Department of Natural Resources

MARYLAND GEOLOGICAL SURVEY

Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 22

AN EVALUATION OF THE MAGOTHY AQUIFER IN THE ANNAPOLIS AREA, MARYLAND

by
Frederick K. Mack

Prepared in cooperation with
Geological Survey
United States Department of the Interior
and
Office of Planning & Zoning
Anne Arundel County

1974

EXPLANATION

Well in which water level was measured. Number is altitude of potentiometric surface, in feet related to mean sea level

Observation well (and its number designation) used as verification point

Potentiometric contour, shows altitude of potentiometric surface, April 1970.

Contour interval is 10 feet
Datum is mean sea level

Structure contour shows altitude of top of Magothy aquifer

Contour interval 100 feet
Datum is mean sea level

0 1 2 3 4 Miles

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TABLE OF CONTENTS

	Page
Abstract	1
Introduction	3
Purpose of investigation	3
Acknowledgements	4
Location and extent of the area	4
Topography	4
Climate	4
Water needs related to future population trends	7
Methods of investigation	8
Hydrogeology	10
Coastal-plain geology of the Annapolis area	10
Magothy aquifer	12
Upper confining beds	13
Lower confining beds	15
Factors in planning development of the aquifer	17
Water-yielding potential	18
Changing hydrologic systems	23
Side effects of heavy pumping	25
Salt-water contamination	26
Sources, direction, and rate of movement of water	27
Leakage from overlying beds	30
Leakage from underlying beds	33
Movement from outcrop	34
Buffer effect of shallow aquifers	34
Thickness of confining beds as a control	34
Dispersion effects	35
Dilution effects	35
Other side effects	35
Guidelines for development of the Magothy aquifer	37
Conclusions	37
Selected references	39
Appendixes	41
Model development (Appendix A)	42
Electric-analog model	42
Digital models	44
Aquifer model	44
Confining-bed model	45
Geologic and hydrologic data from test sites (Appendix B)	47
Description of cuttings from probe holes AA-Dd 41, Cf 100, De 101, and Df 90 (Appendix C)	55
Descriptions of cores from test hole AA-De 100, by John Glaser (Appendix D)	59
Palynological analysis of cores from test hole AA-De 100, by Gilbert J. Brenner (Appendix E)	65

LIST OF ILLUSTRATIONS

Page

Figure 1. Map of Maryland showing the project area 3

2. Map showing topography of Anne Arundel County 5

3. Graphs showing monthly air temperatures and precipitation at Annapolis 6

4. Map showing present and projected population by service areas in Anne Arundel County 8

5. Graph showing predicted population growth by water-service areas 8

6. Map showing location of larger well fields, sites of detailed test work, and observation wells for which continuous water-level records are available 9

7. Geologic map of Anne Arundel County 11

8. Geologic section A-A' across Anne Arundel County 13

9. Map showing thickness of the Magothy aquifer 14

10. Graphs showing particle-size distribution in core samples from the Magothy aquifer at well AA-Cf 101 on Broadneck Peninsula 15

11. Graphs showing particle-size distribution in core samples from the Magothy aquifer at well AA-De 104 at Collison Corner 16

12. Graphs showing particle-size distribution in core samples from the Matawan Formation 17

13. Graphs showing particle-size distribution in core samples from the Patapsco Formation 17

14. Charts showing factors in planning the development of the Magothy aquifer 18

15. Map showing the transmissivity of the Magothy aquifer in the Annapolis area and the location of the constant-head boundaries used in the analog model 19

16. Sketches of four sites within the hydrologic system showing variations of head differentials between the shallow aquifer and the Magothy aquifer, and the resulting differences in the direction of water movement 20

17. Map showing the estimated potentiometric surface of the Magothy aquifer before pumping 22

18. Map showing the outcrop area, potentiometric surface of April 1970, and the altitude of the top of the Magothy aquifer 24

19. Map showing drawdown predicted by the analog model as a result of pumping hypothetical wells at a combined rate of 58.4 mgd from year 1970 to 2000 26

20. Chart showing interrelationship of factors in evaluating the salt-water problem 27

21. Section and diagram used for speculating about the sources, paths, and events involved in movement of water due to heavy pumping of the Magothy aquifer 28

22. Sections showing progress of water through the confining layer 30

Page

23. Map showing areas where salt water overlies the outcropping Magothy aquifer and areas in which heavy pumping will accelerate movement of salt water into the aquifer 31

