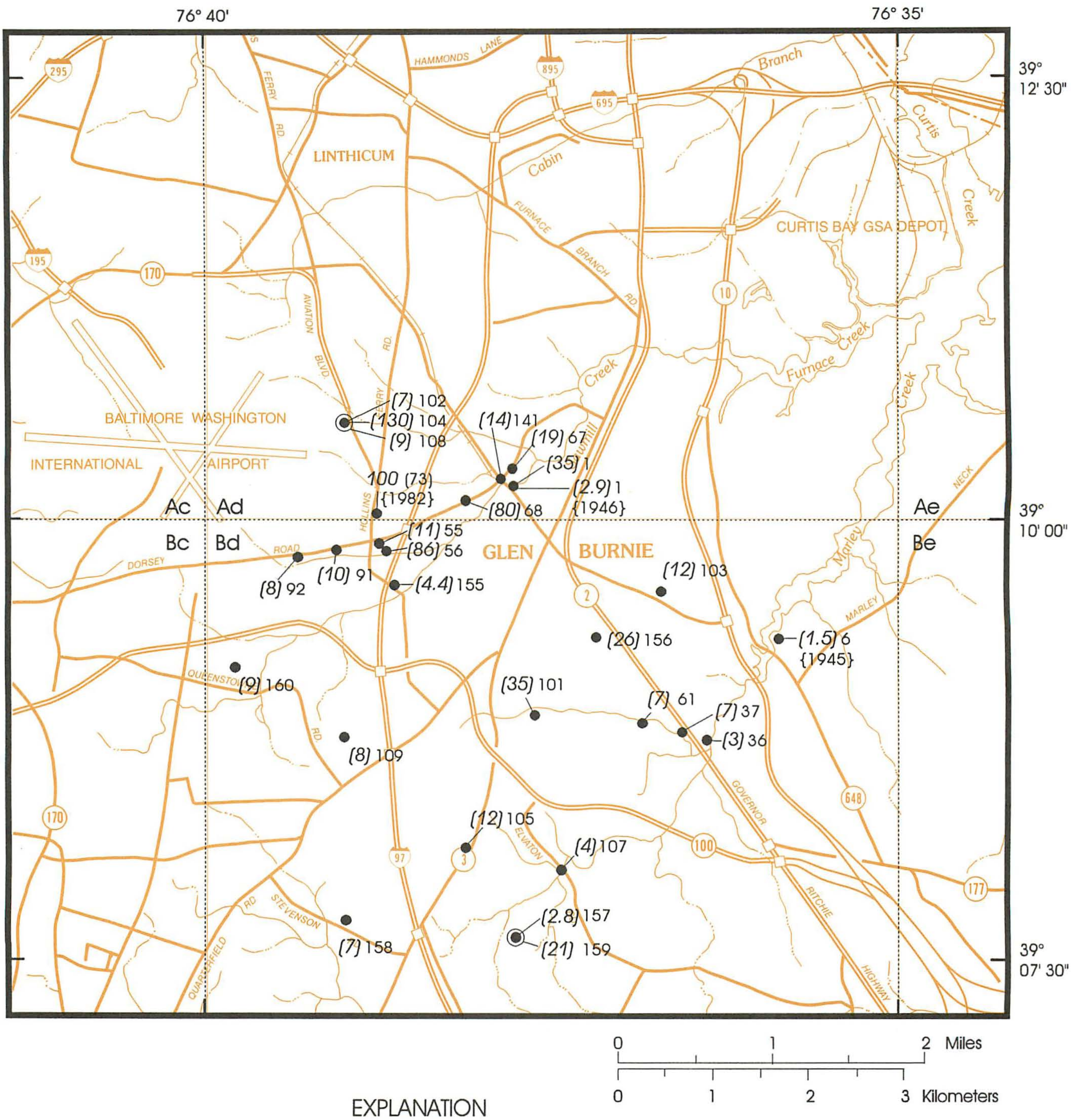
[mg/L = milligrams per liter; meq/L = milliequivalents per liter]

Well number	Date sampled	Concentration (in mg/L)					Percentage cationic composition (with respect to totals in meq/L)		
		Total dis-solved solids	Na^+	K^+	Ca^{2+}	Mg^{2+}	Na^+ plus K^+	Ca^{2+}	Mg^{2+}
Lower Patapsco aquifer wells									
Ad 102	04-10-91	30	2.5	1.3	2.9	1.6	33.9	34.6	31.5
Bd 155	12-10-91	37	2.6	1	2.8	1.2	36.8	37.1	26.2
Bd 156	11-26-91	100	18	3.3	5.2	3.4	61.7	18.5	19.9
Bd 157	11-26-91	29	1.7	0.8	2	0.66	38.0	40.2	21.9
Bd 158	11-27-91	50	5.5	1.6	3	1.7	49.2	26.3	24.6
Upper Patapsco aquifer wells									
Bd 159	11-27-91	104	14	1.5	8.1	4.2	47.3	28.4	24.3

Well number	Date sampled	Concentration (in mg/L)						Percentage anionic composition (with respect to totals in meq/L)			
		Cl^-	F^-	SO_4^{2-}	CO_3^{2-}	HCO_3^-	NO_2^{2-} plus NO_3^- as N	Cl^+ plus F^+	SO_4^{2-}	CO_3^{2-} plus HCO_3^-	NO_3^-
Lower Patapsco aquifer wells											
Ad 102	04-10-91	9	0.2	0.3	0.0	0.06	2.6	51.2	1.2	11.6	36.0
Bd 155	12-10-91	3.9	0.2	0.3	0.0	0.05	3.5	28.0	1.5	12.5	58.1
Bd 156	11-26-91	36	0.2	1	0.0	0.04	5.3	69.8	1.4	3.0	25.8
Bd 157	11-26-91	2.6	0.2	0.4	0.0	0.06	2.4	25.9	2.6	18.5	53.0
Bd 158	11-27-91	9.6	0.2	0.6	0.0	0.07	4.1	43.1	1.9	10.1	44.9
Upper Patapsco aquifer wells											
Bd 159	11-27-91	30	0.2	5.8	0.0	0.07	6.6	56.6	8.0	4.4	31.1

Explanation of abbreviations used in table:

Na^+	= sodium	Cl^-	= chloride	HCO_3^-	= bicarbonate
K^+	= potassium	F^-	= fluoride	NO_2^{2-}	= nitrite
Ca^{2+}	= calcium	SO_4^{2-}	= sulfate	NO_3^-	= nitrate
Mg^{2+}	= magnesium	CO_3^{2-}	= carbonate	N	= nitrogen



EXPLANATION

(2.8) 157 / (21) 159 — Location of well, chloride determination in parenthesis, and well number.

● Solid dot indicates well completed in the Lower Patapsco aquifer.

○ Open circle indicates well completed in the Upper Patapsco aquifer.

All samples collected and analyzed in 1991 or 1992 unless noted otherwise, e.g., {1946}.

Ac ⁞ Ad / Bc ⁞ Bd — 5-minute quadrangle designations for well numbering system. Dashed lines denote quadrangles.

Figure 17. — Concentration of chloride in water samples from the Upper and Lower Patapsco aquifers.

differences in ionic composition.

In the samples collected from the Lower Patapsco aquifer samples in 1991, two (Bd 155 and 157) have nitrate as the most common and chloride as the second most common anion; one (Bd 158) has no dominant anion; two (Ad 102 and Bd 156) have chloride as the most common and nitrate as the second most common anion. The concentration of total dissolved solids are higher in all the Lower Patapsco aquifer samples collected in 1991 than in the water samples collected in the 1940's. The mean value of the total dissolved solids for the five Lower Patapsco aquifer samples collected in 1991 is 49 mg/L while the mean value of total dissolved solids for the two samples from 1945-6 is 20 mg/L. The one sample from the Upper Patapsco aquifer, Bd 159, had a concentration of total dissolved solids of 104 mg/L; in Bd 159, chloride is the most prevalent and nitrate the second most prevalent anion.

Although there are not enough chemical analyses from the nineteen-forties to make statistically significant comparisons between the water quality of the aquifer in 1945 and 1991, the observed differences in the composition of the water may be related to the urbanization of the study area. The water analysis diagrams suggest that increases in the ionic percentages of nitrate and chloride have occurred in the Lower Patapsco aquifer since the mid-1940s. The nitrate concentrations in the samples from 1945-6 and from 1991 are shown on figure 18. The mean and median nitrate concentration for the 1945-6 data is 0.8 mg/L, and for the 1991 nitrate data, the mean is 3.6 mg/L and the median is 3.5 mg/L. These data suggest that nitrates in the Lower Patapsco aquifer are probably elevated compared to pre-development conditions in the area. However, the concentration of nitrate in the 1991 samples are still below the U.S. EPA maximum contaminant level (MCL[1] of 10 mg/L total nitrogen). The 1991 sample from the Upper Patapsco aquifer (Bd 159) had a nitrate concentration of 6.6 mg/L, the highest concentration of all the wells sampled. Nitrate concentrations would be expected to be higher in the Upper Patapsco aquifer than in the Lower Patapsco aquifer because the Upper Patapsco aquifer has, over time, been directly exposed to common sources of nitrate such as septage, sewage and fertilizers. The Anne Arundel County Department of Public Works regularly tests the production wells for nitrate and reports that none of the production wells have concentrations of nitrate exceeding the U.S. EPA MCL of 10 mg/L as nitrogen (Anne Arundel Co. Dept. of Public Works, oral commun., 1994).

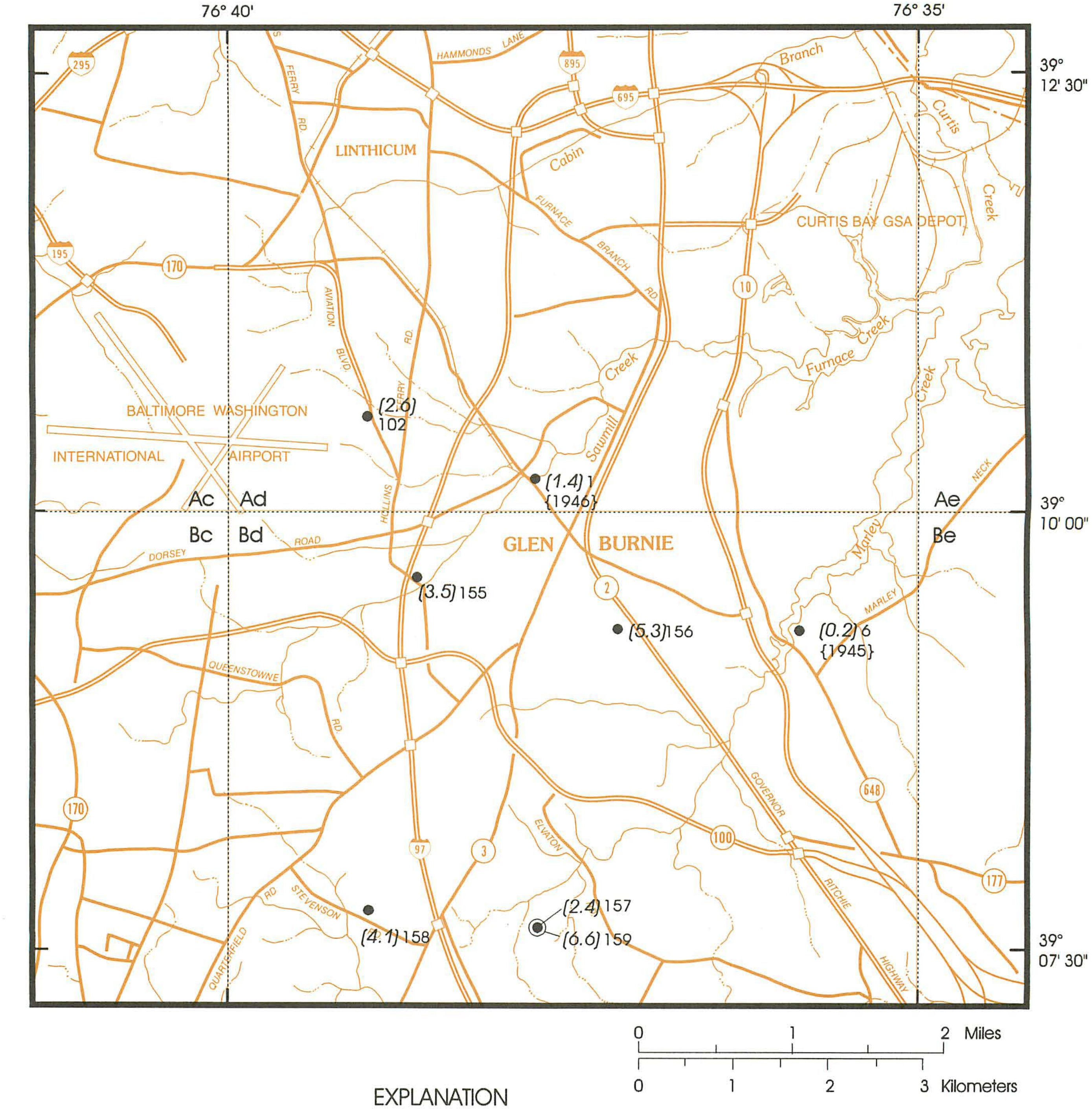
An increase in the concentration of chloride has occurred in at least part and probably throughout most of the Lower Patapsco aquifer from 1945 to 1991. The mean and median of the chloride concentration for the 1945-6 data is 2.2 mg/L. The mean and median of the 1991 chloride concentration data is 23.9 and 9.5 mg/L respectively. All chloride determinations in the study area are below the U.S. EPA secondary maximum contaminant level (SMCL[2]) of 250 mg/L for chloride in drinking water. Chloride concentrations and the locations of the wells sampled in 1945-6, 1982 and 1991-2 are shown on figure 17. The highest chloride determination was 130 mg/L in well Ad 104, a well screened in the upper part of the Lower Patapsco aquifer. Of particular interest is well Ad 1 (Sawmill 1), in which the chloride concentration increased from 2.9 mg/L in 1946 to 35 mg/L in 1991.

The most likely source of chloride to the Lower Patapsco aquifer is road salt. Road salt may enter the ground-water system as both a point and nonpoint source contaminant. The dispersal of road salt by salt trucks applies the salt more or less evenly throughout the study area in relatively low concentrations; this type of dispersal is a nonpoint source application. As a point source application, road salt was stored in uncovered or poorly covered piles at various sites in the study area until approximately sometime between 1975 and 1985 when more effective salt storage structures were built. The wells where the highest chloride levels were determined are near sites where road salt was previously stored. The site of a now demolished State Highway Administration facility lies 700 feet to the northwest and up-gradient from well Ad 104. With respect to wells Bd 55 and Bd 56, road salt was once stored about 300 ft south of Bd 56 at an AA DPW facility. In all the wells sampled, the concentration of chloride is below the 250 mg/L SMCL. The head differences between the Lower and Upper Patapsco aquifers indicate that the brackish estuaries to the east of the study area are not the source of chloride in the Upper or Lower Patapsco aquifer in the study area.

Volatile organic compounds (VOCs) regulated by the U.S. EPA have been measured in several Lower Patapsco aquifer wells in the study area. The presence of these compounds indicates that the Lower Patapsco aquifer is vulnerable to contamination from substances released to the Upper Patapsco aquifer. The VOCs determined, tetrachloroethylene and trichloroethylene, are part of a family of chlorinated hydrocarbon compounds (TCEs) that are common industrial solvents used as degreasing agents and dry cleaning fluids. Concentrations of tetrachloroethylene close to 5 μg/L (micrograms per liter) were determined in Bd 103 (the Glendale well) in 1992; the Glendale well was taken out of service after this substance was determined. Subsequent quarterly testing for TCEs in the Glendale well showed concentrations of tetrachloroethylene in 1993 that exceeded the 1993 U.S. EPA MCL of 5 μg/L (the final U.S. EPA MCL for this substance became effective July 30, 1993). Also in 1993, traces of trichloroethylene and cis-1,2 dichloroethane were determined at concentrations below their 1993 U.S. EPA MCLs in the Glendale well. A trace of tetrachloroethylene (1 μg/L) was measured in Bd 156 in 1992; Bd 156 is an observation well located approximately 2,500 ft southwest of well Bd 103. Traces of two other TCEs, 1,1,2-trichloroethane (0.3 μg/L) and trichloroethylene (0.2 μg/L) were determined

[1] MCL - Maximum Contaminant Level. The maximum permissible level of a contaminant in water which is delivered to any user of a public water system (Code of Federal Regulations, 1993). A MCL is a federally enforceable drinking-water standard. The U.S. EPA defines contaminant as any physical, chemical, biological, or radiological substance or matter in water (Code of Federal Regulations, 1993).

[2] SMCL - Secondary maximum contaminant level. The U.S. EPA suggests the SMCL as a reasonable goal for operators of water-supply systems to achieve in drinking water. A SMCL is not a health-based standard, but an aesthetic standard based on characteristics such as odor, taste, and appearance, and certain other non-aesthetic characteristics (U.S. Environmental Protection Agency, 1991).



EXPLANATION

(2.4) 157 / (6.6) 159 — Location of well, nitrite plus nitrate determination in parenthesis as total nitrogen in milligrams per liter and well number.

● Solid dot indicates well completed in the Lower Patapsco aquifer.

○ Open circle indicates well completed in the Upper Patapsco aquifer.

All samples collected and analyzed in 1991 unless noted otherwise, e.g., {1946}.

Ac ¦ Ad / Bc ¦ Bd — 5-minute quadrangle designations for well numbering system. Dashed lines denote quadrangles.

Figure 18. — Concentration of nitrite plus nitrate as nitrogen in water samples from the Upper and Lower Patapsco aquifers.

in 1991 in a sample from an unused production well, Ad 41 (Sawmill 5). Also in Ad 41, a trace of benzene (2 µg/L) was measured in 1982 (Chapelle, 1982); however, no benzene was measured in Ad 41 when the well was resampled in 1991. A trace of the pesticide Silvex (0.01 µg/L) was determined in observation well Ad 104 (David Bolton, personal communication).

Sites of Potential Contamination

The implementation of a U.S. EPA-approved wellhead protection program includes an inventory of known and potential sites of ground-water contamination. At this time (1993), the Maryland Department of the Environment (MDE) has available field-checked location data only for contaminant sites that were under investigation or remediation in 1991 and 1992. The locations and types of contaminant sites are shown on figure 19. In the study area, leaking underground storage tanks (LUST sites) are the most common types of contaminant sites. LUST sites are usually sites where gasoline or other types of petroleum products have been released into the Upper Patapsco aquifer. There are five CERCLA sites in and two adjacent to the study area. CERCLA sites are sites where past releases of hazardous substances have occurred; these sites are regulated by the federal Comprehensive Environmental Response, Compensation, and Liabilities Act and its amendments (ERT, 1987); CERCLA sites are also known as superfund sites. There is one RCRA site in and one just west of the study area. RCRA sites are regulated under the authority of the Federal Resource Conservation and Recovery Act; this federal law governs facilities where hazardous materials may be treated, stored and disposed of, and also sites that have experienced a release of hazardous materials to the environment (ERT, 1986). Under both CERCLA and RCRA, clean up and remediation of a site may be ordered by the Maryland Department of Environment, which administers the State's RCRA and CERCLA programs under the authorization of the U.S. EPA. Contamination of the Lower Patapsco aquifer from any of the sites shown on figure 19 depends on the hydrogeologic conditions, the type and quantity of material released, and the length of time elapsed between the initial release of a substance and its discovery and remediation. The locations of sites where permits for ground-water discharge have been issued, community septic systems and landfills (fig. 19) were also provided by MDE; some of the landfills contain CERCLA sites.

GROUND-WATER-FLOW MODEL

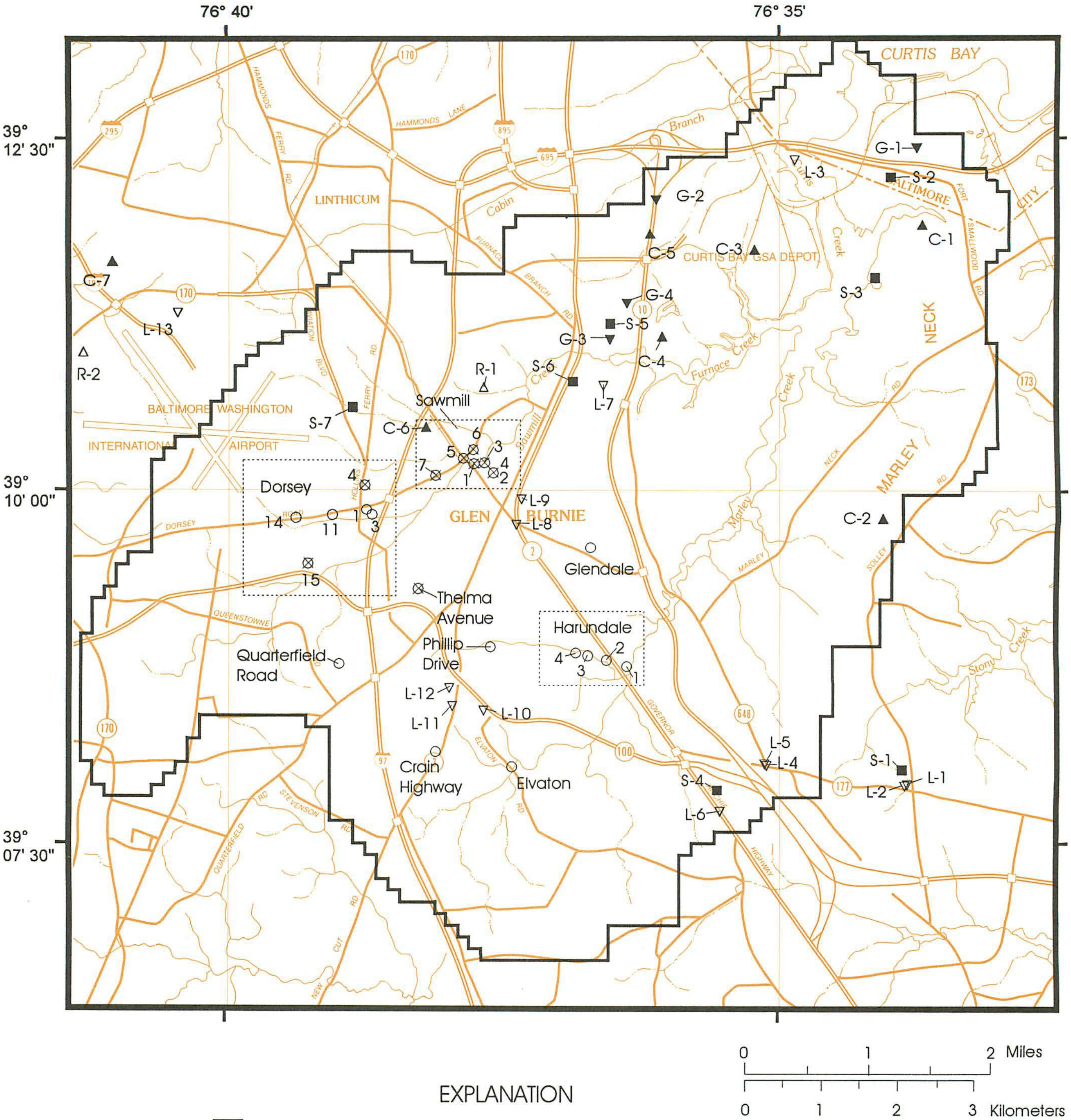
The ground-water-flow model described in this report is a mathematical conceptualization of the Patapsco aquifer system underlying the Sawmill-Furnace Creek and Marley Creek drainage basins. The computer program used to simulate the ground-water-flow system is the U.S. Geological Survey MODFLOW model (McDonald and Harbaugh, 1984).

The ground-water-flow model described herein is an updated version of the ground-water-flow model described in Achmad (1991). The earlier model was used to evaluate the water resources of the study area by simulating the effects of different amounts of pumpage on aquifer water levels and stream base flow. In Achmad (1991) annual average data were input to the ground-water-flow model. In the updated model monthly average values are used so that seasonal changes in ground-water recharge, evapotranspiration, and pumpage can be simulated. In addition, monthly input data permits a more precise model calibration than annual average input data.

MODEL DESIGN AND BOUNDARY CONDITIONS

The model framework consists of the Upper Patapsco aquifer as a water-table aquifer, an underlying leaky confining unit, and the Lower Patapsco aquifer as a confined aquifer (fig. 20). Aquifer transmissivities and storage coefficients from the previous model were assigned unchanged to the updated model. However, the vertical conductivity of the confining unit near the Sawmill and Dorsey Road well fields was increased by 30 percent because recently obtained well logs indicate that the confining unit is more sandy in this locality. The entire model grid consists of 84 columns and 83 rows of uniformly sized, 500 by 500 ft, finite-difference cells. The active area of the model shown on figure 21 consists of 79 columns (numbered 2 to 80) and 79 rows (numbered 1 to 79). The modeled area is about 33 mi^2 and coincides with the Sawmill-Furnace Creek and Marley Creek basins and the upper part of Curtis Creek.

The model boundaries (fig. 20) represent the inflow and outflow of water to the modeled area. The lateral boundaries of the Upper Patapsco aquifer are no-flow boundaries that coincide with ground-water divides as represented by the drainage basin divides of Sawmill-Furnace and Marley Creek basins. The three boundary conditions used to represent the upper boundary of the model are 1) a specified flux boundary that represents ground-water recharge to the Upper Patapsco aquifer from precipitation, 2) a constant head-boundary that represents the water levels in the tidal (northeastern parts) of Furnace and Marley Creeks, and also Curtis Creek, and 3) stream boundaries that represent head dependent leakage through the stream beds of the non-tidal portions of Sawmill and Marley Creeks. The lateral boundaries of the Lower



EXPLANATION

- Boundary of ground-water-flow model.
- ○ Lower Patapsco aquifer production well active in 1990.
- ⊗ Abandoned Lower Patapsco aquifer production well.
- ▽ L-1 LUST site and site number.
- ▲ C-1 CERCLA site and site number.
- △ R-1 RCRA site and site number.
- ▼ G-1 Ground-water discharge permit site and site number.
- ■ S-1 Community septic site and site number.
- ○3 Dorsey — Local name of well and well field, e.g., Dorsey 3.

Figure 19. — Locations of production wells screened in the Lower Patapsco aquifer and sites of surface and shallow subsurface contamination.

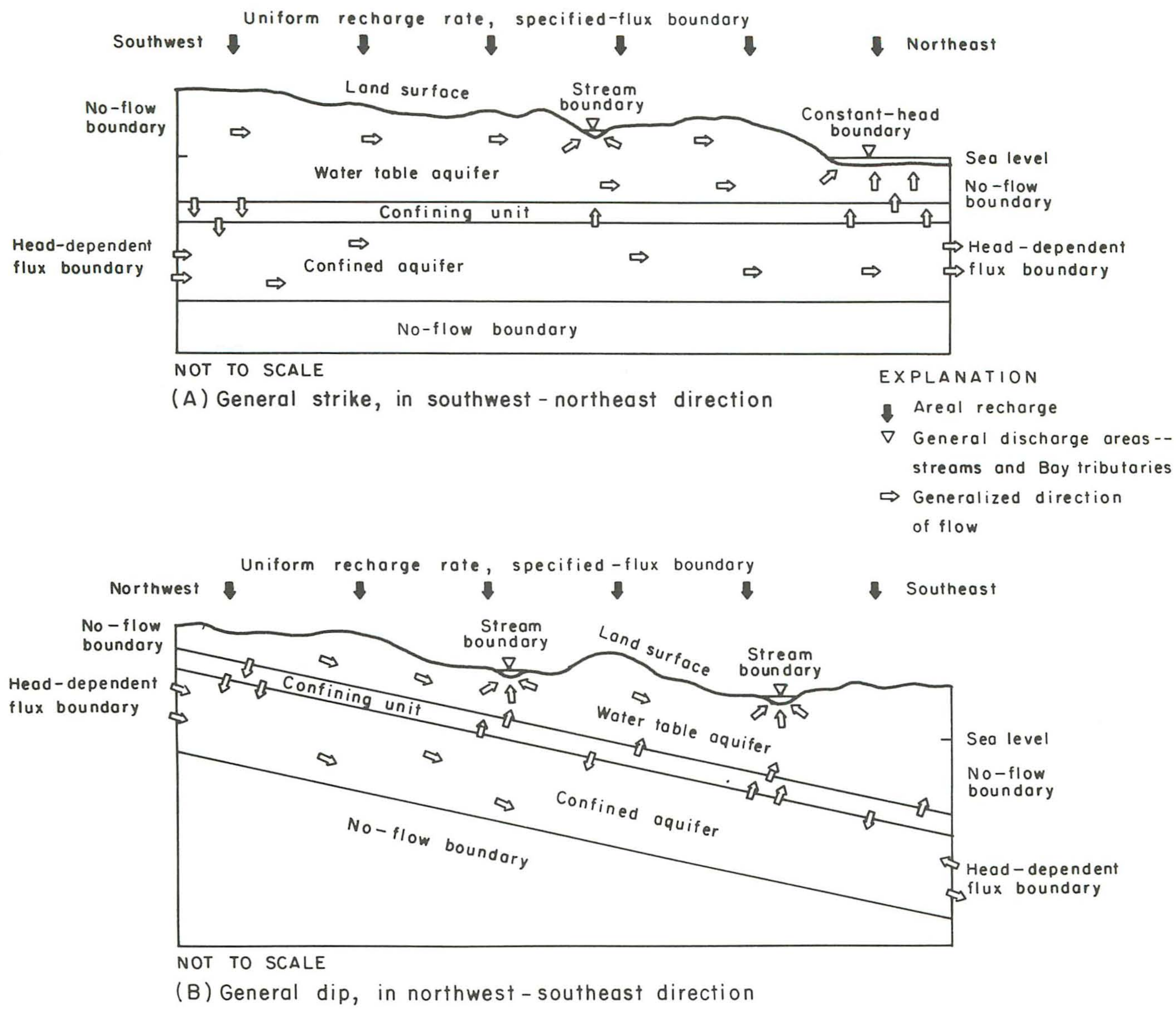


Figure 20. — Cross-sections of conceptualized steady-state ground-water-flow model (from Achmad, 1991).

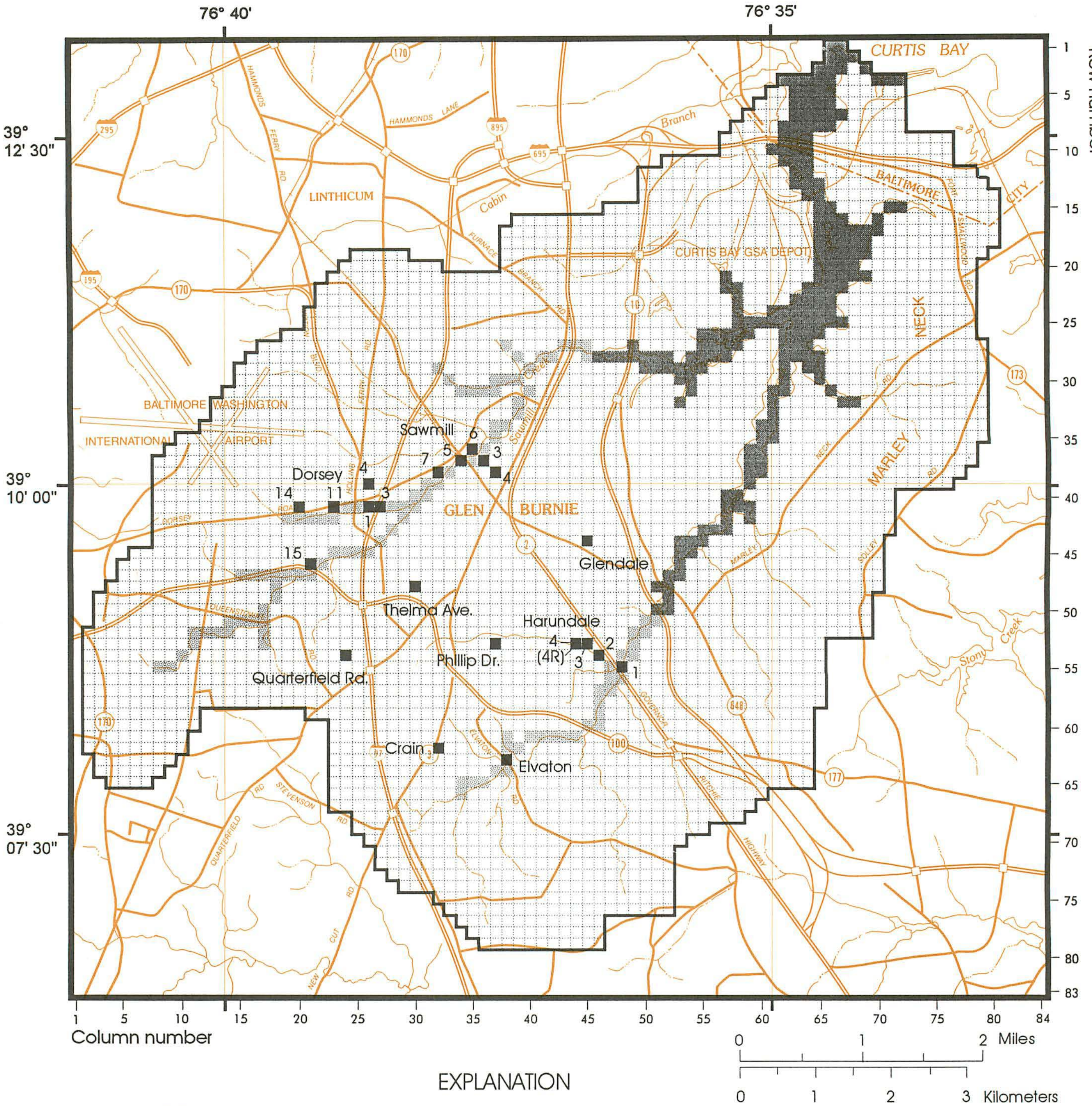
Patapsco aquifer are head-dependent flux boundaries that represent water flowing into or out of the model area within the Lower Patapsco aquifer. The basal boundary of the Lower Patapsco aquifer and the model is a no-flow boundary formed by the Arundel Clay, a tight confining unit (Achmad, 1991).

SIMULATION OF STREAMFLOW

In the model, Sawmill, Marley, Furnace, and Curtis Creeks were simulated using a network of stream cells (fig. 21). The stream bed sediments were assigned a vertical hydraulic conductivity of 1 ft/d and an estimated uniform thickness of 1 ft based on values determined by Willey and Achmad (1986). In most cases, only a portion of each stream cell is covered by the actual stream. Therefore, the vertical conductance of the stream cells range from 60.5 ft^2/d to 2,592 ft^2/d as a function of the length and width of the stream section in a stream cell. The vertical conductance values of the stream cells are unchanged from the earlier version of the ground-water-flow model described in Achmad (1991).

PRECIPITATION, GROUND-WATER RECHARGE AND GROUND-WATER EVAPOTRANSPIRATION

The annual average precipitation in the study area is 41.8 in/yr. The 41.8 in/yr value is the mean (average) of the annual precipitation recorded at Baltimore-Washington International Airport for the thirty-year period from 1951-80; the period



EXPLANATION

Active model cells, cell dimensions are 500 feet by 500 feet.

Pumping cell in model layer two (production well screened in the Lower Patapsco aquifer).

Stream cells in model layers one (the Upper Patapsco aquifer).

Constant-head cells in model layer one (the Upper Patapsco aquifer).

Boundary of model in both model layer one and two. Boundary in model layer one is no-flow. Boundary in model layer two is head-dependent flux.

Dorsey 3 ■ Local name of well and well field, e.g., Dorsey 3, Elvaton. (Note: Harundale 4R replaced Harundale 4 in 1992).

Figure 21. — Grid of the ground-water-flow model and boundary conditions.

1951-80 is used to calculate mean values or "normals" of the various climatic elements (National Oceanic and Atmospheric Administration, 1991). Although the seasonal variation in precipitation is not large in the study area, it is usually highest in the summer and lowest in the autumn and winter months (tab. 8). Monthly normals for precipitation are shown on figure 22. Monthly and departure from monthly normal precipitation from 1984-92 are shown on figure 23; the same parameters on an annual basis are shown on figure 24.

Ground-water recharge as applied to the model represents the volume of water from precipitation that percolates into the aquifer system. Ground-water recharge for the period 1984-92 was applied to the model in monthly time steps as 45.1 percent of the monthly precipitation. The conversion factor (45.1 percent) was obtained by using the earlier version of the flow model (Achmad, 1991) to simulate the 12-month period from June, 1984 to May, 1985. For that 12-month period, the ground-water recharge equaled 14.4 inches and the total precipitation was 31.9 inches. For the period 1984 to 1992, annual ground-water recharge applied to the model ranged from 13.60 in/yr in 1991 to 23.40 in/yr in 1989; it was about normal in 1987 and 1990 (18.53 and 18.89 in/yr respectively), above normal in 1989 (23.40 in/yr) and below normal for the remaining years of that period.

The amount of ground-water evapotranspiration (ET) lost from the water table varies seasonally. Ground-water evapotranspiration is almost zero during the winter months, rises with the start of the growing season in the spring, peaks during the summer and tapers off during autumn (fig. 25). In order to improve the model calibration, the annual ground-water ET rate used in the updated ground-water-flow model was distributed monthly following the convergence approximation method described in Rasmussen and Andreasen (1959) and Achmad (1991). The flow model calculates ground-water ET rates for each model cell based on the depth to the water table from land surface (McDonald and Harbaugh, 1984). The ground-water ET rate is at a maximum when the depth to water table is between zero and 3 ft below land surface. The ground-water ET rate is assumed to decrease linearly as the water table declines from 3 to 8 ft below land surface and a value of zero is assumed when the water table is equal to or deeper than 8 ft below land surface (Wilson and Wiser, 1974). Achmad (1991) determined that under steady-state conditions the effective ground-water evapotranspiration rate for the study area is 4.59 in/yr. This value is within the range established by previous workers in the mid-Atlantic Coastal Plain; Johnston (1976) determined a value of 3 in/yr for several small basins in the coastal plain of Delaware; Rasmussen and Andreasen (1959) determined a value of 9.7 in/yr for a coastal plain basin (Beaverdam Creek basin) near Salisbury, Maryland (Achmad, 1991). The maximum possible rate of ground-water evapotranspiration from any given model cell is 18 in/yr. This value was obtained from the flow model described in Achmad

Table 8. — Normal precipitation in the study area by three-month periods

Months	Normal (mean) precipitation (in inches)
March, April and May	10.6
June, July and August	12.0
September, October and November	9.6
December, January and February	9.7

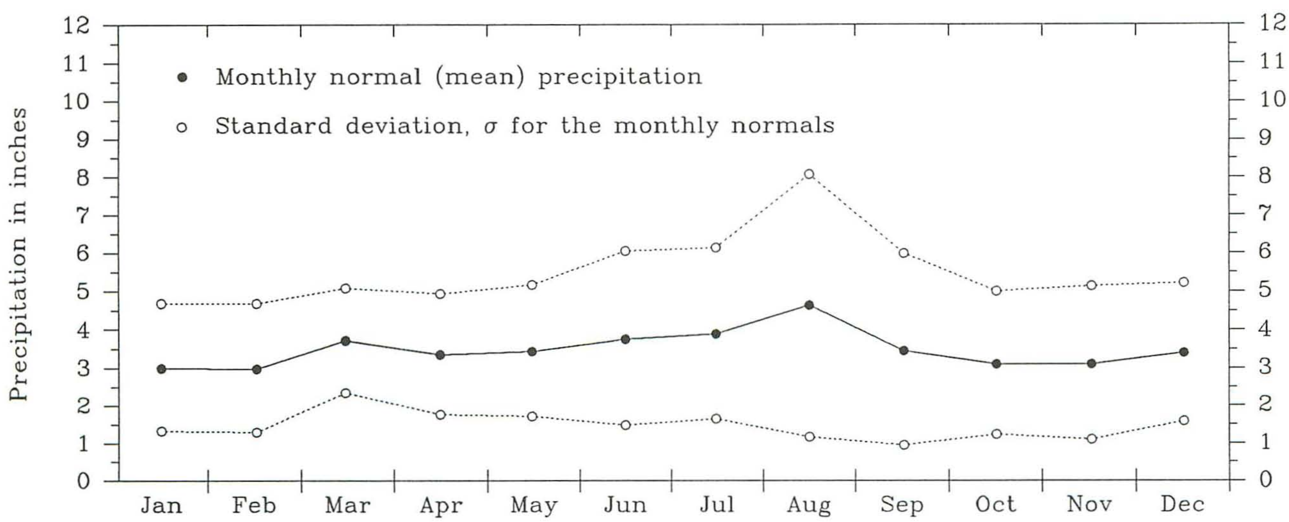


Figure 22. — Monthly normals for precipitation based on normals for the period 1951-80.

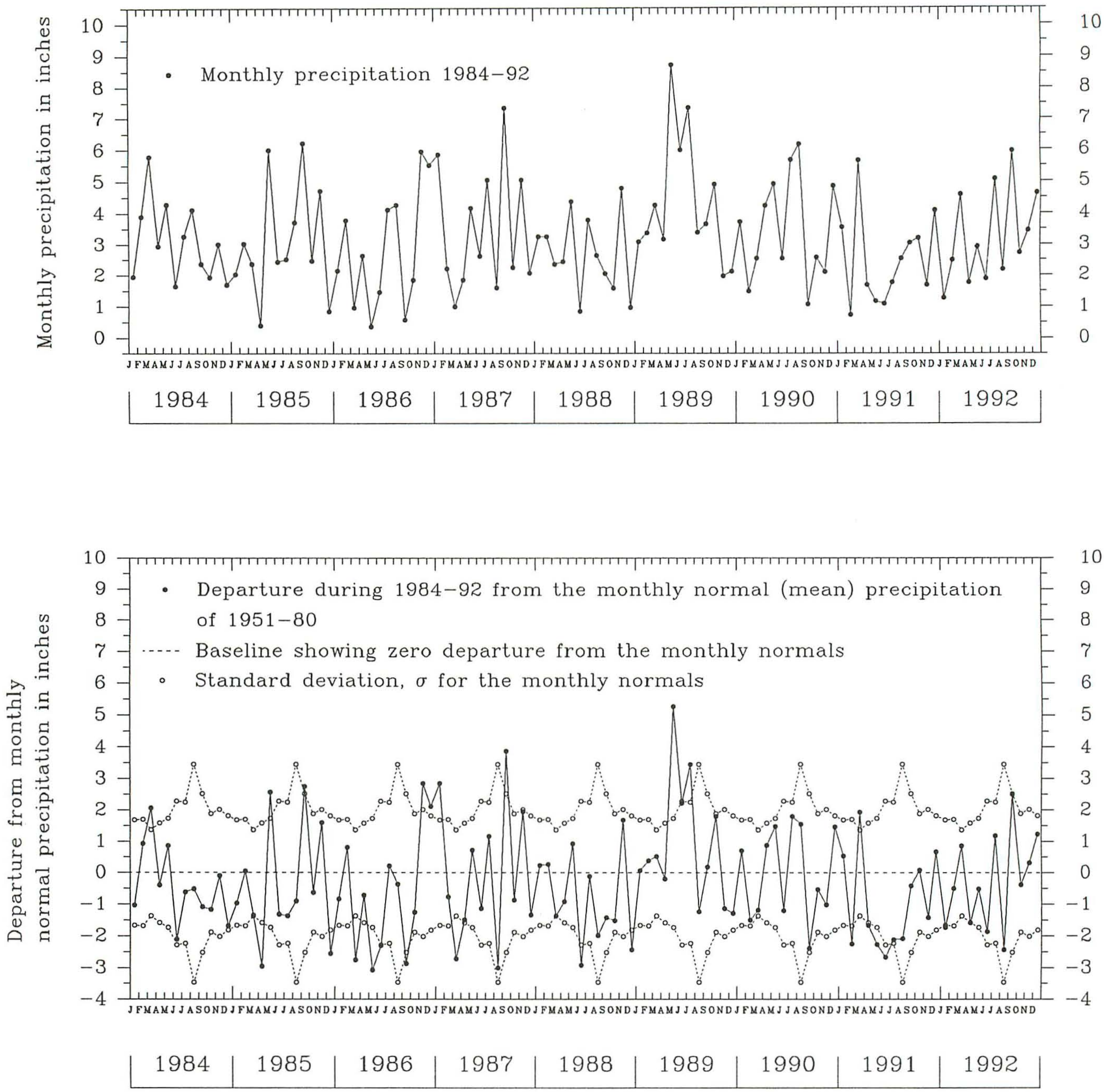
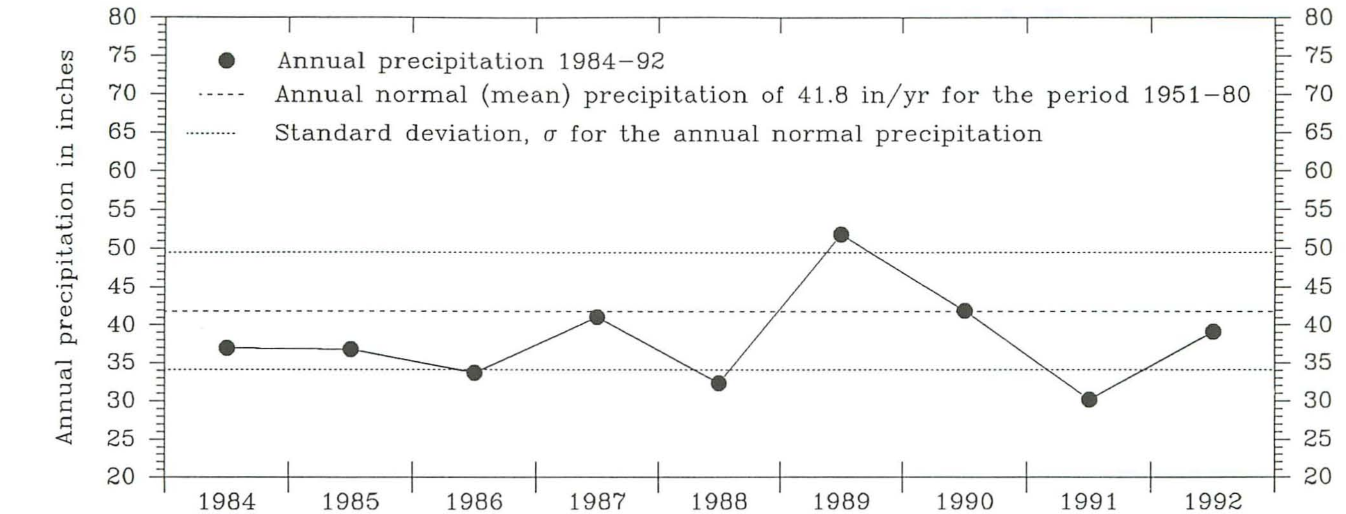


Figure 23. — Monthly and departure from monthly normal precipitation, 1984-92.

(1991) and is unchanged in the updated model. Generally, the highest rates of ground-water evapotranspiration occur in model cells near streams where the water table is closest to the land surface and the lowest rates of ground-water evapotranspiration occur in model cells near divides where the water table is deepest.

PUMPAGE

Ground-water withdrawal from the Lower Patapsco aquifer in the study area increased from 33,000 gal/d (gallons per day) in 1933 to a maximum of 11 Mgal/d (million gallons per day) in 1982 (Achmad, 1991). Since 1982, pumpage has



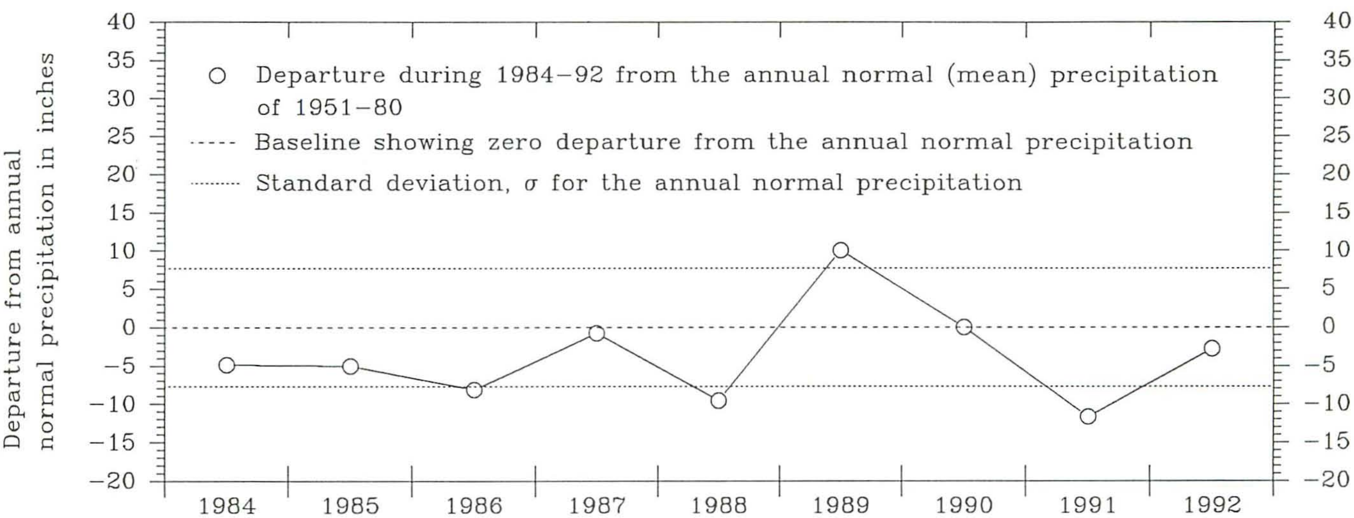


Figure 24. — Annual and departure from annual normal precipitation, 1984-92.

gradually decreased. During 1984-1992, annual average pumpage decreased from 10.6 Mgal/d in 1984 to 5.48 Mgal/d in 1992 (fig. 26). Increased pumpage from the Patuxent aquifer and water obtained from the Baltimore City public-supply system compensated for the decrease in pumpage from the Lower Patapsco aquifer. Demand for ground water is seasonal; it is highest in the summer and declines in the winter. The departure of monthly average pumpage from the annual average pumpage for each year from 1984-92 is compared with the monthly departure from normal precipitation (fig. 27). Monthly average pumpage rates usually exceed the annual average pumpage rate by the greatest amount during the summer months that have below normal precipitation, and therefore, below normal ground-water recharge. For example, during the summer of 1991 monthly average pumpage exceeded the annual average pumpage of that year by 2 Mgal/d and precipitation and ground-water recharge were below normal (fig. 27). Monthly average pumpage is shown in figures 28 and 29 for the Sawmill, Dorsey and Harundale well fields, and for all the single-well well fields. Total annual average pumpage from the Lower Patapsco aquifer for the period 1984-92 is shown in table 9. Neither the Sawmill well field nor the Thelma Avenue well have been used since 1989; the Glendale well has not been used since August of 1992.

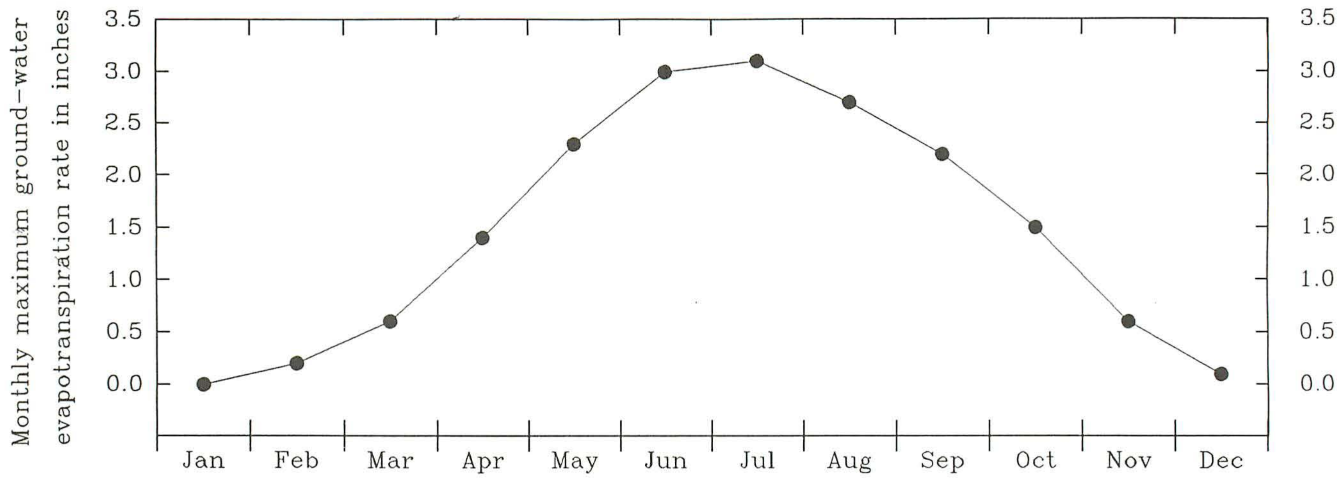


Figure 25. — Monthly maximum ground-water evapotranspiration rate.

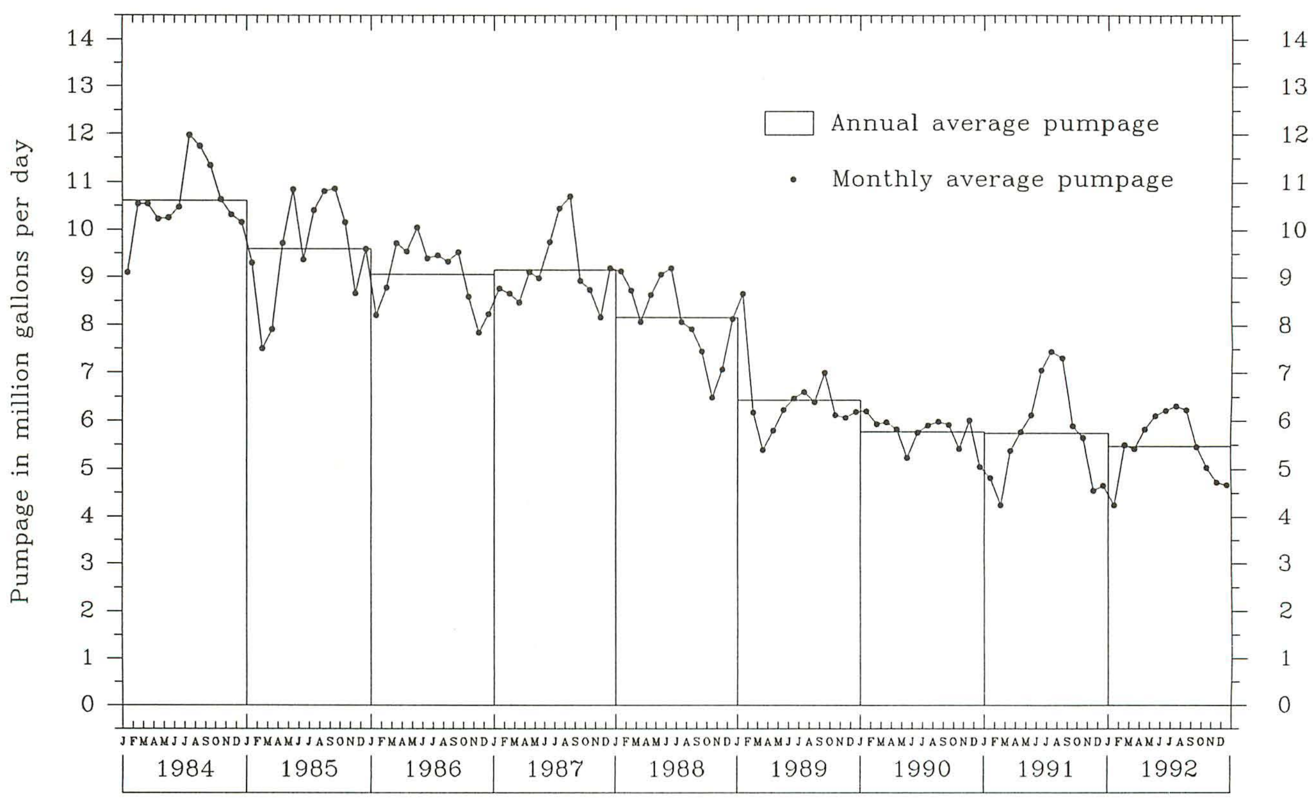


Figure 26. — Annual average and monthly average pumpage for the Lower Patapsco aquifer, 1984-92.

Table 9. — Annual average pumpage for the Lower Patapsco aquifer, 1984-92

[Mgal/d = million gallons per day]

Year	Annual average pumpage (in Mgal/d)
1984	10.61
1985	9.59
1986	9.04
1987	9.14
1988	8.16
1989	6.43
1990	5.77
1991	5.74
1992	5.48

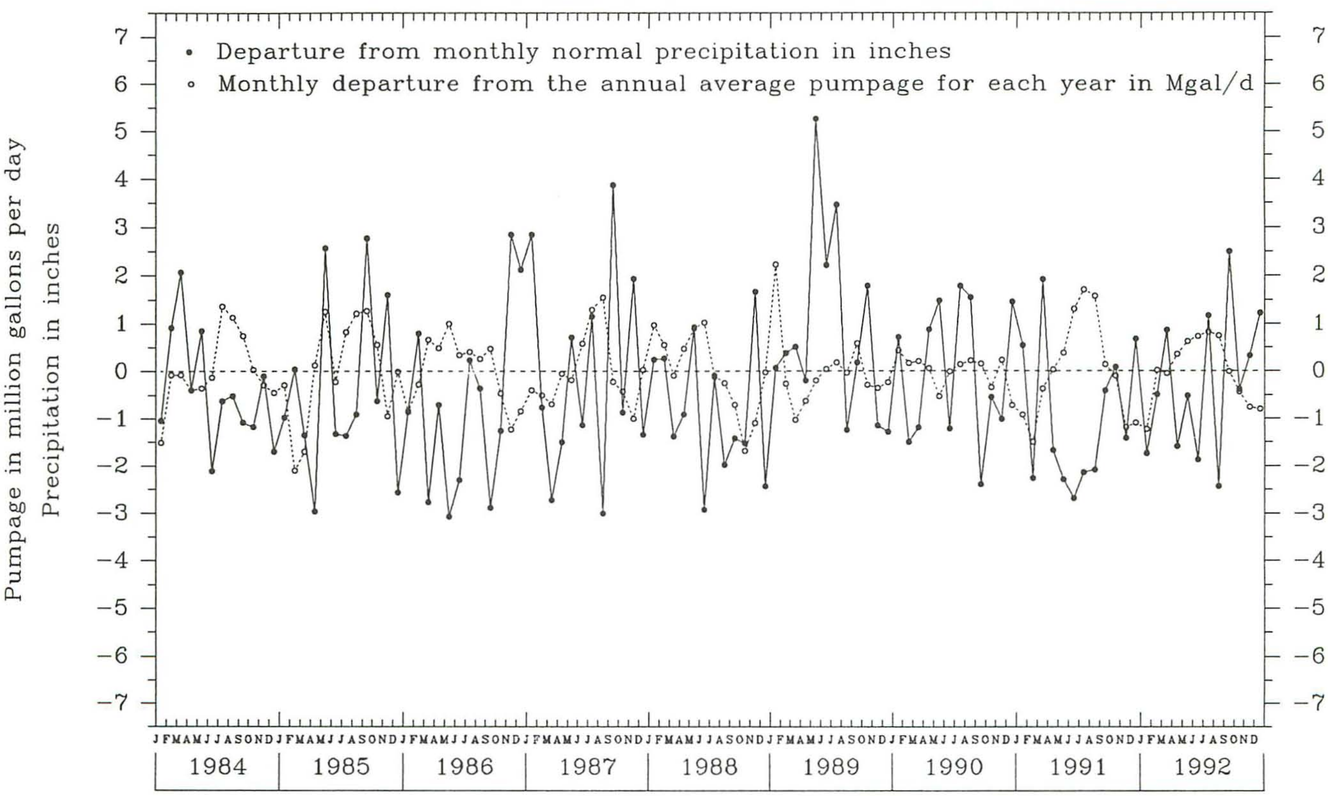


Figure 27. — Departure from monthly normal precipitation and the monthly departure from annual average pumpage for each year, 1984-92.

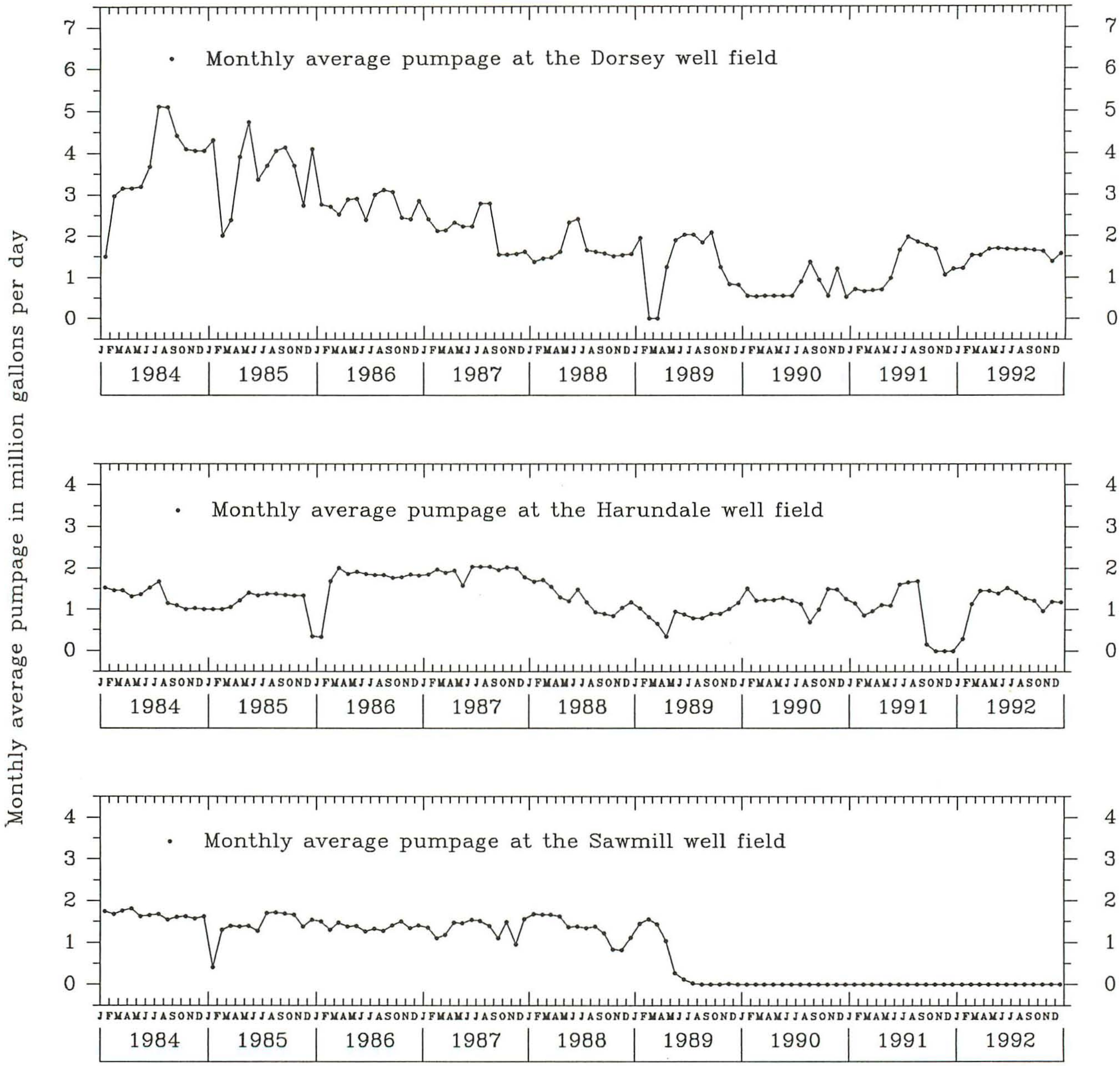


Figure 28. — Monthly average pumpage for the Lower Patapsco aquifer at the Dorsey, Harundale, and Sawmill well fields, 1984-92.

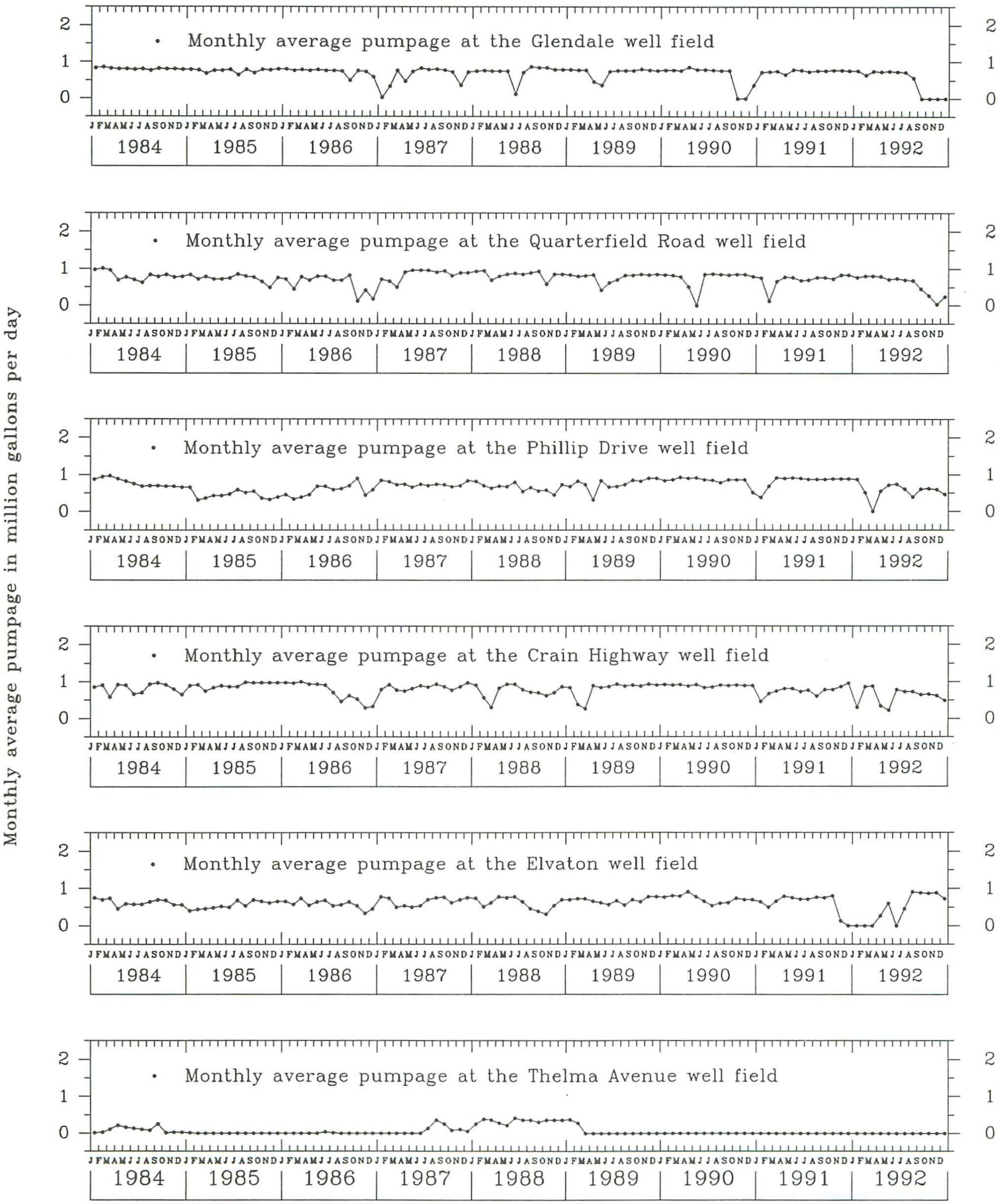


Figure 29. — Monthly average pumpage for the Lower Patapsco aquifer at the single-well well fields, 1984-92.

RECALIBRATION OF THE GROUND-WATER-FLOW MODEL

Using the hydrologic properties described earlier, the ground-water-flow model was reevaluated by matching simulated stream baseflows and ground-water levels with measured values. The model was run as a steady-state simulation (storage coefficients set equal to zero) in order to simulate the 1965 potentiometric surfaces of the Upper and Lower Patapsco aquifers (figs. 14, 10). The 1965 potentiometric surfaces approximate the aquifer's pre-pumping potentiometric surfaces. The 30 percent increase in confining unit vertical hydraulic conductivity for some model cells near Sawmill and Dorsey Road well fields resulted in fractionally lower heads in the Lower Patapsco aquifer and a fractionally higher head in the Upper Patapsco aquifer in the area of the well fields. These differences in head did not alter the regional 1965 potentiometric surfaces nor the 1965 stream baseflow described in Achmad (1991).

The water levels of Lower Patapsco wells drilled prior to 1965 were plotted on the 1965 steady-state potentiometric surface map (Achmad, 1991) (fig. 10). The 1965 static water levels are very close to the pre-pumping potentiometric surface for the aquifer because development of the Lower Patapsco was not extensive in 1965. For the same reason, the 1965 potentiometric surface of the Upper Patapsco aquifer (fig. 14) is assumed to represent the pre-pumping surface.

The 1965 steady-state water levels were used as the initial conditions (starting water levels) for the 1965-1992 transient simulation. The 1965-1992 simulation is divided into two parts; part 1 covers 1965-1984 and part 2 covers 1984-1992. As in the 1965-1984 simulation described in Achmad (1991), part 1 of the updated model uses a long term annual average recharge of 20.5 in/yr, an annual model-calculated ground-

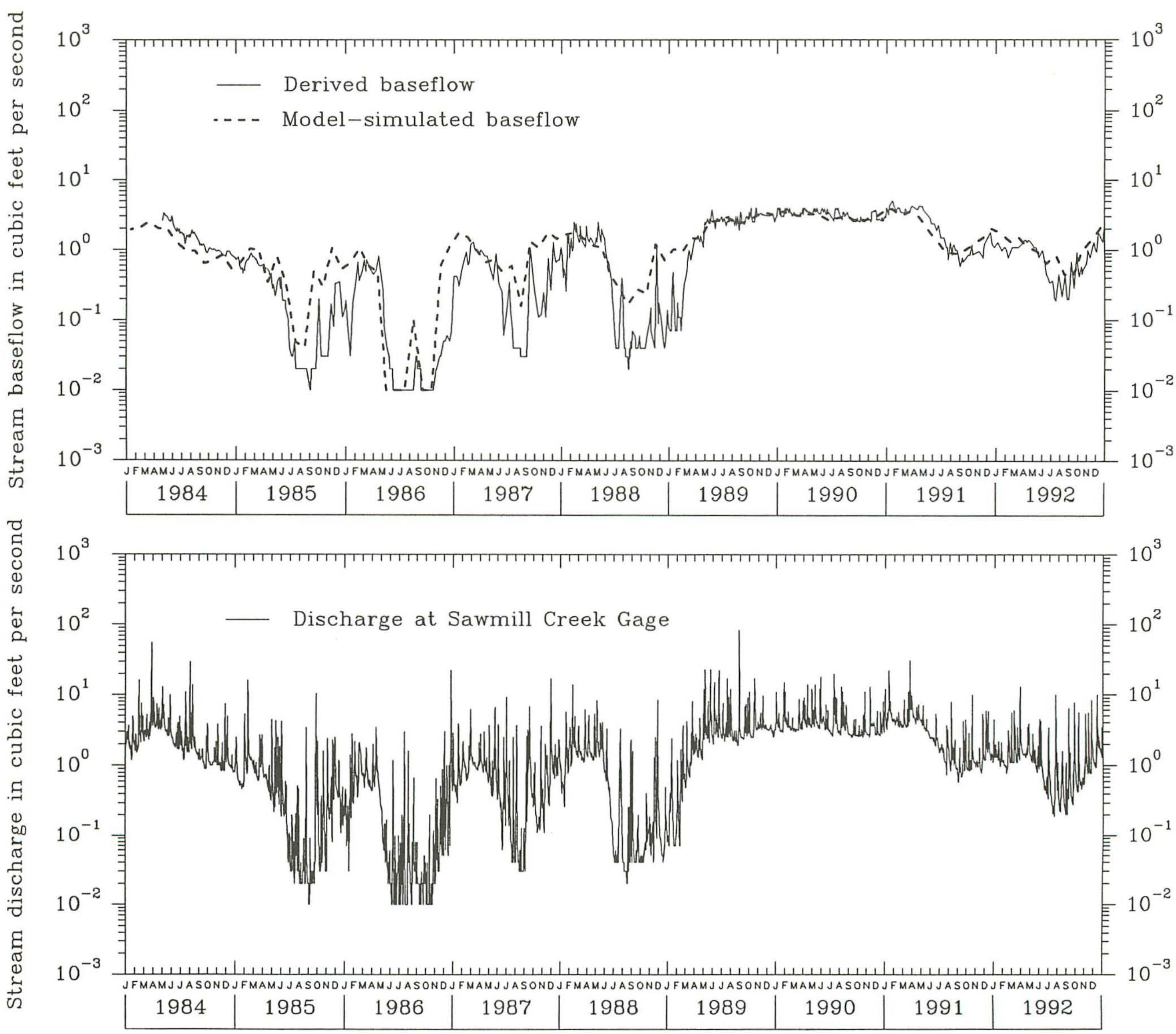


Figure 30. — Simulated and derived baseflow and stream discharge, 1984-92.

water ET rate (specific to each model cell of the water table) that could range between 0 and 18 in/yr, and annual average pumpage for the public-supply wells simulated. The annual average water levels and stream base flows of 1965-1984 obtained from the updated model were very similar to the values obtained using the model described in Achmad (1991).

Part 2 of the transient simulation (1984-92) used monthly values for recharge, evapotranspiration and pumpage. The recalibration of the flow model for 1984-92 is considered satisfactory because the simulated baseflow at the Sawmill Creek gage matches derived baseflow reasonably well (fig. 30), and the simulated 1992 potentiometric surfaces of the Lower and Upper Patapsco aquifers compare acceptably with the water levels measured in 1992 (figs. 31 and 32).

The average difference between the derived and simulated baseflow hydrographs is about 0.2 to 0.4 cubic feet per second (cfs) and the maximum difference is about 1.0 cfs. The derived baseflow hydrograph for 1984-92 (fig. 30) was calculated from the streamflow hydrograph of average daily values recorded at the Glen Burnie gaging station on Sawmill Creek. The derived baseflow was separated from the streamflow hydrograph by constructing a master-baseflow recession curve and overlaying it on a streamflow hydrograph (Riggs, 1963; Achmad, 1991).

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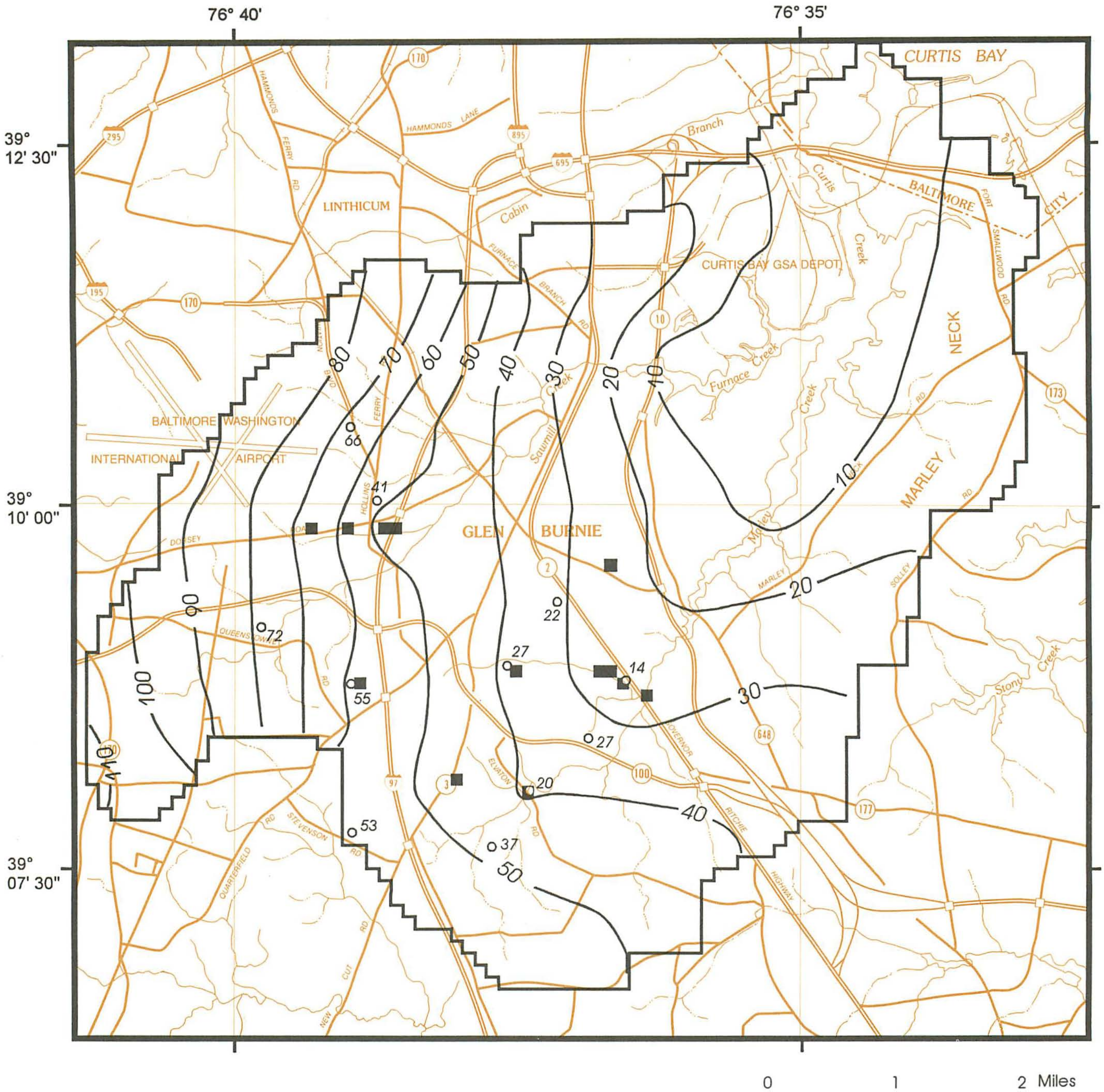
Table 10 and a comparison of figures 23, 24 and 30 show that baseflow is usually at its yearly lowest during the summer months of the years with below normal precipitation. The 1984

Table 10. — Precipitation, pumpage, ground-water recharge, and base-flow for the period 1984-92

[in./yr = inches per year; Mgal/d = million gallons per day; cfs = cubic feet per second]

Year	Precipitation at Baltimore-Washington International Airport (in in./yr)	Ground-water recharge used in the model (in in./yr)	Yearly pumpage from the Lower Patapsco aquifer (in Mgal/d)	Combined yearly pumpage from the Sawmill and Dorsey well fields (in Mgal/d)	Base-flow at Sawmill Creek gaging station, Glen Burnie, Maryland (in cfs)		
					High	Low	Average
1984	36.98	16.68	10.61	5.37	2.54	0.54	1.38
1985	36.77	16.58	9.59	5.01	1.05	0.04	0.55
1986	33.67	15.19	9.04	4.14	1.10	0.01	0.38
1987	41.08	18.53	9.14	3.44	1.81	0.67	1.04
1988	32.30	14.57	8.16	3.02	1.76	0.17	0.87
1989	51.88	23.40	6.43	1.83	3.49	0.97	2.48
1990	41.88	18.89	5.77	0.74	3.59	2.59	3.06
1991	30.16	13.60	5.74	1.24	3.94	0.89	2.03
1992	39.07	17.62	5.48	1.58	1.73	0.45	1.06



EXPLANATION

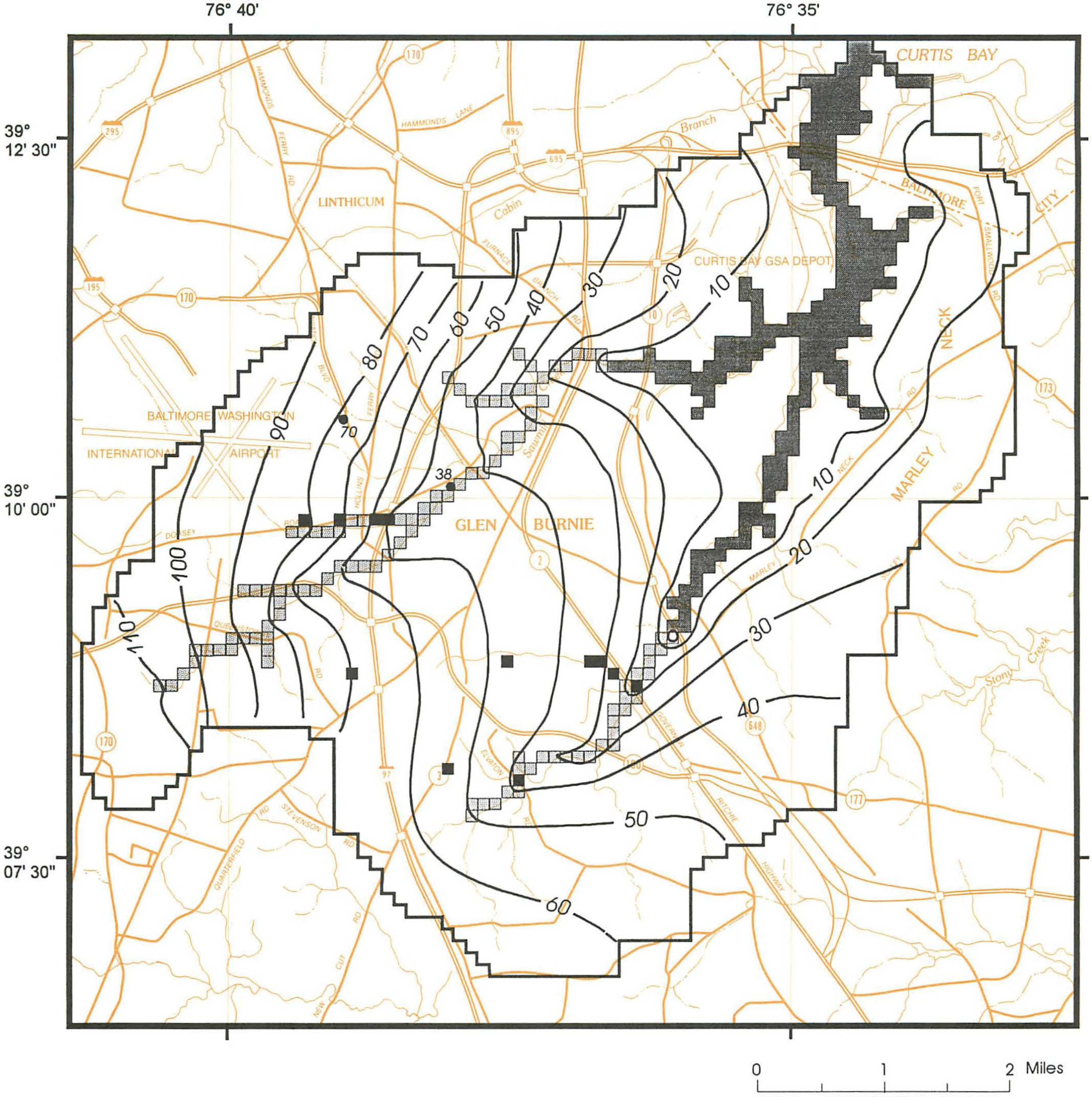
—50— Simulated line of equal water level, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

o 37 Well in the Lower Patapsco aquifer and measured 1992 water level, in feet above sea level.

■ Pumping cell in model layer two (the Lower Patapsco aquifer) active in 1992.

Boundary of the ground-water-flow model.

Figure 31. — Simulated 1992 potentiometric surface of the Lower Patapsco aquifer and 1992 water-level altitudes of the calibration wells.



EXPLANATION

50 Simulated line of equal water level, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

38 Well in the Upper Patapsco aquifer and measured 1992 water level, in feet above sea level.

Pumping cell in model layer two (the Lower Patapsco aquifer) active throughout 1992.

Constant-head cells in model layer one (the Upper Patapsco aquifer). Water-level altitude is zero (sea level) in constant-head cells.

Stream cells in model layer one (the Upper Patapsco aquifer).

Boundary of the ground-water-flow model.

Figure 32. — Simulated 1992 potentiometric surface of the Upper Patapsco aquifer and 1992 water-level altitudes of the calibration wells.

Table 11. — Comparison of measured stream flows with simulated base flow in the Sawmill Creek drainage basin

[Stream flow in cubic feet per second (cfs); open numbers are measured stream flows; numbers in parenthese are base flows derived from a continuous hydrograph; numbers in brackets are simulated base flows; see figure 33 for map locations]

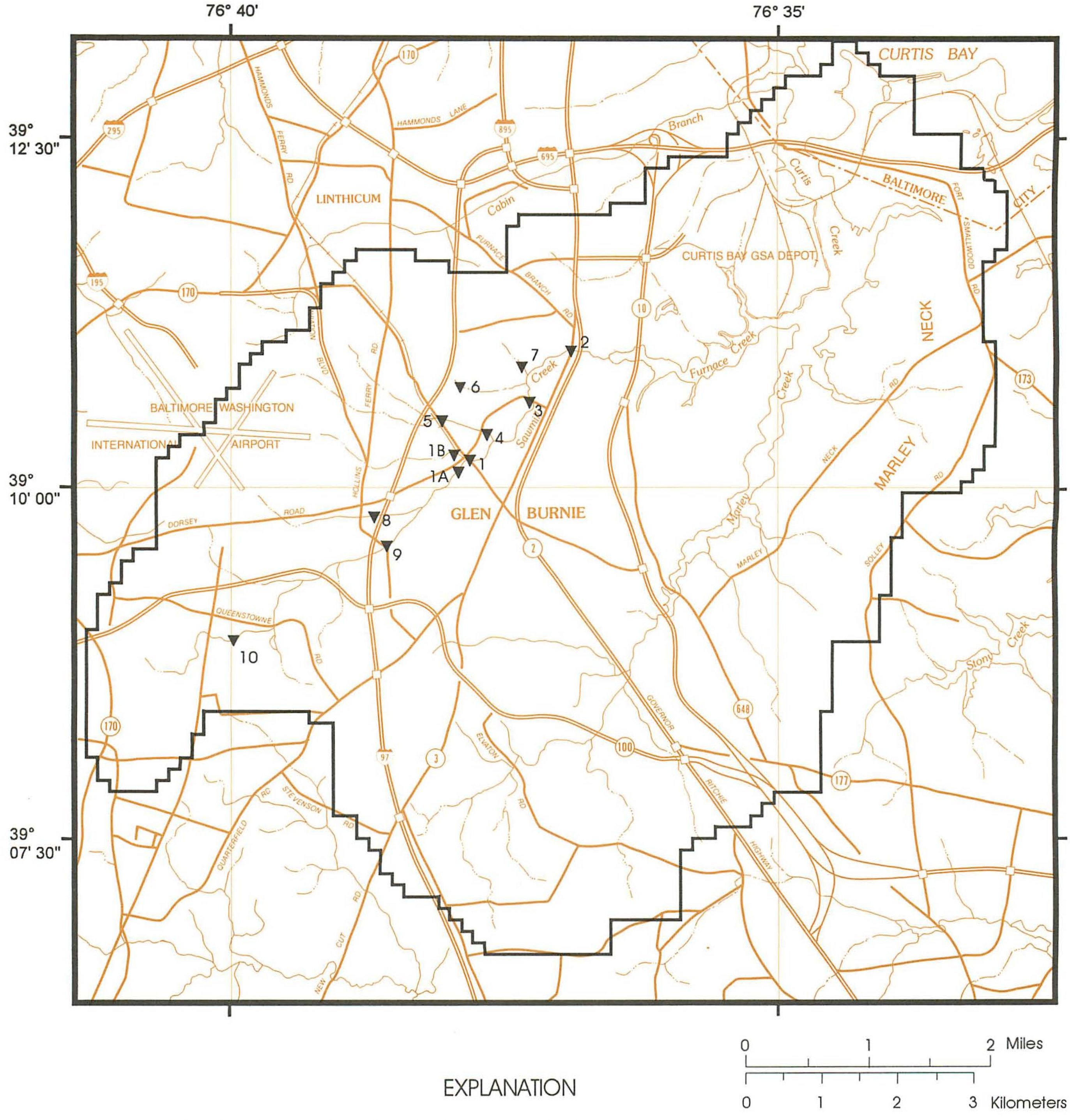
Date	Sites of stream flow measurements (in cfs)											
	#10 Queens- town	#9 Meadow- brook	#8 Stewart Avenue Tributary	#1 Route 648 and Dorsey Rd.	#1A Central Avenue Tributary	#1B Dorsey Rd. Tributary	#5 Eastern Avenue Tributary	#4 Long- wood Avenue Tributary	#6 Olen Drive Tributary	#3 Eighth Avenue	#7 Crest- haven Drive Tributary	#2 Crain High- way
Sep 22 1983				[2.00] 2.09								
Sep 29 1983	[0.35] 0.42	[1.627] 0.81	0.0	[2.00] 0.34	[1.92] 0.31	[0.056] 0.05	[0.22] 0.04	[0.26] 0.0	[0.27] 0.56	[2.54] 0.0	[0.10] 0.25	[4.66] 2.36
Nov 17 1983				1.18								
Dec 14 1983				7.71						13.8	0.42	19.5
Dec 15 1983				3.51						4.88		8.07
Dec 22 1983				15.6						56.1		71.1
Feb 9 1984				[2.095] 1.72							[0.10] 0.28	[5.03] 3.80
Mar 22 1984				[2.5397] 3.47								[6.10] 7.80
May 22 1984	[0.4396] 1.04	[1.803] 2.57	[0.27] 0.03	[1.99] 2.62 (2.60)	[1.965] 2.56	[0.0016] 0.094	[0.268] 0.56	[0.32] 0.44	[0.298] 1.01	[2.65] 3.47	[0.11] 0.38	[4.96] 5.51
June 28 1984												[3.62] 4.21
Aug 8 1984				[0.96] 1.96 (1.92)								[3.265] 4.94
Sep 11 1984	0.74	1.53	0.0	[0.64] 1.3 (1.02)		0.08	0.36	0.28	0.73	1.51	0.24	3.9
Sep 24 1984	[0.206] 0.65	[1.23] 1.24	[0.0] 0.0	[0.64] 0.94 (0.90)	[0.907]	[0.0] 0.3	[0.084] 0.22	[0.093] 0.13	[0.2319] 0.77	[0.925] 0.79	[0.0576] 0.26	[2.668] 2.92
Nov 16 1984												2.77
Nov 27 1984	[0.248] 0.57	[1.312] 1.12	[0.0] 0.0	[0.84] 0.85 (0.97)	[1.05]	[0.0] 0.03	[0.124] 0.09	[0.1477] 0.063	[0.245] 0.65	[1.244] 0.58	[0.065] 0.24	[3.11] 3.0
Feb 15 1985				[1.03] 2.14 (0.82)								[3.45] 4.85

Table 11. — Comparison of measured stream flows with simulated base flow in the Sawmill Creek drainage basin — Continued

Date	Sites of stream flow measurements (in cfs)											
	#10 Queens- town	#9 Meadow- brook	#8 Stewart Avenue Tributary	#1 Route 648 and Dorsey Rd.	#1A Central Avenue Tributary	#1B Dorsey Rd. Tributary	#5 Eastern Avenue Tributary	#4 Long- wood Avenue Tributary	#6 Olen Drive Tributary	#3 Eighth Avenue	#7 Crest- haven Drive Tributary	#2 Crain High- way
Mar 20 1985	[0.174] 0.54	[1.23] 0.97	[0.0] 0.0	[1.00] 0.65 (0.58)	[1.11]	[0.0] 0.02	[0.1376] 0.05	[0.1716] 0.02	[0.2385] 0.61	[1.423] 0.40	[0.046] 0.23	[3.279] 2.05
Mar 22 1985												[5.279] 2.41
June 6 1985				[0.032] 2.04 (0.19)								[2.01] 5.81
July 18 1985				[0.05] 0.02 (0.02)								[2.79] 1.75
Aug 14 1985	[0.045] 0.17	[0.87] 0.224	[0.0] 0.0	[0.04] 0.037 (0.02)	[0.384]	[0.0] 0.02	[0.029] 0.0	[0.029] 0.0	[0.17] 0.42	[0.114] 0.0	[0.0062] 0.195	[1.44] 1.71
Sep 9 1985				0.02								1.47
Sep 18 1985	[0.158] 0.14	[1.13] 0.11		[0.48] 0.01 (0.02)	[0.783]	[0.0] 0.012	[0.0637] 0.0	[0.064] 0.0	[0.21] 0.43	[0.686] 0.0	[0.054] 0.13	[2.31] 1.47
Mar 23 1991	[0.167] 0.81	[1.893] 3.06	[0.049] 0.12	[3.599] 4.25 (3.90)	[3.026]	[0.499]	[0.463]	[0.622] 1.24	[0.32]	[4.757] 5.03	[0.107]	[7.499] 8.91
June 11 1991	[0.0036] 0.34	[1.06] 1.47	[0.0] 0.0	[1.313] 1.94 (1.90)	[1.298]	[0.0]	[0.059]	[0.073] 0.71	[0.188]	[1.567] 2.15	[0.0]	[2.94] 4.68
Sep 4 1991	[0.0025] 0.18	[0.968] 0.50	[0.0]	[1.00] (0.78)	[1.053]	[0.0]	[0.0415]	[0.0445] 0.35	[0.169]	[1.186]	[0.017]	[2.477]
Dec 4 1991	[0.3996] 0.52	[1.2557] 1.81	[0.0]	[2.107] (1.80)	[1.777]	[0.19]	[0.193]	[0.263] 1.09	[0.235]	[2.625] 5.44	[0.0359]	[4.55]

baseflow showed a limited decline during the summer of 1984 because precipitation was high in 1983 (51 in/yr), about 10 inches above normal (National Oceanic and Atmospheric Administration, 1991). In general, however, the amount of pumpage and evapotranspiration is highest in the summer months and net ground-water recharge to the aquifer is at its lowest. During autumn, baseflow increases as pumpage and the ET rate decline. Stream-flow measurements recorded at the other gaging stations in the basin area, along Sawmill Creek at Crain Highway and along Marley Creek at Stewart Avenue were used qualitatively in the model evaluation because at these two sites the bases of the stream gages are not stabilized and the creeks are tidal. Stream flows were also measured (using hand-held flow meters) at 12 locations along Sawmill Creek in 1983, 1984 and 1991 (fig. 33). The primary purpose of these measurements was to determine losing and gaining stream reaches. Measurements from these sites are compiled on table 11.

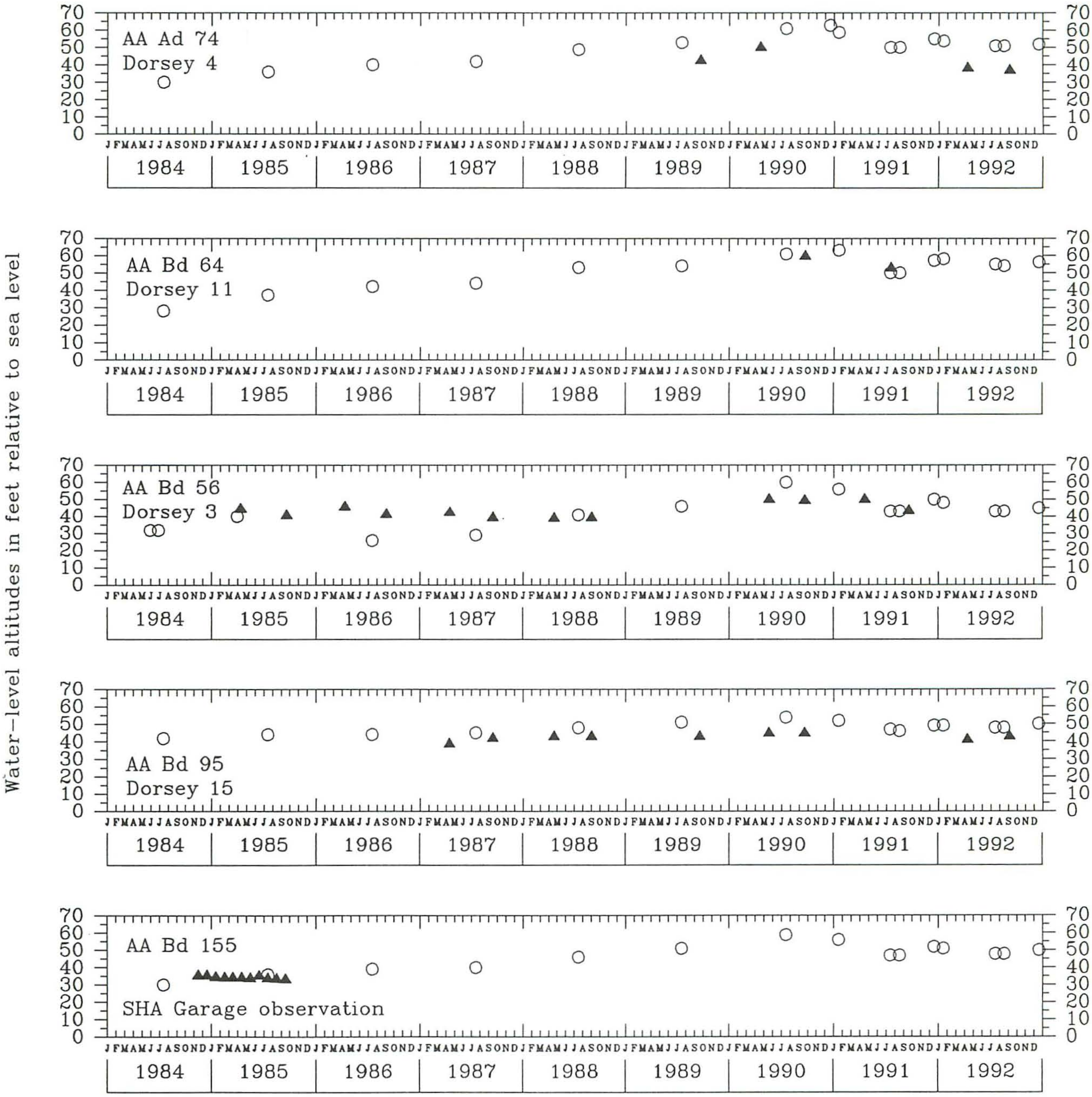
The simulated water levels for 1984-92 were evaluated by matching them with water levels measured in 14 Lower Patapsco and 2 Upper Patapsco wells (tab. 12). On average, the simulated water levels of the 16 wells matched the measured water levels within 5 ft (figs. 34, 35). The 90th-percentile difference was 11 ft or less, and the 99th-percentile difference was 18 ft or less.



EXPLANATION

▼3 Location and number of stream discharge measurement site. Site description and data in table 11.