24. Graph showing the relationship between the thickness of a confining bed and the time for water to move through it 32

25. Graph showing the relationship between the thickness of the confining bed, and the quantity of leakage 33

26. Conceivable changes in the quality of water after long-term pumping from the Magothy aquifer 36

27. Graph showing the relationship between the pumping rate and the time for water to move through the confining layer 38

28. Map showing area and grid spacing used in the digital model of the Magothy aquifer 43

29. Section showing geophysical, geologic, and hydrologic data for test site 1 at Annapolis Jr. High School 49

30. Section showing geophysical, geologic, and hydrologic data for test site 2 at Collison Corner 50

31. Section showing geophysical, geologic, and hydrologic data for test site 3 at Broadneck Peninsula 51

32. Section showing geophysical, geologic, and hydrologic data for test site 4 at Thomas Point 52

33. Section showing geophysical, geologic, and hydrologic data for test site 5 at Rutland Road 53

34. Chart summarizing lithologic data from test hole AA-De 100 61

Plate 1. Palynology of test hole AA-De 100 (Part 1) 73

2. Palynology of test hole AA-De 100 (Part 2) 75

TABLES

Page

Table 1. Population and water-supply requirements, present and predicted, for the Annapolis, Maryland area 7

2. Stratigraphy and hydrologic and lithologic characteristics of geologic formations in the Annapolis area 12

3. Values for vertical hydraulic conductivity (K') of confining layers determined by laboratory methods 16

4. Well fields and pumpage from the Magothy aquifer from 1950 to 1970 25

5. Results of verification trials of the electric-analog model 42

6. Predicted quantities of water derived from storage, leakage, and boundary sources after pumping the hypothetical well field for 30 years 44

7. Data available for test sites 48

AN EVALUATION OF THE MAGOTHY AQUIFER IN THE ANNAPOLIS AREA, MARYLAND

by
Frederick K. Mack

ABSTRACT

This study was made to develop information needed for planning the role of the Magothy aquifer as a source for future water supplies in the Annapolis area in Anne Arundel County, Maryland.

The Magothy aquifer is a layer of coarse gray to white sand from 100 to 200 feet thick cropping out in a belt 2 to 5 miles wide, extending in a northeast-southwest direction, 8 to 12 miles northwest of Annapolis on the west side of Chesapeake Bay. The aquifer dips southeastward beneath younger formations of clay, silt, and sand at approximately 30 feet per mile from an altitude of about 100 feet in upland parts of the outcrop area to about 300 feet below sea level at the southeast end of the Annapolis peninsula. The saline waters of Chesapeake Bay and its estuaries overlie a large part of the area in which the aquifer occurs at depth and also a part of its outcrop area. A confining bed, the Matawan Formation, lies directly above the Magothy aquifer in much of the area.

The Magothy aquifer is a part of a larger hydrologic system (including the streams in its outcrop area, overlying and underlying geologic formations, and Chesapeake Bay and its estuaries), not an isolated source of water. Heavy development of theMagothy aquifer will reduce the amount of water available from the streams and adjacent formations and, conversely, further development of adjacent formations will reduce the availability of water from the Magothy aquifer.

The aquifer is currently yielding water at a rate of 4 mgd (million gallons per day) in the Annapolis area. The cone of depression created by this pumping is relatively shallow and the potentiometric surface for the aquifer, when pumped at this rate, is still at least a few feet above sea level in all but a few areas near larger well fields. Because the potentiometric surface of the Magothy aquifer is still at least a few feet above sea level, the hydraulic gradient is upward in low lying areas such as the estuaries of Chesapeake Bay, and there is presently (1973) little danger of salt-water contamination.

Electric-analog model studies indicate that the Magothy aquifer is capable of yielding about 60 mgd in the Annapolis area, if the potentiometric surface is lowered to near its top. The model also indicates that most of the recharge to the aquifer would be received by leakage from adjacent formations. Concern has been expressed regarding the side effects that might be expected as a result of lowering the potentiometric surface, particularly the possibility that salt water from Chesapeake Bay or its estuaries might be induced into the aquifer, thus impairing the quality of its water. The Matawan Formation and younger formations serve as protective barriers, in most of the area, to impede the vertical movement of water between the estuaries and the Magothy aquifer. About 100 years would be required for water from the estuaries to move through the confining beds to the aquifer under the maximum head differentials that could be developed. However, the aquifer is unprotected by overlying layers in the upper parts of the Severn and Magothy Rivers. In those exposed areas, the aquifer would be most susceptible to contamination, which could migrate downdip to other parts of the aquifer. Probably the amount of water that could leak into the aquifer in this area is relatively small and could be controlled by proper management.