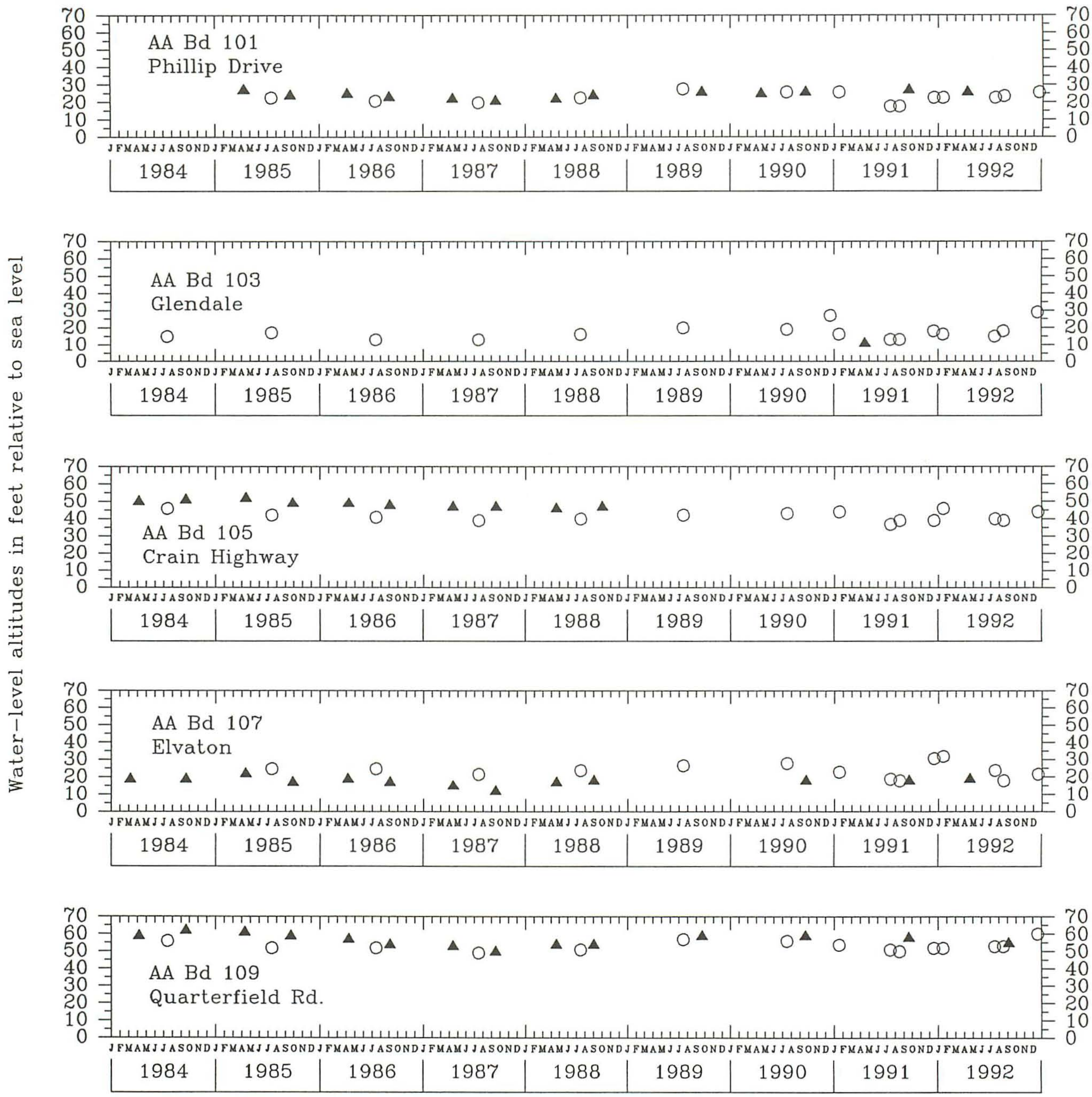
Figure 33. — Location of stream discharge measurement sites along Sawmill Creek.



Explanation

○	Simulated water–level altitude.
▲	Measured water–level altitude.
	Datum for all measurements is sea level.
AA Bd 64	MGS well number.
Dorsey 11	AADPW or local name of well.

Figure 34. — Comparison of measured and simulated water levels for the Lower Patapsco aquifer, 1984-92.

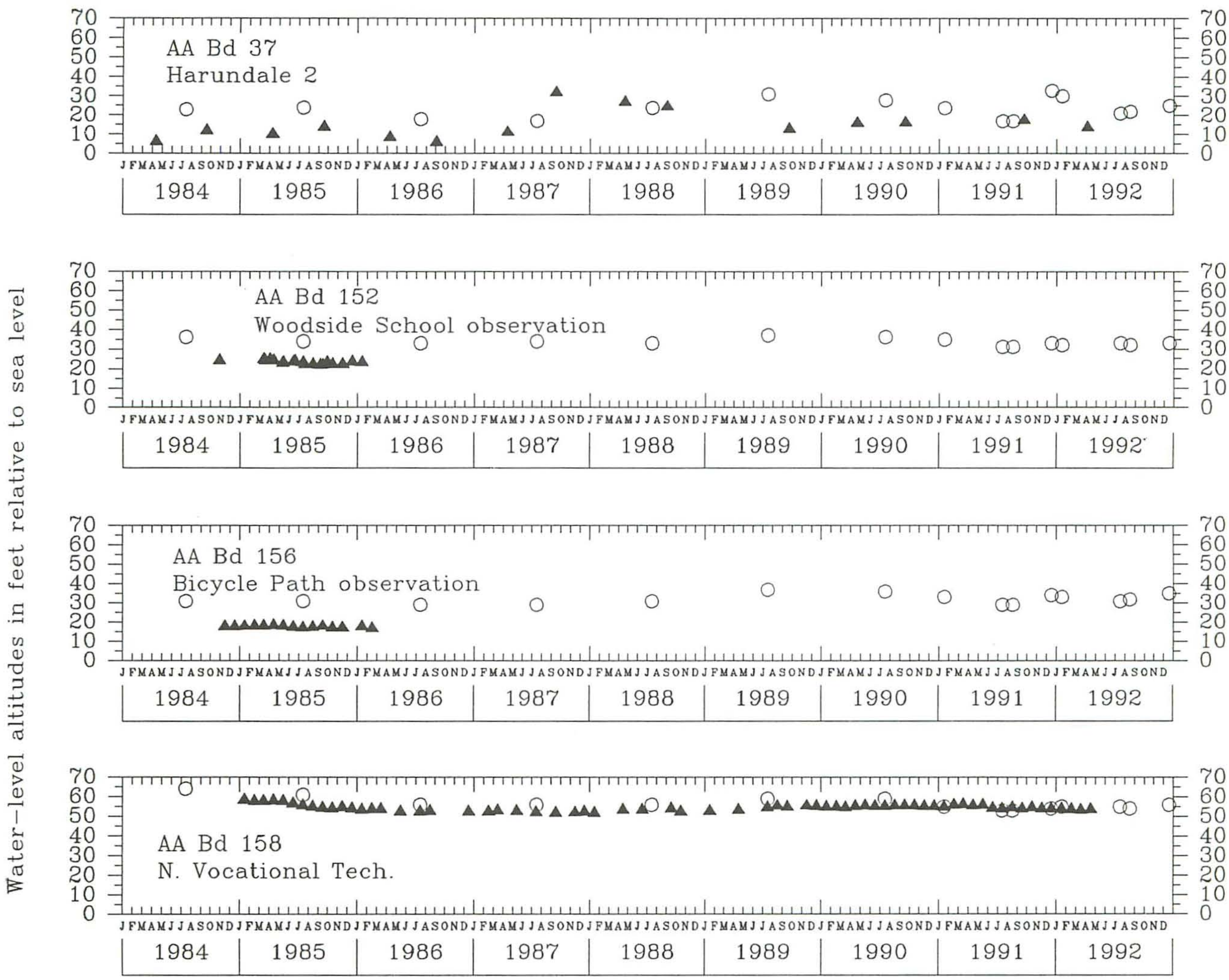


Explanation

○ Simulated water-level altitude.
▲ Measured water-level altitude.
Datum for all measurements is sea level.

AA Bd 101 MGS well number.
Glendale AADPW or local name of well.

Figure 34. — Continued.



Explanation

- ○ Simulated water–level altitude.
- ▲ Measured water–level altitude.
  Datum for all measurements is sea level.

AA Bd 37 — MGS well number.
Harundale 2 — AADPW or local name of well.

Figure 34. — Continued.

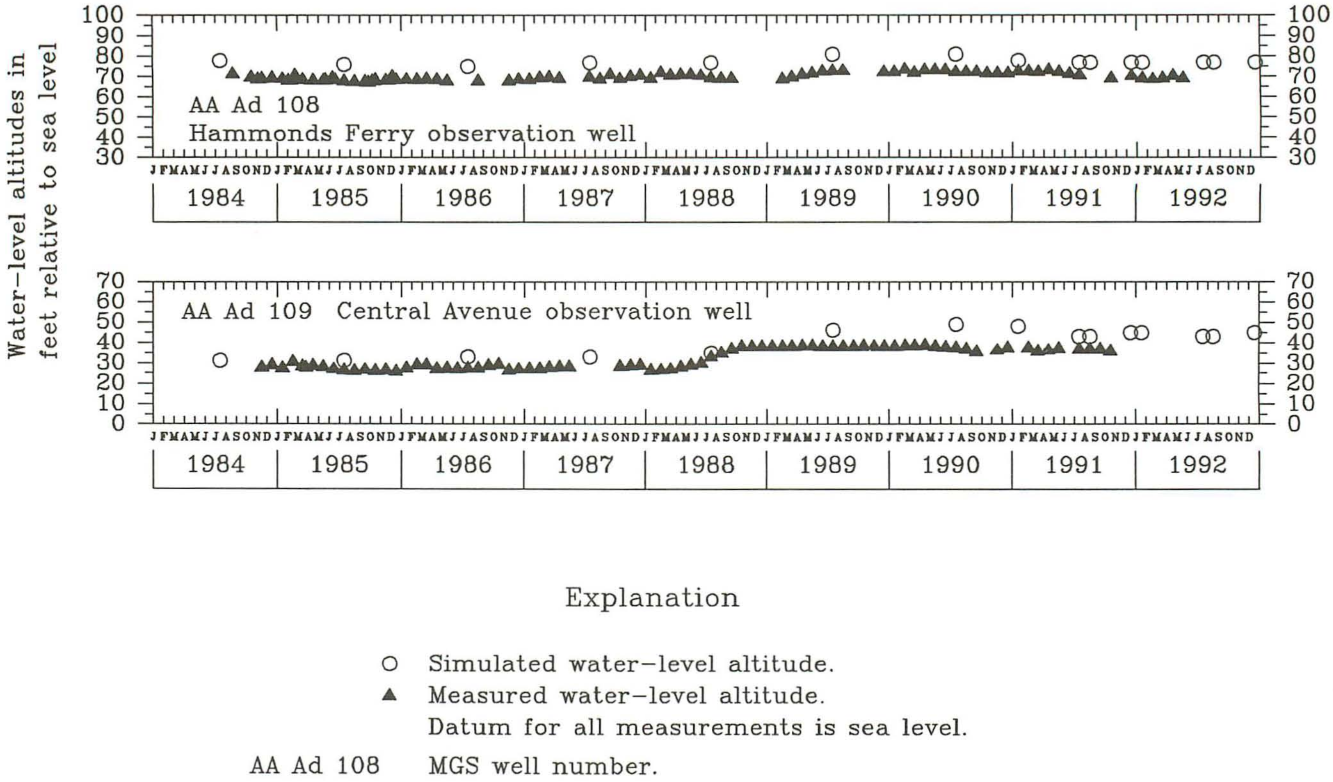


Figure 35. — Comparison of measured and simulated water levels for the Upper Patapsco aquifer, 1984-92.

Table 12. — Wells used to calibrate the ground-water-flow model

Maryland Geological Survey well number	Anne Arundel County Department of Public Works or local well name	Aquifer	Well type
AA Ad 108	Hammonds Ferry Rd. Observation 3	Upper Patapsco	Observation
AA Ad, 109	Central Avenue Observation	Upper Patapsco	Observation
AA Ad 74	Dorsey 4	Lower Patapsco	Unused production
AA Bd 56	Dorsey 3	Lower Patapsco	Production
AA Bd 64	Dorsey 11	Lower Patapsco	Production
AA Bd 95	Dorsey 13	Lower Patapsco	Production
AA Bd 37	Harundale 2	Lower Patapsco	Production
AA Bd 101	Phillip Drive	Lower Patapsco	Production
AA Bd 103	Glendale	Lower Patapsco	Production
AA Bd 105	Crain Highway	Lower Patapsco	Production
AA Bd 107	Elvaton	Lower Patapsco	Production
AA Bd 109	Quarterfield Rd.	Lower Patapsco	Production
AA Bd 152	Woodside School	Lower Patapsco	Observation
AA Bd 155	SHA Garage	Lower Patapsco	Observation
AA Bd 156	Bicycle Path	Lower Patapsco	Observation
AA Bd 158	N. Vocational Tech.	Lower Patapsco	Observation

DELINEATION OF WELLHEAD PROTECTION AREAS

INTRODUCTION

A wellhead protection area (WHPA) is the surface and subsurface area surrounding a water well or well field, supplying a public water system, through which contaminants are reasonably likely to move and reach the well (U.S. Environmental Protection Agency, 1987). WHPAs for wells screened in confined aquifers have one or more of the following purposes: 1) to provide a remedial action zone (a buffer zone) that will provide an adequate amount of time to identify and cleanup contaminants before they reach a well; 2) to provide a protection area that is large enough to allow for the attenuation of potential contaminants to acceptable levels before they reach the production well; and 3) to provide a management zone that will protect all or part of a well's zone of contribution from contamination (Kreitler and Senger, 1991). A zone of contribution is the area surrounding a pumping well that encompasses all areas or features providing ground water recharge to the well (U.S. Environmental Protection Agency, 1987); in this report the term "zone of contribution" is restricted to recharge areas in the water-table (Upper Patapsco) aquifer.

The degree of leakiness of a confining unit should be assessed when delineating WHPAs for wells in confined aquifers. For wellhead protection purposes, a confined aquifer is defined as a section of an aquifer overlain by low-permeability strata that lower the probability of ground-water contamination from surface sources; this definition is based on the hydrogeologic setting that causes confinement and not the hydrologic phenomena ensuing from the confinement (Kreitler and Senger, 1991). Depending on the leakiness of the confining unit, a confined aquifer may be classified as "semiconfined" or "highly" confined. Semiconfined aquifers are more sensitive to contamination from surface sources than highly confined aquifers because the semiconfined aquifers can receive significant quantities of water through the confining unit. Three criteria which indicate semiconfined conditions as opposed to highly confined conditions are: 1) the presence of tritium in concentrations that indicate that much of the ground water is less than 40 years old; 2) the presence of anthropogenic substances in the ground water; and 3) the demonstration by hydrogeologic mapping of breaches or other permeable pathways through the confining unit (Kreitler and Senger, 1991). By these criteria, the Lower Patapsco aquifer is a semiconfined aquifer.

The U.S. Environmental Protection Agency suggested method for delineating a WHPA surrounding a well in a leaky confined aquifer is the determination of the well's zone of transport using time-of-travel analysis (Kreitler and Senger, 1991). A time-specific zone of transport is a subsurface volume bounded by a surface of equal time (an isochronous surface) that represents the locus of points from which the amount of time required for a water particle to travel to a well is equal. A time-specific zone of contribution (or recharge area) is delineated by the intersection of the zone of transport with the top of the water-table aquifer.

A time-related WHPA, implemented by regulation or zoning, is usually depicted on maps as an area surrounding a production well. Generally this area represents the projection of a three-dimensional zone of transport onto the land surface. Depending on the length of time considered and the hydrogeologic conditions (especially the permeability of the confining unit), all, part or none of the zone of transport actually intersects the top of the water-table aquifer. WHPAs based on isochronous zones of transport may differ in size and shape from WHPAs based on isochronous zones of contribution. The methods of WHPA delineation compared in this report are two particle tracking techniques: the GPTRAC semianalytical option of the WHPA code and the MODFLOW-MODPATH model. The methods differ in their conceptualization of the ground-water-flow system and in their capacity to accurately display zones of transport or contribution.

HYDROGEOLOGIC MAPPING

A qualitative wellhead protection strategy could be developed solely on the basis of hydrogeologic mapping. However, with respect to wellhead protection, hydrogeologic mapping is best employed in the conceptualization of the physical framework of the ground-water-flow system, translation of that conceptualization to the design of quantitative models, and understanding and interpreting the results of the quantitative models in the context of a particular hydrogeologic setting. In addition to these uses, hydrogeologic mapping is, in this study, used to make a qualitative assessment of the vulnerability of the Lower Patapsco aquifer to contamination.

Several features of the hydrogeologic framework are key to the susceptibility of the Lower Patapsco aquifer to contamination. Of most importance is the thickness, texture and lateral continuity of the confining unit that overlies the Lower Patapsco aquifer. The confining unit that overlies the Lower Patapsco aquifer is leaky because it is laterally discontinuous (0 to 60 feet thick) and texturally variable (clayey silt to fine sandy clay), and therefore, contains zones of relatively high permeability. The combined sand percentage map of the Upper Patapsco aquifer and underlying confining unit shows that the part of the geologic section overlying the Lower Patapsco aquifer is more sandy in the west-central and north-central parts of the study area, and that it becomes more clayey to the east and west (fig. 13). Relatively abrupt changes in lithology and thickness are characteristic of this confining unit (pls. 1-4). Correlation lines that connect the confining unit from well to well are correlating predominantly clayey zones that occur at approximately the same stratigraphic level within the geologic section. The correlation lines do not preclude the presence of breaches in the confining unit between the well sites shown.

Confining units within the Lower Patapsco aquifer provide additional protection to the lower parts of the aquifer. These internal confining units are, however, more discontinuous than the confining unit overlying the Lower Patapsco aquifer. Similarly, confining units within the Upper Patapsco aquifer also provide additional protection to the Lower Patapsco aquifer. These clay-silt zones are also more laterally discontinuous than the confining unit between the Lower and Upper Patapsco aquifers (pls. 1-4).

The hydrogeologic sections show that the Upper Patapsco aquifer thickens southeastward and becomes more clayey. In the Marley Creek drainage basin clayey beds occur at land surface (fig. 4) and provide further protection to the Lower Patapsco aquifer by retarding the movement of contaminants into the water-table (Upper Patapsco) aquifer. There are few well data documenting the thickness of these beds, but most are probably less than 30 ft thick.

The depositional environment of the Patapsco Formation is the primary factor controlling the distribution, texture and thickness of the clay-silt zones that form the hydrologic confining units within and between the Lower and Upper Patapsco aquifers. The Patapsco Formation in northern Anne Arundel County is a braided stream deposit (Glaser, 1969; Hansen, 1968, 1969). The sedimentological process that dominates a braided river system is the recurrent cutting, filling with sediment and cutting again of the river's channels (Matthews, 1974, p. 142). In a typical braided stream environment, the coarsest grained materials, sands and gravels, are deposited as poorly-sorted longitudinal (sand) bars during flood stages. Moderate to well-sorted, sand-size material is transported and deposited as in-channel transverse (sand) bars during normal and low water stages. Fine grained material, clays and silts, are deposited in abandoned channels and draped over abandoned bars by relatively slow-moving flood waters that have reached the topographically highest points within the river's floodplain. Figure 36 shows the physiography of a modern braided river system and illustrates the lack of both lateral and vertical continuity in a succession of braided river deposits. The Patapsco Formation in the study area is the product of a Cretaceous-age braided river system. Lenticular bar and coarse channel-fill deposits form the sands and gravels of the Lower and Upper Patapsco aquifers and the muds that draped abandoned bars and filled abandoned channels form the clay-silt confining units. Lateral discontinuity and relatively abrupt thickness and textural changes are characteristic of these deposits. The leaky character of the confining units between and within the Lower and Upper Patapsco aquifers also reflects the heterogeneity of braided stream deposits.

In contrast, the confining unit underlying the Lower Patapsco aquifer, the Arundel Clay, is a thick, massive, laterally continuous, and relatively impermeable clay and clay-silt unit. The clays and clay-silts of the Arundel Clay were deposited in a shallow, freshwater, backswamp basin characterized by slow sediment influx (Glaser, 1969). Because of the low-energy characteristic of this depositional setting, mostly fine grained materials were transported and deposited. Burial and compaction of the Arundel Clay has further decreased the unit's permeability. Although 10 to 20 ft thick zones of clayey sand occur within the Arundel Clay, complete breaches of this 125 to 250 ft thick confining unit are unknown in the project area. The amount of leakage through the Arundel Clay is volumetrically inconsequential.

Local topographic relief caused by erosion has truncated the Upper Patapsco aquifer in the northern parts of the study area and affected the aquifer's overall vulnerability to contamination. The truncation of the Upper Patapsco aquifer is evident along the traverse from wells Ad 76 to Ad 90 shown on plate 2. The thinning of the Upper Patapsco aquifer in the northern parts of the study area decreases the protection afforded the Lower Patapsco aquifer by the Upper Patapsco aquifer.

In areas unaffected by pumpage local topographic relief controls the water-level differences between the Upper and Lower Patapsco aquifers. A map approximating the pre-pumping head differences between the Lower and Upper Patapsco aquifers (fig. 37) was constructed by subtracting the simulated 1965 potentiometric surface of the Lower Patapsco aquifer (fig. 10) from the simulated 1965 potentiometric surface of the Upper Patapsco aquifer (fig. 14). Recharge areas of the Lower Patapsco aquifer are areas where the water-level altitudes of the Upper Patapsco aquifer are higher than those of the Lower Patapsco aquifer (positive head differences; fig. 37) and part of the ground-water flow is downward. Topographic highs, particularly the basin divides, form much of the recharge area of the Lower Patapsco aquifer. The discharge areas of the Lower Patapsco aquifer are areas where water-level altitudes in the Lower Patapsco aquifer are higher than those of the Upper Patapsco aquifer (negative head differences; fig. 37) and ground-water flow is upward. Topographic lows, such as the stream valleys in the central and northeastern parts of the study area, form the ground-water discharge areas of the Lower Patapsco aquifer.

Pumpage from the Lower Patapsco aquifer increases the head differences between the Upper and Lower Patapsco aquifers in recharge areas. Figure 38 shows the simulated head differences between the two aquifers under pumping conditions based on the 1990 pumpage appropriation. This head-difference map was constructed by subtracting the potentiometric surface of the Lower Patapsco aquifer shown in figure 40 from the potentiometric surface map of the Upper Patapsco aquifer shown in figure 39. Comparison of figures 37 and 38 shows the changes in the head differential between the two aquifers due to pumpage. Pumpage increases the hydraulic gradient between the Upper and Lower Patapsco aquifers in recharge areas and causes an increase of flow through the confining bed. In parts of the discharge areas, there is a decrease in the head differences.

The degree of vulnerability of the Lower Patapsco aquifer to contamination from the Upper Patapsco aquifer increases where several of the hydrogeologic characteristics that increase the aquifer's vulnerability coincide. Figure 41 is a qualitative assessment of the degree of vulnerability of the Lower Patapsco aquifer to contamination from the overlying water-table (Upper Patapsco) aquifer. This map was constructed by overlaying

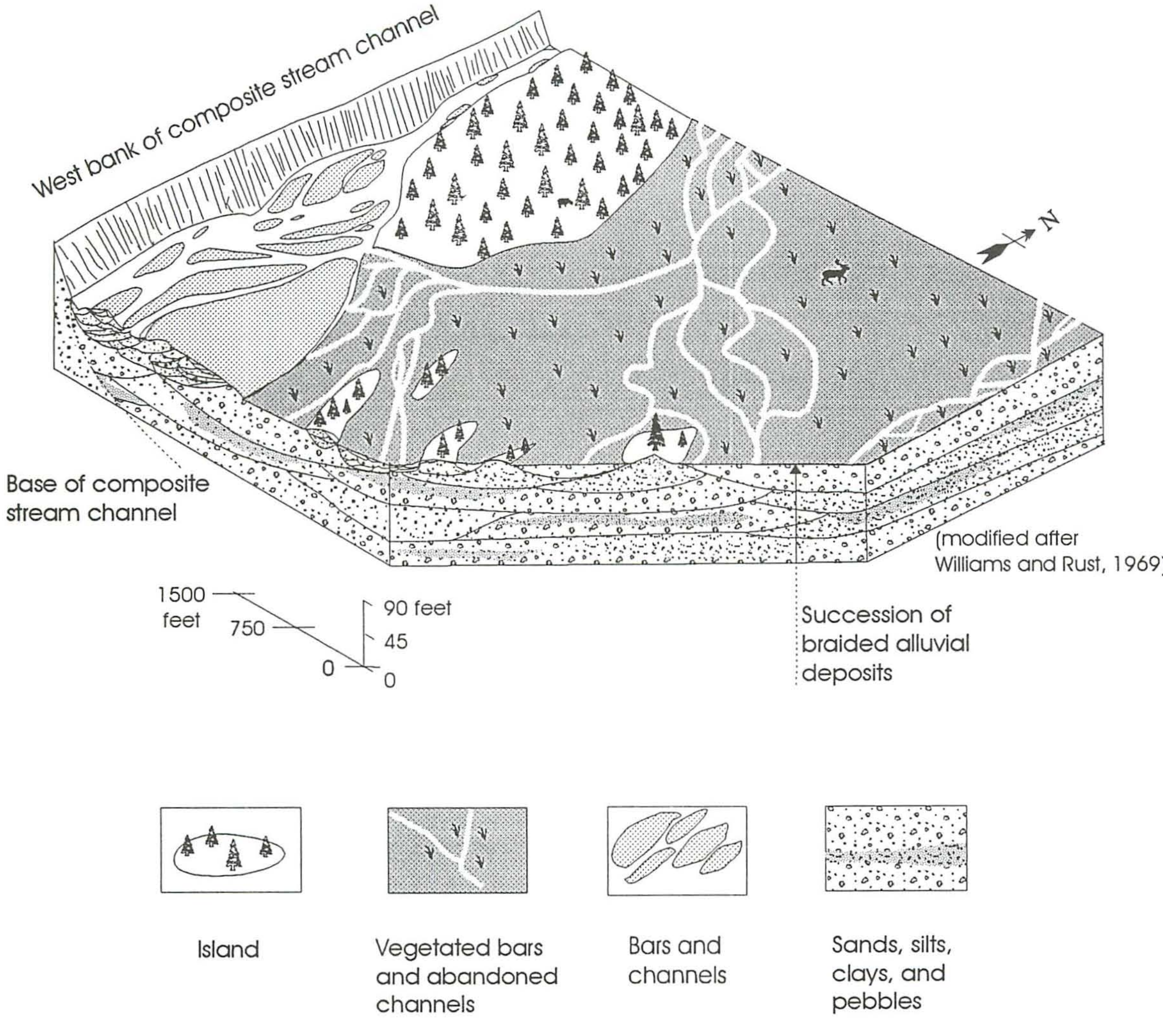
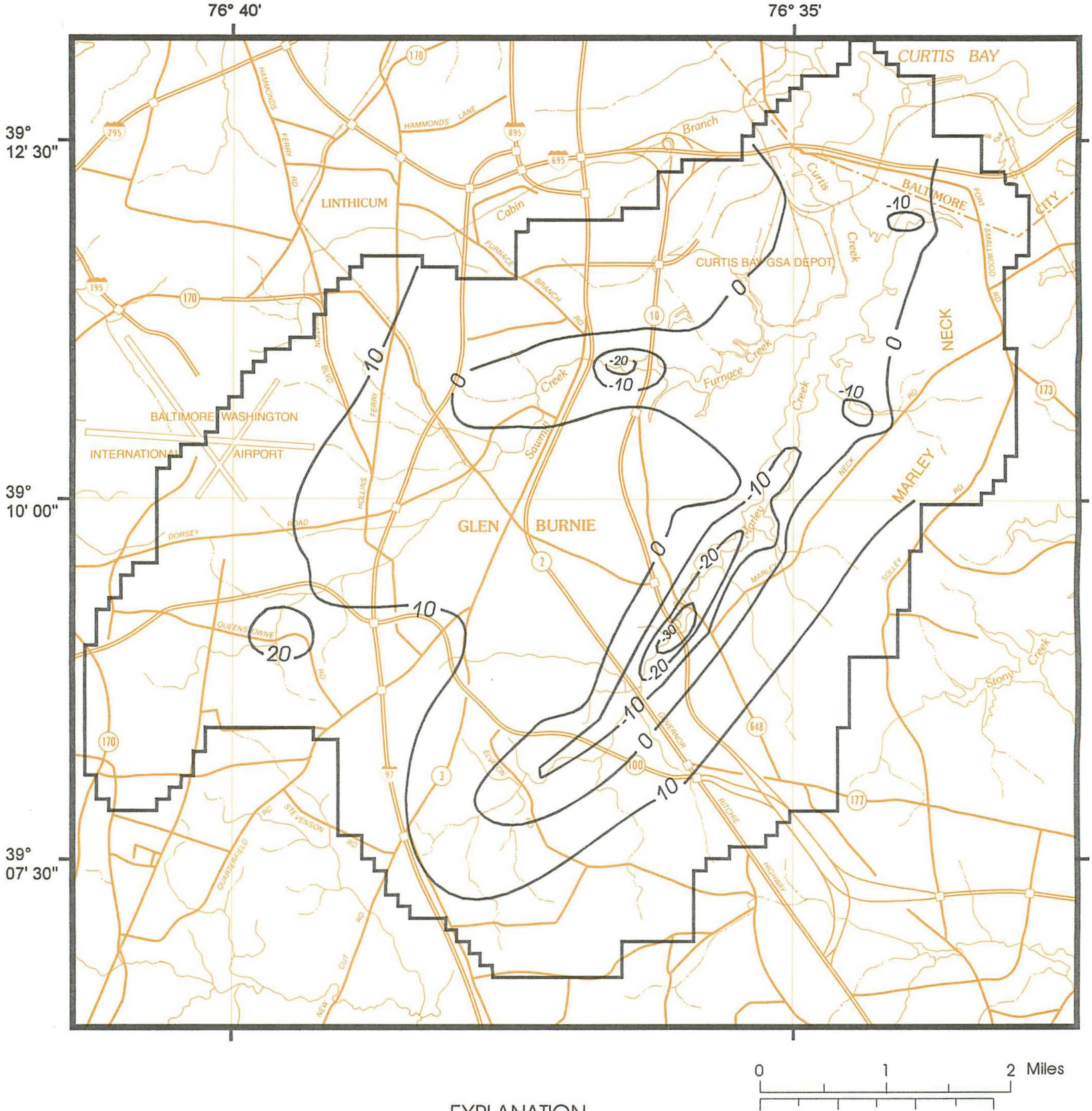


Figure 36. — Schematic representation of a modern braided river system.

areas of greater aquifer vulnerability as indicated by the hydrogeologic mapping and the head-difference map of the Upper and Lower Patapsco aquifers under pumping conditions (the 1990 pumpage appropriation) (fig. 38). The regions of greater relative aquifer vulnerability based on the hydrogeologic mapping are defined as: 1) regions where the confining unit between the Lower and Upper Patapsco aquifer is 25 ft thick or less (fig. 11), and 2) regions where the sand-gravel facies of the Patapsco Formation occurs at land surface (fig. 4). Each of these regions and the regions where the heads in the Upper Patapsco are greater than the heads in the Lower Patapsco aquifer were overlain. The resultant map (fig. 41) shows four qualitative degrees of aquifer vulnerability of the Lower Patapsco aquifer to contamination from pollutants introduced to the Upper Patapsco aquifer. The darker the shade of brown on figure 41, the greater the degree of aquifer vulnerability. The hydrogeologic features in the regions where ground-water flow is upward from the Lower to Upper Patapsco aquifer were assigned to the least vulnerable area; the hydrogeologic features in those areas are not used in constructing figure 41 because the direction of ground-water flow is the controlling factor in assessing the aquifer's vulnerability.

The Dorsey and Crain well fields are in regions where the Lower Patapsco aquifer has the highest degree of vulnerability to contamination. The Harundale well field lies in a region with the least to moderate degree of aquifer vulnerability. The aquifer vulnerability map shown here is specific to the well fields that currently exist and the 1990 pumpage appropriation. New well fields placed in the least vulnerable regions of the Lower Patapsco aquifer would change the head relations between the two aquifers and the vulnerability of the Lower Patapsco aquifer in those areas would increase.



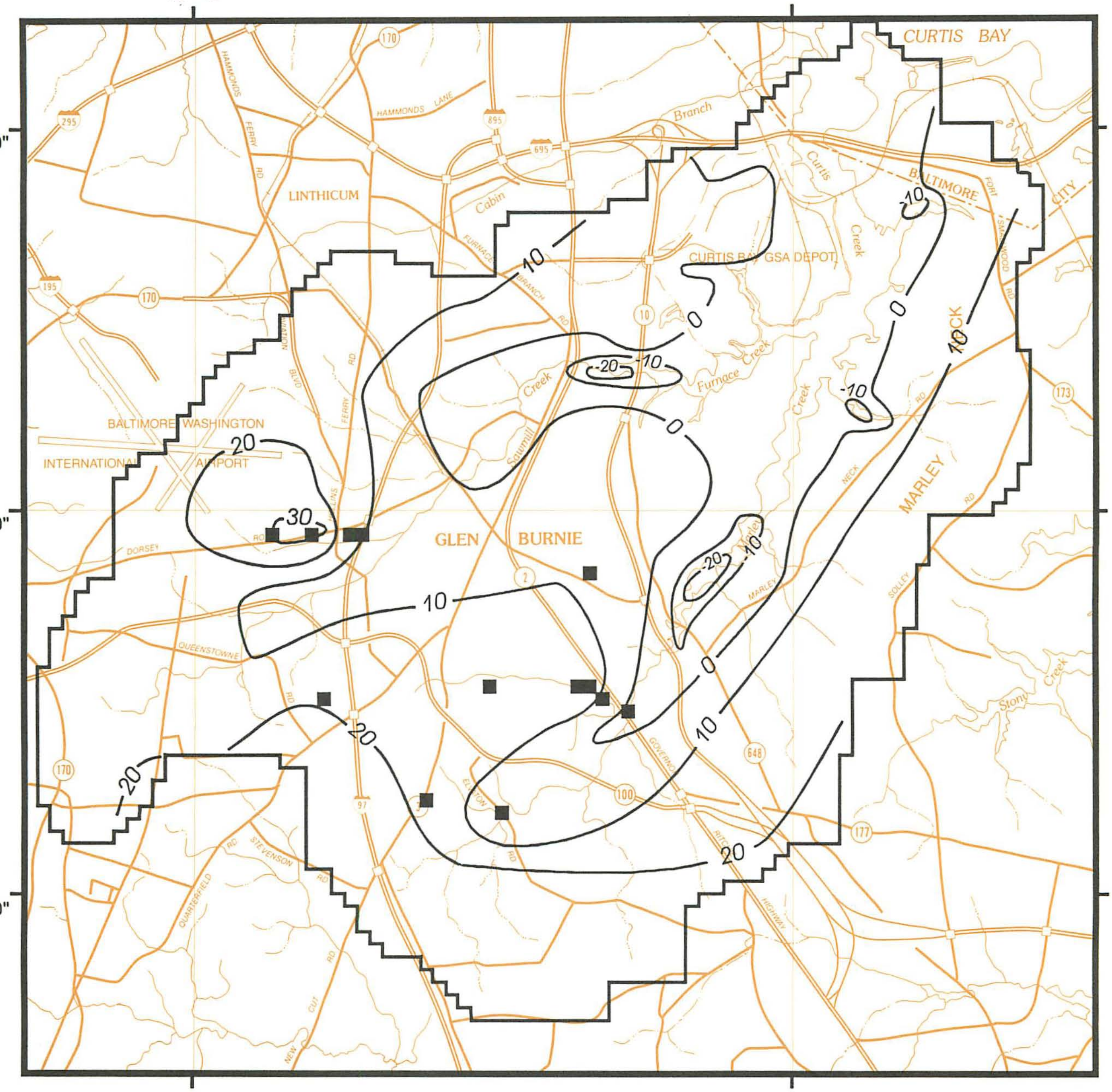
EXPLANATION

— 10 — Line of equal difference in heads (water levels) in feet. The 1965 potentiometric surface of the Upper Patapsco aquifer minus the 1965 potentiometric surface of the Lower Patapsco aquifer. Contour interval is 10 feet.

Positive head difference indicates downward flow from the Upper to Lower Patapsco aquifer.

Boundary of the ground-water-flow model.

Figure 37. — Head difference between the 1965 potentiometric surfaces of the Upper Patapsco aquifer and Lower Patapsco aquifer.



EXPLANATION

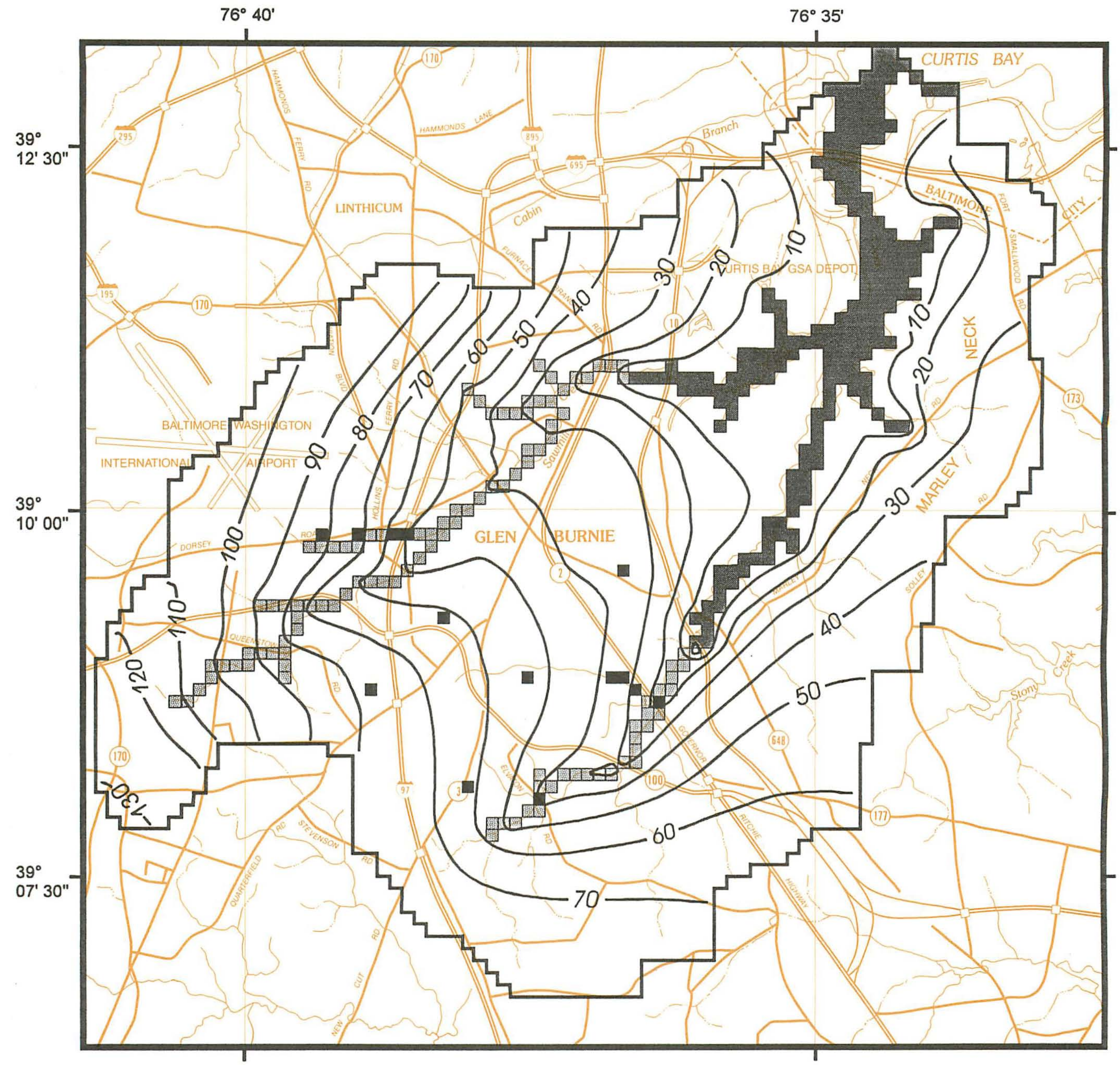
— 10 — Line of equal difference in heads (water levels) in feet. The potentiometric surface of the Upper Patapsco aquifer minus that of the Lower Patapsco aquifer for the surfaces generated with the 1990 pumpage appropriation. Contour interval is 10 feet.

Positive head difference indicates downward flow from the Upper to Lower Patapsco aquifer.

■ Pumping cell used in the 1990 pumpage appropriation scenario.

Boundary of the ground-water-flow model.

Figure 38. — Head difference between the potentiometric surfaces of the Upper Patapsco aquifer and Lower Patapsco aquifer generated with the 1990 pumpage appropriation.



0 1 2 Miles

0 1 2 3 Kilometers

EXPLANATION

— 50 — Simulated line of equal water level, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

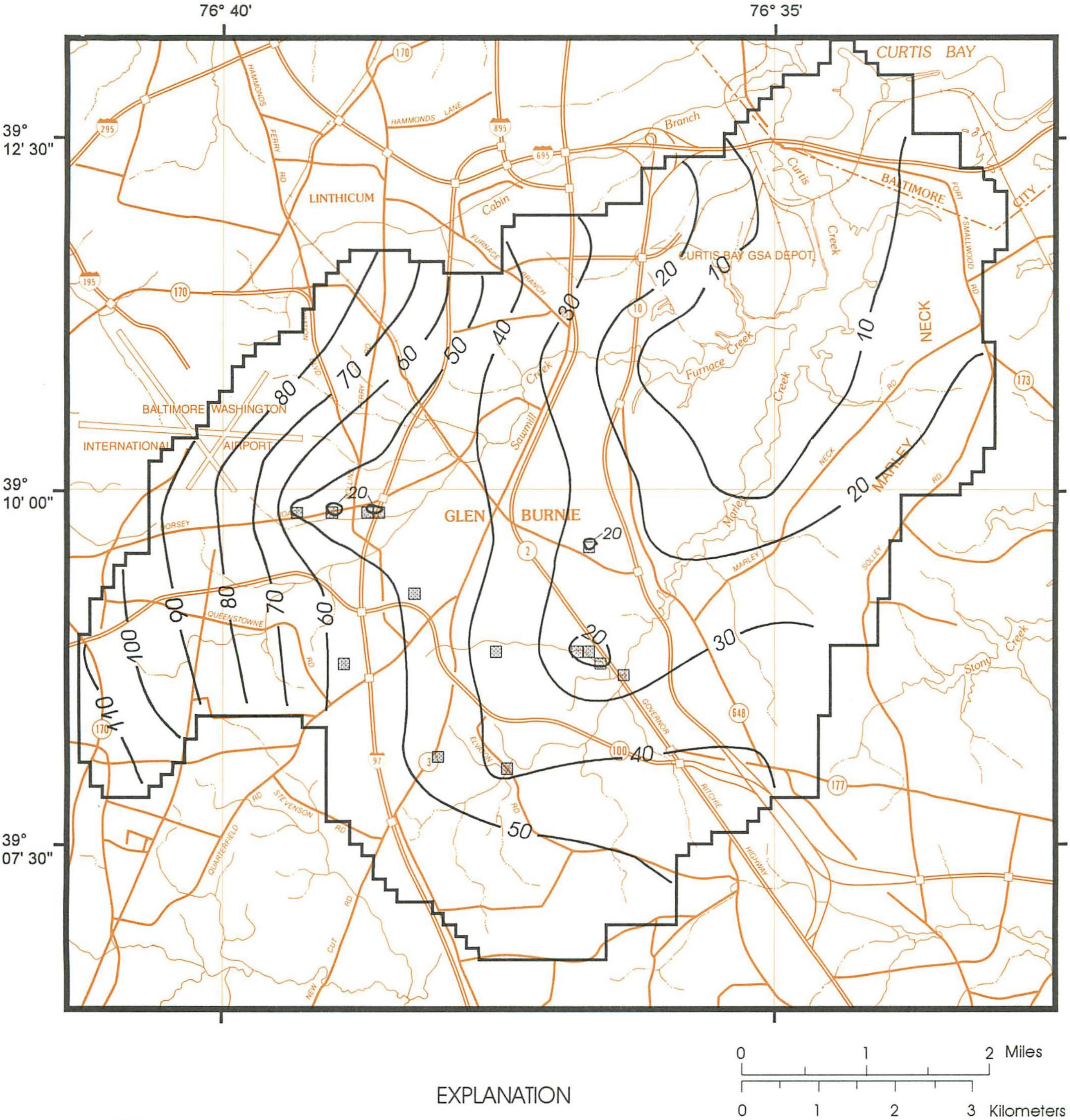
■ Pumping cell in model layer two (the Lower Patapsco aquifer) used in the 1990 pumpage appropriation scenario.

Constant-head cells in model layer one (the Upper Patapsco aquifer). Water-level altitude is zero (sea level) in constant-head cells.

Stream cells in model layer one (the Upper Patapsco aquifer).

Boundary of ground-water-flow model.

Figure 39. — Model-simulated potentiometric surface of the Upper Patapsco aquifer generated with the 1990 pumpage appropriation.



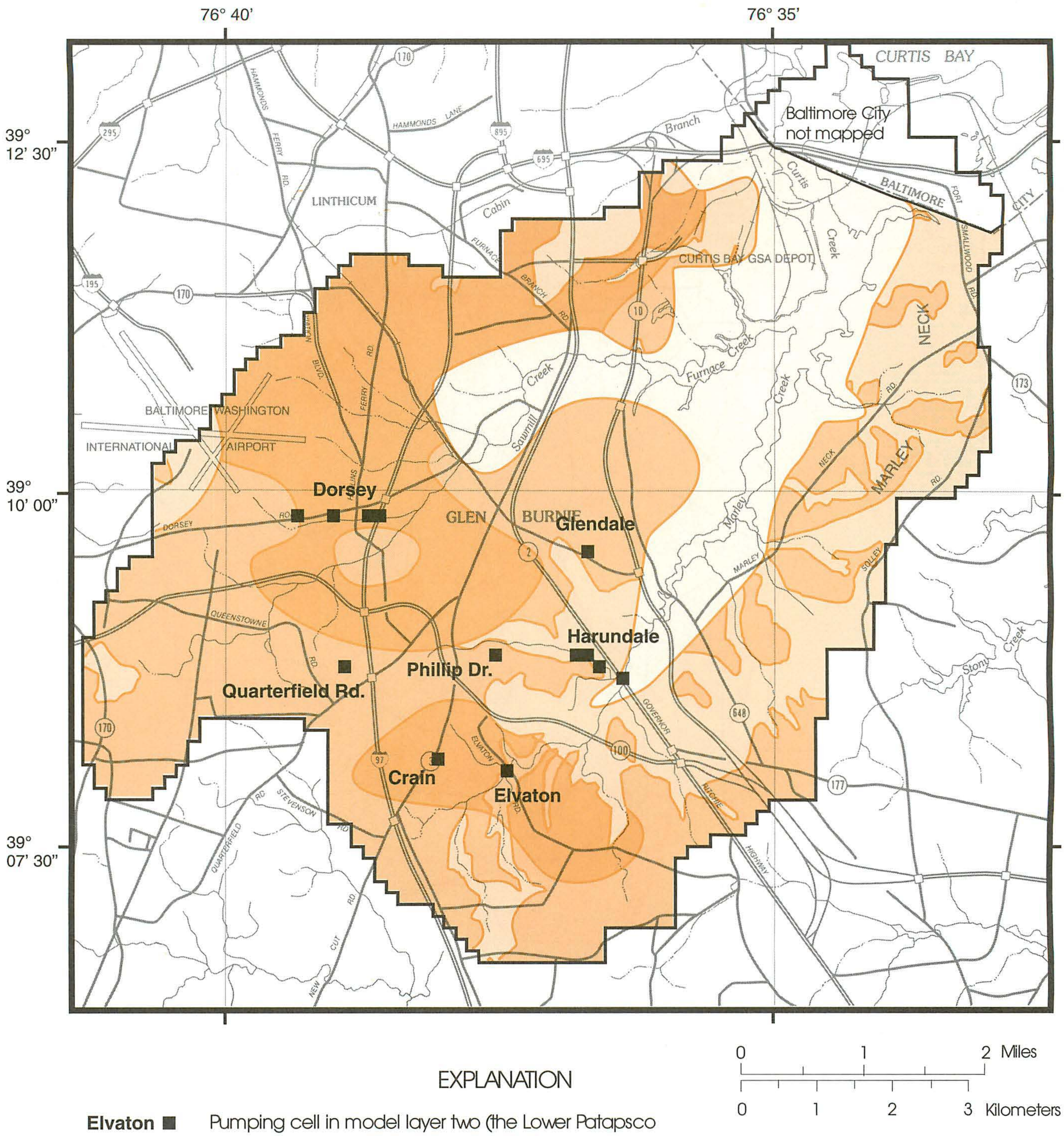
EXPLANATION

— 50 — Simulated line of equal water level, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

▩ Pumping cell in model layer two (the Lower Patapsco aquifer) used in the 1990 pumpage appropriation scenario.

┌ Boundary of the ground-water-flow model.

Figure 40. — Model-simulated potentiometric surface of the Lower Patapsco aquifer generated with the 1990 pumpage appropriation.



EXPLANATION

Elvaton ■ Pumping cell in model layer two (the Lower Patapsco aquifer) and local well name.

Boundary of the ground-water-flow model.

Qualitative degrees of aquifer vulnerability under head conditions simulated by the 1990 pumpage appropriation scenario.

Least degree of vulnerability	Moderate degree vulnerability	Moderate to high degree of vulnerability	High degree of vulnerability

Figure 41. — Qualitative vulnerability assessment of the Lower Patapsco aquifer.

GROUND-WATER DATING USING TRITIUM DETERMINATIONS

Tritium is a radioisotope of hydrogen that can be used to estimate the age of ground water. There are three naturally occurring isotopes of hydrogen: protium (ordinary hydrogen), which consists of one proton; deuterium, which consists of one proton and one neutron; and tritium, which consists of one proton and two neutrons. All three of these isotopes can combine with oxygen to form water molecules because they are chemically similar due to their identical electronic structure. There are about 5,000 atoms of ordinary hydrogen for every deuterium atom and about 10^7 atoms of ordinary hydrogen for every atom of tritium (Nebergall and others, 1976). Tritium is commonly measured in tritium units (TU); one TU equals 3.2 pCi/L (picoCuries per liter).

Tritium can be used to date the age of ground water for two reasons. First, tritium is an unstable radioisotope that decays at a constant rate by ß (beta) emission. The radioactive decay of tritium follows a single exponential decay curve with a half-life of 12.43 years (fig. 42). This means that given a quantity of water with a tritium concentration of C_0 at time t_0, after 12.43 years has elapsed, the concentration of tritium in the water is equal to ½ x C_0; after another 12.43 years has passed, the tritium concentration is equal to ¼ x C_0, and so on. The second reason tritium can be used to date ground water is that atmospheric tritium is formed in two ways: The natural process of tritium creation is the bombardment of N^{14} (nitrogen 14) in the upper atmosphere by cosmic rays; the second way tritium is created is by nuclear reactions, primarily hydrogen bomb explosions.

Natural background levels of tritium in precipitation are estimated at between 3 and 5 TU (Robertson and Cherry, 1989). The 3 to 5 TU background level is lower than the previously accepted range of 5 to 20 TU (Kaufman and Libby, 1954). Robertson and Cherry (1989), however, make a persuasive argument for the lower range of background levels.

Atmospheric testing of hydrogen bombs caused a massive increase in the amount of atmospheric tritium between 1953 and 1963. In 1963, a treaty banning atmospheric testing of nuclear devices was signed by the Soviet Union and the United States, and although some countries continued atmospheric testing of thermonuclear devices after 1963, the levels of atmospheric tritium have been declining since 1963 (figs. 43 and 44). The initial build-up of atmospheric tritium above its pre-nuclear age background levels probably began with the detonation of small nuclear devices between 1945 and 1952 (Robertson and Cherry, 1989); because very few measurements of tritium in precipitation were made prior to 1953, the early rise in atmospheric tritium is not well documented. Peak tritium concentrations of about 9,600 TU were measured in precipitation during the summer of 1963 at Ottawa, Canada and Washington, D.C.; the period from 1962 to 1965 on the tritium graphs form what is commonly referred to as the "tritium bomb spike" (figs. 43, 44 and 45).

Tritiated water enters the hydrologic cycle and becomes part of the ground-water recharge because atmospheric tritium oxidizes rapidly to tritiated water (HTO as opposed to H_2O) and is incorporated into atmospheric water vapors; these vapors condense and fall to earth as precipitation. Tritium is an excellent hydrologic tracer because the tritiated water molecule flows and mixes in the ground-water system in exactly the same manner as normal water (Michel, 1989).

Figure 45 shows the concentration of tritium in precipitation at Washington, D.C. decay-corrected to 1992; the part of the curve prior to 1959 is derived from the Ottawa data. Tritiated water is not created naturally in a ground-water system. Therefore, the age of the ground water can be estimated

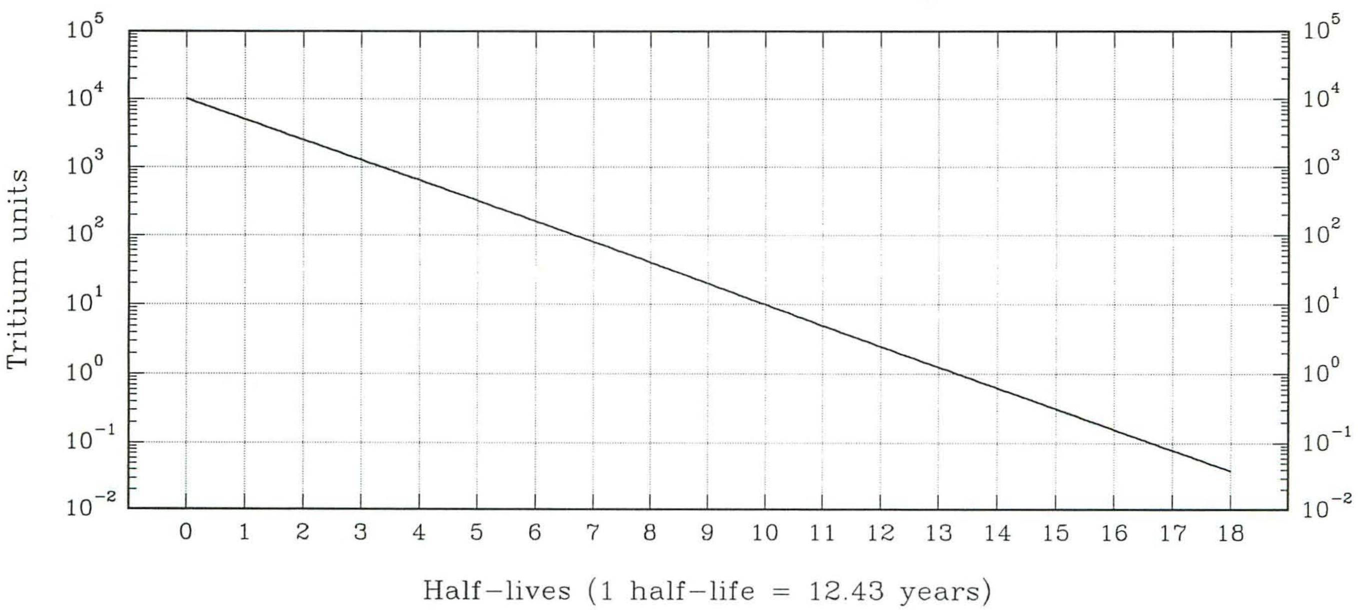
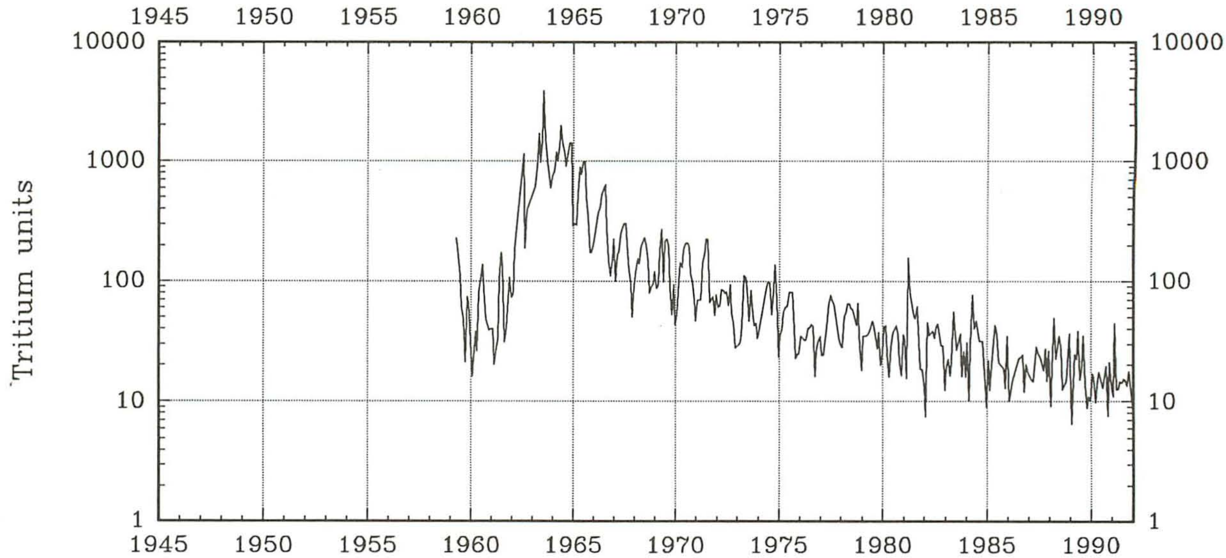
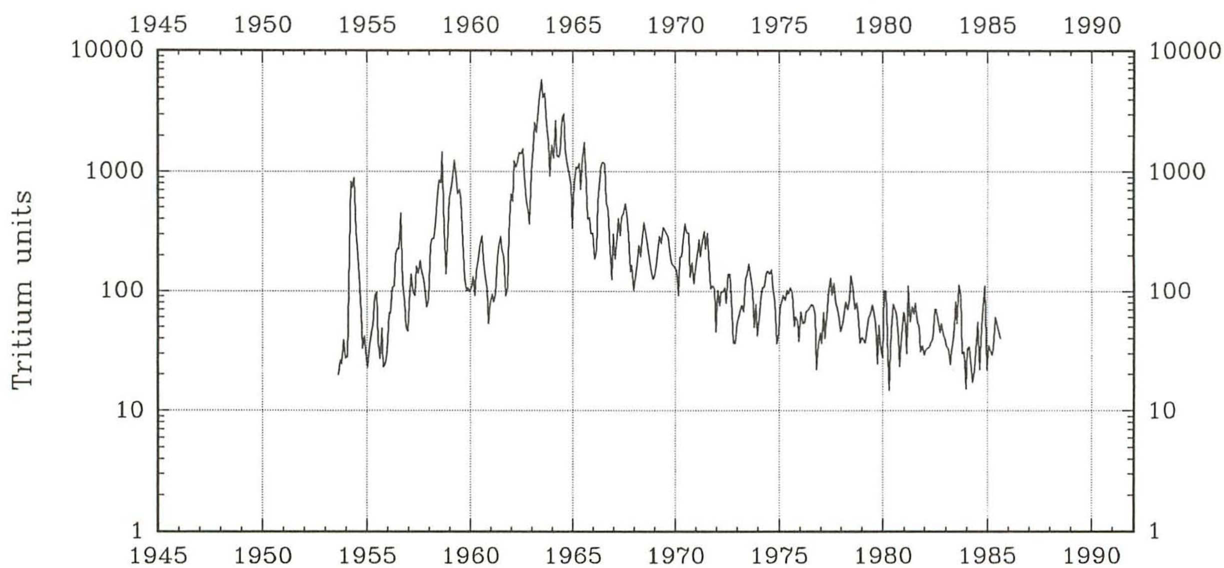


Figure 42. — Tritium decay curve.



(Source of data: R.L. Michel, U.S. Geological Survey, written communication, 1994)

Figure 43. — Tritium concentration in precipitation at Washington, D.C., 1959-1992.



(Source of data: International Atomic Energy Agency, 1969, '70, '71, '73, '75, '79, '83, '86, and '90)

Figure 44. — Tritium concentration in precipitation at Ottawa, Ontario, Canada, 1953-86.

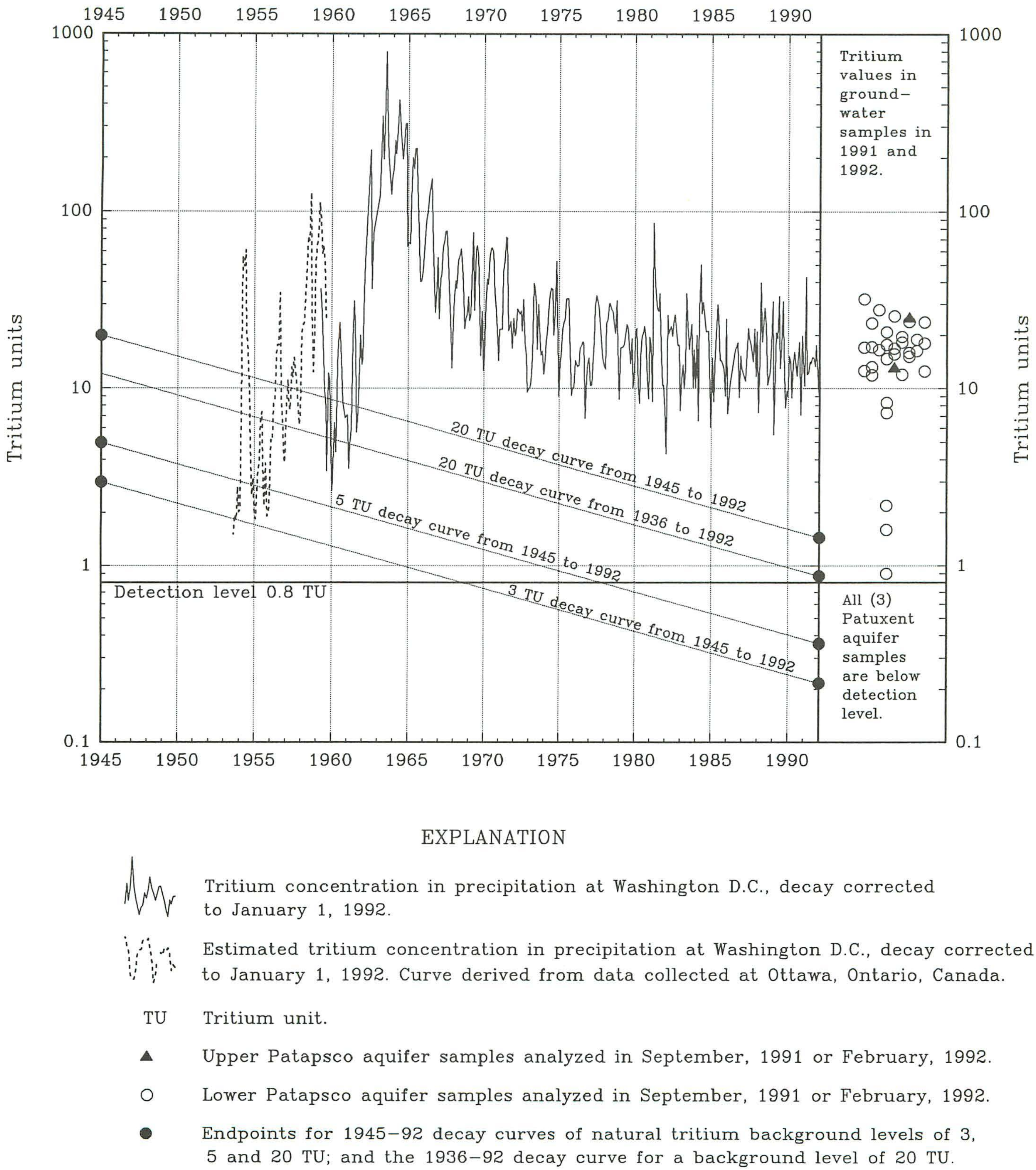


Figure 45. — Tritium concentration in precipitation at Washington, D.C. decay-corrected to January 1, 1992; tritium concentration in ground-water samples; and decay curves for natural tritium background levels.

or in some situations determined by measuring the concentration of tritium in water samples and comparing those concentrations to a tritium concentration curve that is decay-corrected to the date the samples were analyzed.

Tritium determinations were made on 36 water samples from 28 production and observation wells. Eleven of the wells sampled are screened in the Lower Patapsco aquifer, two in the Upper Patapsco aquifer, and three in the Patuxent aquifer (tab. 13; figs. 45 and 46). These samples were electrolytically enriched and analyzed using a liquid scintillation counter by the Environmental Isotope Laboratory, University of Waterloo, Ontario. The analytical method used has a detection level of 0.8 TU.

Determining the exact ages of the ground-water samples collected from the study area is not possible because of evident mixing, via leakage, pumpage and other dispersive mechanisms, of water of different ages. Also, none of the samples had tritium concentrations that would place the age of the sample exclusively within the "bomb spike" years, i.e., no sample had a tritium concentration of more than 100 TU. Although the precise year the ground-water samples fell as precipitation could not be determined, some conclusions can be made regarding the ages of the ground water sampled.

All of the samples from the Upper and Lower Patapsco aquifer had detectable amounts of tritium. The concentration of tritium in the Lower Patapsco aquifer samples ranged from 0.9 TU in Bd 157 to 32.1 TU in Bd 92. In the two Upper Patapsco aquifer wells sampled, the tritium concentration was 25.1 TU in Bd 159 and 13.3 TU in Ad 104; these latter values are averages of replicate analyses (tab. 13).

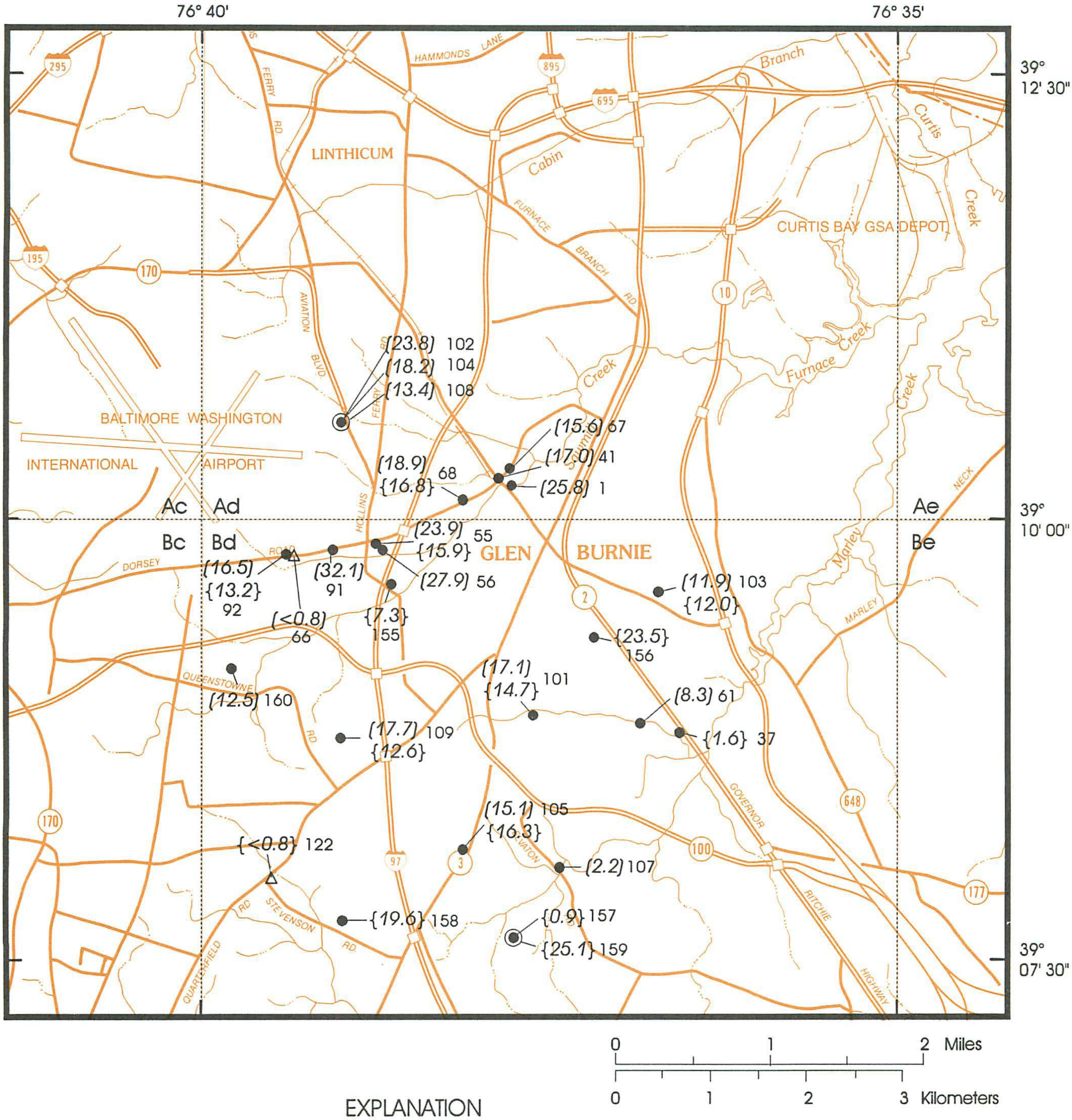
Except for the sample from well Bd 157, all of the Upper and Lower Patapsco aquifer wells sampled produced water in 1991 that must contain a post-1945 component of recharge. This is illustrated by the decay curves of the estimated natural tritium background levels for the period 1945-92 shown on figure 45. These curves show the tritium concentration in 1992 of water that had initial concentrations of tritium equal to 3, 5 and 20 TU in 1945. Since the tritium concentrations of all the samples but the one from Bd 157 lie above both curves, these samples must contain some post-1945 recharge. If the concentration of natural background tritium ranges from 3-5 TU, then the sample from Bd 157 also contains a post-1945 component of recharge; if the concentration of natural background tritium ranges from 5-20 TU, then the sample from Bd 157 must contain a post-1936 component of recharge.

Tritium samples were collected at two sites where there are clusters of observation wells. Differences in tritium concentrations at the well clusters illustrate the vertical variability of tritium concentrations in the aquifers. At one of the well clusters, the sites of well Bd 159 and Bd 157, the

Table 13. — Tritium concentrations in ground-water samples

[Samples collected prior to May 31, 1991 were analyzed in September of 1991; samples collected after November 1, 1991 were analyzed in February of 1992. All well locations shown on figure 46 except for Bc 209 which is located on figure 63]

Well number	Local name	Date sampled	Concentration in tritium units	Aquifer
AA Ad 1	Sawmill 1	05-15-91	26.6 ± 1.9 24.9 ± 1.8	Lower Patapsco
AA Ad 41	Sawmill 5	05-15-91	17.0 ± 1.4	Lower Patapsco
AA Ad 67	Sawmill 6	05-15-91	15.6 ± 1.3	Lower Patapsco
AA Ad 68	Sawmill 7	05-15-91	18.9 ± 1.5	Lower Patapsco
		01-30-92	16.8 ±1.3	
AA Ad 102	Hammonds Ferry Observation 1	04-10-91	23.8 ± 1.8	Lower Patapsco
AA Ad 104	Hammonds Ferry Observation 2	04-10-91	18.2 ± 1.4	Lower Patapsco
AA Ad 108	Hammonds Ferry Observation 3	04-10-91	12.5 ± 1.1 14.0 ± 1.3	Upper Patapsco
AA Bc 209	Telegraph Rd.	01-30-92	<0.8 ± 0.5	Patuxent
AA Bd 37	Harundale 2	01-30-92	1.6 ± 0.5	Lower Patapsco
AA Bd 55	Dorsey 1	05-07-91	23.9 ± 1.8	Lower Patapsco
		01-30-92	15.9 ± 1.2	
AA Bd 56	Dorsey 3	05-07-91	27.9 ± 2.0	Lower Patapsco
AA Bd 61	Harundale 4	06-06-91	8.3 ± 0.9	Lower Patapsco
AA Bd 64	Dorsey 11	05-07-91	20.8 ± 1.6	Lower Patapsco
		01-30-92	18.0 ± 1.3	
AA Bd 66	Dorsey 13	05-17-91	<0.8 ± 0.7	Patuxent
AA Bd 91	Dorsey Observation	05-17-91	32.1 ± 2.3	Lower Patapsco
AA Bd 92	Dorsey 14	05-22-91	16.5 ± 1.4	Lower Patapsco
		01-30-92	13.2 ± 1.1	
AA Bd 101	Phillip Drive	05-22-91	17.1 ± 1.4	Lower Patapsco
		01-30-92	14.7 ± 1.1	
AA Bd 103	Glendale	05-23-91	11.9 ± 1.1	Lower Patapsco
		01-30-92	11.7 ± 1.0 12.3 ± 1.0	
AA Bd 105	Crain Highway	05-22-91	15.1 ± 1.1	Lower Patapsco
		01-30-92	16.3 ± 1.2	
AA Bd 107	Elvaton	05-23-91	2.2 ± 0.6	Lower Patapsco
AA Bd 109	Quarterfield Rd.	05-15-91	17.7 ± 1.4	Lower Patapsco
		01-30-92	12.6 ± 1.0	
AA Bd 122	Stevenson Road	01-30-92	<0.8 ± 0.5	Patuxent
AA Bd 155	SHA Garage Observation	12-10-91	7.3 ± 0.7	Lower Patapsco
AA Bd 156	Bicycle Path Observation	11-26-91	23.5 ± 1.7	Lower Patapsco
AA Bd 157	Rippling Woods Observation 1	11-26-91	0.9 ± 0.5	Lower Patapsco
AA Bd 158	Northern Voc. Tech. Observation	11-27-91	19.6 ± 1.5	Lower Patapsco
AA Bd 159	Rippling Woods Observation 2	11-27-91	24.8 ± 1.8 25.3 ± 1.8	Upper Patapsco
AA Bd 160	Queenstown Park Observation	04-11-91	12.5 ± 1.2	Lower Patapsco



EXPLANATION

(20.8) {18.0} 157 — Location of well, tritium determination in tritium units and well number.

( ) Indicates sample analyzed in September, 1991.

{ } Indicates sample analyzed in February, 1992.

● Solid dot indicates a well completed in the Lower Patapsco aquifer.

○ Open circle indicates a well completed in the Upper Patapsco aquifer.

△ Open triangle indicates a well completed in the Patuxent aquifer. Average of replicate samples shown; data is in table 13.

Ac ⁞ Ad / Bc ⁞ Bd — 5-minute quadrangle designations for well numbering system. Dashed lines denote quadrangles.

Figure 46. — Tritium concentrations and locations of wells sampled.

concentration of tritium was 25.1 TU in Bd 159, an Upper Patapsco aquifer well, and 0.9 TU in Bd 157, a Lower Patapsco aquifer well (fig. 46).

The other observation well cluster (wells Ad 108, 104, and 102) (fig. 46) is near the Sawmill Creek-Cabin Creek basin divide in the recharge area of the Dorsey and Sawmill well fields. Differentiation of the Upper Patapsco aquifer from the Lower Patapsco aquifers is somewhat arbitrary at this site (pl. 2). Based on analysis using the ground-water particle tracking programs for this area, the water in these wells is probably post "bomb spike" water. If so, qualitative dates may be estimated for the water samples collected from these wells in 1991 by comparison of the tritium data with the decay-corrected tritium curve shown in figure 45.

In wells Ad 108, 104 and 102, the tritium concentrations were 13.4, 18.2, and 23.8 TU respectively. Ad 108 is a very shallow (screened from 6-11 ft below land surface) Upper Patapsco aquifer well; the tritium concentrations in Ad 108 are about equal to the average 1985-92 tritium values in precipitation. Ad 104 is screened in the upper part of the Lower Patapsco aquifer from 18 to 28 ft below land surface; the tritium concentration of 18.2 TU in Ad 104 suggests that this sample was recharged sometime after 1975. The deepest well at this cluster (Ad 102) is screened from 80 to 90 feet below land surface and has a tritium concentration of 23.8 TU. If the water sample represents mostly post "bomb spike" water, then the water in this sample entered the ground-water system sometime between 1965 and 1975.

None of the samples from the Patuxent aquifer had detectable amounts of tritium. The absence of tritium indicates that water from the Patuxent aquifer in the study area is older than water of either the Lower or Upper Patapsco aquifers; it also suggests that there is no significant hydraulic connection between the Lower Patapsco and Patuxent aquifers in the study area. This is consistent with the modeling of the confining unit between these two aquifers as a no-flow boundary.

PARTICLE TRACKING TECHNIQUES

Introduction

Particle tracking techniques track trajectories of particles released in a ground-water-flow system either forward in the direction of ground-water flow or backward in the opposite direction. Backward-tracked particles are released in a pumping cell of the model and tracked from the pumping cell outward, opposite to the direction of ground-water flow, to either the particles origin in the water table, or to a point within the aquifer system that represents the location of the particle at some specified period of time (e.g., 10 years) prior to entering the well. The particle pathlines delineated by backtracking from a pumping cell show the movement taken by water particles flowing towards a well. Backward tracking is used to determine zones of contribution (recharge areas) or time-related zones of transport. Forward tracking is generally used to track particles from potential contaminant sites in order to determine whether a contaminant could flow towards a production well; it may also be used to delineate recharge areas and zones of transport.

Time-related zones of transport (ZOT) were generated with the MODFLOW-MODPATH and GPTRAC (semi-analytical) techniques using three different scenarios of well-field pumpage because the size and shape of a zone of transport is in part dependent on the amount of pumpage from the wells. The pumpage scenarios are: 1) the 1990 pumpage appropriations issued by the Maryland Water Resources Administration for production wells and well fields in the study area applied to the wells that were active in 1990, 2) the average

Table 14. — Distribution of the 1990 pumpage appropriation used in the simulation of 10 and 20-year zones of transport

[Mgal/d = million gallons per day; ft^3/d = cubic feet per day]

Anne Arundel County Department of Public Works well name	Maryland Geological Survey well number	Simulated pumpage (in Mgal/d)	Simulated pumpage (in ft^3/d)	Percentage of the 1990 well field appropriation[1]
Dorsey well field				
Dorsey 1	AA Bd 55	0.321	43,000	10.7
Dorsey 3	AA Bd 56	0.398	53,000	13.3
Dorsey 11	AA Bd 64	1.262	169,000	42.0
Dorsey 14	AA Bd 92	1.02	136,000	34.0
Total simulated pumpage Dorsey well field	--	**3.00**	**401,000**	**100**
Harundale well field				
Harundale 1	AA Bd 36	0.25	33,000	11.4
Harundale 2	AA Bd 37	0.583	78,000	26.5
Harundale 3	AA Bd 63	0.804	108,000	36.6
Harundale 4	AA Bd 61	0.563	75,000	25.6
Total simulated pumpage Harundale well field	--	**2.20**	**294,000**	**100**
Sawmill well field Total simulated pumpage[2]	--	**0**	**0**	**0**
Single-well well fields	--			
Phillip Drive well	AA Bd 101	0.70	94,000	100
Glendale well	AA Bd 103	0.75	100,000	100
Crain Highway well	AA Bd 105	0.75	100,000	100
Elvaton well	AA Bd 107	1.0	134,000	100
Thelma Avenue well[3]	AA Bd 108	0	0	0
Quarterfield Rd. well	AA Bd 109	0.75	100,000	100
Total simulated pumpage single-well well fields	--	**3.95**	**528,000**	--
Total simulated pumpage from all wells	--	**9.15**	**1,223,000**	**77.5**

[1] Total 1990 appropriation for all well fields, both active and inactive, equals 11.80 Mgal/d (1,577,000 ft^3/d).
[2] 1990 pumpage appropriation for the Sawmill well field = 2.2 Mgal/d.
[3] 1990 pumpage appropriation for the Thelma Avenue well = 0.45 Mgal/d.

Table 15. — Distribution of the average 1984-88 pumpage used in the simulation of 10 and 20-year zones of transport

[Mgal/d = million gallons per day; ft³/d = cubic feet per day]

Anne Arundel County Department of Public Works well name	Maryland Geological Survey well number	Simulated pumpage (in Mgal/d)	Simulated pumpage (in ft³/d)	Percentage of well field pumpage	Percentage of the 1990 well field appropriation
Dorsey well field					
Dorsey 1	AA Bd 55	0.494	66,000	17.8	--
Dorsey 3	AA Bd 56	0.355	47,000	12.7	--
Dorsey 4	AA Ad 76	0.733	98,000	26.4	--
Dorsey 11	AA Bd 64	0.325	43,000	11.6	--
Dorsey 14	AA Bd 92	0.289	39,000	10.5	--
Dorsey 15	AA Bd 95	0.580	78,000	21.0	--
Total pumpage Dorsey well field	--	**2.776**	**371,000**	**100.0**	**92.5**
Harundale well field					
Harundale 1	AA Bd 36	0.367	49,000	25.0	--
Harundale 2	AA Bd 37	0.367	49,000	25.0	--
Harundale 3	AA Bd 63	0.367	49,000	25.0	--
Harundale 4	AA Bd 61	0.367	49,000	25.0	--
Total pumpage Harundale well field	--	**1.468**	**196,000**	**100.0**	**66.7**
Sawmill well field					
Sawmill 3	AA Ad 23	0.157	21,000	11.0	--
Sawmill 4	AA Ad 40	0.207	28,000	14.5	--
Sawmill 5	AA Ad 41	0.296	40,000	20.7	--
Sawmill 6	AA Ad 67	0.395	53,000	27.6	--
Sawmill 7	AA Ad 68	0.375	50,000	26.2	--
Total pumpage Sawmill well field	--	**1.430**	**191,000**	**100.0**	**65.0**
Single-well well fields					
Phillip Drive well	AA Bd 101	0.644	86,000	100.0	92.0
Glendale well	AA Bd 103	0.729	97,000	100.0	97.2
Crain Highway well	AA Bd 105	0.808	108,000	100.0	107.7
Elvaton well	AA Bd 107	0.602	80,000	100.0	60.2
Thelma Avenue well	AA Bd 108	0.105	14,000	100.0	23.3
Quarterfield Rd. well	AA Bd 109	0.762	102,000	100.0	101.6
Total pumpage single-well well fields	--	**3.65**	**487,000**	--	--
Total pumpage all wells	--	**9.32**	**1,246,000**	--	**76.1**

pumpage for the period 1984-88 applied to all the wells active during that period (a "historical" pumpage scenario), and 3) the actual 1992 pumpage of all the well fields that were in use throughout 1992 (tabs. 14, 15 and 16). The Glendale well was not simulated in this 1992 pumpage scenario because it was shut down in September of 1992. The two particle tracking techniques were used to simulate 10-year zones of transport with the 1990 pumpage appropriation. The 1990 pumpage appropriations are used because the approved State wellhead protection program describing the implementation of WHPAs in Maryland bases the determination of the WHPA on the pumpage appropriations issued by the Maryland Water Resources Administration (Maryland Department of the Environment, oral commun., 1994). Representative historical pumpage was used because it helps define the paths contaminants may take towards production wells; it is possible that past pumpage from a now-abandoned production well may have drawn contaminants into the zone of transport of a production well presently in use. The zone of transport of the current pumping well may not, however, include the contaminant source. Additionally, the 1992 pumpage scenario was used in several examples to illustrate aspects of the particle-tracking techniques.

Delineation of Zones of Transport and Zones of Contribution Using MODPATH

The U.S. Geological Survey program MODPATH (Pollock, 1989) is one of the particle tracking programs used in this study to delineate zones of transport and zones of contribution. MODPATH calculates steady-state particle pathlines using the head distributions and flow rates calculated for each active cell of the previously described MODFLOW ground-water-flow model. MODPATH is an advection model that computes particle pathlines solely on the basis of flow velocity. The particle pathlines are calculated under the assumption that the components of velocity in each of the three directions of flow within a finite-difference cell of the MODFLOW model vary linearly with the flow rates calculated by MODFLOW at each face of the cell. MODPATH does not account for the effects of diffusion or dispersion, properties which may cause the particles to move faster than by advective flow alone.

The accuracy of MODPATH is inherently dependent on the accuracy of the ground-water-flow model because MODPATH is a post-processor to the ground-water-flow model that uses the same aquifer conceptualization and parameters as the MODFLOW model. In general, the smaller the finite-difference cell of the flow model, the better the model represents the ground-water-flow system. For the degree of resolution required for this study, the 500 by 500 ft size of the grid cell adequately represents the position of the wells in plan view and ensures the calculation of accurate particle trajectories. Uncertainties in aquifer boundary conditions, hydrologic properties beyond the vicinity of the control wells, and the amount of inter-aquifer leakage were evaluated during the calibration of the flow model. Updating and recalibrating the flow model using monthly data acquired since 1984 improved the reliability of the flow model and the subsequent MODPATH particle tracking analyses.

Table 16. — Distribution of the 1992 pumpage used in the simulation of 10-year zones of transport for selected wells

[Mgal/d = million gallons per day; ft³/d = cubic feet per day]

Anne Arundel County Department of Public Works well name	Maryland Geological Survey well number	Actual pumpage (in Mgal/d)	Actual pumpage (in ft³/d)	Percentage of well field pumpage	Percentage of the 1990 well field appropriation
Dorsey well field					
Dorsey 1	AA Bd 55	0.209	28,000	13.3	7.0
Dorsey 3	AA Bd 56	0.169	23,000	10.7	5.6
Dorsey 11	AA Bd 64	0.663	89,000	42.0	22.1
Dorsey 14	AA Bd 92	0.536	72,000	34.0	17.9
Total pumpage Dorsey well field	--	**1.577**	**212,000**	**100.0**	**52.6**
Harundale well field					
Harundale 1	AA Bd 36	0.137	18,000	11.2	6.2
Harundale 2	AA Bd 37	0.319	43,000	26.2	14.5
Harundale 3	AA Bd 63	0.321	43,000	26.4	14.6
Harundale 4	AA Bd 61	0.441	59,000	36.2	20
Total pumpage Harundale well field	--	**1.218**	**163,000**	**100.0**	**55.3**
Single-well well fields[1]					
Phillip Drive well	AA Bd 101	0.611	82,000	100.0	87.3
Crain Highway well	AA Bd 105	0.612	82,000	100.0	81.6
Elvaton well	AA Bd 107	0.699	93,000	100.0	69.9
Quarterfield Rd. well	AA Bd 109	0.586	78,000	100.0	78.1
Total pumpage single-well well fields	--	**2.508**	**335,000**	--	--
Total all wells	--	**5.303**	**710,000**	--	**44.9**

[1]The Glendale well was not simulated in this scenario.

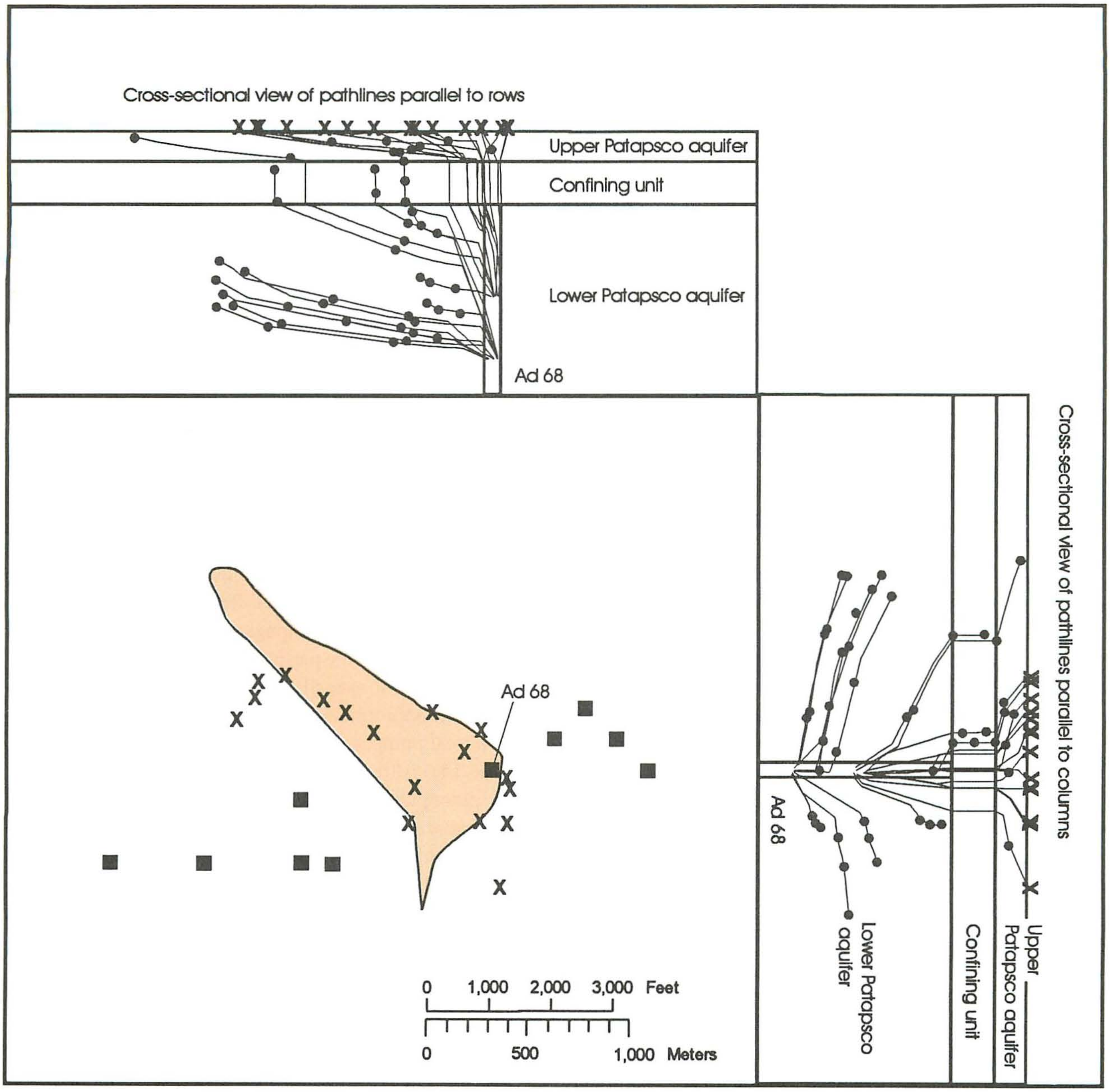
In this study, the Lower Patapsco aquifer is modeled as one layer (fig. 20). As a consequence, MODFLOW simulates the pumping wells as if they were pumping from the entire thickness of the Lower Patapsco aquifer. Therefore, the head distributions calculated by MODFLOW represent an average value for each Lower Patapsco aquifer model cell. The actual screen lengths of the production wells, however, generally range from 20 to 30 percent of the aquifer thickness (App. A). Barlow (1994) and Reilly and Pollock (1993) discuss situations where the position of the screened interval (the part of the well open to the aquifer) effects the location of a pumping well's zone of contribution. Simulating the Lower Patapsco aquifer as two or three model layers would allow an assessment of the effects of the screen position on the size and location of the zones of contribution and transport. However, given the heterogeneity of the Lower Patapsco aquifer in the study area, the available hydrogeologic data probably does not justify that degree of vertical discretization of the model framework. Additionally, because of the confining unit overlying the Lower Patapsco aquifer, pumping wells tend to intercept particles that originate in zones of contribution located upgradient near the basin boundaries, rather than particles that originate in the immediate vicinity of the pumping wells.

The actual vertical dimensions of the aquifers and confining beds are used by MODPATH when calculating the positions and velocities of the particles at discrete points in the flow system. MODFLOW does not require entering vertical dimensions because it represents the aquifers and confining beds using transmissivity and leakance respectively; these two parameters incorporate aquifer and confining bed thicknesses. In MODPATH, particles may be released at any depth. In the particle tracks shown herein (figs. 47-57, pls. 5-7), the particles were released in the upper middle and basal parts of the Lower Patapsco aquifer.

In figures 47, 49, 50, and 55-57 a total of 27 particles were initially positioned in the pumping cell of each well for which particle tracks or endpoints are shown. The 27 particles were placed in three sets of nine particles at three different depths in each pumping cell; each set of nine particles was positioned as three equally spaced particles on each X, Y, and Z axis within the pumping cell. In figures 48 and 52-54, a total of 125 particles were released from each pumping cell. The 125 particles were placed in five sets of 25 particles at five different depths in each pumping cell. Each set of 25 particles was positioned as five equally spaced particles on each X, Y, and Z axis within a pumping cell.

Back-tracking particle pathlines from pumping wells

Figure 47 illustrates, in three dimensions, pathlines and endpoints of designated particles backtracked from a pumping cell in the Lower Patapsco aquifer; the modeled system consists of a confined aquifer (the Lower Patapsco), an overlying leaky confining unit, and a water-table aquifer (the Upper Patapsco). The pathlines shown in figure 47 are from Ad 68, a production well in the Sawmill well field; the average 1984-88 pumpage scenario (tab. 15) was used to generate these pathlines. The plotted 30-year particle trajectories are marked with circles that indicate 10-year isochronal increments along each particle pathline. The particles backtracked from the deepest section in the pumping cell moved laterally in the Lower Patapsco aquifer and did not reach the confining unit in 30 years; these particles delineate 10-year, 20-year, and 30-year zones of transport. Particles backtracked from the middle section of the pumping cell traveled laterally within the aquifer and vertically in the confining unit. The particles backtracked from the highest section of the aquifer in the pumping cell traveled laterally in the Lower Patapsco aquifer, vertically in the confining unit, and reached the Upper Patapsco aquifer within 20 years. In the 30-year simulation, some of the particles reached the water table where they delineate a 30-year zone of contribution or recharge area in the Upper Patapsco aquifer. A comparison (in plan view) shows the different dimensions of the 30-year zone of transport in the Lower Patapsco aquifer and the 30-year zone of contribution in the Upper Patapsco aquifer (fig. 47). The irregular distribution of the particles in plan view is caused by interference effects from nearby



EXPLANATION

■ Pumping cell in model layer two (the Lower Patapsco aquifer).

Thirty-year zone of transport in the Lower Patapsco aquifer for well Ad 68 under the 1984-88 average pumpage scenario.

X Particles originating at the water table that delineate a thirty-year zone of contribution in the Upper Patapsco aquifer for well Ad 68 under the 1984-88 average pumpage scenario.

Ten-year increments along particle pathlines in cross-sectional view.

Figure 47. — Thirty-year pathlines with 10-year isochronal increments backtracked from well Ad 68 under the average 1984-88 pumpage scenario.

pumping wells. The particle pathlines from these wells are not shown.

Pathlines backtracked from well Bd 64 (Dorsey 11) are plotted on figure 48. The pumpage used in this illustration is the 1990 pumpage appropriation applied to the pumping wells in the model area. The pathlines of the other pumping wells are not plotted on figure 48. The plan and cross-sectional views show that all 125 of the steady-state pathlines backtracked from Bd 64 reached the model boundaries. The endpoints of these particle pathlines delineate zones of contribution (recharge areas) in the water-table aquifer. The V-shaped gap in the plan view of the particle tracks is caused primarily by well interference from well Bd 92 which is located to the west of Bd 64. Other nearby pumping wells also distort the pathlines of Bd 64. If particles were released from all points along the z (vertical) axis of the pumping cell, the gaps (except for those caused by well interference) in the particle pathlines from Bd 64 would be completely filled by particle pathlines. The pathlines of additional particles would also extend to the aquifer boundaries.

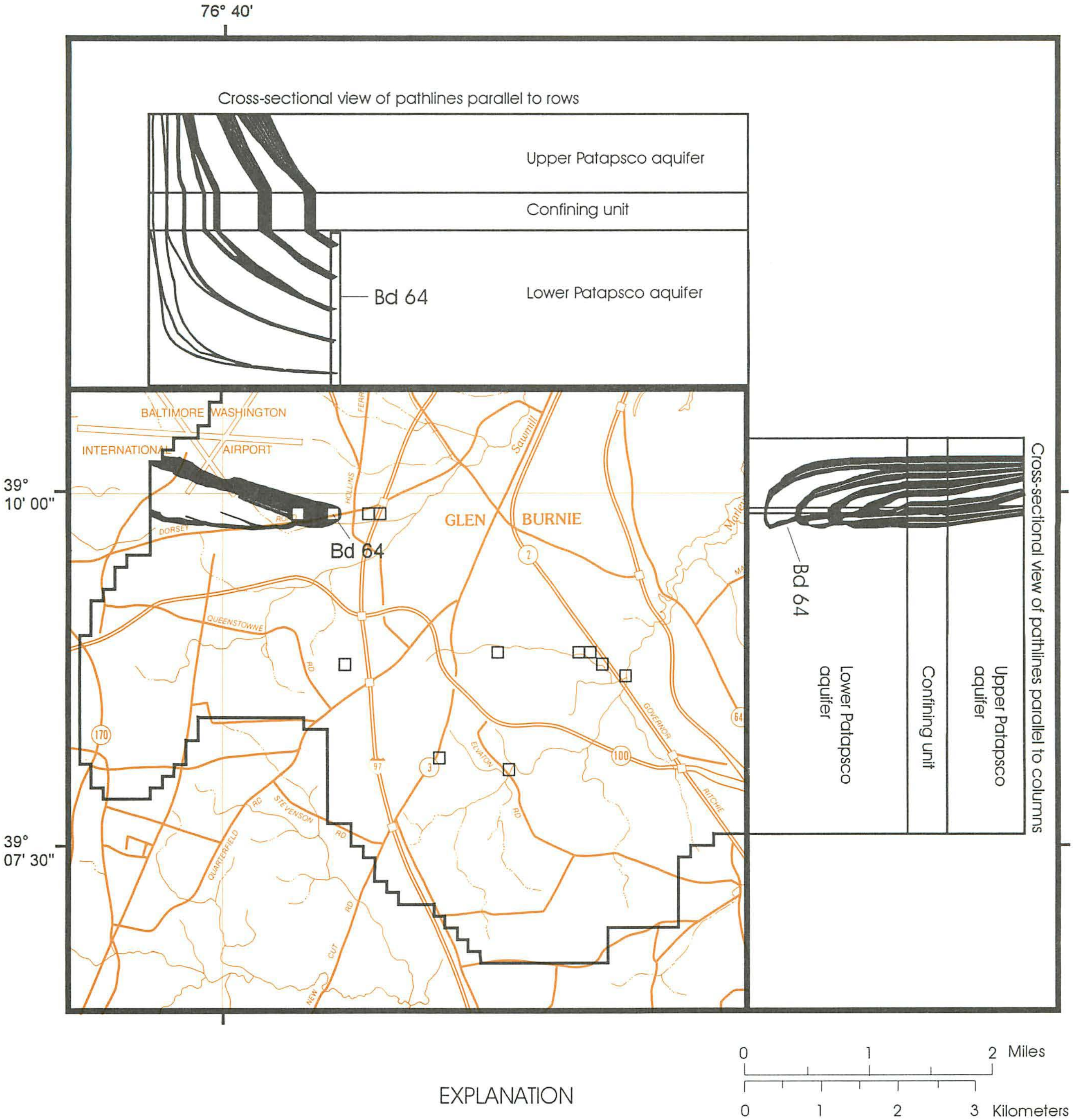
In figures 49, 50 and 51, respectively, 10-year zones of transport in the Lower Patapsco aquifer are shown in plan and cross-sectional view for simulations using the 1990 pumpage appropriation, the average 1984-88 pumpage (historical scenario), and the 1992 pumpage scenario. A comparison of these figures illustrates the effects of pumpage on the size of the zones of transport and how the transport zone's shapes are affected by well interference and ground-water-flow patterns. Comparing figures 49 and 51 shows that the 10-year zone of transport for the Dorsey well field with a pumpage of 3.0 Mgal/d (fig. 49) is larger than the zone of transport when only 1.6 Mgal/d is pumped (fig. 51). The potentiometric surface of the Lower Patapsco aquifer is also plotted on figure 49 in order to show the orientation of the zones of transport with respect to the different directions of ground-water flow. The cross-sectional views shown on figures 47-51 and 55-57 are partially schematic because the vertical dimension of the cross-sectional views are not to scale. The horizontal scale is, however, the same as the map scale, and the cross-sectional views accurately show the relative position of the particle pathlines and endpoints.

MODPATH was used to determine the zones of contribution (recharge areas) of the well fields in the model area by backtracking particle pathlines to their intersection with the top of the water table. Figures 52, 53 and 54 show the endpoints of pathlines at the top of the water table under the three different pumpage scenarios. Generally, the recharge areas cover about half the Sawmill and Marley Creek basins; they extend from the western and southern ground-water divides toward the middle parts of the basins. The recharge areas for the actual 1992 pumpage (5.3 Mgal/d) (fig. 54) are about half the size of the recharge areas for the 1990 pumpage appropriation (9.3 Mgal/d) (fig. 52). The time required for water to flow from the recharge areas to the wells ranges from less than 10 to 60 years using the 1990 pumpage appropriation and average 1984-88 pumpage, but this time ranged from 40 to 60 years in the 1992 pumpage scenario. The recharge areas are larger and closer to the wells under the higher pumpage rates. Although recharge areas do not plot in the immediate area surrounding some of the pumping wells, some recharge may originate in the immediate vicinity of the well. This is because in the model the heads driving the recharge to the wells are average heads for the model cell. As a consequence, drawdowns in the immediate vicinity of the well are greater than the model simulates. Therefore, as Barlow (1994) notes, in some cases the lack of recharge originating in the immediate vicinity of the well may be caused by the inability of the MODFLOW model to simulate accurate drawdowns near the well. Using a finely discretized grid at the pumping sites would increase the accuracy of the simulation near the wells. In the study area, however, the presence of the confining unit will ameliorate this problem except near wells where the confining unit may be thinner or leakier than modeled.