The source of most recharge to the aquifer will be land areas. Therefore, the concentration of salt water that may eventually reach well fields will be substantially diluted by water from the fresh-water sources.

Because many broad assumptions have had to be made in the preparation of the models of the Magothy aquifer, the models would be made more accurate by updating and verification as new data become available.

INTRODUCTION

PURPOSE OF INVESTIGATION

Annapolis is a rapidly developing area in rapidly developing Anne Arundel County. The city of Annapolis is on the south bank of the Severn River, 2 miles from its mouth at Chesapeake Bay. The average daily water requirements by the year 2000 are expected to increase threefold to 25 mgd for the Annapolis area and to increase fourfold to 120 mgd for Anne Arundel County as a whole. To be sure that these demands will be satisfied, planners have had to consider all potential sources of water. Earlier studies had shown that surface-water sources in the county are not adequate to justify further development, but that several aquifers capable of yielding large quantities of water underlie the area. However, the information essential for good planning was not complete. A detailed study of the hydrologic properties of the aquifer systems underlying the area was needed. The data from such a study could then be used to determine whether or not the quantity and quality of ground water available is adequate to supply expected demands of the future. This report presents the results of a study made for this purpose.

The Magothy aquifer, the most productive aquifer in the Annapolis area in 1970, was singled out for intensive study as a first step in estimating the amount of ground water available. This aquifer is especially important because of its ability to yield large quantities of water from relatively shallow depths. It has yielded an average of 3 to 4 mgd for the last 20 years and is capable of furnishing water at this rate for an unlimited length of time. Because the Magothy is the shallowest high-yielding aquifer in the area and because of the proximity of saline water in Chesapeake Bay, study of the aquifer entailed: (1) the determination of the amount of water available from the aquifer if it were developed to full capacity with no concern about leakage of water from nearby salt-water sources; (2) the evaluation of the hazard of contamination by saline water from Chesapeake Bay; and (3) the determination of steps to be taken to protect the aquifer.