MODPATH can be used to estimate the time and rate of flow of particles traveling from a recharge area to a pumping well. For example, figure 55 shows the endpoints of 27 particle pathlines released from well Bd 61 (Harundale 4) after 0, 10, 20 and 30 years of pumpage. The pathlines were omitted in this figure so that the particle positions at specified times could be followed more easily. The model scenario used is the 1990 pumpage appropriation, in which Bd 61 pumped 0.8 Mgal/d out of a total pumpage for all the simulated wells of 9.15 Mgal/d (tab. 14). Although no particle pathlines were tracked from the other pumping wells, these wells were pumped at the 1990 pumpage appropriation rate in the simulation. Figure 55 shows the endpoints in plan view and projected onto a vertical plane parallel to the columns and the rows of the model grid respectively. At the initial time of release (t_0) all 27 particles from Bd 61 are positioned in the model cell that represents the pumping well; note that several of the endpoints coincide when observed in plan view (fig. 55). After 10, 20, and 30 years of pumpage the lateral distances traveled are approximately 2800, 3800, and 5400 ft from the well. The average rates of travel of the particles at 10, 20, and 30 years are, therefore, 280, 190, and 180 ft/yr respectively (tab. 17). The rates of travel indicate that particles move faster as they approach the well because near the well the same volume of water is moving through a smaller cross-section of aquifer.

The vertical distances that the particle traveled from well Bd 61 after 10, 20, and 30 years of pumping are about 32, 56, and 72 ft (fig. 55) (tab. 18). The average vertical flow rates of particles range from 2.4 to 3.2 ft/yr. For each particle, the magnitude of the vertical component of flow is one tenth or less than the magnitude of the horizontal component of flow. The time required for the backtracked particles to reach the confining unit is 11 to 12 years. Another 8 to 9 years is required for the particles to travel the full thickness of the confining unit, and about another 10 years are needed for the particles

(Text continues on p. 79.)



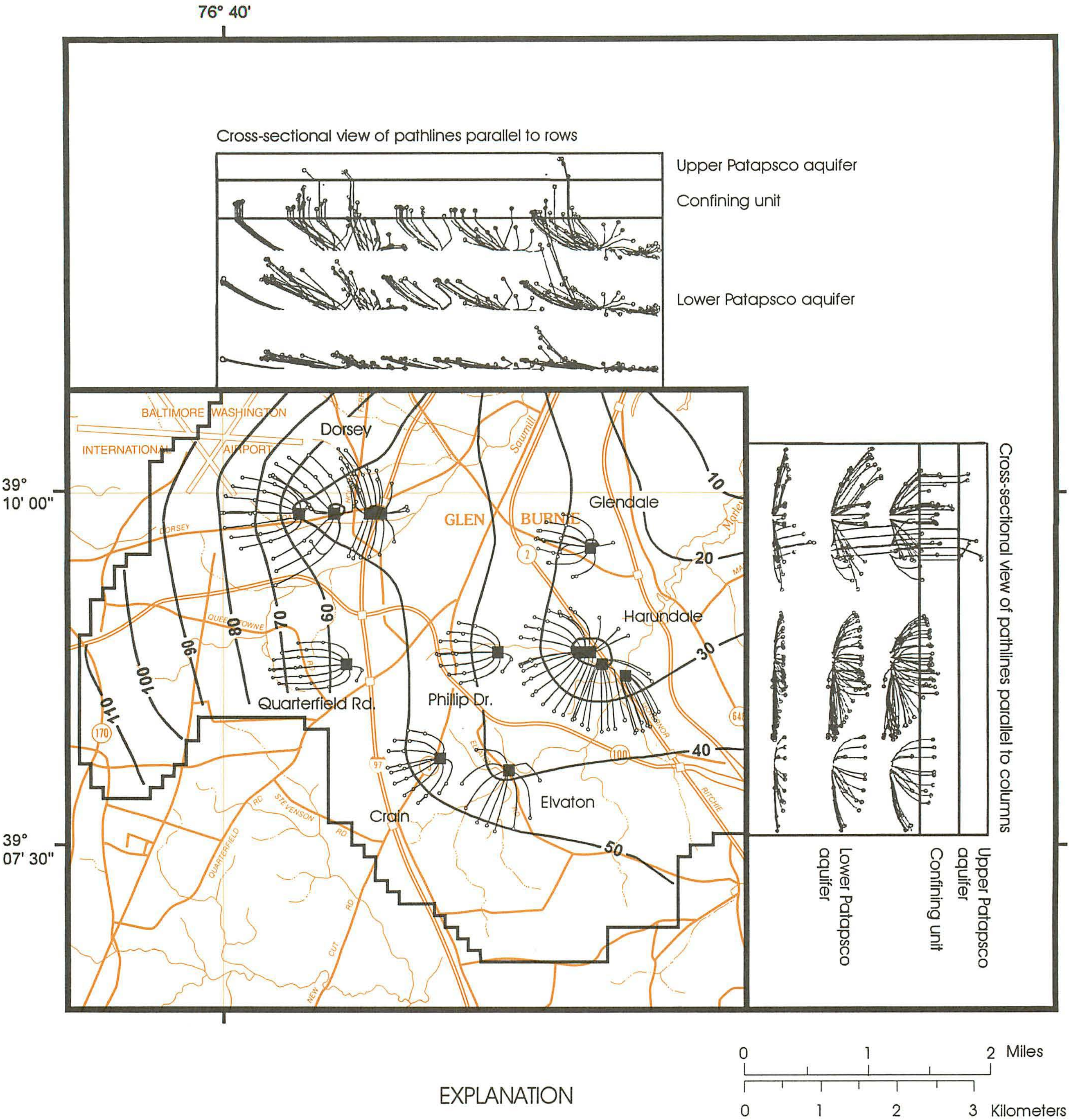
EXPLANATION

□ Pumping cell in model layer two (the Lower Patapsco aquifer).

Steady-state pathlines in plan view backtracked from well Bd 64 (Dorsey 11) under the 1990 pumpage appropriation scenario.

Boundary of the ground-water-flow model.

Figure 48. — Pathlines in plan and cross-sectional views backtracked from well Bd 64 showing the steady-state zones of transport under the 1990 pumpage appropriation scenario.



EXPLANATION

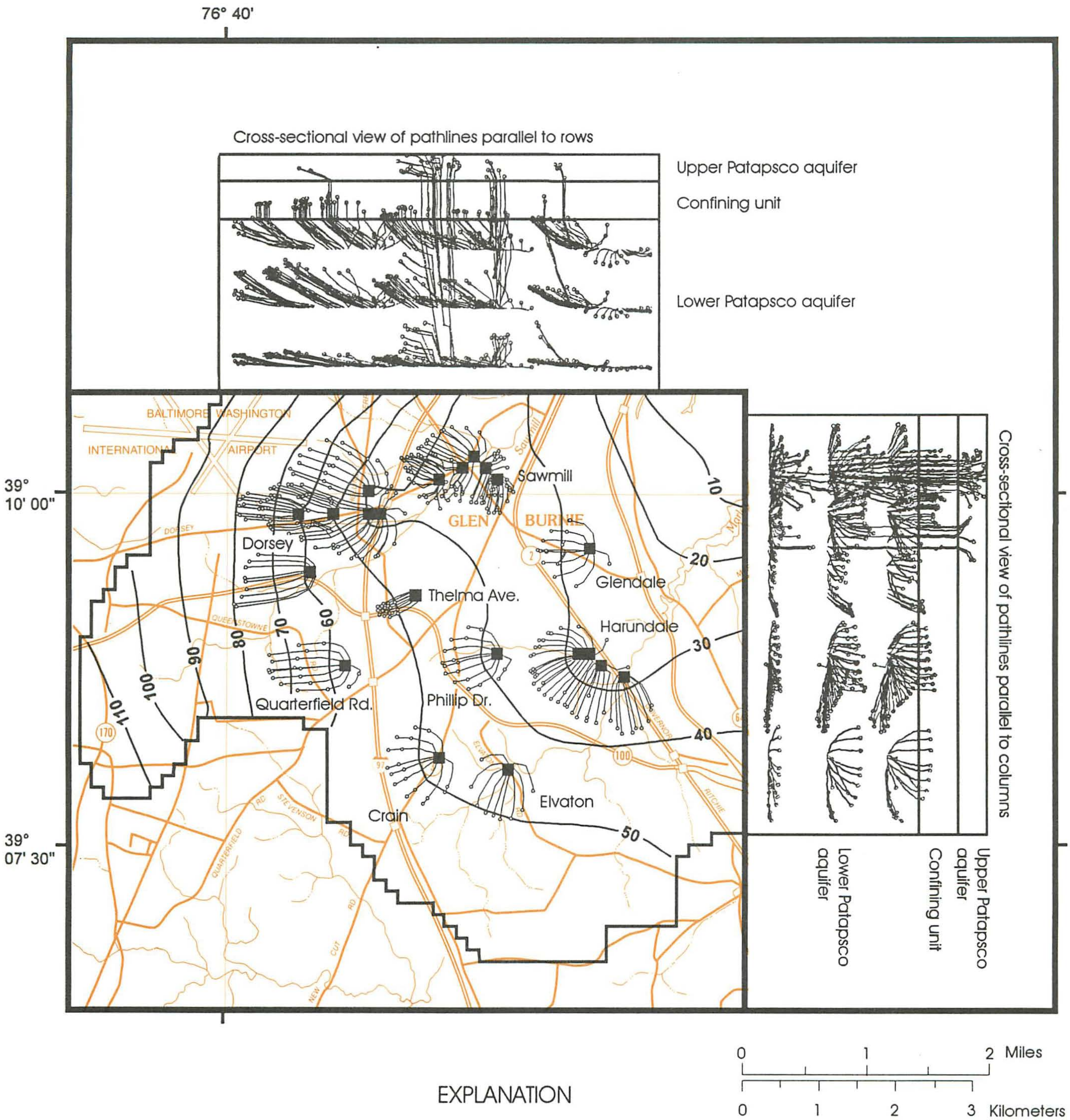
Dorsey ■ Pumping cell in model layer two (the Lower Patapsco aquifer) and local name of well field.

Pathlines in plan view backtracked from pumping cell.
Circles indicate position of endpoints after ten years of pumping. (Some pathlines partially coincide; in these cases, two endpoints may appear as though they occur on one pathline).

— 40 — Simulated line of equal water level, in feet above sea level.
Contour interval is 10 feet. Datum is sea level.

Boundary of the ground-water-flow model.

Figure 49. — Ten-year pathlines in plan and cross-sectional views backtracked from public-supply wells after 10 years of pumping at the 1990 pumpage appropriation of 9.15 million gallons per day.



EXPLANATION

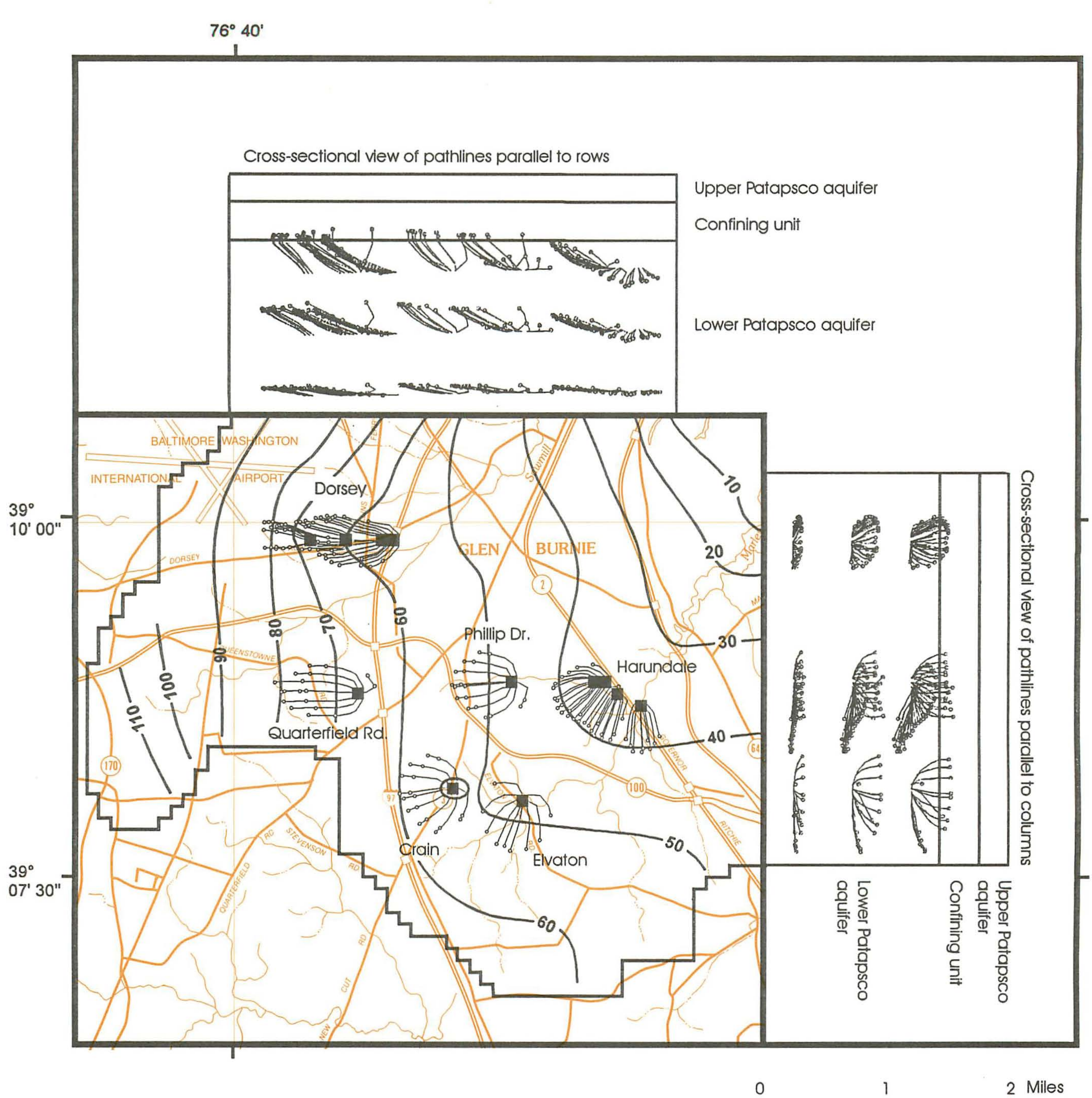
Dorsey ■ Pumping cell in model layer two (the Lower Patapsco aquifer) and local name of well field.

Pathlines in plan view backtracked from pumping cell.
Circles indicate position of endpoints after ten years of pumping. (Some pathlines partially coincide; in these cases, two endpoints may appear as though they occur on one pathline).

—40— Simulated line of equal water level, in feet above sea level.
Contour interval is 10 feet. Datum is sea level.

Boundary of the ground-water-flow model.

Figure 50. — Ten-year pathlines in plan and cross-sectional views backtracked from public-supply wells pumping at the average 1984-88 pumpage of 9.3 million gallons per day.



EXPLANATION

Dorsey ■ Pumping cell in model layer two (the Lower Patapsco aquifer) and local name of well field.

Pathlines in plan view backtracked from pumping cell.
Circles indicate position of endpoints after ten years of pumping. (Some pathlines partially coincide; in these cases, two endpoints may appear as though they occur on one pathline).

— 40 — Simulated line of equal water level, in feet above sea level.
Contour interval is 10 feet. Datum is sea level.

Boundary of the ground-water-flow model.

Figure 51. — Ten-year pathlines in plan and cross-sectional views backtracked from selected public-supply wells pumping at their 1992 pumpage of 5.3 million gallons per day.

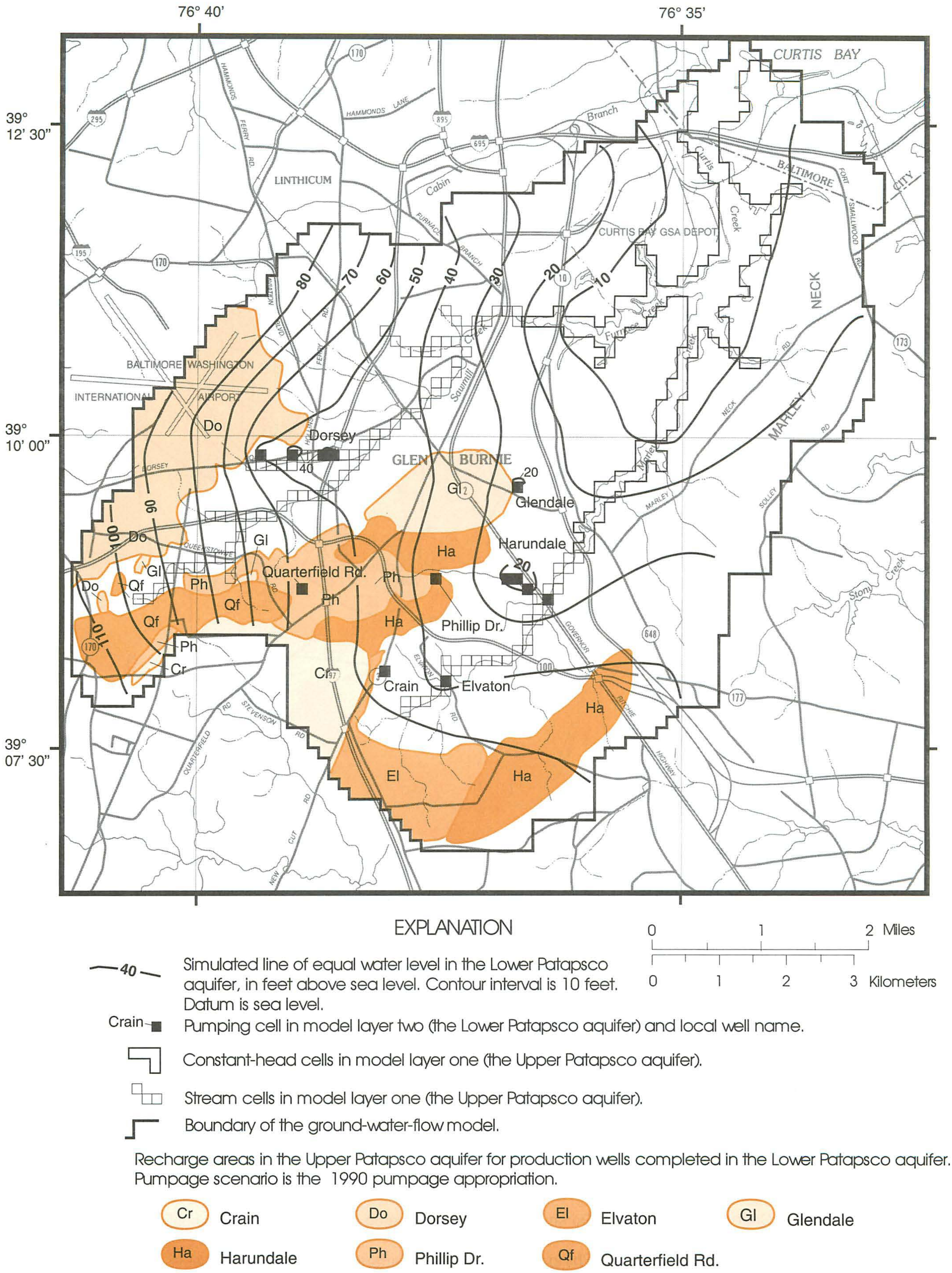
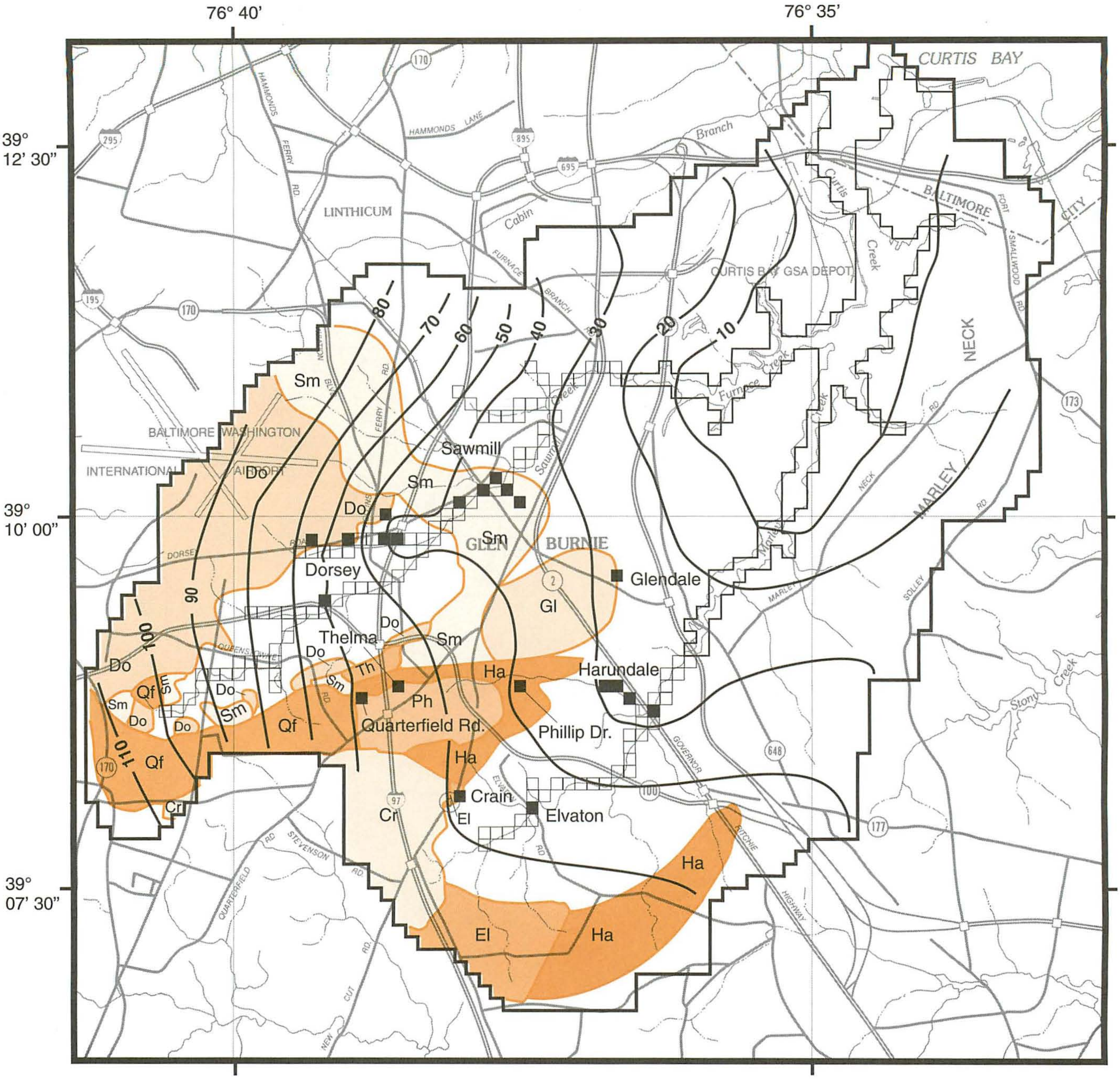


Figure 52. — Zones of contribution in the Upper Patapsco aquifer under the 1990 pumpage appropriation scenario for the Lower Patapsco aquifer.



EXPLANATION

0 1 2 Miles
0 1 2 3 Kilometers

—40— Simulated line of equal water level in the Lower Patapsco aquifer, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

Crain ■ Pumping cell in model layer two (the Lower Patapsco aquifer) and local well name.

Constant-head cells in model layer one (the Upper Patapsco aquifer).

Stream cells in model layer one (the Upper Patapsco aquifer).

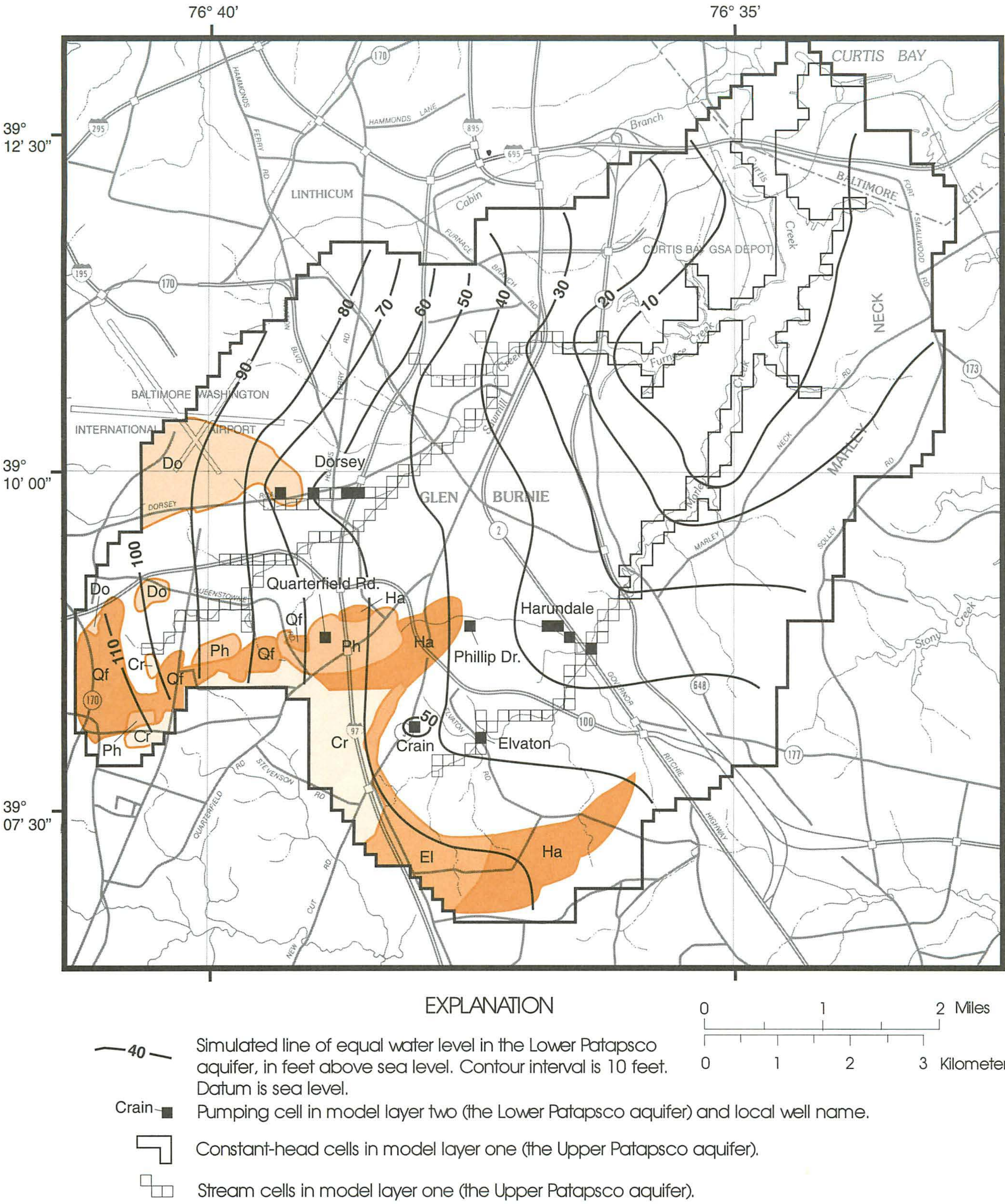
Boundary of the ground-water-flow model.

Recharge areas in the Upper Patapsco aquifer for production wells completed in the Lower Patapsco aquifer. Pumpage scenario is the average 1984-88 pumpage.

Cr Crain — Do Dorsey — El Elvaton — Gl Glendale

Ha Harundale — Ph Phillip Dr. — Qf Quarterfield Rd. — Sm Sawmill — Th Thelma Ave.

Figure 53. — Zones of contribution in the Upper Patapsco aquifer under the average pumpage rate (1984-88) scenario for the Lower Patapsco aquifer.



EXPLANATION

0 1 2 Miles
0 1 2 3 Kilometers

—40— Simulated line of equal water level in the Lower Patapsco aquifer, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

Crain ■ Pumping cell in model layer two (the Lower Patapsco aquifer) and local well name.

Constant-head cells in model layer one (the Upper Patapsco aquifer).

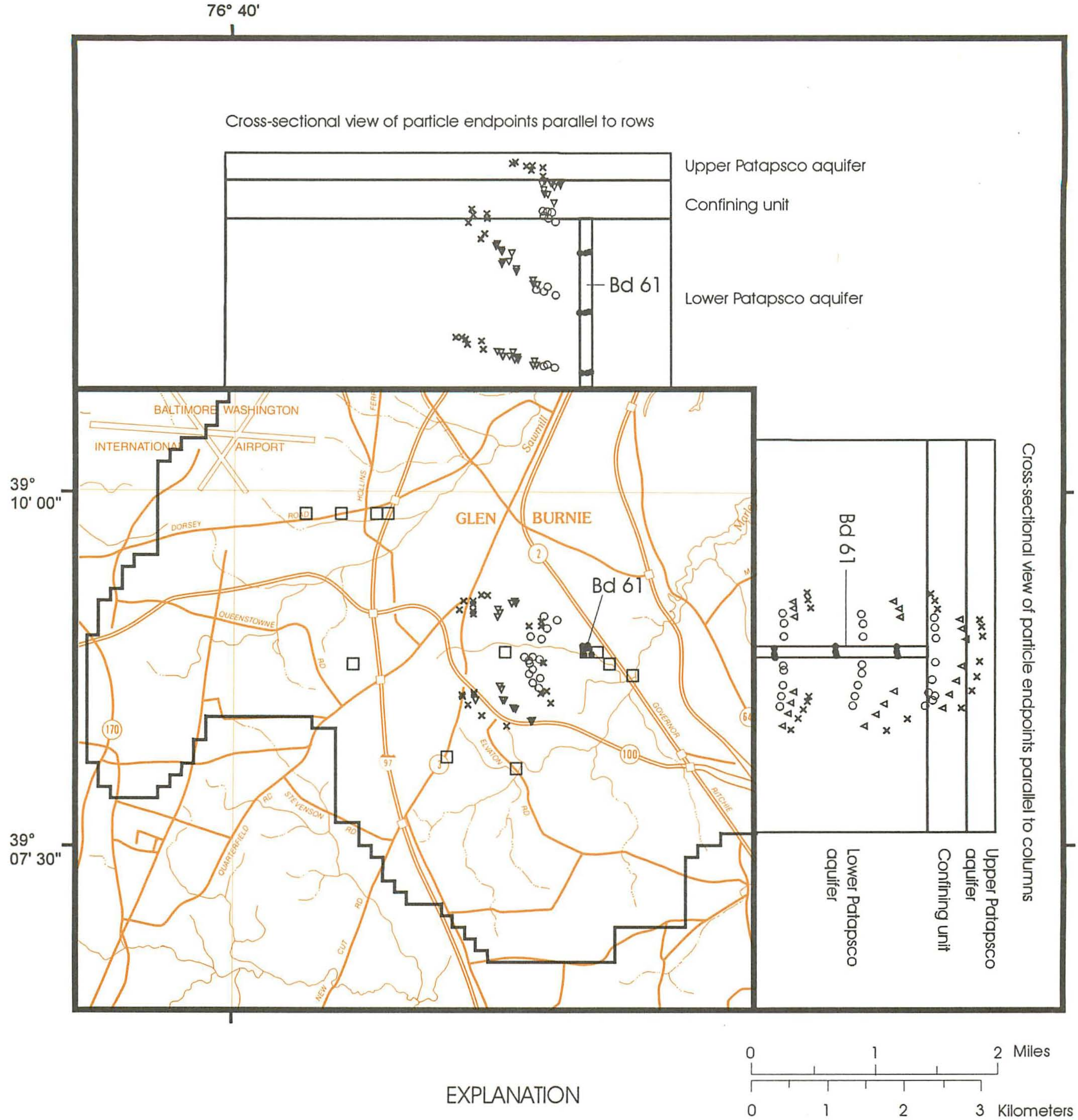
Stream cells in model layer one (the Upper Patapsco aquifer).

Boundary of the ground-water-flow model.

Recharge areas in the Upper Patapsco aquifer for production wells completed in the Lower Patapsco aquifer. Pumpage scenario is the 1992 selected well simulation.

Cr	Crain	Do	Dorsey	El	Elvaton
Ha	Harundale	Ph	Phillip Dr.	Qf	Quarterfield Rd.

Figure 54. — Zones of contribution in the Upper Patapsco aquifer under the 1992 pumpage scenario for the Lower Patapsco aquifer.



EXPLANATION

□ Pumping cell in model layer two (the Lower Patapsco aquifer).

Position of particle endpoints released from well Bd 61 (Harundale 4R) after:

- ● 0 years
- o 10 years
- ▽ 20 years
- × 30 years of pumping under the 1990 pumpage appropriation scenario.

Boundary of the ground-water-flow model.

Figure 55. — Endpoints of pathlines backtracked from well Bd 61 in plan and cross-sectional views after 0, 10, 20, and 30 years of pumping at the 1990 pumpage appropriation of 9.15 million gallons per day.

Table 17. — Horizontal distance traveled in plan view and the rate of travel of particles released from well Bd 61 at 10, 20, and 30 years of pumping

[ft = feet]

Simulation time (in years)	Distance traveled (in ft)	Rate of flow of particles (in ft/year)
10	2800	280
20	3800	190
30	5400	180

to reach the upper parts of the water-table aquifer. These numbers are average values for the flow pattern in the vicinity of well Bd 61 using the 1990 pumpage appropriation.

Ground-water ages as indicated by the particle pathlines are corroborated by the tritium determinations. As discussed previously, most of the tritium concentrations greater than 20 TU were determined in samples from wells in the Sawmill Creek basin at or near the Dorsey and Sawmill well fields (fig. 46; tab. 13). These are the well fields with the greatest proportion of 20-year pathlines reaching the water table (a few of the pathlines reach the water table within 10 years) (fig. 56). Together, the higher tritium concentrations and the pathline analysis suggest that much of the water pumped from these wells in 1991 entered the ground-water-flow system after 1961.

Most of the Lower Patapsco aquifer samples with low tritium concentrations are from wells in the southwest-central part of the Marley Creek basin, the Harundale well field, the Elvaton well and observation well Bd 157. This is consistent with the 20-year pathline distribution for the Elvaton and Harundale well fields; only a few of the 20-year pathlines from the Elvaton well field and a few 10 and 20-year pathlines from the Harundale well field reach the base of the confining unit (figs. 56 and 57). Together, the tritium data and pathline analysis indicate that most of the water pumped from these wells in 1991 entered the ground-water system prior to 1961 and may include a large percentage of pre-1945 water. For example, the pathline analysis for Bd 61 (Harundale 4) indicated backtracked particles require about 30 years to reach the upper part of the water-table aquifer from their release points in the Lower Patapsco aquifer.

Table 18. — Vertical distance traveled in cross-sectional view and the rate of travel of particles released from well Bd 61 at 10, 20, and 30 years of pumping

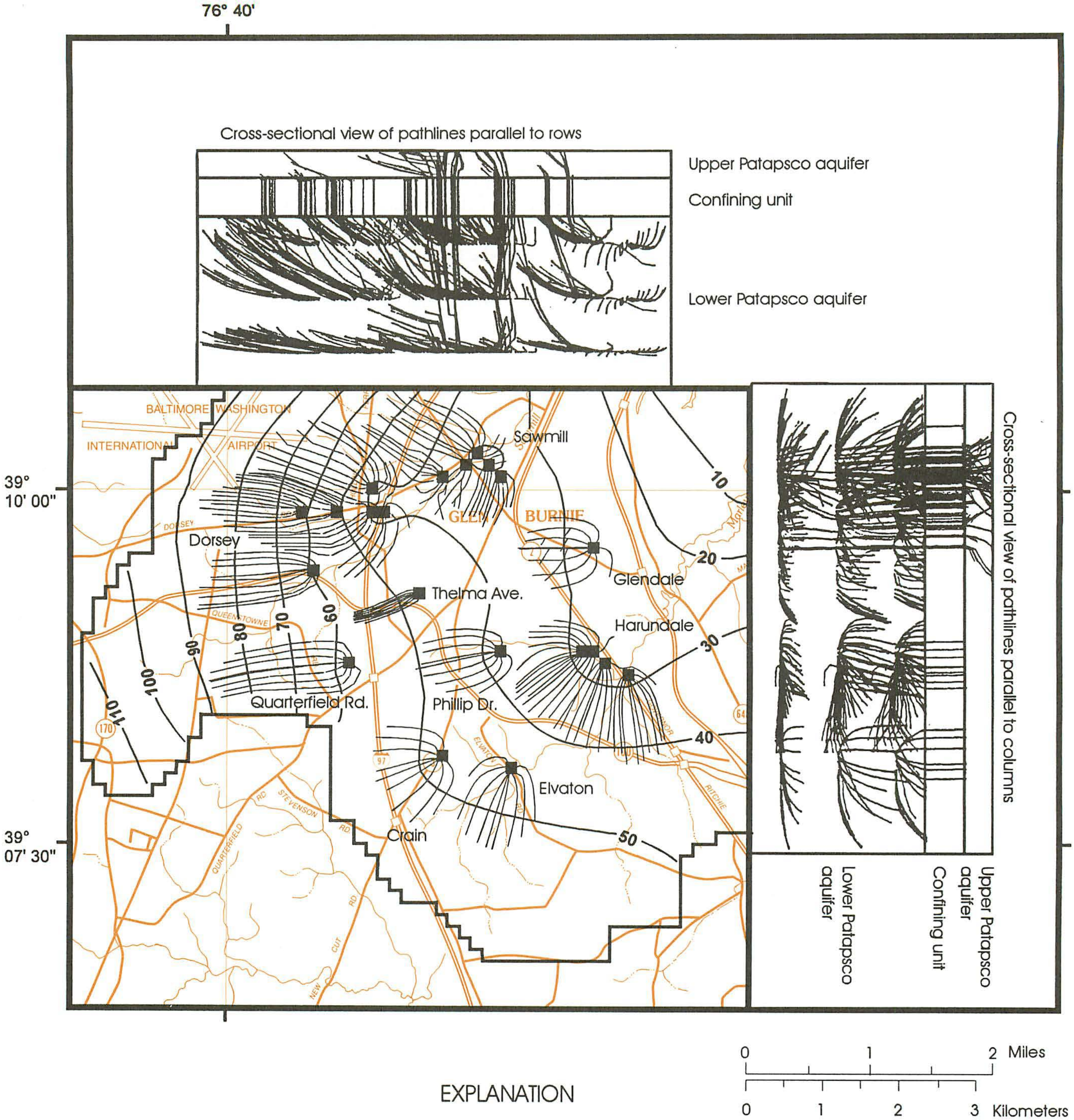
[ft = feet]

Simulation time (in years)	Distance traveled (in ft)	Rate of flow of particles (in ft/year)
10	32	Ranges from
20	56	2.4 to
30	72	3.2

MODFLOW generates volumetric balances for each cell in the model in order to test whether the flux in and out of each cell satisfies the principle of conservation of mass. In this study the model simulations were terminated if the difference in the average inflow and outflow of 100 or more cells exceeded 0.1 percent. In computing a volumetric balance, the amount of flux through each of the six faces of a cell is calculated. Using this feature, the flow into and out of model cells of particular interest, such as pumping cells and water-table cells that represent contaminant sources, may be examined. For example, the volumetric balance for the pumping cell representing Bd 61 (Harundale 4) indicates that 98.8 percent of the inflow occurs as lateral flux from the Lower Patapsco aquifer and only 1.2 percent is vertical leakage from the Upper Patapsco aquifer. No flux crosses the bottom boundary because a no-flow boundary represents the confining unit (the Arundel Clay) that separates the Lower Patapsco from the Patuxent aquifer (fig. 20). The actual distribution of lateral and vertical inflow to pumping cells in the model will vary as a function of the amount of pumpage, the leakance of the overlying confining unit, the position and length of the well screen, the distance to nearby wells, and the distance to ground-water divides. Of the lateral influx supplying Bd 61, 43.8 percent flows from the east, 31.7 percent flows from the south, and 23.4 percent flows from the north; these fluxes represent 98.8 percent of the total influx to the pumping cell. Outflow from pumping cell Bd 61 consists of 84.8 percent pumpage and 15.3 percent flow to the adjacent pumping cell representing well Bd 63.

Forward-tracking particle pathlines from contaminant sources

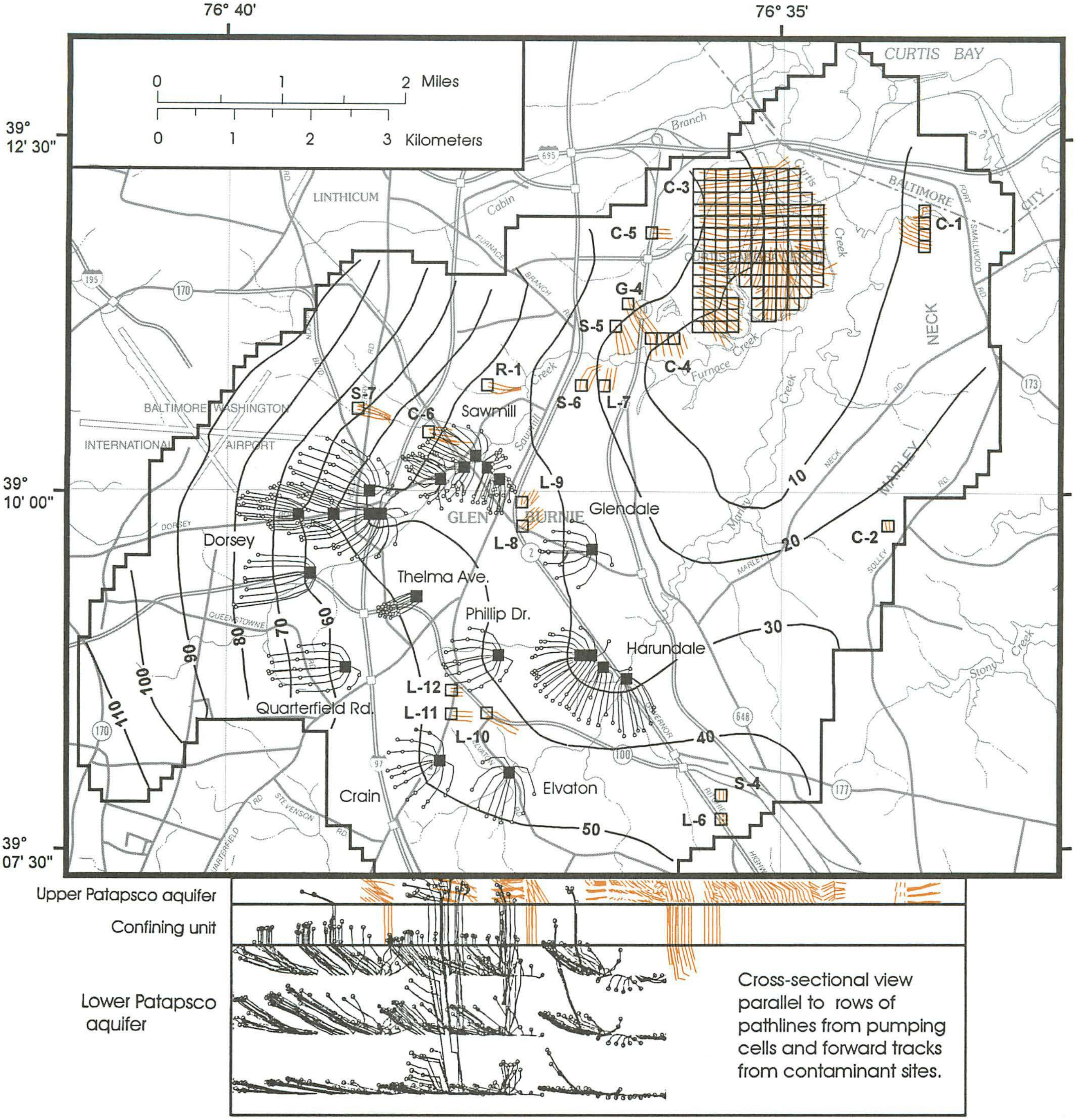
Buried underground storage tanks, superfund sites, landfills, community septic systems, and sewage treatment facilities are potential contaminant sources that could leak hazardous materials to the ground-water system. In the examples shown here, the forward-tracking option of MODPATH is used to analyze the potential for contaminant intrusion to the ground-water system. The locations of potential contaminant sources in the study area were obtained from the Maryland Department of the Environment (fig. 19). In the forward-tracking simulations, particles are placed in water-



EXPLANATION

Dorsey ■	Pumping cell in model layer two (the Lower Patapsco aquifer) and local name of well field.
	Pathlines in plan view backtracked from pumping cell. Some pathlines coincide.
—40—	Simulated line of equal water level, in feet above sea level. Contour interval is 10 feet. Datum is sea level.
	Boundary of the ground-water-flow model.

Figure 56. — Twenty-year pathlines in plan and cross-sectional views backtracked from the public-supply wells pumping at the average 1984-88 pumpage of 9.3 million gallons per day.



EXPLANATION

Dorsey ■ Pumping cell in model layer two (the Lower Patapsco aquifer) and local name of well field.

Pathlines in plan view backtracked from pumping cell. Circles indicate position of endpoints after ten years of pumping. (Some pathlines partially coincide; in some of these cases, two endpoints may appear to occur on one pathline).

L-10 Ten-year forward tracks in plan view from contaminant sites, starter model cell in model layer one (the Upper Patapsco aquifer) and site designation: L = LUST site R = RCRA site C = CERCLA site S = Community septic site G = Ground-water discharge site.

— 40 — Simulated line of equal water level, in feet above sea level. Contour interval is 10 feet. Datum is sea level.

Boundary of the ground-water-flow model.

Figure 57. — Ten-year pathlines forward tracked from contaminant sources and 10-year pathlines back-tracked from the public-supply wells pumping at the average 1984-88 pumpage of 9.3 million gallons per day.

table cells that coincide with the approximate locations of the potential contaminant sources at the water table. Particles are placed in one water-table cell if the area covered by the contaminant source is equal to or smaller than the size of one model cell (500 ft x 500 ft). The liquid underground storage tanks (LUST sites), community septic systems, ground-water discharge permit sites, and RCRA sites in the study area were represented by individual water-table cells. Some superfund (CERCLA) sites and waste disposal sites were depicted with groups of water-table cells that represented the approximate boundary of the property the sites are on. The entire area shown by the groups of water-table cells is not classified as a CERCLA site.

Both 10-year forward-tracked particle pathlines from contaminant sources and 10-year backward-tracked particle pathlines from the public-supply wells are shown in plan and cross-sectional views in figure 57. After 10 years of pumping using the average 1984-88 pumpage, a few pathlines from the C-4 landfill site crossed the confining unit and entered the Lower Patapsco aquifer (fig. 57). However, if the C-4 landfill were to fail, a contaminant leaking from that site would not pose a threat to the public-supply wells in the study area because in the aquifer flow regime site C-4 is downgradient from the public-supply wells. Particles released from LUST sites L-8 and L-9 reached the contact of the water table and the confining unit after 10 years of pumpage (fig. 57). Were these sites not remediated, a contaminant leak could pose a threat to certain public-supply wells because the sites are located in a region of the flow regime that recharges the Sawmill and Glendale well fields. The Sawmill and Glendale well fields have not been pumped since 1989 and 1992 respectively.

The volumetric balance and flux distribution for the cell representing LUST site L-8 (located near the Harundale well field) indicates that inflows to the cell are 38.9 percent from the west, 45.6 percent from the south and 15.6 percent from ground-water recharge. The lateral outflows are 34.0 percent to the east and 39.86 percent to the north. Downward leakage to the Lower Patapsco aquifer is 26.1 percent of the outflow and the rate of downward leakage is 0.0216 ft/d. In comparison, the volumetric balance for the cell representing LUST site L-10 (located near the Elvaton well) indicates that downward leakage is only 10.8 percent of the total outflow and that the rate of downward leakage is 0.0076 ft/d. Pathlines from site L-8 cross the confining unit earlier than the pathlines from site L-10 because the rate of downward leakage at L-8 is three times the rate at L-10 (fig. 57).

Delineation of Zones of Transport Using GPTRAC Semi-Analytical Option

The U.S. EPA WHPA model used in this study is the General Particle Tracking semi-analytical module (GPTRAC) of the WHPA code version 2.1 (Blandford and Huyakorn, 1991). GPTRAC applies an analytical formulation to compute ground-water velocities and trace pathlines. The GPTRAC semi-analytical module was developed to provide an "easy-to-use" method for delineating wellhead protection areas by state and local authorities. The semi-analytical option of the GPTRAC module was used in this study because it is versatile enough to handle the physical flow system of the Lower Patapsco aquifer, and yet requires only basic hydrologic data for model input. In contrast to numerical particle tracking methods, the GPTRAC semi-analytical module does not use output from a flow model. However, the numerical option of GPTRAC can use head distributions output from a ground-water-flow model.

The semi-analytical option of GPTRAC simulates a two-dimensional steady-state flow system in the following: a) an unconfined aquifer with areal recharge, b) a confined aquifer with leakage from the overlying or underlying confining unit, and c) a fully confined aquifer. Barrier or fully penetrating stream boundaries may be simulated. However, only one of these boundaries can be simulated in unconfined aquifers; two boundaries can be simulated in confined aquifers. Output from GPTRAC (version 2.1) consists of plan views of time-related zones of transport delineated by particle pathlines backtracked from production wells (fig. 58). Forward and backward tracking of particles released at sites other than production wells is also an option. Additionally, the effects of well interference are simulated by the GPTRAC module. The input parameters required for the GPTRAC semi-analytic option to simulate leaky-aquifer conditions are listed in table 19.