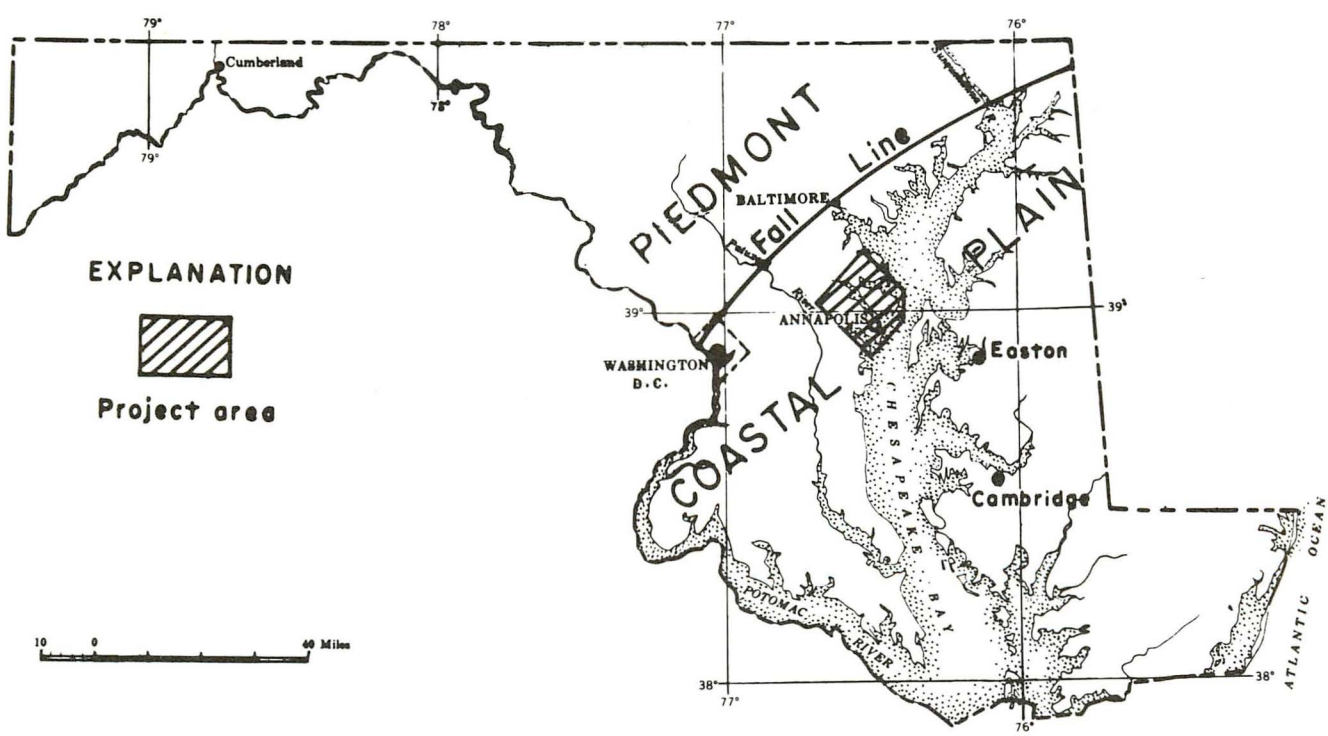

Figure 1.—Map of Maryland showing the project area.

ACKNOWLEDGEMENTS

Assistance with this project was rendered by well drillers, well owners, and Federal, State, County, and City agencies. H. H. Bunker & Sons, Inc., Layne-Atlantic Company, Delmarva Drilling Company, and East Coast Well and Pump Company, were especially helpful in providing well-construction data and other information. Lithologic and petrologic studies of core samples from test holes AA-De 100 were made by John Glaser of the Maryland Geological Survey. Spore and pollen studies by Gilbert Brenner of several samples from the test hole were used in conjunction with the work of Glaser in preparing a stratigraphic classification for the site. This classification was used as a reference point for the correlation of geologic data from other parts of the project area. Personnel of the Ground Water Management Division of the Maryland Water Resources Administration provided support for much of the fieldwork, including the semi-annual measurements of the observation-well network, pumping tests, geophysical logging, power augering, and many other activities. Roger Wolff and Peter Trescott of the U. S. Geological Survey made several tests of the vertical hydraulic conductivity of clay beds and developed digital models of both the Magothy aquifer and the confining beds. The electric-analog model of the aquifer was designed, constructed and modified by the U. S. Geological Survey in Phoenix, Arizona. Harry Hansen of the Maryland Geological Survey participated in early planning of the project and provided helpful comments and criticisms during its several stages of development.

LOCATION AND EXTENT OF THE AREA

The project area is in the east-central part of Anne Arundel County, Maryland along the western shore of Chesapeake Bay (fig. 1). Annapolis, the capital of Maryland, is in the central part of the project area, 30 miles east of Washington, D. C., and 25 miles southsoutheast of Baltimore, Md. The project area includes about 110 square miles of land and about 50 square miles of water.

TOPOGRAPHY

The topography influences the hydrology of the Magothy aquifer. Circulation is natural throughout the aquifer--it is recharged at the higher elevations and discharged at lower elevations.

The project area is entirely within the Coastal Plain physiographic province. Its northwestern boundary is about 10 miles southeast of the Fall Line. The area includes parts of four peninsulas separated by the Magothy, Severn, and South Rivers, which are estuaries of Chesapeake Bay (fig. 2). The estuaries are extensive but shallow, commonly less than 20 feet deep. Parts of the peninsulas are flat and low lying, with irregular shorelines. However, precipitous escarpments are common along the Severn and South Rivers. Many steep-sided gullies dissect the relatively high ridge areas. The highest part of the project area is 200 feet above sea level.

CLIMATE

Climate is one of many controls affecting availability of water. An excess of precipitation over evapotranspiration in the northeastern part of the United States favors replenishment of surface-water reservoirs and recharge of water-bearing formations. Precipitation is year-round but the precipitation during the non-growing season is most effective in replenishing shallow ground-water reservoirs. A large proportion of water from summer rains (during the growing season) is returned to the atmosphere almost immediately by evaporation and transpiration.

Anne Arundel County lies in the humid temperate climatic belt of the eastern United States. It has warm summers and relatively mild winters.

Precipitation and temperature data for Annapolis, based on more than 88 years of record, are shown on figure 3. Mean annual precipitation is about 44 inches, but its amount and distribution differ somewhat from year to year. The lowest annual precipitation was 21.16 inches in 1930, and the highest was 66.6 inches in 1907. Thus, precipitation during the wettest year was more than three times greater than that during the driest year. Although no particular month or season is exceptionally wet or dry, precipitation during individual months is extremely variable and unpredictable. Rainfall in August 1943 was only 0.19 inch, whereas in August 1867 it was 14.5 inches. An average of 107 days per year have 0.01 inch or more of precipitation. Average annual snowfall is about 21 inches.

Figure 3 shows that the minimum temperature was -6°F and the maximum was 106°F. Temperatures generally range between 35°F and 77°F. Average annual temperature is about 56°F. The highest annual temperature was 59.4°F in 1954, and the lowest was 51.3°F in 1856.

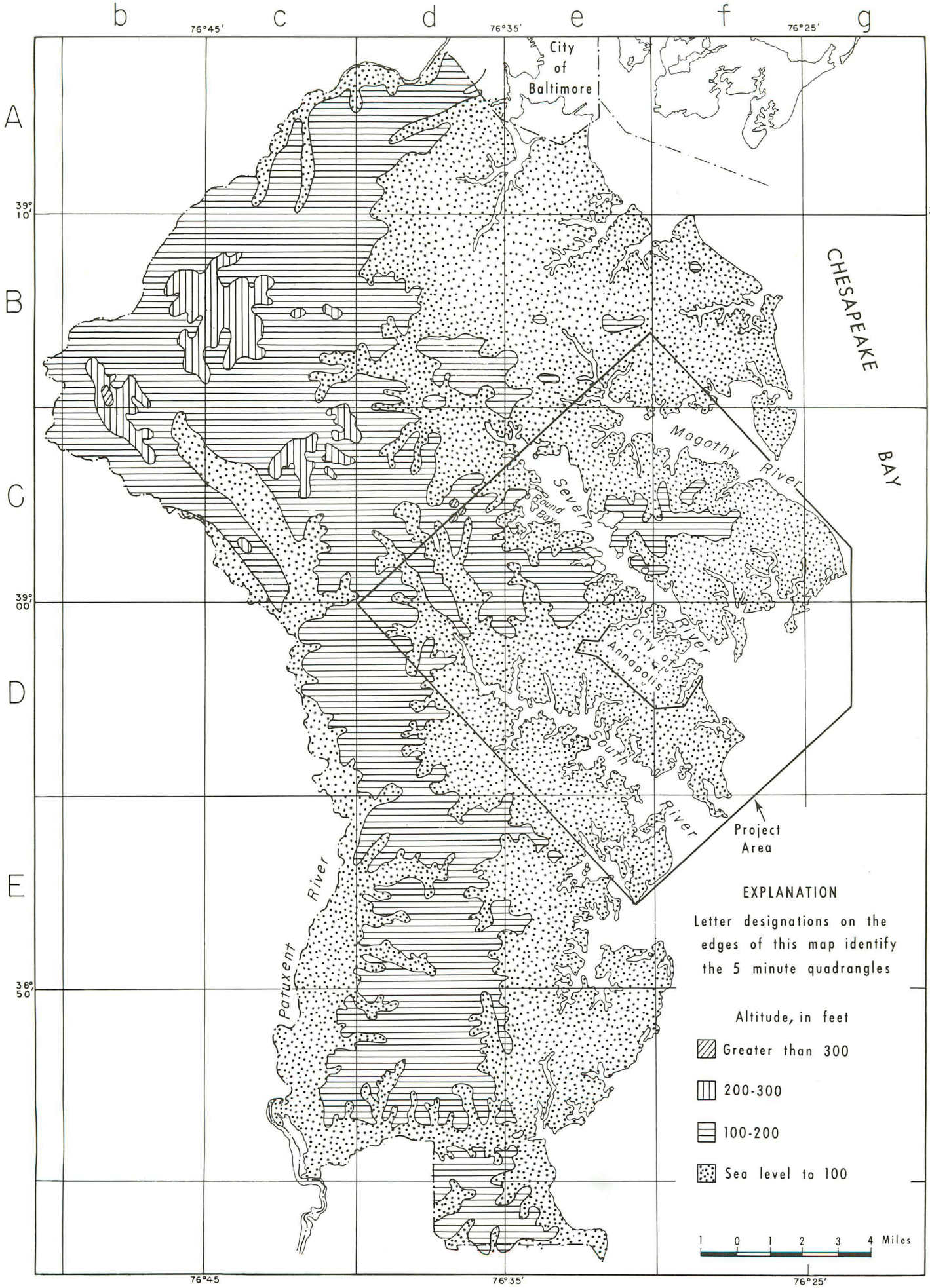

Figure 2.—Map showing topography of Anne Arundel County.

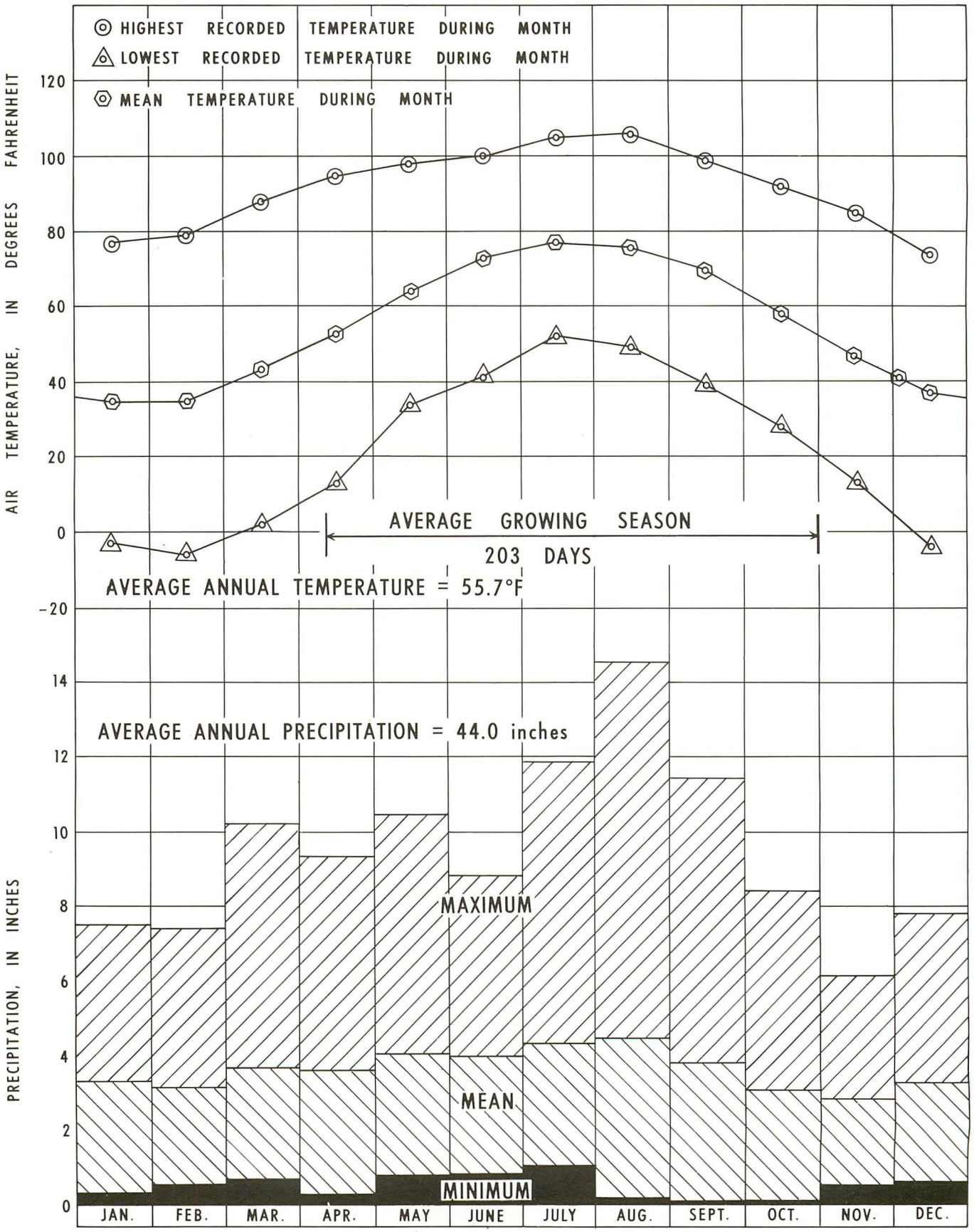

Figure 3.—Graphs showing monthly air temperatures and precipitation at Annapolis.