In order to compare the zones of transport delineated using the GPTRAC semi-analytical option and MODPATH, the aquifer properties and other input data entered into GPTRAC had to be as similar as possible to the values used in MODPATH. One assumption on which the comparison of the GPTRAC and MODPATH is premised is that the MODPATH zones of transport are more accurate than the GPTRAC zones of transport because the MODPATH simulations are based on a calibrated, and in this case verified (over the period 1984-92), three-dimensional ground-water-flow model. Working under this assumption, a certain amount of manipulation of the GPTRAC output based on the MODPATH output was allowed in order to determine how much averaging of flow model parameters was acceptable in deriving average input parameters for GPTRAC. However, once the acceptable amount of averaging was determined, no additional manipulation of input parameters was allowed. This process did not bias the results of the comparisons as much as it may first appear because the aquifer and confining unit hydrologic properties used in the flow model are all derived from field data. This is the same field data that would be available if one used GPTRAC to delineate zones of transport without the benefit of a pre-existing flow model; the underlying assumption is that the aquifer and confining unit properties estimated from the field data would be about the same as those derived from the calibrated flow model.

The GPTRAC semi-analytical module is most applicable to aquifers with homogeneous conditions that can be

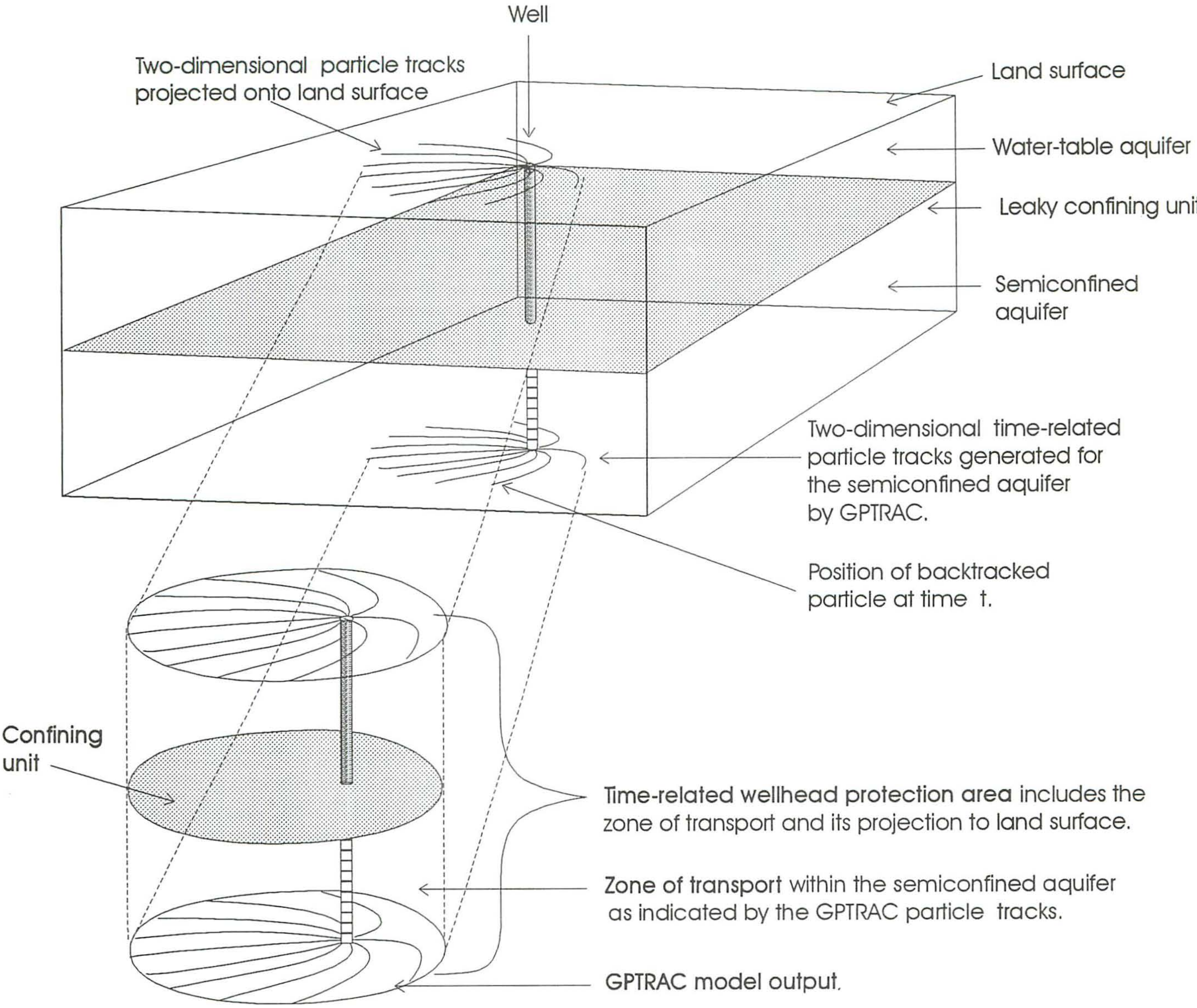


Figure 58. — Schematic showing the application of the GPTRAC model output to the determination of zones of transport and time-related wellhead protection areas in semiconfined aquifers.

represented by one value for each input parameter: transmissivity, confining unit thickness, confining unit vertical hydraulic conductivity, hydraulic gradient and angle of ambient flow. In contrast, MODFLOW-MODPATH can accommodate heterogeneity in the hydrogeologic system. There are three different zones of transmissivity and several different zones of confining unit conductivity in the study area. The hydraulic gradient and angle of ambient flow are not input directly into MODFLOW because they are functions of the head distribution calculated by MODFLOW.

The 21 production wells in the project area were divided into 7 groups in order for GPTRAC to simulate as closely as possible the spatially variable input parameters (tab. 20). The Dorsey, Sawmill, and Harundale well fields were placed into separate groups. The Crain and Elvaton wells form one group as do the Phillip Drive and Quarterfield Road wells. The Glendale and Thelma Avenue wells were simulated as single-well groups because their input parameters were too dissimilar from those of the other groups and each other. The confining unit thickness used in GPTRAC is 35 ft, which is an average of the confining unit thickness used in MODFLOW-MODPATH. The vertical hydraulic conductivity values used in GPTRAC are values derived from each vertical hydraulic conductivity zone in the confining unit of the MODFLOW model. A uniform porosity value of 30 percent is used for the Lower Patapsco aquifer in both the MODPATH and GPTRAC models and also for the Upper Patapsco aquifer in MODPATH.

Table 19. — Input required for the GPTRAC semi-analytic option when simulating leaky-aquifer conditions

Model dimensions
Boundary conditions: none; or barrier and/or fully penetrating stream boundary.
Number of pumping wells
Amount of discharge for each pumping well
Number of recharge wells
Amount of recharge from each recharge well
Location of wells
Aquifer transmissivity
Regional hydraulic gradient
Angle of ambient flow, i.e., the bearing of the pre-pumping regional flow system; the bearing is input as an angle (0-360°) with respect to the orientation of the model, not with respect to the cardinal points.
Aquifer porosity
Confining bed vertical hydraulic conductivity
Confining bed thickness
Time period for simulation
Time value for time-related zone of transport

The GPTRAC simulations were run with no lateral boundaries specified for the Lower Patapsco aquifer. This is the closest approximation to the natural lateral boundary of the aquifer available in GPTRAC. The basal no-flow boundary of GPTRAC is essentially the same as the basal no-flow boundary used by the MODFLOW model. In the GPTRAC module both the semiconfined aquifer and the water-table aquifer start with the same initial head. Leakage through the confining bed is supplied by superposition when pumpage creates a hydraulic gradient between the pumping aquifer (Lower Patapsco) and the constant-head water-table aquifer (Upper Patapsco). In contrast the MODFLOW model has an active water-table aquifer that simulates recharge from precipitation and losses due to evapotranspiration and stream base flow. Flow between the Upper Patapsco aquifer and the Lower Patapsco aquifer occurs through a leaky confining bed which in the MODFLOW simulations may be in either direction.

The transmissivity input to GPTRAC for wells within each group is the same as that used for the comparable area in the flow model. The angle of ambient flow and the hydraulic gradient are an average value only for the wells within each group and therefore more closely represent the actual values for each group of wells. The angle of ambient flow and the hydraulic gradient input to GPTRAC were measured from the model-generated 1965 potentiometric surface map of the Lower Patapsco aquifer (fig. 10). The reason the model-generated 1965 potentiometric surface map was used is that this potentiometric surface was calibrated against the earliest measured water levels for the study area; a potentiometric surface map drawn by hand using the 1965 and earlier measured water levels showed no significant difference from the model-generated map in the vicinity of the wells.

One of the options available in GPTRAC is the ability to overlay zones of transport generated by different simulations. This feature was used to run separate simulations using parameters specific to each group of wells, but only plot pathlines for the group of wells associated with the input parameters specified for that simulation. The individual plots for each group were then superposed to produce a single map showing zones of transport for the entire set of wells in each pumpage scenario. Some of the interference effects between adjacent groups of wells was preserved by simulating all of the wells. The GPTRAC analysis was improved by this method in areas where two groups of wells were close to each other and had similar input parameters, for example, the Dorsey and Sawmill well fields (pl. 7).

The GPTRAC zones of transport for the 1990 pumpage appropriation scenario are a composite of five simulations from the groups listed in table 20 (pls. 5 and 6). The Thelma Avenue well, the Sawmill well field and some of the wells in the Dorsey well field were not included in these simulations because these wells are no longer used. In the scenario that used the average 1984-88 pumpage, all 21 production wells were pumped (pl. 7). The zones of transport generated under this latter scenario are a composite of seven simulations.

Comparison of Zones of Transport Generated by Pumpage in the Lower Patapsco Aquifer

The GPTRAC semi-analytical module used in this study generates zones of transport in the Lower Patapsco aquifer that depict the areal extent through which water moves toward a pumping well under the influence of a cone of depression. Because GPTRAC is a two-dimensional model, it can not actually track recharge particles from the water table and therefore does not differentiate between zones of transport and zones of contribution. Only under the assumption that water leaking through the confining bed is instantaneously recharged from the water-table aquifer (Upper Patapsco aquifer) can the output from GPTRAC be considered a zone of contribution.

The MODPATH numerical program used in this study generates three-dimensional zones of transport surrounding pumping wells in the Lower Patapsco aquifer. Backtracked pathlines may cross the upper confining unit of the Lower Patapsco aquifer and a portion of the zone of transport may

Table 20. — Parameters of the Lower Patapsco aquifer used for the well fields in the GPTRAC module of the WHPA code to generate time-related zones of transport

[ft = feet; ft/d = feet per day; ft^2/d = feet squared per day]

Anne Arundel County Department of Public Works well name (Maryland Geological Survey well number)	Trans-missivity (in ft^2/d)	Aquifer thickness (in ft)	Aquifer porosity	Hydraulic gradient	Angle of ambient flow in WHPA degree (and true bearing)	Confining unit thickness (in ft)	Confining unit vertical hydraulic conduc-tivity (in ft/d)
Dorsey well field[1]	4,500	125	0.3	0.004	4 (N86°E)	35	3.9×10^{-2}
Sawmill well field[2]	4,500	125	0.3	0.0033	18 (N72°E)	35	3.9×10^{-2}
Glendale well (AA Bd 103)	4,500	125	0.3	0.003	20 N70°E)	35	3.0×10^{-2}
Harundale well field[3]	6,000	185	0.3	0.003	45 (N45°E)	35	3.0×10^{-2}
Phillip Drive well (AA Bd 101)	6,000	185	0.3	0.003	14 (N76°E)	35	3.0×10^{-2}
Quarterfield Rd. well (AA Bd 109)	6,000	185	0.3	0.003	14 (N76°E)	35	3.0×10^{-2}
Crain Highway well (AA Bd 105)	6,000	185	0.3	0.0026	20 (N70°E)	35	3.0×10^{-2}
Elvaton well (AA Bd 107)	6,000	185	0.3	0.0026	20 (N70°E)	35	3.0×10^{-2}
Thelma Avenue well (AA Bd 108)	6,000	185	0.3	0.0029	32 (N58°E)	35	3.0×10^{-2}

[1] Dorsey well field includes: Dorsey 1 (AA Bd 55), Dorsey 3 (AA Bd 56), Dorsey 4 (AA Ad 76), Dorsey 11 (AA Bd 64), Dorsey 14 (AA Bd 92), and Dorsey 15 (AA Bd 95).

[2] Sawmill well field includes: Sawmill 3 (AA Ad 23), Sawmill 4 (AA Ad 40), Sawmill 5 (AA Ad 41), Sawmill 6 (AA Ad 67), Sawmill 7 (AA Ad 68).

[3] Harundale well field includes: Harundale 1 (AA Bd 37), Harundale 2 (AA Bd 37), Harundale 3 (AA Bd 63), and Harundale 4 (AA Bd 61) or its replacement, Harundale 4R (AA Bd 160).

reach the water table where recharge occurs. These areas of the water-table aquifer are defined as zones of contribution in this report.

The Lower Patapsco zones of transport generated by GPTRAC are displayed in plan view. Zones of transport generated by MODPATH are likewise displayed and compared to those made by GPTRAC under the 1990 pumpage appropriation scenario and average 1984-88 pumpage scenario. Plan views of MODPATH zones of contribution in the Upper Patapsco aquifer are also shown, but they are not quantitatively compared to the GPTRAC output in this report (figs. 52-54).

The plan view of time-related zones of transport generated using GPTRAC and MODPATH are shown on the following plates: plate 5 shows the 10-year time-related zone of transport for the 1990 pumpage appropriation, plate 6 shows the 20-year time-related zone of transport for the 1990 pumpage appropriation, and plate 7 shows the 10-year time-related zone of transport for the average 1984-88 pumpage scenario. The MODPATH particle tracks are shown in black with the zones of transport outlined in black. The GPTRAC zones of transport are delineated by the particle pathlines shown in brown. The pumpage applied to the wells in the simulations using the 1990 pumpage appropriation and average 1984-88 pumpage are listed on tables 14 and 15.

The plan views of 10 and 20-year zones of transport generated by the GPTRAC and MODPATH were compared on the basis of three quantitative measures. The measures are: 1) the amount of area covered by the zones, 2) the percentage coincident area of the zones—this is a measure of the degree to which the GPTRAC and MODPATH zones of transport cover the same area, and 3) the degree of similarity of the shapes of the zones of transport as indicated by their length to width ratios.

Model scenario using the 1990 pumpage appropriation

Tables 21 to 24 compare the plan views of 10 and 20-year zones of transport in the Lower Patapsco aquifer generated by GPTRAC to those generated by MODPATH using the 1990 pumpage appropriation. Table 25 compares the size of the areas (in plan view) of the 10-year to the 20-year GPTRAC zones of transport and also compares the areas (in plan view) of the 10-year to 20-year MODPATH zones of transport.

Six of the seven 10-year GPTRAC zones of transport covered less area, ranging from 17 to 36 percent less, than the 10-year MODPATH zones of transport (pl. 5; tabs. 21 and 22, col. 1). Only the GPTRAC zone of transport for the Glendale well (Bd 103) covered more area (18 percent more) than the

Table 21. — Comparison of the area covered by the 10-year zones of transport generated using the 1990 pumpage appropriation and wells active in 1990

[mi^2 = square miles]

Well field Anne Arundel County Department of Public Works well name, (Maryland Geological Survey well number)	Area of GPTRAC zones of transport in mi^2 and in (acres)	Area of MODPATH zones of transport in mi^2 and in (acres)	Area of the GPTRAC zone of transport minus the area of the MODPATH zone of transport in mi^2 and in (acres)	Total area covered by the union of the GPTRAC and MODPATH zones of transport in mi^2 and in (acres)[1]	Coincident area of the GPTRAC and MODPATH zones of transport in mi^2 and in (acres)[2]
Dorsey (Dorsey 1, AA Bd 55) (Dorsey 3, AA Bd 56) (Dorsey 11, AA Bd 64) (Dorsey 14, AA Bd 92)	0.977 (625)	1.199 (767)	-0.222 (-142)	1.199 (767)	0.977 (625)
Glendale well (AA Bd 103)	0.288 (184)	0.245 (157)	0.043 (28)	0.294 (188)	0.232 (149)
Harundale (Harundale 1, AA Bd 36) (Harundale 2, AA Bd 37) (Harundale 3, AA Bd 63) (Harundale 4, AA Bd 61)	0.552 (353)	0.859 (550)	-0.307 (-196)	0.859 (550)	0.552 (353)
Phillip Drive well (AA Bd 101)	0.176 (113)	0.224 (143)	-0.048 (-31)	0.237 (152)	0.165 (106)
Quarterfield Rd. well (AA Bd 109)	0.201 (129)	0.245 (157)	-0.044 (-28)	0.270 (173)	0.176 (113)
Crain Highway well (AA Bd 105)	0.205 (131)	0.248 (159)	-0.043 (-28)	0.260 (166)	0.195 (125)
Elvaton well (AA Bd 107)	0.264 (169)	0.399 (255)	-0.135 (-86)	0.399 (255)	0.264 (169)

[1] In set notation: GPTRAC area $\cup$ MODPATH area.
[2] In set notation: GPTRAC area $\cap$ MODPATH area.

Table 22. — Comparison of 10-year zones of transport generated with the 1990 pumpage appropriation and wells active in 1990 using various measures

Well field Anne Arundel County Department of Public Works well name, (Maryland Geological Survey well number)	Percentage difference in the area of the GPTRAC zone of transport with respect to the MODPATH zone of transport[1]	Percentage difference in the area of the MODPATH zone of transport with respect to the GPTRAC zone of transport[2]	Percentage of coincident area of GPTRAC and MODPATH zones of transport with respect to the area covered by the union of the two zones of transport[3]
Dorsey (Dorsey 1, AA Bd 55) (Dorsey 3, AA Bd 56) (Dorsey 11, AA Bd 64) (Dorsey 14, AA Bd 92)	-19	23	81
Glendale well (AA Bd 103)	18	-15	79
Harundale (Harundale 1, AA Bd 36) (Harundale 2, AA Bd 37) (Harundale 3, AA Bd 63) (Harundale 4, AA Bd 61)	-36	56	64
Phillip Drive well (AA Bd 101)	-21	27	70
Quarterfield Rd. well (AA Bd 109)	-18	22	65
Crain Highway well (AA Bd 105)	-17	21	75
Elvaton well (AA Bd 107)	-34	51	66

Variables in the following formulas are as follows:

G = area of GPTRAC zone of transport
M = area of MODPATH zone of transport
G ∩ M = the area belonging to both G and M, the area of overlap.
G ∪ M = the area belonging to either G or M, the union of the two areas.

[1] Percentage difference of the GPTRAC area with respect to the MODPATH area: ((G-M) / M) X 100
[2] Percentage difference of the MODPATH area with respect to the GPTRAC area: ((M-G) / G) X 100
[3] Percentage of coincident area of the MODPATH and GPTRAC zones of transport with respect to the area covered by the union of the two zones: ((G ∩ M) / (G ∪ M)) X 100

MODPATH zone of transport. The percentage coincident area of the GPTRAC and MODPATH zones of transport under this pumpage scenario ranged from 64 to 81 percent (tab. 22, col. 3).

In general the 20-year zones of transport generated with GPTRAC and MODPATH using the 1990 pumpage appropriation were similar to the 10-year zones of transport (pl. 6; tabs. 23 and 24). However, for some of the zones of transport, significant differences occurred with the increased simulation time. Except for the zone of transport of the Glendale well, the area covered by the GPTRAC zones of transport ranged from 10 to 42 percent less than the MODPATH zones of transport; the GPTRAC zone of transport for the Glendale well covered 30 percent more area than the corresponding MODPATH zone of transport (tab. 24, col. 1). The percentage coincident area for the 20-year zones of transport ranged from 54 to 86 percent (tab. 24, col. 3). In four of the seven zones of transport, the percentage of coincident area in the 20-year analysis was lower by 5 to 12 percent than in the corresponding 10-year zones of transport; one zone of transport showed no significant change, and two showed increases of about 8 and 9 percent.

The GPTRAC and MODPATH zones of transport showing the greatest difference in size in both the 10 and 20-year comparisons were those for the Harundale well field. In the 20-year simulation, the GPTRAC zone of transport was 42 percent smaller than the MODPATH zone of transport (tab. 24, col. 1); in the 10-year simulation, the GPTRAC zone of transport was 36 percent smaller than the MODPATH zone of transport (tab. 22, col. 1). The size difference between the GPTRAC and MODPATH zones of transport is due to the widely differing angle of ambient flow for the four wells that comprise the Harundale well field and other spatial differences in aquifer parameters such as hydraulic gradient. The angle of ambient flow for the Harundale well field ranges from almost due east to due north because of the location of the well field in the roughly elliptically shaped Marley Creek basin. MODPATH simulates the spatial variation in these parameters. In contrast, an average value for the angle of ambient flow was input to GPTRAC so that the Harundale well field could be simulated as one entity. The restriction to one angle of ambient flow limited the effectiveness of GPTRAC to simulate the flow system at the Harundale well field; this limitation became more significant as the simulation time was lengthened

Table 23. — Comparison of the area covered by the 20-year zones of transport generated with the 1990 pumpage appropriation and wells active in 1990

[mi² = square miles]

Well field Anne Arundel County Department of Public Works well name, (Maryland Geological Survey well number)	Area of GPTRAC zones of transport in mi² and in (acres)	Area of MODPATH zones of transport in mi² and in (acres)	Area of the GPTRAC zone of transport minus the area of the MODPATH zone of transport in mi² and in (acres)	Total area covered by the union of the GPTRAC and MODPATH zones of transport in mi² and in (acres)[1]	Coincident area of the GPTRAC and MODPATH zones of transport in mi² and in (acres)[2]
Dorsey (Dorsey 1, AA Bd 55) (Dorsey 3, AA Bd 56) (Dorsey 11, AA Bd 64) (Dorsey 14, AA Bd 92)	1.449 (927)	1.944 (1,244)	-0.495 (-317)	2.026 (1297)	1.406 (900)
Glendale well (AA Bd 103)	0.475 (304)	0.366 (234)	0.109 (70)	0.494 (316)	0.356 (228)
Harundale (Harundale 1, AA Bd 36) (Harundale 2, AA Bd 37) (Harundale 3, AA Bd 63) (Harundale 4, AA Bd 61)	0.943 (604)	1.613 (1,032)	-0.670 (-429)	1.611 (1,031)	0.943 (604)
Phillip Drive well (AA Bd 101)	0.333 (213)	0.370 (237)	-0.037 (-24)	0.406 (260)	0.316 (202)
Quarterfield Rd. well (AA Bd 109)	0.379 (243)	0.468 (300)	-0.089 (-57)	0.552 (353)	0.300 (192)
Crain Highway well (AA Bd 105)	0.374 (239)	0.423 (271)	-0.049 (-31)	0.405 (259)	0.347 (222)
Elvaton well (AA Bd 107)	0.476 (305)	0.621 (397)	-0.145 (-93)	0.650 (416)	0.433 (277)

[1] In set notation: GPTRAC area ∪ MODPATH area.
[2] In set notation: GPTRAC area ∩ MODPATH area.

and the size of the zone of transport increased. If the Harundale well field simulation had been divided into separate simulations for each well and then superposed, the zone of transport for the Harundale well field would have been more similar to the MODPATH zone of transport.

The effects of increasing the time variable from 10 to 20 years on the size of the zones of transport generated by the same method are shown in table 25. For the GPTRAC zones of transport, the 20-year zones of transport cover an area that is 48 to 89 percent larger than the 10-year GPTRAC zones of transport (tab. 25, col. 3). Similarly, the 20-year MODPATH zones of transport are 49 to 91 percent larger than the 10-year MODPATH zones of transport (tab. 25, col. 6). Although the overall increase in the area of the GPTRAC 20-year zones of transport and the area of the 20-year MODPATH zones of transport is comparable, the percentage increase generally differed between corresponding zones of transport. The most likely cause for the different percentage increases in area (when comparing corresponding zones of transport) is the different ways the two methods handle leakage from the overlying Upper Patapsco aquifer. GPTRAC uses a uniform confining unit conductivity and thickness while MODFLOW-MODPATH responds to spatial variability in these parameters. Also, GPTRAC assumes a constant head in the water-table aquifer whereas MODFLOW simulates an active water table with both inflow and outflow.

The length to width ratio of a zone of transport provides a measure of its shape (Bair and Roadcap, 1992). For the mostly regularly shaped zones of transport described in this report, a length to width ratio of one represents a roughly circular zone of transport; a length to width ratio of two represents a roughly elliptical zone of transport with a major axis twice the length of the minor axis. The length of the zone of transport is defined as the long axis of the zone of transport; the width is defined as the length of a line orthogonal to the long axis drawn at the widest point of the zone of transport. The length to width ratio provides a simple measure of the similarity of the shape of a zone of transport generated by different methods. For more irregularly shaped areas, such as the zone of contribution simulated by MODPATH in figure 47, a more comprehensive measure of shape should be used.

Comparison of the length to width ratio of zones of 10-year zones of transport generated with the 1990 pumpage appropriation indicates that the shapes of the GPTRAC and MODPATH zones are very similar (pl. 5). Only the zones of transport for the Quarterfield Road well show significant shape

Table 24. — Comparison of 20-year zones of transport generated with the 1990 pumpage appropriation and wells active in 1990 using various measures[1]

Well field Anne Arundel County Department of Public Works well name, (Maryland Geological Survey well number)	Percentage difference in the area of the GPTRAC zone of transport with respect to the MODPATH zone of transport	Percentage difference in the area of the MODPATH zone of transport with respect to the GPTRAC zone of transport	Percentage of coincident area of GPTRAC and MODPATH zones of transport with respect to the area covered by the union of the two zones of transport
Dorsey (Dorsey 1, AA Bd 55) (Dorsey 3, AA Bd 56) (Dorsey 11, AA Bd 64) (Dorsey 14, AA Bd 92)	-25	34	69
Glendale well (AA Bd 103)	30	-25	72
Harundale (Harundale 1, AA Bd 36) (Harundale 2, AA Bd 37) (Harundale 3, AA Bd 63) (Harundale 4, AA Bd 61)	-42	71	59
Phillip Drive well (AA Bd 101)	-10	11	78
Quarterfield Rd. well (AA Bd 109)	-19	23	54
Crain Highway well (AA Bd 105)	-12	13	86
Elvaton well (AA Bd 107)	-23	30	67

[1] See table 23 for explanation of measures used to compare zones of transport.

differences; the MODPATH zone of transport is more elongated and more narrow than the GPTRAC zone of transport (tab. 26; pl. 5). These differences become more pronounced in the 20-year zones of transport (pl. 6, tab. 27). Both the MODPATH and GPTRAC zones of transport for the Quarterfield Road well responded to the increased simulation time by becoming more elongated, but the 20-year MODPATH zone of transport became much more elongated than the 20-year GPTRAC zone of transport; the 20-year MODPATH zone of transport for the Quarterfield Road well has a length to width ratio of 3.2 while the length to width ratio of the 20-year GPTRAC zone of transport is 1.7. The greater differences of shape were caused by flow lines in the MODPATH analysis reaching areas of the aquifer with steeper hydraulic gradients and a consequent increase in the rate of flow and distance travelled by the backtracked particle. GPTRAC, however, only can use one value for the hydraulic gradient and it responded accordingly. The other 20-year MODPATH and GPTRAC zones of transport remain similar in shape, although they all showed some increase in shape difference when compared to the shape difference of their 10-year counterparts.

Model scenario using the average 1984-88 pumpage

The 10-year zones of transport generated by GPTRAC and MODPATH using the average 1984-88 pumpage are compared in tables 28 and 29. This scenario constitutes a historical pumpage scenario because the Sawmill well field, two wells at the Dorsey well field and the Thelma Avenue well were pumped regularly prior to and during this period, but were permanently discontinued by 1990. Seven of the nine GPTRAC zones of transport in the Lower Patapsco aquifer covered less area (14 to 33 percent less) than the corresponding MODPATH zones of transport (pl. 7, tabs. 28 and 29, col. 1). The GPTRAC zone of transport for the Glendale well, however, covered about 11 percent more area than the MODPATH zone of transport, and the GPTRAC zone of transport for the Sawmill well field was about 3 percent larger than the MODPATH zone of transport (tab. 29, col. 1). In eight of the nine zones of transport, the percentage of coincident area of the MODPATH and GPTRAC zones of transport ranges from 56 to 84 percent (tab. 29, col. 3).

In the zone of transport for the Thelma Avenue well, the percentage of coincident area is only 12 percent (tab. 29, col. 3) because the manually measured angle of ambient flow used in GPTRAC is not the same as the angle of ambient flow implicit in the head distribution used by MODPATH. At the Thelma Avenue well, the angle of ambient flow had a disproportionate effect on the orientation of the GPTRAC zone of transport because the pumpage rate was comparatively low. Overlaying several GPTRAC simulations using different angles of ambient flow would be a prudent approach when computing zones of transport for wells that derive most of

Table 25. — Comparison of the area covered by the 10 and 20-year zones of transport generated by each method using the 1990 pumpage appropriation and wells active in 1990

[mi^2 = square miles]

Well field Anne Arundel County Department of Public Works well name, (Maryland Geological Survey well number)	Area of 10-year GPTRAC zones of transport in mi^2 and in (acres)	Area of 20-year GPTRAC zones of transport in mi^2 and in (acres)	Percentage difference of 20-year GPTRAC with respect to the 10-year GPTRAC zone of transport[1]	Area of 10-year MODPATH zones of transport in mi^2 and in (acres)	Area of 20-year MODPATH zones of transport in mi^2 and in (acres)	Percentage difference of 20-year MODPATH zone of transport with respect to the 10-year MODPATH zone[2] of transport
Dorsey (Dorsey 1, AA Bd 55) (Dorsey 3, AA Bd 56) (Dorsey 11, AA Bd 64) (Dorsey 14, AA Bd 92)	0.977 (625)	1.449 (927)	48	1.199 (767)	1.944 (1,244)	62
Glendale well (AA Bd 103)	0.288 (184)	0.475 (304)	65	0.245 (157)	0.366 (234)	49
Harundale (Harundale 1, AA Bd 36) (Harundale 2, AA Bd 37) (Harundale 3, AA Bd 63) (Harundale 4, AA Bd 61)	0.552 (353)	0.943 (604)	71	0.878 (562)	1.613 (1,032)	84
Phillip Drive well (AA Bd 101)	0.176 (113)	0.333 (213)	89	0.224 (143)	0.370 (237)	65
Quarterfield Rd. well (AA Bd 109)	0.201 (129)	0.379 (243)	89	0.245 (157)	0.468 (300)	91
Crain Highway well (AA Bd 105)	0.205 (131)	0.374 (239)	82	0.248 (159)	0.423 (271)	71
Elvaton well (AA Bd 107)	0.264 (169)	0.476 (305)	80	0.399 (255)	0.621 (397)	56

[1] $(G_{20}-G_{10}) / G_{10} \times 100$
where: G_{10} is the area covered by the 10-year GPTRAC zone of transport and G_{20} is the area covered by the 20-year GPTRAC zone of transport.

[2] $(M_{20}-M_{10}) / M_{10} \times 100$
where: M_{10} is the area covered by the 10-year MODPATH zone of transport and M_{20} is the area covered by the 20-year MODPATH zone of transport.

Table 26. — Comparison of the shape of the 10-year zones of transport generated using the 1990 pumpage appropriation

[ft = feet]

Zone of transport	GPTRAC			MODPATH		
	length (in ft)	width (in ft)	length/width	length (in ft)	width (in ft)	length/width
Dorsey Rd.	7,500	4,600	1.6	7,800	5,600	1.4
Glendale	3,600	2,800	1.3	3,400	2,600	1.3
Harundale	5,000	4,000	1.3	7,000	4,600	1.5
Phillip Drive	2,800	2,400	1.2	3,200	2,600	1.2
Quarterfield Rd.	3,000	2,400	1.3	4,000	2,200	1.8
Crain Highway	2,800	2,400	1.2	3,000	2,800	1.1
Elvaton	3,200	2,800	1.1	4,200	3,400	1.2

Table 27. — Comparison of the shape of the 20-year zones of transport generated using the 1990 pumpage appropriation

[ft = feet]

Zone of transport	GPTRAC			MODPATH		
	length (in ft)	width (in ft)	length/width	length (in ft)	width (in ft)	length/width
Dorsey Rd.	9,600	5,800	1.7	9,600	7,600	1.3
Glendale	5,000	3,400	1.5	4,600	2,700	1.7
Harundale	6,000	5,600	1.1	9,600	6,400	1.5
Phillip Drive	4,000	2,800	1.4	4,600	2,800	1.6
Quarterfield Rd.	4,800	2,800	1.7	7,000	2,200	3.2
Crain Highway	4,200	3,000	1.4	4,200	4,000	1.1
Elvaton	4,600	3,800	1.2	4,600	4,600	1.0

Table 28. — Comparison of the area covered by the 10-year zones of transport generated with the average 1984-88 pumpage

[mi^2 = square miles]

Well field Anne Arundel County Department of Public Works well name, (Maryland Geological Survey well number)	Area of GPTRAC zones of transport in mi^2 and in (acres)	Area of MODPATH zones of transport in mi^2 and in (acres)	Area of the GPTRAC zone of transport minus the area of the MODPATH zone of transport in mi^2 and in (acres)	Total area covered by the union of the GPTRAC and MODPATH zones of transport in mi^2 and in (acres)[1]	Coincident area of the GPTRAC and MODPATH zones of transport in mi^2 and in (acres)[2]
Dorsey (Dorsey 1, AA Bd 55) (Dorsey 3, AA Bd 56) (Dorsey 4, AA Ad 76) (Dorsey 11, AA Bd 64) (Dorsey 14, AA Bd 92) (Dorsey 15, AA Bd 95)	1.037 (664)	1.211 (775)	-0.174 (-111)	1.264 (809)	0.979 (627)
Glendale well (AA Bd 103)	0.275 (176)	0.247 (158)	0.028 (18)	0.286 (183)	0.231 (148)
Sawmill (Sawmill 3, AA Ad 23) (Sawmill 4, AA Ad 40) (Sawmill 5, AA Ad 41) (Sawmill 6, AA Ad 67) (Sawmill 7, AA Ad 68)	0.504 (323)	0.488 (312)	0.016 (10)	0.539 (345)	0.451 (289)
Harundale (Harundale 1, AA Bd 36) (Harundale 2, AA Bd 37) (Harundale 3, AA Bd 63) (Harundale 4, AA Bd 61)	0.440 (282)	0.603 (386)	-0.163 (-104)	0.627 (401)	0.413 (264)
Phillip Drive well (AA Bd 101)	0.174 (111)	0.211 (135)	-0.037 (-24)	0.224 (143)	0.158 (101)
Quarterfield Rd. well (AA Bd 109)	0.209 (134)	0.245 (157)	-0.036 (-23)	0.301 (193)	0.169 (108)
Crain Highway well (AA Bd 105)	0.228 (146)	0.265 (170)	-0.037 (-24)	0.298 (191)	0.192 (123)
Elvaton well (AA Bd 107)	0.166 (106)	0.234 (150)	-0.068 (-44)	0.248 (159)	0.155 (99)
Thelma Avenue (AA Bd 108)	0.033 (21)	0.049 (31)	-0.016 (-10)	0.077 (49)	0.009 (6)

[1] In set notation: GPTRAC area $\cup$ MODPATH area.
[2] In set notation: GPTRAC area $\cap$ MODPATH area.

Table 29. — Comparison of 10-year zones of transport generated with the average 1984-88 pumpage using various measures[1]

Well field Anne Arundel County Department of Public Works well name, (Maryland Geological Survey well number)	Percentage difference in the area of the GPTRAC zone of transport with respect to the MODPATH zone of transport	Percentage difference in the area of the MODPATH zone of transport with respect to the GPTRAC zone of transport	Percentage of coincident area of GPTRAC and MODPATH zones of transport with respect to the area covered by the union of the two zones of transport
Dorsey (Dorsey 1, AA Bd 55) (Dorsey 3, AA Bd 56) (Dorsey 4, AA Ad 76) (Dorsey 11, AA Bd 64) (Dorsey 14, AA Bd 92) (Dorsey 15, AA Bd 95)	-14	17	78
Glendale well (AA Bd 103)	11	-10	81
Sawmill (Sawmill 3, AA Ad 23) (Sawmill 4, AA Ad 40) (Sawmill 5, AA Ad 41) (Sawmill 6, AA Ad 67) (Sawmill 7, AA Ad 68)	3	-3	84
Harundale (Harundale 1, AA Bd 36) (Harundale 2, AA Bd 37) (Harundale 3, AA Bd 63) (Harundale 4, AA Bd 61)	-27	37	66
Phillip Drive well (AA Bd 101)	-18	21	71
Quarterfield Rd. well (AA Bd 109)	-15	17	56
Crain Highway well (AA Bd 105)	-14	16	64
Elvaton well (AA Bd 107)	-29	41	63
Thelma Avenue (AA Bd 108)	-33	48	12

[1] See table 22 for explanation of measures used to compare and contrast zones of transport.

their water from intersecting ambient ground-water flow. In the case of the Thelma Avenue well, overlapping two additional runs with angles of ambient flow that differed by ±10 degrees from the originally determined angle would have ensured inclusion of all the area contributing ground water to the well in the zone of transport. The angle of ambient flow is less critical when using GPTRAC to determine zones of transport for wells that have pumpage of sufficient magnitude to effect significantly the path of ground-water flow near the well.

SUMMARY

The hydrogeologic framework of the Sawmill-Furnace Creek and Marley Creek basins in northern Anne Arundel County was initially described in Achmad (1991). The framework was refined in this project as a result of more detailed hydrogeologic mapping using additional bore-hole data. Hydrogeologic mapping identified areas in the semi-confined Lower Patapsco aquifer that potentially are the most vulnerable to contaminants released into the water-table aquifer (Upper Patapsco aquifer). The Dorsey and Crain well fields are located in the most vulnerable areas. In these areas the confining unit separating the aquifers is thinner and more sandy than in other parts of the basin and clays do occur at land surface. The other well fields are located in areas where contaminants are less likely to reach the Lower Patapsco aquifer. The direction of ground-water flow and the head differences between the Upper and Lower Patapsco aquifers in the vicinity of a well field are other factors that determine the vulnerability of public-supply wells. In regions where flow

is upward from the Lower Patapsco aquifer to the Upper Patapsco aquifer, the Lower Patapsco aquifer is considerably less vulnerable to contamination than are upgradient areas or areas near production wells where downward leakage to the Lower Patapsco aquifer occurs.

The overall water quality of the Lower Patapsco aquifer is good, although some contaminants have been determined at several sites. The water has no dominant cation and the dominant anions are chloride and nitrate. The total dissolved solids are low, generally less than 50 mg/L; the water is slightly acidic and low in hardness. Comparison of water samples from the mid-1940s with samples from 1991 suggest that concentrations of both nitrate and chloride have increased in parts of the aquifer during the last 50 years; at present neither of these substances are above U.S. EPA standards. The parts of the Lower Patapsco aquifer that have the highest concentration of contaminants coincide with the more vulnerable regions of the aquifer. In 1993 concentrations of tetrachloroethylene (an industrial solvent) were detected in the Glendale well that exceeded the U.S. EPA maximum contaminant level (5 µg/L).

The ground-water-flow model described in Achmad (1991) was updated and verified through the period 1984-92 using monthly data in order to simulate seasonal changes in recharge, evapotranspiration and pumpage. Output from the flow model was used to generate steady-state head distributions for the Lower and Upper Patapsco aquifers under pumpage scenarios that represent the 1990 pumpage appropriation (9.15 Mgal/d), the average 1984-88 pumpage (9.32 Mgal/d) and the 1992 pumpage (5.30 Mgal/d) applied to the well fields in use throughout 1992. The head distributions generated by the flow model were input to the MODPATH particle tracking program in order to determine the zones of contribution (recharge areas) and time-related zones of transport for the public-supply wells in the Lower Patapsco aquifer. Ten and twenty-year zones of transport were generated for the well fields using the 1990 pumpage appropriation and 1984-88 pumpage.

Zones of transport in the Lower Patapsco aquifer generated with MODPATH were compared on the basis of the size and shape of the areal plan view with zones of transport made with the semi-analytical GPTRAC module of the U.S. EPA WHPA code (version 2.1). The MODPATH zones of transport are considered more realistic than the GPTRAC zones of transport because the MODPATH zones are based on data from a calibrated (for the period 1965-92) ground-water-flow model. The aquifer parameters input to GPTRAC were based on those used in the MODFLOW model and are as similar as possible to those input to MODPATH; this allowed a valid comparison of the output of the two models. Differences between the zones of transport generated by the two methods are primarily due to the capability of MODFLOW-MODPATH to simulate heterogeneous, multi-layered aquifer systems and complex boundary conditions that cannot be simulated with GPTRAC. However, the more homogeneous the aquifer system is within the zone of transport, the more closely the GPTRAC zones of transport approximate the MODPATH zones of transport.

Plan views of the zones of transport generated by the two techniques are generally similar, although there are differences between the zones. The seven 10-year zones of transport generated by GPTRAC using the 1990 pumpage appropriation (9.15 Mgal/d) range from 36 percent smaller to 18 percent larger in area than the corresponding MODPATH zones of transport. The percentage of coincident area of these 10-year MODPATH and GPTRAC zones of transport range from 64 to 81 percent. Differences between zones increased when the simulation time was increased to 20 years. The 20-year GPTRAC zones of transport were 42 percent smaller to 30 percent larger than their corresponding MODPATH zones of transport. The most significant differences occurred in the size and shape of the corresponding MODPATH and GPTRAC 20-year zones of transport for the Quarterfield Road well and the Harundale well field. The percentage of coincident area of the 20-year MODPATH and GPTRAC zones of transport range from 54 to 86 percent. Results of the 10-year zone of transport comparison using the average 1984-88 pumpage (9.3 Mgal/d) are comparable to the results of the comparisons made under the 1990 pumpage appropriation scenario.

The three-dimensional capability of MODPATH was used to backtrack particle pathlines to the water table in order to delineate zones of contribution (recharge areas) in the Upper Patapsco aquifer (the water-table aquifer) for the production wells in the Lower Patapsco aquifer. The zones of contribution obtained using the 1990 pumpage appropriation covered about half the area between the production wells and the northwestern, western and southwestern basin divides. At lower pumpage rates, the size of the zones of contribution are smaller. Simulated recharge from the zones of contribution reach the public-supply wells in 10 to 60 years. GPTRAC was not used to delineate zones of contribution in the water table because GPTRAC is a two-dimensional model that cannot simulate zones of contribution in multi-layered aquifer systems.

Most of the known sites of ground-water contamination are downgradient from the public-supply wells and do not pose a threat under the pumpage conditions simulated. Several LUST sites and one RCRA site are located upgradient from the public-supply wells. Particle tracking indicates that unremediated ground water from these sites could potentially affect downgradient public-supply wells at the Sawmill (now abandoned) and Glendale well fields.

All of the ground-water samples collected in 1991 from the Upper and Lower Patapsco aquifers had detectable amounts of tritium. All but one of the samples from the Lower Patapsco aquifer must contain a component of post-1945 water; the one exception must have a component of post-1936 water. Even though precise tritium-based ages of the ground water could not be determined, all of the tritium determinations were consistent with the particle tracking analyses. In conjunction with particle tracking analyses, the tritium data suggest that the samples collected at the Dorsey and Sawmill well fields in 1991 probably had a large component of "post-bomb spike" water, which entered the ground-water system after 1961. Water produced from the Elvaton and Harundale well fields in 1991 is the oldest water sampled from the Lower Patapsco aquifer in the project area. The samples from these wells are probably a composite of pre-1945 and post-1945 water. None of the samples collected from the Patuxent aquifer had detectable amounts of tritium; this indicates that water from the Patuxent aquifer in the project area is older than water from both Patapsco aquifers. Also, it indicates that there is little leakage through the confining unit (the Arundel Clay) that separates the Patuxent and Lower Patapsco aquifers.

CONCLUSIONS

Detailed hydrogeologic mapping and a correct conceptualization of the ground-water-flow system are essential in order to accurately determine the zones of transport and zones of contribution (recharge areas) surrounding public-supply wells. In order to delineate reliable wellhead protection areas, the assumptions and constraints of each WHPA method should be evaluated within the context of the aquifer system being studied.

The advantages of the MODFLOW-MODPATH method used in this study are: 1) it is based on a calibrated flow model which gives added confidence to the MODPATH simulations, 2) it is a quasi three-dimensional model that realistically simulates multi-layered systems and aquifer heterogeneities, 3) it can quantify and portray the vertical component of ground-water flow; this is especially important when analyzing contaminant releases in a multi-layered aquifer system, and 4) it can delineate both zones of contribution (recharge areas) and zones of transport surrounding wells in a multi-aquifer system. The major disadvantage of the MODFLOW-MODPATH method is that its use requires a significant amount of time and hydrogeologic data.

The advantages of the GPTRAC semi-analytical method are: 1) relative "ease of use," 2) input data preparation requires less time and effort than in MODFLOW-MODPATH, and 3) in a homogeneous aquifer system, GPTRAC can generate reasonably accurate zones of transport in plan view. The disadvantages of GPTRAC stem from the limitations inherent in applying a two-dimensional model to a three-dimensional flow field. In practice, this means that GPTRAC cannot: 1) quantify the vertical component of ground-water flow, 2) track particles through multi-layered aquifer systems, and 3) determine zones of contribution (recharge areas) for semiconfined systems.

REFERENCES CITED

Achmad, Grufron, 1991, Simulated hydrologic effects of the development of the Patapsco aquifer system in Glen Burnie, Anne Arundel County, Maryland: Maryland Geological Survey Report of Investigations No. 54, 90 p.

Bair, E.S., and Roadcap, G. S., 1992, Comparison of flow models used to delineate capture zones of wells: 1. Leaky-confined fractured-carbonate aquifer: Ground Water, vol. 30, no. 2, p. 199-211.

Barlow, P. M., 1994, Two- and three-dimensional pathline analysis of contributing area to public-supply wells of Cape Cod, Massachusetts: Ground Water, vol. 32, no. 3, p. 399-410.

Bennion, V. R., 1949, The surface water resources, *in* The water resources of Anne Arundel County: Maryland Department of Geology, Mines and Water Resources Bulletin 5, p. 1-27.

Blandford, T. N., and Huyakorn, P. S., 1991, WHPA—A modular semi-analytical model for the delineation of wellhead protection areas, version 2.0: Office of Ground-Water Protection, U.S. Environmental Protection Agency, Washington, D.C., 10-9 p. with appendixes.

Brookhart, J. W., 1949, The ground-water resources, *in* The water resources of Anne Arundel County: Maryland Department of Geology, Mines and Water Resources Bulletin 5, p. 28-143.

Chapelle, F. H., 1985, Hydrogeology, digital solute-transport simulation, and geochemistry of the Lower Cretaceous aquifer system near Baltimore, Maryland: Maryland Geological Survey Report of Investigations No. 43, 120 p.

Code of Federal Regulations, 1993, National primary drinking water standards: CFR 40, Part 141, Sec. 141.2, 141.41, Washington, D.C.

ERT, 1986, RCRA Handbook, A guide to permitting, compliance and closure under the Resource Conservation and Recovery Act: ERT, Concord, Mass., 126 p.

_____ 1987, Superfund Handbook, A guide to managing response to toxic releases under the superfund amendments and reauthorization act: ERT, Concord, Mass., 114 p.

Freeze, R. A., and Cherry, J. A., 1979, Groundwater: Prentice-Hall, Englewood, N. J., 604 p.

Glaser, J. D., 1969, Petrology and origin of Potomac and

Magothy (Cretaceous) sediments, Middle Atlantic Coastal Plain: Maryland Geological Survey Report of Investigations No. 11, 101 p.

_____ 1976, Geologic map of Anne Arundel County: Maryland Geological Survey, scale 1:62,500, one sheet.

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

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

_____ 1972, A user's guide for the artesian aquifers of the Maryland Coastal Plain, Part two: Aquifer characteristics: Maryland Geological Survey Open File Report No. 72-02-1, 123 p.

Hansen, H. J., and Edwards, Jonathan, Jr., 1986, The lithology and distribution of Pre-Cretaceous basement rocks beneath the Maryland Coastal Plain: Maryland Geological Survey Report of Investigations No. 44, 27 p.

International Atomic Energy Agency, 1969, Environmental isotope data no. 1: World survey of isotope concentration in precipitation (1953-1963): International Atomic Energy Agency Technical Reports Series No. 96, Vienna.

_______ 1970, Environmental isotope data no. 2: World survey of isotope concentration in precipitation (1964-1965): International Atomic Energy Agency Technical Reports Series No. 117, Vienna.

_______ 1971, Environmental isotope data no. 3: World survey of isotope concentration in precipitation (1966-1967): International Atomic Energy Agency Technical Reports Series No. 129, Vienna.

_______ 1973, Environmental isotope data no. 4: World survey of isotope concentration in precipitation (1968-1969): International Atomic Energy Agency Technical Reports Series No. 147, Vienna.

_______ 1975, Environmental isotope data no. 5: World survey of isotope concentration in precipitation (1970-1971): International Atomic Energy Agency Technical Reports Series No. 165, Vienna.

_______ 1979, Environmental isotope data no. 6: World survey of isotope concentration in precipitation (1972-1975): International Atomic Energy Agency Technical Reports Series No. 192, Vienna.

_______ 1983, Environmental isotope data no. 7: World survey of isotope concentration in precipitation (1976-1979): International Atomic Energy Agency Technical Reports Series No. 226, Vienna.

_______ 1986, Environmental isotope data no. 8: World survey of isotope concentration in precipitation (1980-1983): International Atomic Energy Agency Technical Reports Series No. 264, Vienna.

_______ 1990, Environmental isotope data no. 9: World survey of isotope concentration in precipitation (1984-1987): International Atomic Energy Agency Technical Reports Series No. 311, Vienna.

Johnston, R. H. 1976, Relation of ground water to surface water in four small basins of the Delaware Coastal Plain: Delaware Geological Survey Report of Investigations No. 24, 56 p.

Kaufman, S., and Libby, W. F., 1954, The natural distribution of tritium: Physical Review Letters, vol. 93, p. 1337-1344.