WATER NEEDS RELATED TO FUTURE POPULATION TRENDS

The population of the Annapolis area was about 82,000 in 1970 and is expected to increase to 204,000 by the year 2000. Figures 4 and 5 summarize predictions of population increases and distribution for all of Anne Arundel County. The data were taken from "Water and Waste Water Master Plan for Anne Arundel County," by Whiteford, Falk, and Mask, Inc., 1969.

In 1970, an average of about 30 mgd of water was used in all of Anne Arundel County, and about 8 mgd was used in the Annapolis area. Predictions in the master plan (Whiteford, Falk, and Mask, Inc., 1969) indicate that by the year 2000 an average of 120 mgd will be required by the entire county and about 26 mgd will be required by the Annapolis area. Maximum daily requirements will probably be almost twice the daily average requirements. Table 1 summarizes predictions from the master plan of water requirements through the year 2000.

Table 1.—Population and water-supply requirements, present and predicted, for the Annapolis, Maryland area [1]

Year / Subarea	1960			1970			1980			1990			2000			
	Persons (x 1000)	Water requirement (mgd)		Persons (x 1000)	Water requirement (mgd)		Persons (x 1000)	Water requirement (mgd)		Persons (x 1000)	Water requirement (mgd)		Persons (x 1000)	Water requirement (mgd)		Reference
		Ave.	Max.		Ave.	Max.		Ave.	Max.		Ave.	Max.		Ave.	Max.	
Broadneck																
Arnold	7.7	0.44	0.88	13.2	0.90	1.80	19.6	1.59	3.18	33.5	3.10	6.20	47.6	5.28	10.38	2)
Whitehall	1.9	0.11	0.22	3.3	.30	.55	4.9	0.70	1.22	8.2	1.11	2.01	11.9	1.74	3.18	2)
Annapolis																
Bay Ridge	9.4	0.55	1.07	17.6	1.36	2.54	26.4	2.33	4.36	42.0	4.45	8.43	57.8	7.12	13.40	3)
North Basin	24.0	2.38	4.68	36.0	4.09	7.96	45.6	5.60	10.88	50.5	6.81	13.13	52.2	8.00	15.16	3)
Southeastern																
Rhode River North	7.8	0.44	.88	11.8	1.20	2.40	16.3	0.83	1.43	25.4	1.70	3.12	34.7	3.55	6.62	4)
Total for Annapolis area	50.8	3.92	7.73	81.9	7.85	15.25	112.8	11.05	21.07	159.6	17.17	26.89	204.2	25.69	48.74	
Total for all of Anne Arundel County [6]	196.3	20.0		304.2	30.0		431.0	58.5		576.1	89.2		732.2	120.0		5) 7)

1) Compiled from: Whiteford, Falk, & Mask, Inc., 1969 Water and Waste Water Master Plan, Anne Arundel County, Md. References in last column designate specific parts of this report used for source material.
2) Table B-12, p. B-16
3) Table B-15, p. B-19
4) Table B-16, p. B-20
5) Table 6-2, p. 6-10
6) Does not include Fort Meade or Maryland House of Correction, Jessup, Md.
7) Table 3-1, p. 3-2.

METHODS OF INVESTIGATION

First steps in the study of the Magothy aquifer entailed refinement of earlier concepts of the geologic framework of the Annapolis area and of the hydrologic system functioning within the geologic framework. Geologic and hydrologic data from earlier studies were compiled, and new data were collected by test drilling, geophysical logging, laboratory studies, aquifer tests, and by the development of an observation-well network. Detailed testing was done in the field at five sites. Table 7 lists the data obtained at each of these sites. Figure 6 shows active well fields, observation wells, and test sites in the project area. The data were used to prepare potentiometric maps, geologic sections, and maps of the transmissivity of the aquifer.