Kreitler, C. W., and Senger, R. K., 1991, Wellhead protection strategies for confined-aquifer settings: Office of Ground Water and Drinking Water, U.S. Environmental Protection Agency, Washington, D.C., 168 p.

Lucas, R. C., 1976, Anne Arundel County ground-water information: selected well records, chemical-quality data, pumpage, appropriation data, and selected well logs: Maryland Geological Survey Basic Data Report No. 8, 149 p.

Mack, F. K., 1962, Ground-water supplies for industrial and urban development in Anne Arundel County: Maryland Department of Geology, Mines and Water Resources Bulletin 26, 90 p.

Mack, F. K., and Achmad, Grufron, 1986, Evaluation of water-supply potential of aquifers in the Potomac Group of Anne Arundel County, Maryland: Maryland Geological Survey Report of Investigations No. 46, 111 p.

Matthews, R. K., 1974, Dynamic stratigraphy: Prentice-Hall, Englewood Cliffs, N.J., 370 p.

McDonald, M. G., and Harbaugh, A. W., 1984, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 83-875, 528 p.

Michel, R. L., 1989, Tritium deposition in the continental United States, 1953-83: U.S. Geological Survey Water-Resources Investigations Report 89-4072, 46 p.

National Oceanic and Atmospheric Administration, 1991, Digital climatological data from the weather station at Baltimore-Washington International Airport, Maryland, 1950-1990: Department of Commerce, National Climatic Center, Asheville, N. C.

Nebergall, W. H., Holtzclaw, H. F., and Robinson, W. R., 1976, General chemistry, sixth edition: D.C. Heath and Company, Lexington, Mass., 992 p.

Pollock, D. W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89-381, 188 p.

Rasmussen, W. C., and Andreasen, G. E., 1959, Hydrologic budget of the Beaverdam Creek basin, Maryland: U.S. Geological Survey Water-Supply Paper No. 1472, 106 p.

Reilly, T. E., and Pollock, D. W., 1993, Factors affecting areas contributing recharge to wells in shallow aquifers, U.S. Geological Survey Water-Supply Paper 2412, 21 p.

Riggs, H. C., 1963, The base-flow recession curve as an indicator of ground water: International Association of Scientific Hydrology, Publication 63, p. 352-363.

Robertson, W. D., and Cherry, J. A., 1989, Tritium as an indicator of recharge and dispersion in a groundwater system in central Ontario: Water Resources Research, vol. 25, no. 6, p. 1097-1109.

U.S. Environmental Protection Agency, 1987, Guidelines for the delineation of wellhead protection areas: Office of Ground-Water Protection, U.S. Environmental Protection Agency, Washington, D.C., D-14 p.

______ 1991, Fact Sheet, National secondary drinking water standards: Office of Water, U.S. Environmental Protection Agency, Washington, D.C.

Vokes, H. E., and Edwards, Jonathan, Jr., 1974, Geography and geology of Maryland: Maryland Geological Survey Bulletin 19, 242 p.

Weaver, K. N., Cleaves, E. T., Edwards, Jonathan, Jr., and Glaser, J. D., 1968, Geologic map of Maryland: Maryland Geological Survey, scale 1:250,000, one sheet.

Willey, R. E., and Achmad, Grufron, 1986, Simulation of ground-water flow and base flow in weathered crystalline rock, upper Cattail Creek, Howard County, Maryland: Maryland Geological Survey Report of Investigations No. 45, 68 p.

Williams, P. F., and Rust, B. R., 1969, The sedimentology of a braided river: Journal of Sedimentary Petrology, vol. 39, no. 2, p. 649-679.

Wilson, T. V., and Wiser, E. H., 1974, Groundwater-baseflow relationships and baseflow predictions from groundwater levels on Piedmont watersheds: American Society of Agricultural Engineering-1974, Transactions, p. 269-279.

APPENDICES

Appendix A. — Selected well and test hole records.

[ft = feet; lsd = land surface datum; gpm = gallons per minute; gpm/ft = gallons per minute per foot of drawdown; hrs = hours]

WELL NUMBER (LOCAL NAME)	STATE PERMIT NUMBER	AQUIFER*	OWNER	DRILLER	YEAR WELL CONSTRUCTED	ALTITUDE OF LAND SURFACE (in ft)	DEPTH DRILLED (in ft below lsd)	DEPTH OF WELL (in ft below lsd)
AA Ac 11	AA-00-2445	PATUXENT	BWI AIRPORT	WASH. WELL CO.	1948	136	320	320
AA Ac 14	AA-00-5217	PATUXENT	KULIS, S.	LAYNE ATLANTIC	1950	150	220	210
AA Ac 15	AA-00-5218	PATUXENT	GODDARD, S. I.	LAYNE ATLANTIC	1950	180	273	266
AA Ac 23	AA-00-9403	PATUXENT	CAVEY, L. E.	LAYNE ATLANTIC	1952	190	337	332
AA Ac 27	--	L. PATAPSCO	BWI AIRPORT	--	--	165	60	60
AA Ac 47	--	L. PATAPSCO	USGS	USGS	1959	90	77	--
AA Ad 1 SAWMILL 1 PRODUCTION WELL	--	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1926	30	111	63
AA Ad 2 SAWMILL 2 PRODUCTION WELL	--	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1941	40	119	95
AA Ad 3 OVERLOOK #1	--	L. PATAPSCO	AA DPW	--	1927	40	--	62
AA Ad 4 WELL #1	--	L. PATAPSCO	AA DPW	HOSHALL	1919	45	--	94
AA Ad 5 WELL #2	--	L. PATAPSCO	AA DPW	HOSHALL	1919	45	--	127
AA Ad 6 WELL #3	--	L. PATAPSCO	AA DPW	HOSHALL	1919	45	--	157
AA Ad 7 WELL #4	--	L. PATAPSCO	AA DPW	HOSHALL	1923	45	--	312
AA Ad 20	--	PATUXENT	KAVANAUGH INC.	WASH. WELL CO	1944	40	--	392
AA Ad 23 SAWMILL 3 PRODUCTION WELL	--	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1945	45	--	78
AA Ad 29	--	PATUXENT	AA DPW	LAYNE ATLANTIC	1947	37	530	500
AA Ad 30	--	U. PATAPSCO	AA DPW	USGS	1948	35	--	13
AA Ad 33	AA-00-1896	L. PATAPSCO	HALL, A.	G. E. CROUSE	1947	140	147	147
AA Ad 40 SAWMILL 4	AA-00-1629	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1947	55	107	102

*Aquifer Codes:
L. Patapsco = Lower Patapsco
U. Patapsco = Upper Patapsco

Owner/Driller Codes:
AA DPW = Anne Arundel County Department of Public Works
MD DNR = Maryland Department of Natural Resources
USGS = U.S. Geological Survey

TOP OF OPEN SCREEN (in ft below lsd)	BOTTOM OF OPEN SCREEN (in ft below lsd)	STATIC WATER LEVEL (in ft below or above lsd)	DATE STATIC MEASURED	PUMPING WATER LEVEL (in ft below or above lsd)	DATE DISCHARGE MEASURED	DISCHARGE (in gpm)	PUMPING PERIOD (in hrs)	SPECIFIC CAPACITY (in gpm/ft)	PRIMARY* USE OF WATER OR SITE	WELL NUMBER
312	320	90	04-23-48	175	04-23-48	60	12	0.7	U	AA Ac 11
210	220	136	06-59	--	--	10	8	--	H	AA Ac 14
261	266	--	--	--	--	10	8	--	H	AA Ac 15
324	329	156	02-13-52	186	02-13-52	20	3	0.6	H	AA Ac 23
--	--	50	06-59	--	--	--	--	--	H	AA Ac 27
--	--	--	--	--	--	--	--	--	T	AA Ac 47
43	63	18	1926	--	1943	220	--	--	U	AA Ad 1
65	95	34	06-24-41	54	06-24-41	280	--	8.8	U	AA Ad 2
49	62	1.2	09-21-59	--	1943	175	--	--	U	AA Ad 3
--	--	--	--	--	1942	28	24	--	U	AA Ad 4
--	--	--	--	--	1942	32	24	--	U	AA Ad 5
--	--	--	--	--	1942	46	24	--	U	AA Ad 6
--	--	--	--	--	1942	48	24	--	U	AA Ad 7
--	--	76	1944	90	1944	130	--	9.3	N	AA Ad 20
63	73	--	--	--	1945	150	--	--	U	AA Ad 23
395 460	400 500	+10.9	06-04-48	--	06-03-48	11.7 (Flowing)	--	--	U	AA Ad 29
460	500	8.8	06-17-48	--	--	--	--	--	U	AA Ad 30
--	--	123	10-31-47	130	10-31-47	8	4	1.1	H	AA Ad 33
80	102	28	04-09-47	62	04-09-47	292	--	8.6	U	AA Ad 40

*Primary use of water or site codes:

O Observation
T Test
U Unused
Z Destroyed

C Commercial
F Fire
H Domestic
I Irrigation
N Industrial

P Production
R Recreation
S Stock
T Institution

Other codes:

LSD = Land surface datum
GAL/MIN = Gallons per minute
GAL/MIN/FT = Gallons per minute per foot

Appendix A. — Selected well and test hole records—Continued.

WELL NUMBER (LOCAL NAME)	STATE PERMIT NUMBER	AQUIFER*	OWNER	DRILLER	YEAR WELL CONSTRUCTED	ALTITUDE OF LAND SURFACE (in ft)	DEPTH DRILLED (in ft below lsd)	DEPTH OF WELL (in ft below lsd)
AA Ad 41 SAWMILL 5	AA-00-1630	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1947	45	153	146
AA Ad 67 SAWMILL 6 PRODUCTION WELL	AA-01-3957	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1953	39	167	151
AA Ad 68 SAWMILL 7 PRODUCTION WELL	AA-01-3958	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1953	55.5	167	160
AA Ad 69	AA-02-7725	L. PATAPSCO	--	H. H. BUNKER	1957	55	119	119
AA Ad 73	AA-02-7834	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1957	87	201	186
AA Ad 74 DORSEY 4 PRODUCTION WELL	AA-02-8580	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1957	90.3	--	186
AA Ad 75	AA-02-7835	--	AA DPW	LAYNE ATLANTIC	1957	75	535	--
AA Ad 76 DORSEY 5 PRODUCTION WELL	AA-02-9134	PATUXENT	AA DPW	LAYNE ATLANTIC	1957	68.3	--	474
AA Ad 80	AA-02-8728	L. PATAPSCO	HOLY TRINITY CH.	H. H. BUNKER	1957	63	168	168
AA Ad 83	AA-01-6106	L. PATAPSCO	WILFONG, J.	LAYNE ATLANTIC	1954	81	82	81
AA Ad 87	AA-03-9464	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1960	70	249	152
AA Ad 88	AA-03-9818	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1960	78.3	--	164
AA Ad 89	AA-03-9764	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1960	79	346	128
AA Ad 90 HAMMONDS FERRY RD. OBSERVATION WELL 4	AA-04-0298	PATUXENT	USGS	LAYNE ATLANTIC	1960	77.8	483	453
AA Ad 92	AA-04-2030	PATUXENT	AA DPW	LAYNE ATLANTIC	1961	70	--	453
AA Ad 93	AA-76-0156	L. PATAPSCO	COOP FERTILIZER	WALTER FRANK	1966	17	260	260
AA Ad 94	AA-02-6010	PATUXENT	MATLACK INC	SHANNAHAN	1957	38	214	213
AA Ad 96	AA-77-0179	PATUXENT	USS AGRI. CHEM.	WALTER FRANK	1967	15	370	370
AA Ad 99	AA-73-4665	PATUXENT	USS AGRI. CHEM.	WALTER FRANK	1975	12	371	371
AA Ad 102 HAMMONDS FERRY RD. OBSERVATION WELL 1	AA-81-2641	L. PATAPSCO	USGS	WALTER FRANK	1983	76.8	108	108
AA Ad 104 HAMMONDS FERRY RD. OBSERVATION WELL 2	AA-81-2760	L. PATAPSCO	USGS	MD DNR	1984	77.0	34	28
AA Ad 108 HAMMONDS FERRY RD OBSERVATION WELL 3	AA-81-3475	U. PATAPSCO	USGS	MD DNR	1984	78.3	11.5	11.5
AA Ad 109	AA-81-4890	L. PATAPSCO	USGS	MD DNR	1985	38.5	52.5	46

TOP OF OPEN SCREEN (in ft below lsd)	BOTTOM OF OPEN SCREEN (in ft below lsd)	STATIC WATER LEVEL (in ft below or above lsd)	DATE STATIC MEASURED	PUMPING WATER LEVEL (in ft below or above lsd)	DATE DISCHARGE MEASURED	DISCHARGE (in gpm)	PUMPING PERIOD (in hrs)	SPECIFIC CAPACITY (in gpm/ft)	PRIMARY* USE OF WATER OR SITE	WELL NUMBER
126	146	10	06-04-47	68	06-04-47	250	--	4.3	U	AA Ad 41
131	151	12	11-18-53	120	11-18-53	487	--	4.5	U	AA Ad 67
140	160	16	12-11-53	128	12-11-53	400	--	3.6	U	AA Ad 68
97	119	32	07-22-57	62	07-22-57	270	8	9.0	Z	AA Ad 69
171	186	31	09-11-57	182	09-11-57	184	3	1.2	U	AA Ad 73
171	186	33	10-19-57	157	10-19-57	375	8	3.0	Z	AA Ad 74
--	--	--	--	--	--	--	--	--	T	AA Ad 75
449	474	34.4	11-15-57	169	11-15-57	450	8	3.3	P	AA Ad 76
156	168	38	09-07-58	83	09-07-57	200	3	4.4	U	AA Ad 80
76	81	56	08-27-54	64	08-27-54	8	3	1.0	U	AA Ad 83
132	152	20.4	07-01-60	--	--	258	8	--	T	AA Ad 87
159	164	--	--	--	--	--	--	--	U	AA Ad 88
96 118	106 128	6.6	08-16-60	84.1	08-16-60	302	8	3.9	T	AA Ad 89
438	453	34.4	10-08-60	117.4	10-08-60	315	8	3.8	O	AA Ad 90
443	453	52	06-14-61	370	06-14-61	260	--	0.8	Z	AA Ad 92
--	--	30	06-17-66	60	06-17-61	70	6	2.3	N	AA Ad 93
198	213	34	05-28-57	65	05-28-57	75	10	2.4	C	AA Ad 94
355	370	20	06-11-67	45	06-12-67	400	25	16.0	N	AA Ad 96
361	371	20	07-25-75	35	07-25-75	50	3	3.3	C	AA Ad 99
80	90	11.2	12-09-83	37	12-09-83	60	3	2.3	O	AA Ad 102
19	29	5.2	05-09-84	14	05-09-84	20	2	2.3	O	AA Ad 104
6.5	11.5	6.9	08-15-84	10	08-15-84	3	1	1.0	O	AA Ad 108
36	46	8.4	10-08-85	--	--	--	--	--	O	AA Ad 109

Appendix A. — Selected well and test hole records—Continued.

WELL NUMBER (LOCAL NAME)	STATE PERMIT NUMBER	AQUIFER*	OWNER	DRILLER	YEAR WELL CONSTRUCTED	ALTITUDE OF LAND SURFACE (in ft)	DEPTH DRILLED (in ft below lsd)	DEPTH OF WELL (in ft below lsd)
AA Ae 36	AA-04-6091	PATUXENT	DIAM. SHAMROCK	SHANNAHAN	1962	30	567	555
AA Bc 209 TELEGRAPH RD WELL	AA-81-0366	PATUXENT	AA DPW	A. C. SCHULTES	1982	126	362	295
AA Bc 210 TELEGRAPH RD TEST WELL	AA-81-0367	PATUXENT	AA DPW	A. C. SCHULTES	1982	126	305	296
AA Bc 216	AA-73-9300	L. PATAPSCO	MD DNR	BRANHAM	1978	20	70	70
AA Bd 6	--	L. PATPASCO	RAE	H. H. BUNKER	1945	2	84	84
AA Bd 7	--	L. PATAPSCO	G. B. FURMAN	--	--	20	80	80
AA Bd 23 HARUNDALE 1 TEST HOLE	AA-00-2803	PATUXENT	AA DPW	LAYNE ATLANTIC	1948	30	617	617
AA Bd 36 HARUNDALE 1 PRODUCTION WELL	AA-00-2803	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1948	30	123	123
AA Bd 37 HARUNDALE 2 PRODUCTION WELL		L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1949	38.2	118	115
AA Bd 45 DORSEY 1 TEST HOLE	AA-01-1809	--	AA DPW	LAYNE ATLANTIC	1953	70	556	--
AA Bd 55 DORSEY 1 PRODUCTION WELL	AA-02-1548	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1955	69.5	137	131
AA Bd 56 DORSEY 3 PRODUCTION WELL	AA-02-1550	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1956	61.6	515.5	153
AA Bd 57 DORSEY 2 PRODUCTION WELL	AA-02-1549	PATUXENT	AA DPW	LAYNE ATLANTIC	1956	70	518	510
AA Bd 60 HARUNDALE 4 TEST HOLE	AA-01-9686	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1955	40	236	--
AA Bd 61 HARUNDALE 4 PRODUCTION WELL	AA-01-9874	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1955	42	206	206
AA Bd 63 HARUNDALE 3 PRODUCTION WELL	AA-02-0138	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1955	28	180	180
AA Bd 64 DORSEY 11 PRODUCTION WELL	AA-02-8059	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1957	81.4	187	181
AA Bd 65 DORSEY 13 TEST HOLE	AA-02-7939	PATUXENT	AA DPW	LAYNE ATLANTIC	1957	90	545	--
AA Bd 66 DORSEY 13 PRODUCTION WELL	AA-02-8416	PATUXENT	AA DPW	LAYNE ATLANTIC	1957	89.4	517	517
AA Bd 67 DORSEY TEST HOLE 2	AA-01-1809	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1953	70	188	--

TOP OF OPEN SCREEN (in ft below lsd)	BOTTOM OF OPEN SCREEN (in ft below lsd)	STATIC WATER LEVEL (in ft below or above lsd)	DATE STATIC MEASURED	PUMPING WATER LEVEL (in ft below or above lsd)	DATE DISCHARGE MEASURED	DISCHARGE (in gpm)	PUMPING PERIOD (in hrs)	SPECIFIC CAPACITY (in gpm/ft)	PRIMARY* USE OF WATER OR SITE	WELL NUMBER
450 532	500 555	36	04-19-62	76	04-19-62	740	24	18.5	N	AA Ae 36
275	295	67	05-27-82	120	05-27-82	277	27	5.2	P	AA Bc 209
276	296	--	--	--	--	--	--	--	O	AA Bc 210
60	70	20	07-19-78	40	07-19-78	20	2	1.0	I	AA Bc 216
--	--	FLOWED	1946	--	03-06-46	6 (FLOW)	--	--	H	AA Bd 6
--	--	FLOWED	1946	--	--	20	--	--	H	AA Bd 7
--	--	--	--	--	--	16	8	--	T	AA Bd 23
90	123	3	07-03-51	70*	07-03-51	439	--	--	P	AA Bd 36
				(*PUMPING WATER LEVEL REPORTED IN 1948)						
90	115	7	01-49	67	01-49	450	48	7.5	P	AA Bd 37
--	--	--	--	--	--	--	--	--	TZ	AA Bd 45
111	131	13	12-06-55	52	12-06-55	450	8	11.5	P	AA Bd 55
133	153	7	02-08-55	118	02-08-56	350	4	3.2	P	AA Bd 56
485	510	12	01-13-56	127	01-13-56	475	4	4.1	P	AA Bd 57
--	--	--	--	--	--	--	--	--	TZ	AA Bd 60
186	206	13	08-02-55	45	08-02-55	500	5	15.6	P	AA Bd 61
160	180	0	09-09-55	110	09-09-55	500	5	4.6	P	AA Bd 63
161	181	13	09-12-57	170	09-12-57	375	8	2.4	P	AA Bd 64
--	--	--	--	--	--	--	--	--	TZ	AA Bd 65
497	517	31	10-31-57	214	10-31-57	375	8	2.0	P	AA Bd 66
--	--	--	--	--	--	--	--	--	TZ	AA Bd 67

Appendix A. — Selected well and test hole records—Continued.

WELL NUMBER (LOCAL NAME)	STATE PERMIT NUMBER	AQUIFER*	OWNER	DRILLER	YEAR WELL CONSTRUCTED	ALTITUDE OF LAND SURFACE (in ft)	DEPTH DRILLED (in ft below lsd)	DEPTH OF WELL (in ft below lsd)
AA Bd 73	AA-02-4386	L. PATAPSCO	PIONEER REST.	GILLELAND	1956	95	110	96
AA Bd 75	AA-01-7547	L. PATAPSCO	W. F. MEWSHAW	LAYNE ATLANTIC	1955	100	126	125
AA Bd 78	AA-02-0137	L. PATAPSCO	SUNNYSIDE SCH.	LAYNE ATLANTIC	1955	140	126	126
AA Bd 91	AA-04-2029	L. PATAPSCO	USGS	LAYNE ATLANTIC	1961	82.6	160	160
AA Bd 92 DORSEY 14 PRODUCTION WELL	AA-04-2472	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1961	85.6	162	157
AA Bd 94 DORSEY 15 TEST WELL	AA-04-8154	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1962	70	190	176
AA Bd 95 DORSEY 15 PRODUCTION WELL	AA-05-0489	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1963	70	190	178
AA Bd 96 DORSEY 16 TEST WELL	AA-04-8154	PATUXENT	AA DPW	LAYNE ATLANTIC	1962	75	548	530
AA Bd 97 DORSEY 16 PRODUCTION WELL	AA-04-9554	PATUXENT	AA DPW	LAYNE ATLANTIC	1962	75	548	534
AA Bd 98 DORSEY 17 PRODUCTION WELL	AA-05-7226	PATUXENT	AA DPW	H. A. GROPP	1964	75	625	625
AA Bd 101 PHILLIP DRIVE PRODUCTION WELL	AA-69-0871	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1969	55	265	212
AA Bd 102 GLENDALE TEST WELL	AA-69-0802	L. PATAPSCO	USGS	LAYNE ATLANTIC	1969	80	275	225
AA Bd 103 GLENDALE PRODUCTION WELL	AA-69-0954	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1969	80	275	221
AA Bd 105 CRAIN HIGHWAY PRODUCTION WELL	AA-69-1128	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1969	90	265	237
AA Bd 107 ELVATON PRODUCTION WELL	AA-69-1195	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1969	20	288	240
AA Bd 108 THELMA AVE. PRODUCTION WELL	AA-71-0554	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1971	70	242	205
AA Bd 109 QUARTERFIELD RD. PRODUCTION WELL	AA-71-0553	L. PATAPSCO	AA DPW	LAYNE ATLANTIC	1971	190	334	300
AA Bd 121 STEVENSON RD. TEST WELL	AA-81-0368	PATUXENT	AA DPW	A. C. SCHULTES	1982	107.9	381	346
AA Bd 122 STEVENSON RD PRODUCTION WELL	AA-81-0368	PATUXENT	AA DPW	A. C. SCHULTES	1982	110	362	349
AA Bd 152 WOODSIDE SCHOOL OBSERVATION WELL	AA-81-3463	L. PATAPSCO	USGS	EAST COAST	1984	53.3	305	100

TOP OF OPEN SCREEN (in ft below lsd)	BOTTOM OF OPEN SCREEN (in ft below lsd)	STATIC WATER LEVEL (in ft below or above lsd)	DATE STATIC MEASURED	PUMPING WATER LEVEL (in ft below or above lsd)	DATE DISCHARGE MEASURED	DISCHARGE (in gpm)	PUMPING PERIOD (in hrs)	SPECIFIC CAPACITY (in gpm/ft)	PRIMARY* USE OF WATER OR SITE	WELL NUMBER
90	96	44	08-20-56	75	08-20-56	8	5	0.3	C	AA Bd 73
120	125	47	01-18-55	53	01-18-55	50	3	8.3	C	AA Bd 75
121	126	70	08-19-55	80	08-19-55	30	3	3.0	P	AA Bd 78
155	160	17.6	03-29-61	--	--	--	--	--	O	AA Bd 91
132	157	22	05-31-61	120	05-31-61	200	24	2.0	P	AA Bd 92
150 166	160 176	18.7	08-21-62	132.6	08-21-62	350	72	3.1	TZ	AA Bd 94
150 168	160 178	19	02-21-63	142	02-21-63	350	24	2.8	P	AA Bd 95
510	530	26	10-04-62	217.8	10-04-62	300	72	1.6	TZ	AA Bd 96
504	534	25.6	11-05-62	146.3	11-05-62	500	40	4.1	P	AA Bd 97
552	591	58	08-03-64	205	08-03-64	907	8	6.2	P	AA Bd 98
172	212	20	04-25-69	83	04-25-69	608	24	9.7	P	AA Bd 101
176 206	196 221	66	05-06-69	108	05-06-69	220	16	5.2	TZ	AA Bd 102
176 206	196 221	67	05-21-69	152	05-21-69	554	24	6.5	P	AA Bd 103
197	237	32	06-20-69	70	06-20-69	554	24	14.6	P	AA Bd 105
185 220	200 240	FLOWED	07-08-69	64	07-08-69	650	24	>10.2	P	AA Bd 107
175	205	30	05-05-71	158	05-05-71	325	24	2.5	P	AA Bd 108
260	300	125	07-20-71	164	07-20-71	326	24	8.4	P	AA Bd 109
326	346	63	05-05-82	142	05-05-82	266	24	3.4	O	AA Bd 121
329	349	61	06-23-82	--	--	--	--	--	P	AA Bd 122
84	94	29.3	04-18-85	47	04-18-85	30	4	1.7	O	AA Bd 152

Appendix A. — Selected well and test hole records—Continued.

WELL NUMBER (LOCAL NAME)	STATE PERMIT NUMBER	AQUIFER*	OWNER	DRILLER	YEAR WELL CONSTRUCTED	ALTITUDE OF LAND SURFACE (in ft)	DEPTH DRILLED (in ft below lsd)	DEPTH OF WELL (in ft below lsd)
AA Bd 154 QUEENSTOWN PARK OBSERVATION WELL 1	AA-81-3461	L. PATAPSCO	USGS	EAST COAST	1984	88	183	115
AA Bd 155 STATE HIGHWAY ADMN. OBSERVATION WELL	AA-81-3460	L. PATAPSCO	USGS	EAST COAST	1984	57.5	167	159
AA Bd 156 BICYCLE PATH OBSERVATION WELL	AA-81-3462	L. PATAPSCO	USGS	EAST COAST	1984	69.0	180	173
AA Bd 157 RIPPLING WOODS ELEM. SCHOOL OBSERVATION WELL 1	AA-81-3464	L. PATAPSCO	USGS	EAST COAST	1984	75.8	180	177
AA Bd 158 NORTHERN VOCATIONAL TECH. OBSERVATION WELL	AA-81-3459	L. PATAPSCO	USGS	EAST COAST	1984	108.2	260	188
AA Bd 159 RIPPLING WOODS ELEM. SCHOOL OBSERVATION WELL 2	AA-81-3949	U. PATAPSCO	USGS	EAST COAST	1984	75.5	110	110
AA Bd 160 QUEENSTOWN PARK OBSERVATION WELL 2	AA-81-3461	L. PATAPSCO	USGS	EAST COAST	1985	88	118	118
AA Bd 161 DORSEY 2R PRODUCTION WELL	AA-88-4521	L. PATAPSCO	AA DPW	A. C. SCHULTES	1990	70	550	516
AA Bd 162 HARUNDALE 4R PRODUCTION WELL (Replaces AA Bd 61, Harundale)	AA-88-7363	L. PATAPSCO	AA DPW	A. C. SCHULTES	1992	42	250	220
AA Be 47	AA-00-0158	L. PATAPSCO	KLASMIER, H. J.	W. H. EILER	1946	20	147	147
AA Be 48	AA-00-0119	L. PATAPSCO	REISER, J.	W. H. EILER	1946	23	254	254

TOP OF OPEN SCREEN (in ft below lsd)	BOTTOM OF OPEN SCREEN (in ft below lsd)	STATIC WATER LEVEL (in ft below or above lsd)	DATE STATIC MEASURED	PUMPING WATER LEVEL (in ft below or above lsd)	DATE DISCHARGE MEASURED	DISCHARGE (in gpm)	PUMPING PERIOD (in hrs)	SPECIFIC CAPACITY (in gpm/ft)	PRIMARY* USE OF WATER OR SITE	WELL NUMBER
105	115	17.4	04-30-85	38	04-30-85	60	4	2.9	Z	AA Bd 154
145	155	21.2	10-09-84	47	10-09-84	60	4	2.3	O	AA Bd 155
160	170	40.4	10-23-84	132	10-23-84	75	4	0.8	O	AA Bd 156
165	175	51.7	10-31-84	104	10-31-84	75	4	1.4	O	AA Bd 157
140	188	51.8	11-01-84	140	11-01-84	70	4	0.8	O	AA Bd 158
89	99	39.7	01-24-84	52	01-24-84	35	4	2.8	O	AA Bd 159
88	98	17.4	03-27-84	23.8	03-27-85	60	--	9.4	O	AA Bd 160
478	516	80.4	07-17-90	228	07-17-90	500	24	3.4	P	AA Bd 161
172 185	175 215	39	04-30-92	121	04-30-92	776	24	9.5	P	AA Bd 162
--	--	14	04-25-46	18	04-25-46	8.00	12	2.0	H	AA Be 47
--	--	18	04-17-46	24	04-17-46	8.00	12	1.3	H	AA Be 48

Appendix B. — Chemical analyses of ground water from the Lower and Upper Patapsco aquifers.

[mg/L = milligrams per liter; µg/L = micrograms per liter; µS/cm = microsiemens per centimeter]

WELL NUMBER	DATE	AQUIFER	SODIUM, DIS-SOLVED (mg/L as Na)	POTAS-SIUM, DIS-SOLVED (mg/L as K)	CALCIUM DIS-SOLVED (mg/L as Ca)	MAGNE-SIUM, DIS-SOLVED (mg/L as Mg)	CHLO-RIDE, DIS-SOLVED (mg/L as Cl)	FLUO-RIDE, DIS-SOLVED (mg/L as F)	BROMIDE DIS-SOLVED (mg/L as Br)
AA Ad 1	06-21-43	LOWER PATAPSCO	--	--	--	--	2.8	--	--
AA Ad 1	04-01-46	LOWER PATAPSCO	2.1	0.50	1.6	0.80	2.9	<0.05	--
AA Ad 1	05-15-91	LOWER PATAPSCO	--	--	--	--	35	--	--
AA Ad 2	06-21-43	LOWER PATAPSCO	--	--	--	--	3.5	--	--
AA Ad 3	06-21-43	LOWER PATAPSCO	--	--	--	--	5.5	--	--
AA Ad 3	04-01-46	LOWER PATAPSCO	4.1	0.70	3.3	1.5	6.1	0.10	--
AA Ad 4	08-19-43	LOWER PATAPSCO	--	--	--	--	5.0	<0.05	--
AA Ad 5	08-02-43	LOWER PATAPSCO	--	--	--	--	13	--	--
AA Ad 5	06-15-45	LOWER PATAPSCO	3.5	1.0	2.2	0.90	5.5	<0.05	--
AA Ad 6	08-19-43	LOWER PATAPSCO	--	--	--	--	5.0	<0.05	--
AA Ad 7	08-19-43	LOWER PATAPSCO	--	--	--	--	2.0	<0.05	--
AA Ad 7	06-15-45	LOWER PATAPSCO	1.8	0.70	1.3	0.50	1.4	<0.05	--
AA Ad 33	04-22-60	LOWER PATAPSCO	--	--	--	--	1.8	--	--
AA Ad 41	11-19-81	LOWER PATAPSCO	8.1	1.9	6.2	2.4	15	<0.10	--
AA Ad 41	04-07-82	LOWER PATAPSCO	--	--	--	--	--	--	--
AA Ad 41	05-15-91	LOWER PATAPSCO	--	--	--	--	14	--	--
AA Ad 41	05-23-91	LOWER PATAPSCO	--	--	--	--	16	--	--
AA Ad 63	04-20-60	LOWER PATAPSCO	--	--	--	--	1.1	--	--
AA Ad 67	05-15-91	LOWER PATAPSCO	--	--	--	--	19	--	--
AA Ad 68	05-15-91	LOWER PATAPSCO	--	--	--	--	80	--	--
AA Ad 73	05-17-82	LOWER PATAPSCO	60	1.8	8.5	3.1	120	<0.10	--
AA Ad 74	03-08-60	LOWER PATAPSCO	--	--	--	--	2.4	--	--
AA Ad 80	04-20-60	LOWER PATAPSCO	--	--	--	--	1.2	--	--
AA Ad 83	04-20-60	LOWER PATAPSCO	--	--	--	--	1.7	--	--
AA Ad 102	12-09-83	UPPER PATAPSCO	2.4	1.3	2.7	1.2	5.0	0.20	--
AA Ad 102	04-10-91	UPPER PATAPSCO	2.5	1.3	2.9	1.6	9.0	0.10	--
AA Ad 104	12-07-87	LOWER PATAPSCO	25	3.2	28	4.2	44	0.20	--
AA Ad 104	03-15-88	LOWER PATAPSCO	28	3.2	23	4.5	50	0.20	--
AA Ad 104	05-17-88	LOWER PATAPSCO	30	1.8	23	4.7	56	0.20	--
AA Ad 104	07-11-88	LOWER PATAPSCO	38	3.5	29	5.2	81	<0.10	--
AA Ad 104	12-26-89	LOWER PATAPSCO	38	3.0	27	5.3	65	0.10	--
AA Ad 104	07-19-90	LOWER PATAPSCO	82	3.2	35	6.1	100	<0.10	--
AA Ad 104	04-11-91	LOWER PATAPSCO	--	--	--	--	130	--	--
AA Ad 104	05-21-92	LOWER PATAPSCO	50	3.4	35	8.3	95	<0.10	--
AA Ad 108	04-11-91	LOWER PATAPSCO	--	--	--	--	7.0	--	--
AA Bd 6	03-28-46	LOWER PATAPSCO	1.2	0.30	1.1	0.50	1.5	0.10	--
AA Bd 7	03-13-46	LOWER PATAPSCO	--	--	--	--	3.0	--	--
AA Bd 36	05-23-91	LOWER PATAPSCO	--	--	--	--	3.0	--	--
AA Bd 55	05-07-91	LOWER PATAPSCO	--	--	--	--	11	--	--
AA Bd 56	05-07-91	LOWER PATAPSCO	--	--	--	--	86	--	--
AA Bd 63	03-08-60	LOWER PATAPSCO	--	--	--	--	2.5	--	--
AA Bd 64	05-17-82	LOWER PATAPSCO	--	--	--	--	--	--	--
AA Bd 73	04-22-60	LOWER PATAPSCO	--	--	--	--	1.5	--	--
AA Bd 75	04-22-60	LOWER PATAPSCO	--	--	--	--	1.9	--	--
AA Bd 78	04-15-60	LOWER PATAPSCO	--	--	--	--	1.0	--	--
AA Bd 91	05-17-91	LOWER PATAPSCO	--	--	--	--	10	--	--
AA Bd 92	05-12-82	LOWER PATAPSCO	2.2	0.80	2.1	1.0	4.1	<0.10	--
AA Bd 92	05-22-92	LOWER PATAPSCO	3.2	1.40	3.9	1.5	5.6	<0.10	--
AA Bd 95	05-11-82	LOWER PATAPSCO	5.1	0.80	14	1.9	4.2	<0.10	--
AA Bd 101	05-22-91	LOWER PATAPSCO	--	--	--	--	35	--	0.08
AA Bd 152	09-13-84	LOWER PATAPSCO	3.3	1.5	2.1	1.5	6.0	<0.10	--
AA Bd 154	09-24-84	LOWER PATAPSCO	1.5	1.3	1.1	0.30	2.2	<0.10	--
AA Bd 155	10-09-84	LOWER PATAPSCO	2.6	1.0	3.2	1.1	4.4	<0.10	--
AA Bd 155	12-10-91	LOWER PATAPSCO	2.6	1.0	2.8	1.2	3.9	0.20	0.02
AA Bd 156	10-23-84	LOWER PATAPSCO	12	2.5	4.1	2.8	26	0.20	--
AA Bd 156	11-26-91	LOWER PATAPSCO	18	3.3	5.2	3.4	36	0.20	0.15
AA Bd 157	10-31-84	LOWER PATAPSCO	2.3	0.70	2.0	0.66	2.8	0.20	--
AA Bd 157	11-26-91	LOWER PATAPSCO	1.7	0.80	2.0	0.66	2.6	0.20	0.01
AA Bd 158	01-25-85	LOWER PATAPSCO	4.2	1.5	2.4	1.2	7.0	<0.10	--
AA Bd 158	11-27-91	LOWER PATAPSCO	5.5	1.6	3.0	1.7	9.6	0.20	0.03
AA Bd 159	01-24-85	LOWER PATAPSCO	9.7	2.2	7.2	3.6	21	<0.10	--
AA Bd 159	11-27-91	LOWER PATAPSCO	14	2.5	8.1	4.2	30	0.20	0.06
AA Bd 160	03-28-85	LOWER PATAPSCO	4.6	1.4	4.5	1.9	1.6	<0.10	--
AA Bd 160	04-11-91	LOWER PATAPSCO	--	--	--	--	9.0	--	--

Appendix B. — Chemical analyses of ground water from the Lower and Upper Patapsco aquifers—Continued.

SULFATE DIS-SOLVED (mg/L as SO4)	ALKA-LINITY FIELD L=LAB VALUE (mg/L as CaCO3)	NITRO-GEN, AMMONIA DIS. T=TOTAL (mg/L as N)	NITRO-GEN, AM-MONIA + ORGANIC DIS. (mg/L as N)	NITRO-GEN, NITRITE DIS. T=TOTAL (mg/L as N)	NITRO-GEN, NO2+NO3 DIS-SOLVED (mg/L as N)	NITRO-GEN, NO2+NO3 TOTAL (mg/L as N)	NITRO-GEN, NITRATE DIS-SOLVED (mg/L as N)	PHOS-PHORUS ORTHO, DIS-SOLVED (mg/L as P)	PHOS-PHORUS TOTAL (mg/L as P)	WELL NUMBER
1.0	3	--	--	--	--	--	1.30	--	--	AA Ad 1
1.0	2	--	--	--	--	--	1.40	--	--	AA Ad 1
--	6	--	--	--	--	--	--	--	--	AA Ad 1
1.0	3	--	--	--	--	--	1.90	--	--	AA Ad 2
1.0	5	--	--	--	--	--	2.30	--	--	AA Ad 3
1.2	3	--	--	--	--	--	2.70	--	--	AA Ad 3
1.0	5	--	--	--	--	--	1.90	--	--	AA Ad 4
1.0	5	--	--	--	--	--	0.95	--	--	AA Ad 5
0.60	5	--	--	--	--	--	1.30	--	--	AA Ad 5
1.0	4	--	--	--	--	--	1.40	--	--	AA Ad 6
7.0	1	--	--	--	--	--	<0.01	--	--	AA Ad 7
6.5	2	--	--	--	--	--	<0.01	--	--	AA Ad 7
--	16	--	--	--	--	--	--	--	--	AA Ad 33
8.7	<1.0 L	--	--	--	--	--	--	--	--	AA Ad 41
--	10 L	--	--	--	--	--	--	--	--	AA Ad 41
--	4	--	--	--	--	--	--	--	--	AA Ad 41
--	4	--	--	--	--	--	--	--	--	AA Ad 41
--	7	--	--	--	--	--	--	--	--	AA Ad 63
--	3	--	--	--	--	--	--	--	--	AA Ad 67
--	3	--	--	--	--	--	--	--	--	AA Ad 68
9.0	3.0 L	--	--	--	--	--	--	--	--	AA Ad 73
--	4	--	--	--	--	--	--	--	--	AA Ad 74
--	11	--	--	--	--	--	--	--	--	AA Ad 80
--	16	--	--	--	--	--	--	--	--	AA Ad 83
--	--	--	--	--	2.60	--	--	<0.010	--	AA Ad 102
0.30	3	<0.010	--	--	2.60	--	--	--	<0.010	AA Ad 102
19	76	<0.010	--	--	0.027	<0.100	--	0.026	0.050	AA Ad 104
19	67	--	--	--	--	<0.300	--	--	--	AA Ad 104
20	57	--	--	--	--	<0.200	--	--	<0.010	AA Ad 104
15	67	--	--	--	--	<0.100	--	--	0.030	AA Ad 104
12	77	--	--	--	--	<0.100	--	--	0.070	AA Ad 104
13	99	--	--	--	--	<0.100	--	--	0.020	AA Ad 104
--	68	--	--	--	--	--	--	--	--	AA Ad 104
6.3	99	2.30 T	--	0.020 T	--	<0.050	--	--	0.030	AA Ad 104
--	12	--	--	--	--	--	--	--	--	AA Ad 108
4.6	2	--	--	--	--	--	0.020	--	--	AA Bd 6
3.0	--	--	--	--	--	--	0.020	--	--	AA Bd 7
--	6	--	--	--	--	--	--	--	--	AA Bd 36
--	--	--	--	--	--	--	--	--	--	AA Bd 55
--	3	--	--	--	--	--	--	--	--	AA Bd 56
--	2	--	--	--	--	--	--	--	--	AA Bd 63
--	2.0 L	--	--	--	--	--	--	--	--	AA Bd 64
--	10	--	--	--	--	--	--	--	--	AA Bd 73
--	21	--	--	--	--	--	--	--	--	AA Bd 75
--	5	--	--	--	--	--	--	--	--	AA Bd 78
--	6	--	--	--	--	--	--	--	--	AA Bd 91
2.0	2.0 L	--	--	--	--	--	--	--	--	AA Bd 92
3.8	1.0	0.03 T	--	--	--	3.0	--	--	0.01	AA Bd 92
1.0	2.0 L	--	--	--	--	--	--	--	--	AA Bd 95
--	--	--	--	--	--	--	--	--	--	AA Bd 101
1.0	3.0 L	--	--	--	3.10	--	--	0.010	--	AA Bd 152
1.2	3.0 L	--	--	--	0.58	--	--	0.010	--	AA Bd 154
0.2	3.0 L	--	--	--	3.50	--	--	<0.010	--	AA Bd 155
0.3	2.7 L	<0.01	<0.20	<0.01	3.50	--	--	<0.010	--	AA Bd 155
0.7	3.0 L	--	--	--	3.80	--	--	<0.010	--	AA Bd 156
1.0	2.2 L	<0.01	<0.20	<0.01	5.30	--	--	<0.010	--	AA Bd 156
0.4	3.0 L	--	--	--	5.20	--	--	0.090	--	AA Bd 157
0.4	3.0 L	<0.01	<0.20	<0.01	2.40	--	--	<0.010	--	AA Bd 157
0.3	2.0 L	--	--	--	2.60	--	--	0.020	--	AA Bd 158
0.6	3.3 L	<0.01	<0.20	<0.01	4.10	--	--	<0.010	--	AA Bd 158
1.0	4.0 L	--	--	--	5.40	--	--	<0.010	--	AA Bd 159
5.8	3.3 L	<0.01	<0.20	<0.01	6.60	--	--	<0.010	--	AA Bd 159
0.3	2.0 L	--	--	--	5.10	--	--	<0.010	--	AA Bd 160
--	2	--	--	--	--	--	--	--	--	AA Bd 160

Appendix B. — Chemical analyses of ground water from the Lower and Upper Patapsco aquifers— Continued.

WELL NUMBER	DATE	AQUIFER	IRON, DIS-SOLVED T=TOTAL (µg/L as Fe)	MANGA-NESE DIS-SOLVED T=TOTAL (µg/L as Mn)	SILICA, DIS-SOLVED (mg/L as SiO2)	SPE-CIFIC CON-DUCT-ANCE (µS/cm)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (mg/L)	PH WATER WHOLE FIELD (STAND-ARD UNITS)
AA Ad 1	06-21-43	LOWER PATAPSCO	--	--	--	44	--	6.7
AA Ad 1	04-01-46	LOWER PATAPSCO	280 T	--	6.3	32	22	5.2
AA Ad 1	05-15-91	LOWER PATAPSCO	--	--	--	178	--	5.2
AA Ad 2	06-21-43	LOWER PATAPSCO	--	--	--	40	--	6.0
AA Ad 3	06-21-43	LOWER PATAPSCO	--	--	--	53	--	6.9
AA Ad 3	04-01-46	LOWER PATAPSCO	90 T	--	6.4	57	37	5.1
AA Ad 4	08-19-43	LOWER PATAPSCO	--	--	--	44	--	6.8
AA Ad 5	08-02-43	LOWER PATAPSCO	--	--	--	64	--	6.4
AA Ad 5	06-15-45	LOWER PATAPSCO	40 T	--	7.7	42	30	5.7
AA Ad 6	08-19-43	LOWER PATAPSCO	350 T	--	--	40	--	6.4
AA Ad 7	08-19-43	LOWER PATAPSCO	570 T	--	--	27	--	5.1
AA Ad 7	06-15-45	LOWER PATAPSCO	40 T	--	9.3	28	22	5.0
AA Ad 33	04-22-60	LOWER PATAPSCO	210 T	--	--	60	--	6.8
AA Ad 41	11-19-81	LOWER PATAPSCO	19	28	9.1	120	--	4.4
AA Ad 41	04-07-82	LOWER PATAPSCO	--	--	--	--	--	--
AA Ad 41	05-15-91	LOWER PATAPSCO	--	--	--	97	--	5.0
AA Ad 41	05-23-91	LOWER PATAPSCO	--	--	--	96	--	5.2
AA Ad 63	04-20-60	LOWER PATAPSCO	340 T	--	--	53	--	5.9
AA Ad 67	05-15-91	LOWER PATAPSCO	--	--	--	120	--	5.0
AA Ad 68	05-15-91	LOWER PATAPSCO	--	--	--	312	--	5.0
AA Ad 73	05-17-82	LOWER PATAPSCO	58	45	7.8	500	212	5.1
AA Ad 74	03-08-60	LOWER PATAPSCO	50 T	--	--	33	--	5.8
AA Ad 80	04-20-60	LOWER PATAPSCO	750 T	--	--	38	--	6.5
AA Ad 83	04-20-60	LOWER PATAPSCO	340 T	--	--	94	--	6.4
AA Ad 102	12-09-83	UPPER PATAPSCO	15	13	8.2	43	24	5.9
AA Ad 102	04-10-91	UPPER PATAPSCO	130	26	8.6	52	30	4.8
AA Ad 104	12-07-87	LOWER PATAPSCO	1600	140	6.2	292	178	6.4
AA Ad 104	03-15-88	LOWER PATAPSCO	1300	170	4.9	321	174	6.3
AA Ad 104	05-17-88	LOWER PATAPSCO	1000	180	5.0	330	176	6.0
AA Ad 104	07-11-88	LOWER PATAPSCO	2800	160	4.8	415	220	6.1
AA Ad 104	12-26-89	LOWER PATAPSCO	1500	170	6.0	384	204	5.9
AA Ad 104	07-19-90	LOWER PATAPSCO	1800	220	4.2	630	305	6.1
AA Ad 104	04-11-91	LOWER PATAPSCO	--	--	--	568	--	6.0
AA Ad 104	05-21-92	LOWER PATAPSCO	3600	310	4.1	552	265	6.2
AA Ad 108	04-11-91	LOWER PATAPSCO	--	--	--	104	--	5.5
AA Bd 6	03-28-46	LOWER PATAPSCO	80 T	--	8.0	21	18	5.0
AA Bd 7	03-13-46	LOWER PATAPSCO	--	--	--	29	--	4.5
AA Bd 36	05-23-91	LOWER PATAPSCO	--	--	--	21	--	5.5
AA Bd 55	05-07-91	LOWER PATAPSCO	--	--	--	86	--	4.5
AA Bd 56	05-07-91	LOWER PATAPSCO	--	--	--	358	--	4.9
AA Bd 63	03-08-60	LOWER PATAPSCO	50 T	--	--	22	--	6.1
AA Bd 64	05-17-82	LOWER PATAPSCO	60 T	20 T	--	52	--	4.9
AA Bd 73	04-22-60	LOWER PATAPSCO	150 T	--	--	34	--	6.1
AA Bd 75	04-22-60	LOWER PATAPSCO	920 T	--	--	116	--	6.5
AA Bd 78	04-15-60	LOWER PATAPSCO	120 T	--	--	27	--	6.1
AA Bd 91	05-17-91	LOWER PATAPSCO	--	--	--	64	--	5.0
AA Bd 92	05-12-82	LOWER PATAPSCO	<9	16	8.0	46	22	4.9
AA BD 92	05-22-92	LOWER PATAPSCO	25	22	8.3	66	32	4.6
AA Bd 95	05-11-82	LOWER PATAPSCO	<3	<3	8.6	53	37	4.8
AA Bd 101	05-22-91	LOWER PATAPSCO	--	--	--	510	--	4.8
AA Bd 152	09-13-84	LOWER PATAPSCO	75	40	7.6	56	39	5.5
AA Bd 154	09-24-84	LOWER PATAPSCO	55	10	7.3	23	19	5.1
AA Bd 155	10-09-84	LOWER PATAPSCO	46	13	7.3	56	37	5.9
AA Bd 155	12-10-91	LOWER PATAPSCO	6	12	7.7	55	37	4.7
AA Bd 156	10-23-84	LOWER PATAPSCO	150	54	7.2	125	74	5.6
AA Bd 156	11-26-91	LOWER PATAPSCO	220	53	7.9	184	100	4.4
AA Bd 157	10-31-84	LOWER PATAPSCO	170	19	7.7	32	42	5.8
AA Bd 157	11-26-91	LOWER PATAPSCO	6	8	8.4	39	29	4.8
AA Bd 158	01-25-85	LOWER PATAPSCO	23	13	2.2	42	32	4.9
AA Bd 158	11-27-91	LOWER PATAPSCO	16	15	7.8	76	50	4.8
AA Bd 159	01-24-85	LOWER PATAPSCO	13	42	7.6	135	79	5.2
AA Bd 159	11-27-91	LOWER PATAPSCO	20	56	8.0	170	104	4.8
AA Bd 160	03-28-85	LOWER PATAPSCO	160	30	7.2	81	45	4.5
AA Bd 160	04-11-91	LOWER PATAPSCO	--	--	--	74	--	4.7

Appendix C. — Chemical analyses of ground water from the Patuxent aquifer.

[mg/L = milligrams per liter; µg/L = micrograms per liter; µS/cm = microsiemens per centimeter]

WELL NUMBER	DATE	AQUIFER	SODIUM, DIS-SOLVED (mg/L as Na)	POTAS-SIUM, DIS-SOLVED (mg/L as K)	CALCIUM DIS-SOLVED (mg/L as Ca)	MAGNE-SIUM, DIS-SOLVED (mg/L as Mg)	CHLO-RIDE, DIS-SOLVED (mg/L as Cl)	FLUO-RIDE, DIS-SOLVED (mg/L as F)	ALKALINITY WATER WHOLE TOTAL FET* FIELD L=LAB (mg/L as CaCO3)
AA Ad 20	06-15-45	PATUXENT	2.0	0.80	0.90	0.50	1.4	<0.05	2
AA Ad 29	05-13-48	PATUXENT	1.5	1.0	0.90	0.50	1.2	0.10	1
AA Ad 76	03-08-60	PATUXENT	--	--	--	--	0.50	--	--
AA Ad 76	11-18-81	PATUXENT	1.0	0.50	0.53	0.32	1.4	<0.10	3.0 L
AA Ad 76	05-07-91	PATUXENT	--	--	--	--	--	--	--
AA Ad 99	12-09-81	PATUXENT	1.5	0.90	1.3	0.81	2.5	<0.10	8.0 L
AA Bd 66	05-11-82	PATUXENT	0.80	0.60	0.43	0.35	1.1	<0.10	1.0 L
AA Bd 97	05-12-82	PATUXENT	0.70	0.40	0.41	0.28	1.1	<0.10	<1.0 L
AA Bd 97	05-07-91	PATUXENT	--	--	--	--	--	--	--
AA Bd 98	05-10-82	PATUXENT	1.1	0.60	0.52	0.30	1.1	<0.10	2.0 L

*FET = Fixed Endpoint Titration (pH = 4.5)

NITRO-GEN, AM-MONIA + ORGANIC DIS. (mg/L as N)	NITRO-GEN, NITRITE TOTAL, (mg/L as N)	NITRO-GEN, NO2+NO3, DIS-SOLVED (mg/L as N)	NITRO-GEN, TOTAL (mg/L as N)	SULFATE DIS-SOLVED (mg/L as SO4)	IRON DIS-SOLVED T=TOTAL (µg/L as Fe)	MANGA-NESE, DIS-SOLVED T=TOTAL (µg/L as Mn)	SILICA, DIS-SOLVED (mg/L as SiO2)	SPE-CIFIC CON-DUCT-ANCE (µS/cm)	SOLIDS, SUM OF CONSTI-TUENTS, DIS-SOLVED (mg/L)	PH WATER WHOLE FIELD (STAND-ARD UNITS)	WELL NUMBER
--	--	--	--	5.9	--	--	9.5	24	22	5.2	AA Ad 20
--	--	--	--	6.9	2200 T	20 T	11	30	24	4.7	AA Ad 29
--	--	--	--	--	--	--	--	31	--	4.4	AA Ad 76
--	--	--	--	7.5	30	23	9.7	35	23	4.3	AA Ad 76
--	--	--	--	--	--	--	--	38	--	--	AA Ad 76
0.13	0.01	0.06	0.19	12	5100	76	9.5	55	37	6.0	AA Ad 99
--	--	--	--	5.0	460	19	8.9	32	18	4.6	AA Bd 66
--	--	--	--	6.0	170	16	8.6	37	18	4.5	AA Bd 97
--	--	--	--	--	--	--	--	36	--	--	AA Bd 97
--	--	--	--	7.0	1200	35	9.0	33	23	4.9	AA Bd 98

Appendix D. — Chemical analyses of wells analyzed for contaminants.

[-- = not detected; μg/L = micrograms per liter; pCi/L = picoCuries per liter]

WELL NUMBER: AA Ad 41 (Sawmill 5)
DATE OF COLLECTION: 07-15-1982

CONSTITUENT	VALUE (in μg/L) Detection level = 1.0
Dichlorobromomethane, total	--
Carbon tetrachloride, total (μg/L)	--
1,2-Dichloroethane, total (μg/L)	--
Bromoform, total (μg/L)	--
Chlorodibromomethane, total (μg/L)	--
Chloroform, total (μg/L)	--
Toluene, total (μg/L)	--
Benzene, total (μg/L)	2.0
Chlorobenzene, total (μg/L)	--
Chloroethane, total (μg/L)	--
Ethylbenzene, total (μg/L)	--
Methylbromide, total (μg/L)	--
Methylenechloride, total (μg/L)	--
Tetrachloroethylene, total (μg/L)	--
Trichlorofluoromethane, total (μg/L)	--
1,1-Dichloroethane, total (μg/L)	--
1,1-Dichloroethylene, total (μg/L)	--
1,1,1-Trichloroethane, total (μg/L)	--
1,1,2-Trichloroethane, total (μg/L)	--
Ethane, 1,1,2,2-Tetrachloro-, water, unfiltered, recoverable,(μg/L)	--
1,2-Dichloropropane, total (μg/L)	--
1,2-Transdichloroethene, total, in water (μg/L)	--
1,3-Dichloropropene, total, in water (μg/L)	--
2-Chloroethylvinylether, total (μg/L)	--
Dichlorodifluoromethane, total (μg/L)	--
Vinyl chloride, total (μg/L)	--
Trichloroethylene, total (μg/L)	--

WELL NUMBER: AA Ad 41 (Sawmill 5)
DATE OF COLLECTION: 05-23-1991

CONSTITUENT	VALUE (in μg/L) Detection level = 0.2
Dichlorobromomethane, total (μg/L)	--
Carbon tetrachloride, total (μg/L)	--
1,2-Dichloroethane, total (μg/L)	--
Bromoform, total (μg/L)	--
Chlorodibromomethane, total (μg/L)	--
Chloroform, total (μg/L)	--
Toluene, total (μg/L)	--
Benzene, total (μg/L)	--
Chlorobenzene, total (μg/L)	--
Chloroethane, total (μg/L)	--
Ethylbenzene, total (μg/L)	--
Methylbromide, total (μg/L)	--
Methylchloride, total (μg/L)	--
Methylenechloride, total (μg/L)	--
Tetrachloroethylene, total (μg/L)	--
Trichlorofluoromethane, total (μg/L)	--
1,1-Dichloroethane, total (μg/L)	--
1,1-Dichloroethylene, total (μg/L)	--
1,1,1-Trichloroethane, total (μg/L)	0.3
1,1,2-Trichloroethane, total (ug/l)	--
Ethane, 1,1,2,2-tetrachloro-, water, unfiltered, recoverable, (μg/L)	--
Benzene, O-chloro-, water, unfiltered, recoverable (μg/L)	--
1,2-Dichloropropane, total (μg/L)	--
1,2-Transdichloroethene, total, in water (μg/L)	--
1,3-Dichloropropene, total, in water (μg/L)	--
Benzene, 1,3-dichloro-, water, unfiltered, recoverable (μg/L)	--
Benzene, 1,4-dichloro-, water, unfiltered, recoverable,(μg/L)	--
2-Chloroethylvinylether, total (μg/L)	--
Dichlorodifluoromethane, total (μg/L)	--
Trans-1,3-dichloropropene, total (μg/L)	--
Cis-1,3-dichloropropene, total (μg/L)	--
Vinyl chloride, total (μg/L)	--
Trichloroethylene, total (μg/L)	0.2
Styrene, total (μg/L)	--
1,2-Dibromoethane, water, whole, total (μg/L)	--
Xylene, water, unfiltered, recoverable (μg/L)	--

WELL NUMBER: AA Ad 104 (Hammonds Ferry Road observation well cluster)
DATE OF COLLECTION: 12-07-1987

CONSTITUENT	VALUE (in µg/L) Detection level = 3.0
Dichlorobromomethane, total (µg/L)	--
Carbon tetrachloride, total (µg/L)	--
1,2-Dichloroethane, total (µg/L)	--
Bromoform, total (µg/L)	--
Chlorodibromomethane, total (µg/L)	--
Chloroform, total (µg/L)	--
Toluene, total (µg/L)	--
Benzene, total (µg/L)	--
Chlorobenzene, total (µg/L)	--
Chloroethane, total (µg/L)	--
Ethylbenzene, total (µg/L)	--
Methylbromide, total (µg/L)	--
Methylchloride, total (µg/L)	--
Methylenechloride, total (µg/L)	--
Tetrachloroethylene, total (µg/L)	--
Trichlorofluoromethane, total (µg/L)	--
1,1-Dichloroethane, total (µg/L)	--
1,1-Dichloroethylene, total (µg/L)	--
1,1,1-Trichloroethane, total (µg/L)	--
1,1,2-Trichloroethane, total (µg/L)	--
Ethane, 1,1,2,2-tetrachloro-, water, unfiltered, recoverable (µg/L)	--
Benzene, O-chloro-, water, unfiltered, recoverable (µg/L)	--
1,2-Dichloropropane, total (µg/L)	--
1,2-Transdichloroethene, total, in water (µg/L)	--
1,3-Dichloropropene, total, in water (µg/L)	--
Benzene, 1,3-dichloro-, water, unfiltered, recoverable (µg/L)	--
Benzene, 1,4-dichloro-, water, unfiltered, recoverable (µg/L)	--
2-Chloroethylvinylether, total (µg/L)	--
Dichlorodifluoromethane, total (µg/L)	--
Trans-1,3-dichloropropene, total (µg/L)	--
Cis-1,3-dichloropropene, total (µg/L)	--
1,2-Dibromoethylene, total (µg/L)	--
Vinyl chloride, total (µg/L)	--
Trichloroethylene, total (µg/L)	--
Styrene, total (µg/L)	--
Xylene, water, unfiltered, recoverable (µg/L)	--

WELL NUMBER: AA Ad 104 (Hammonds Ferry Road observation well cluster)
DATE OF COLLECTION: 12-07-1987

CONSTITUENT	VALUE (in µg/L) Detection level = 1.0
Toxaphene, dissolved (µg/L)	--

CONSTITUENT	VALUE (in µg/L) Detection level = 0.1
Propazine, total (µg/L)	--
Trifluralin, total recoverable (µg/L)	--
Simetryne, total (µg/L)	--
Simazine, total (µg/L)	--
Prometone, total (µg/L)	--
Prometryne, total (µg/L)	--
Cyanazine, total (µg/L)	--
Alachlor, total recoverable (µg/L)	--
PCB, dissolved (µg/L)	--
Chlordane, dissolved (µg/L)	--
Malathion, dissolved (µg/L)	--
Diazinon, dissolved (µg/L)	--
Methyl parathion, dissolved (µg/L)	--
PCN, dissolved (µg/L)	--
Metribuzin, water, whole, total recoverable, (µg/L)	--
Metolachlor, water, whole, total recoverable (µg/L)	--
Atrazine, water, unfiltered, recoverable (µg/L)	--
Ametryne, total (µg/L)	--

CONSTITUENT	VALUE (in µg/L) Detection level = 0.01
DDD, dissolved (µg/L)	--
DDE, dissolved (µg/L)	--
DDT, dissolved (µg/L)	--
Dieldrin, dissolved (µg/L)	--
Endrin, dissolved (µg/L)	--
Heptachlor, dissolved (µg/L)	--
Heptachlor epoxide, dissolved (µg/L)	--
Parathion, dissolved (µg/L)	--
2,4-D, total (µg/L)	--
2,4,5-T, total (µg/L)	--
Mirex, dissolved (µg/L)	--
Silvex, total (µg/L)	0.01
Aldrin, dissolved (µg/L)	--
Lindane, dissolved (µg/L)	--
2, 4-Dp total (µg/L)	--
Trithion, dissolved (µg/L)	--
Methyltrithion, dissolved (µg/L)	--
Ethion, dissolved (µg/L)	--
Perthane, dissolved (µg/L)	--
Methoxychlor, dissolved (µg/L)	--
Endosulfan, dissolved (µg/L)	--

WELL NUMBER: AA Bd 92 (Dorsey 14)
DATE OF COLLECTION: 05-22-1991

CONSTITUENT	VALUE (in μg/L) Detection level = 0.2
Dichlorobromomethane, total (μg/L)	--
Carbon tetrachloride, total (μg/L)	--
1,2-Dichloroethane, total (μg/L)	--
Bromoform, total (μg/L)	--
Chlorodibromomethane, total (μg/L)	--
Chloroform, total (μg/L)	--
Toluene, total (μg/L)	--
Benzene, total (μg/L)	--
Chlorobenzene, total (μg/L)	--
Chloroethane, total (μg/L)	--
Ethylbenzene, total (μg/L)	--
Methylbromide, total (μg/L)	--
Methylchloride, total (μg/L)	--
Methylenechloride, total (μg/L)	--
Tetrachloroethylene, total (μg/L)	--
Trichlorofluoromethane, total (μg/L)	--
1,1-Dichloroethane, total (μg/L)	--
1,1-Dichloroethylene, total (μg/L)	--
1,1,1-Trichloroethane, total (μg/L)	--
1,1,2-Trichloroethane, total (μg/L)	--
Ethane, 1,1,2,2-tetrachloro-, water, unfiltered, recoverable (μg/L)	--
Benzene, O-chloro-, water, unfiltered, recoverable (μg/L)	--
1,2-Dichloropropane, total (μg/L)	--
1,2-Transdichloroethene, total, in water (μg/L)	--
1,3-Dichloropropene, total, in water (μg/L)	--
Benzene, 1,3-dichloro-, water, unfiltered, recoverable (μg/L)	--
Benzene, 1,4-dichloro-, water, unfiltered, recoverable (μg/L)	--
2-Chloroethylvinylether, total (μg/L)	--
Dichlorodifluoromethane, total (μg/L)	--
Trans-1,3-dichloropropene, total (μg/L)	--
Cis-1,3-dichloropropene, total (μg/L)	--
Vinyl chloride, total (μg/L)	--
Trichloroethylene, total (μg/L)	--
Xylene, water, unfiltered, recoverable (μg/L)	--
Styrene, total (μg/L)	--
1,2-Dibromoethane, water, whole, total (μg/L)	--

WELL NUMBER: AA Bd 92 (Dorsey 14)
DATE OF COLLECTION: 05-22-1991

CONSTITUENT	VALUE
Radium 226 dissolved, Radon method (pCi/L)	1.4 ± 0.2
Radium 228, dissolved (pCi/L as Ra-228)	2.8 ± 0.9
Alpha radioactivity, gross, dissolved (μg/L as U natural)	8.7 ± 1.7
Alpha radioactivity, gross, suspended total (μg/L as U natural)	less than 0.6
Beta radioactivity, gross, dissolved (pCi/L as Cs-137)	4.7 ± 1.2
Beta radioactivity, gross, suspended (pCi/L as Cs-137)	less than 0.6
Beta radioactivity, gross, dissolved, (pCi/L as Sr-90/Yt-90)	4.4 ± 0.9
Beta radioactivity, gross, suspended total, (pCi/L as Sr-90/Yt-90)	less than 0.6

WELL NUMBER: AA Bd 156 (Bicycle Path observation well)
DATE OF COLLECTION: 07-30-1992
Analyzed by Gascoyne Laboratories, Baltimore, Maryland

CONSTITUENT	VALUE (in μg/L) Detection level = 1.0
Benzene (μg/L)	--
Carbon tetrachloride (μg/L)	--
p-Dichlorobenzene (μg/L)	--
1,1-Dichloroethene (μg/L)	--
1,2-Dichloroethane (μg/L)	--
1,1,1-Trichloroethane (μg/L)	--
Trichloroethene (μg/L)	--
Vinyl chloride (μg/L)	--
Tetrachloroethene (tetrachloroethylene) (μg/L)	1.0

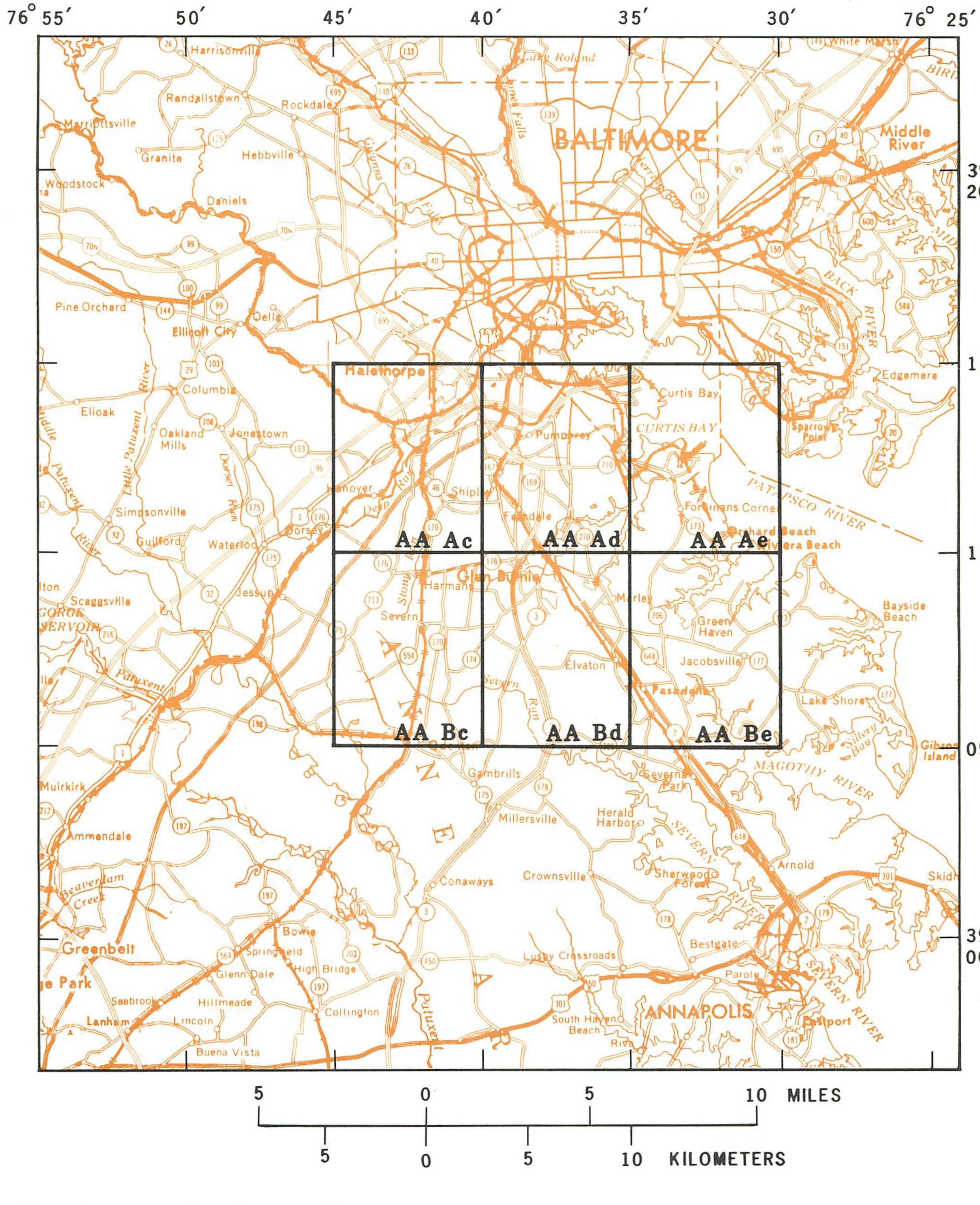


Figure 59. — Location of selected 5-minute quadrangles.

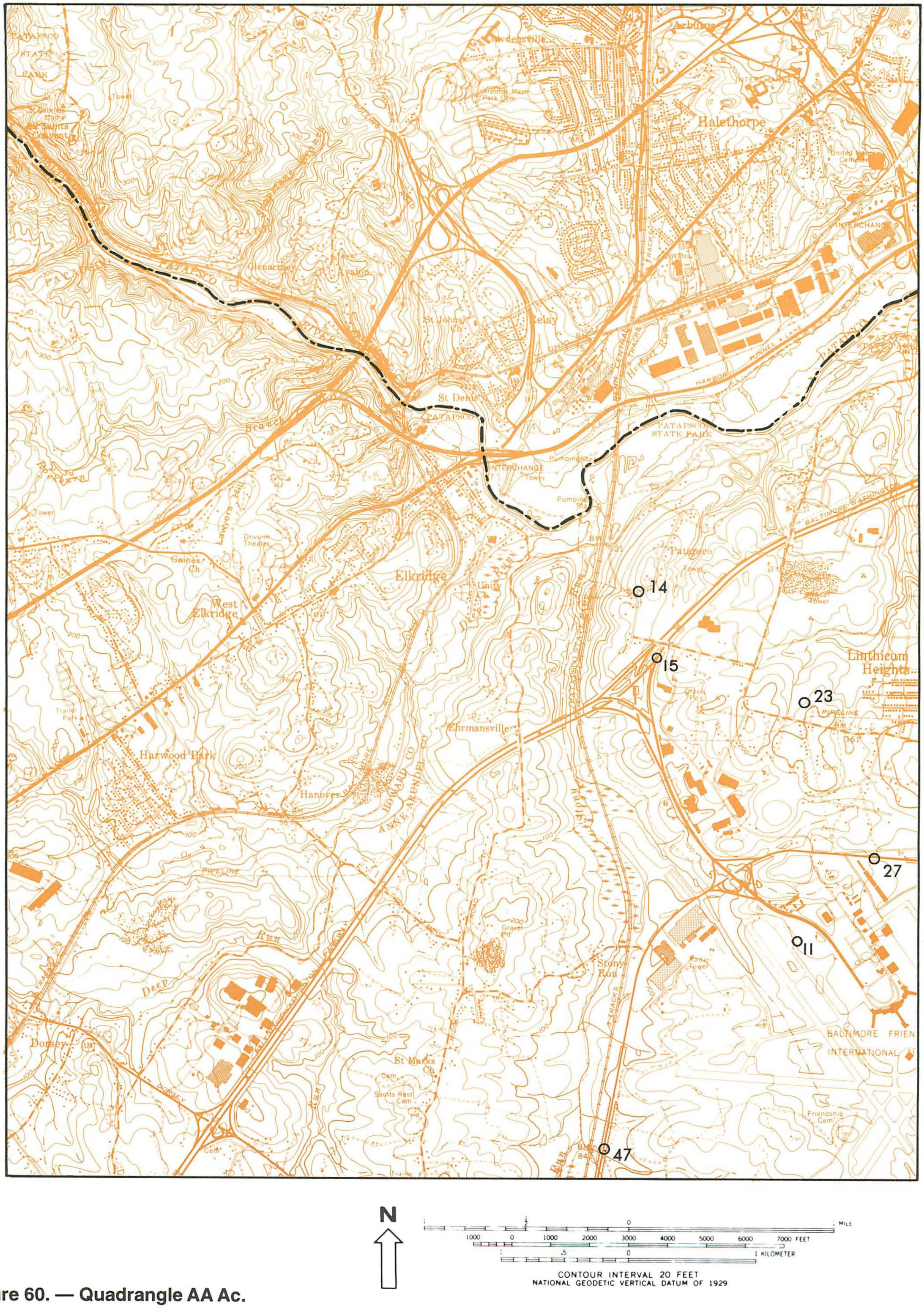


Figure 60. — Quadrangle AA Ac.

Figure 61. — Quadrangle AA Ad.

Figure 62. — Quadrangle AA Ae.

Figure 63. — Quadrangle AA Bc.

Figure 64. — Quadrangle AA Bd.

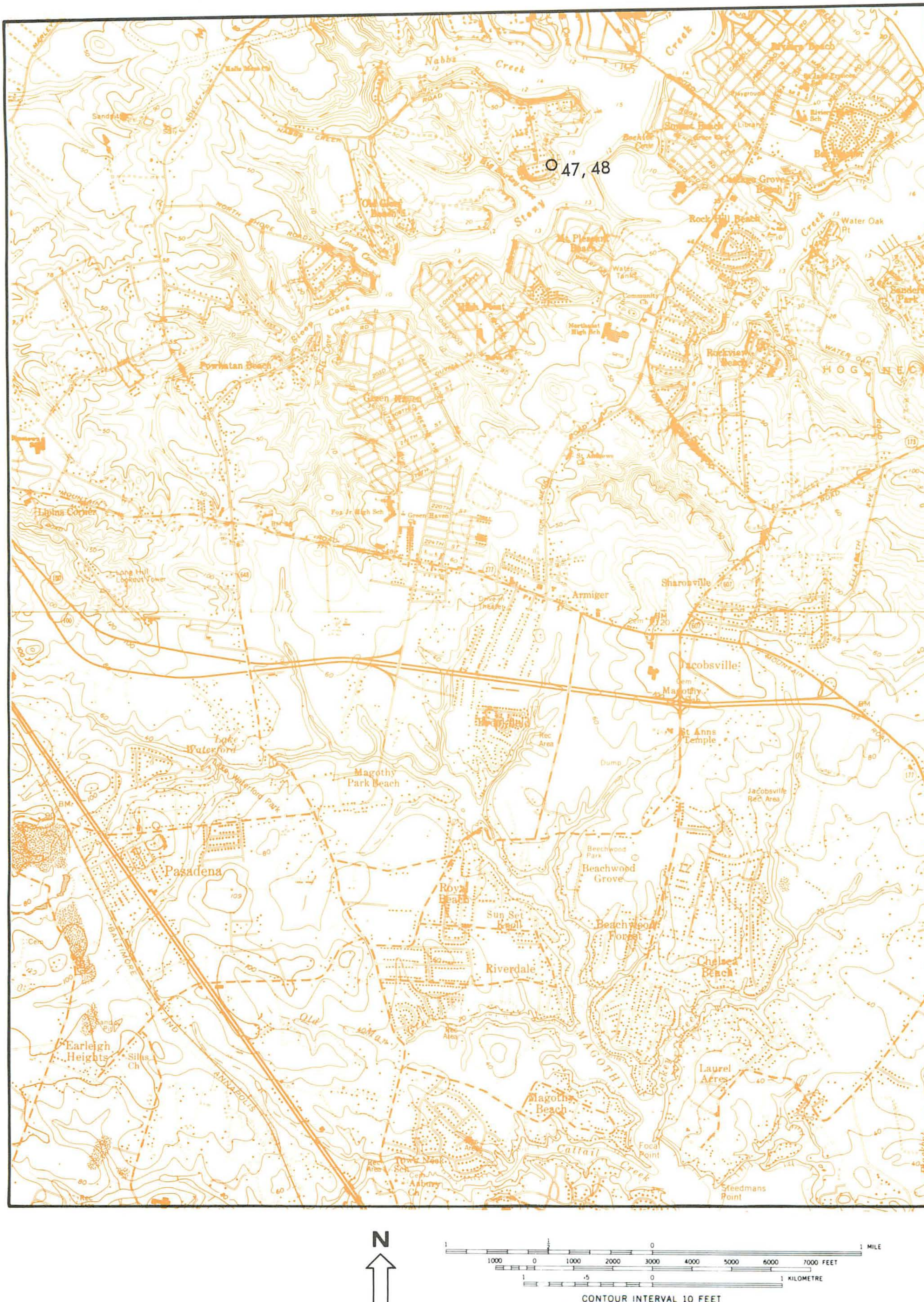


Figure 65. — Quadrangle AA Be.

Plate 1. Hydrogeologic section A - A'

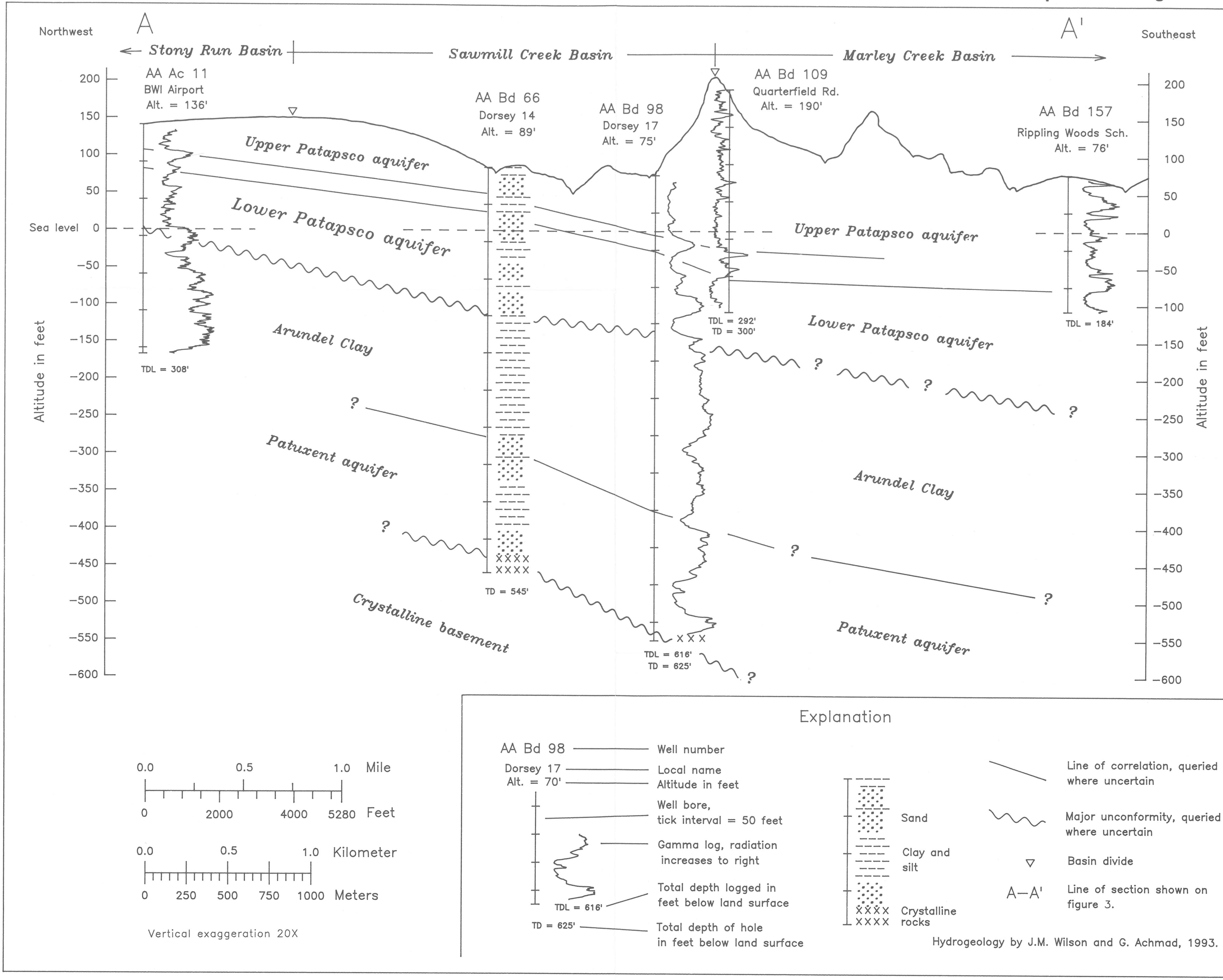


Plate 2. Hydrogeologic section B - B'

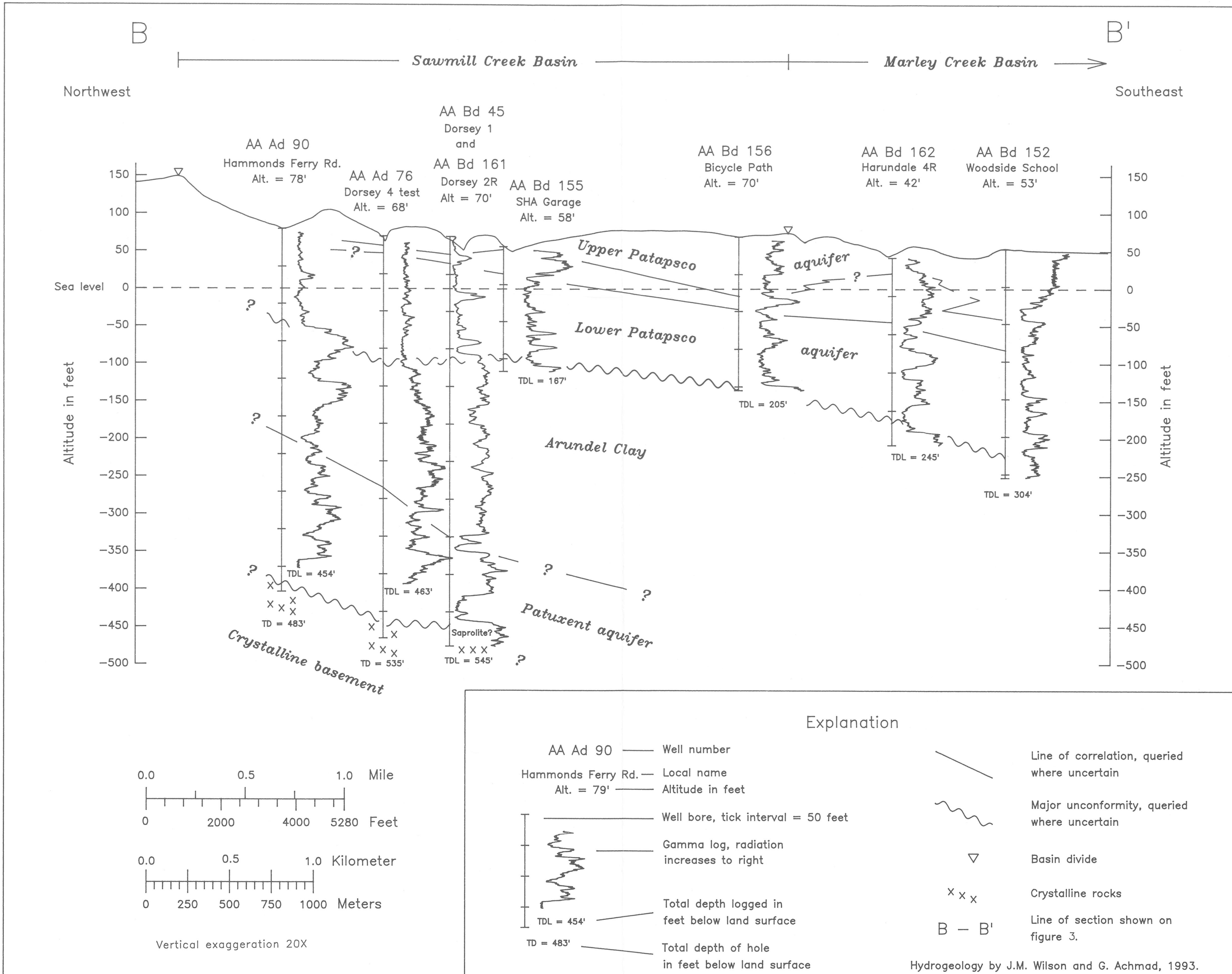


Plate 3. Hydrogeologic section C - C'

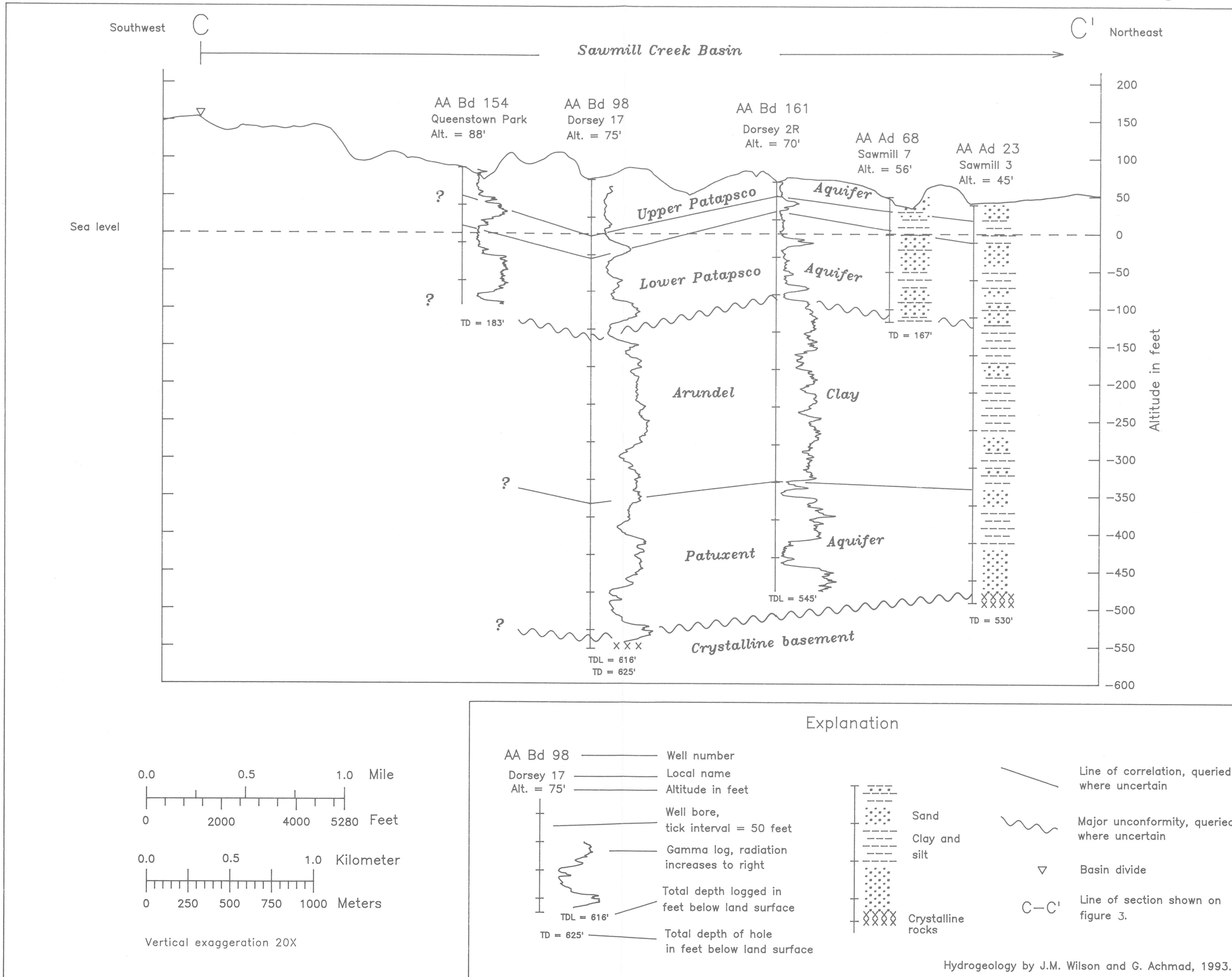


Plate 4. Hydrogeologic section D - D'

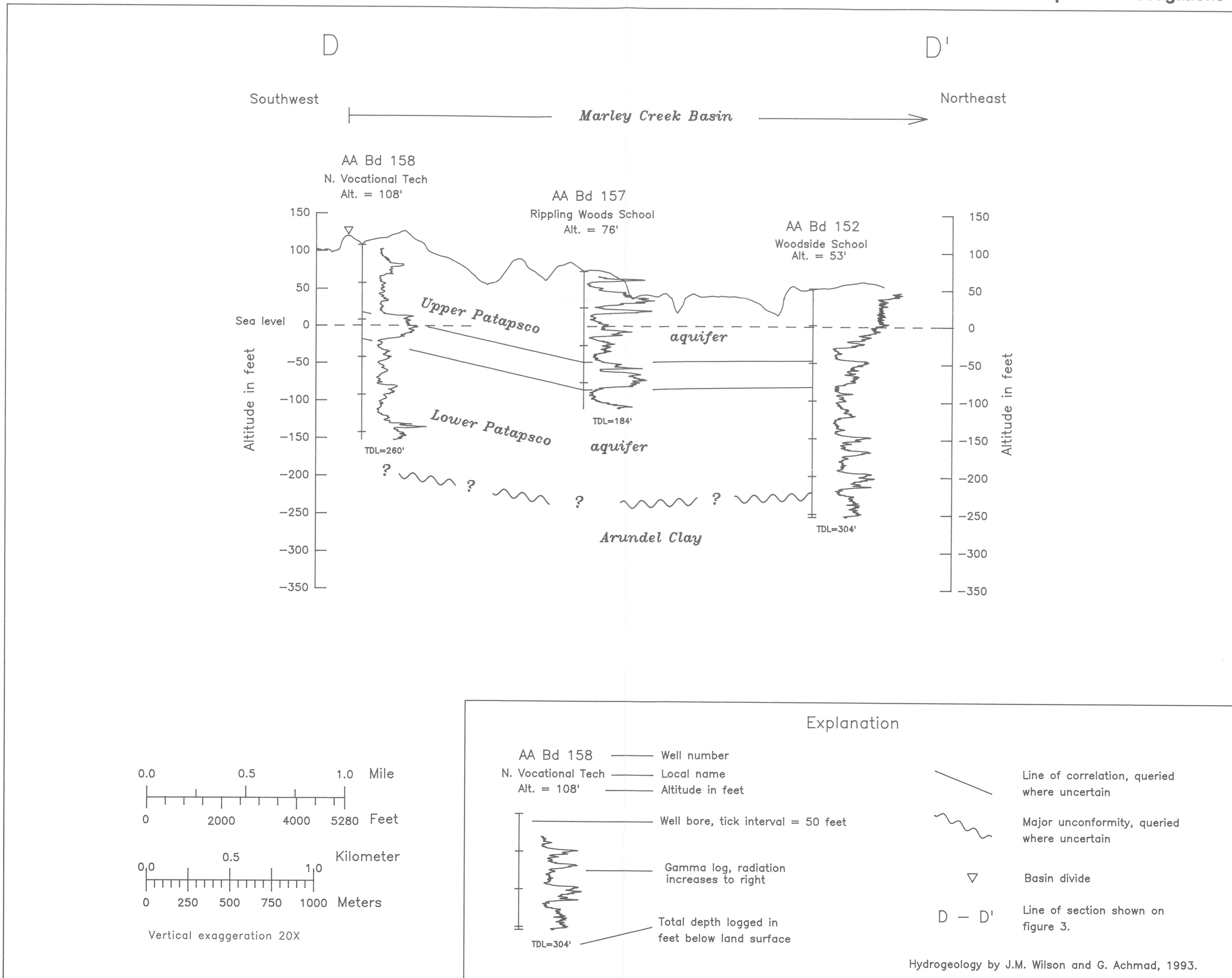


Plate 5. Comparison of the ten-year GPTRAC and MODPATH zones of transport in plan view made with the 1990 pumpage appropriation.

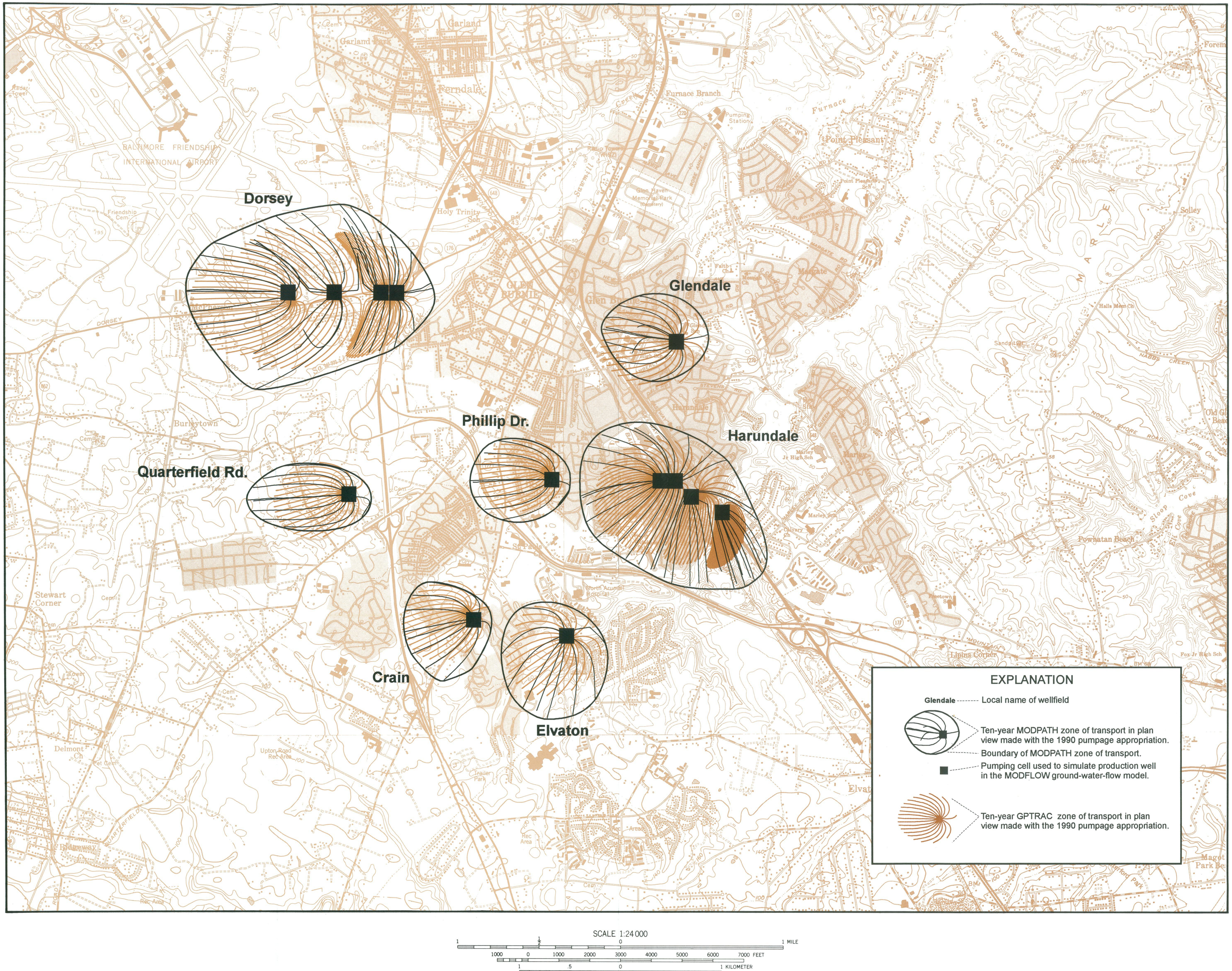


Plate 6. Comparison of the twenty-year GPTRAC and MODPATH zones of transport in plan view made with the 1990 pumpage appropriation.

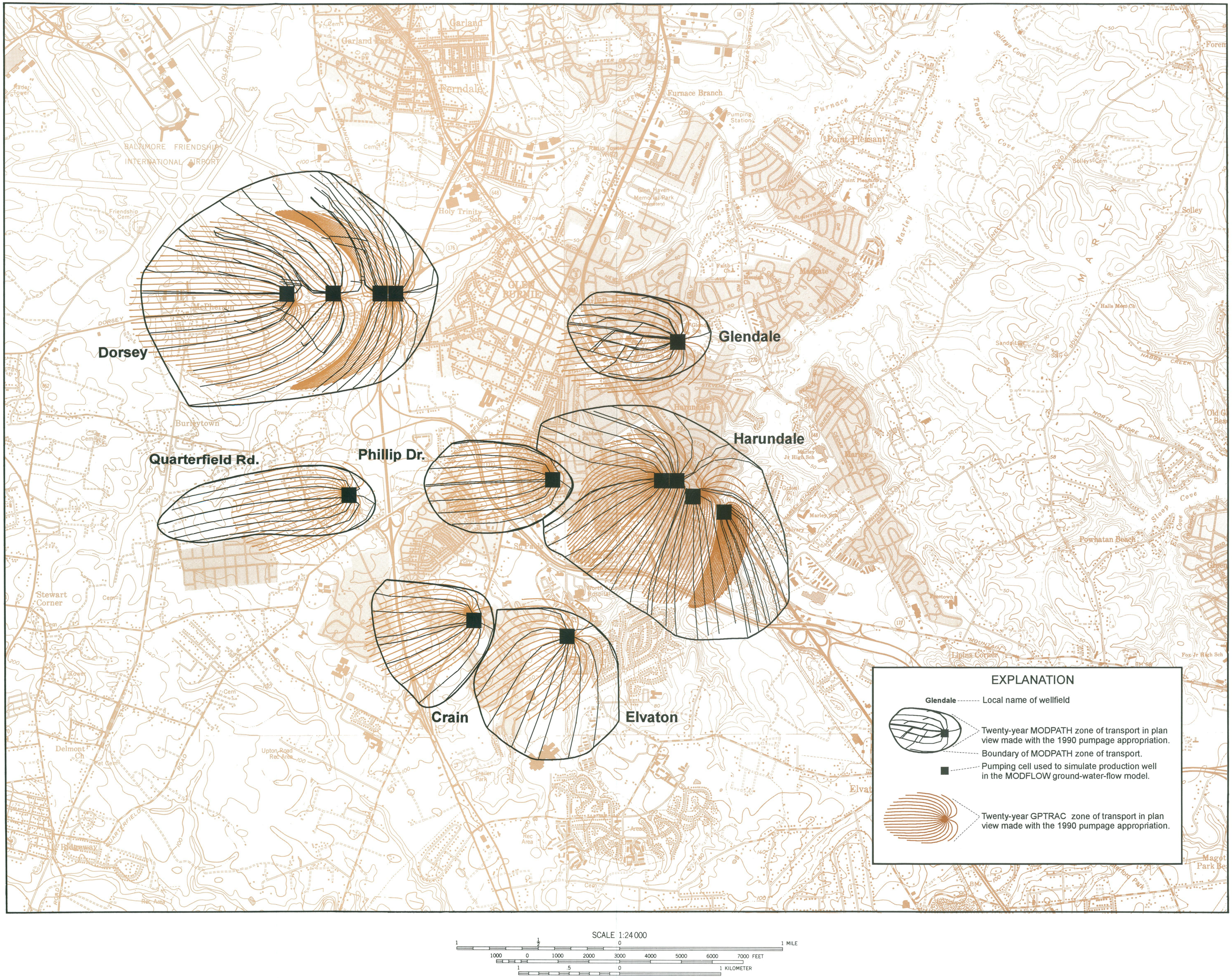


Plate 7. Comparison of the ten-year GPTRAC and MODPATH zones of transport in plan view made with the average 1984-88 pumpage.