Electric-analog and digital models of the Magothy aquifer were constructed using the above data. Historical water levels and pumpage data for the aquifer were gathered for use as a basis for verifying the models. The electric-analog model and one digital model approximate conditions in the aquifer but do not give information on the hazard of salt-water contamination or the effects of pumping on other parts of the hydrologic system. The second

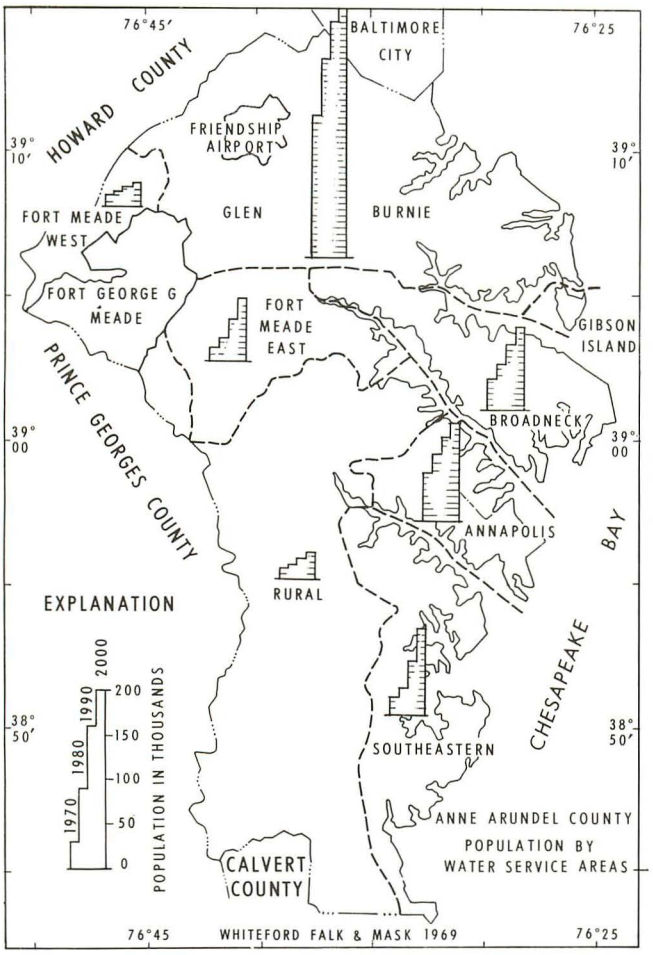

Figure 4.—Map showing present and projected population by service areas in Anne Arundel County.

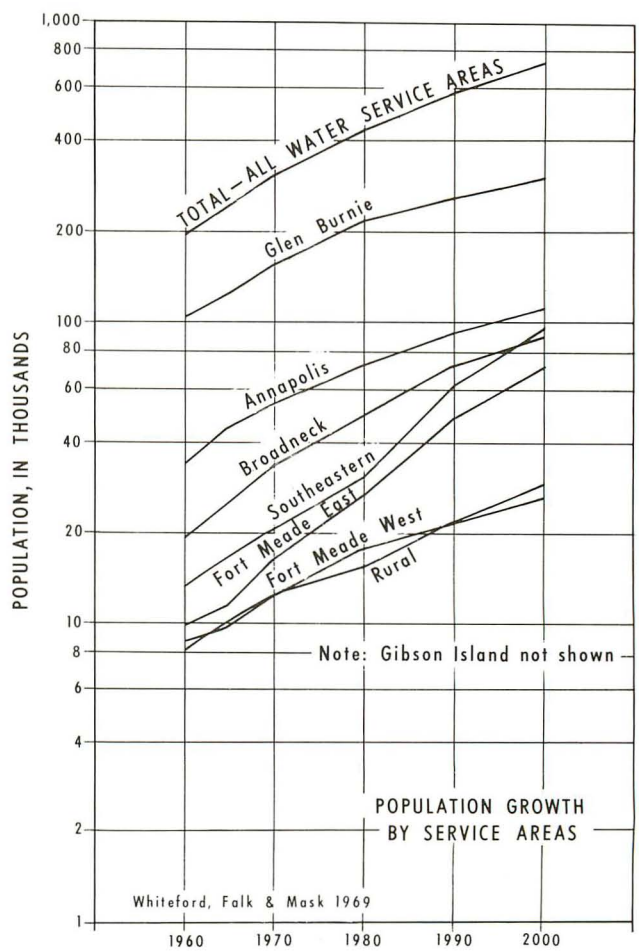

Figure 5.—Graph showing predicted population growth by water-service areas.

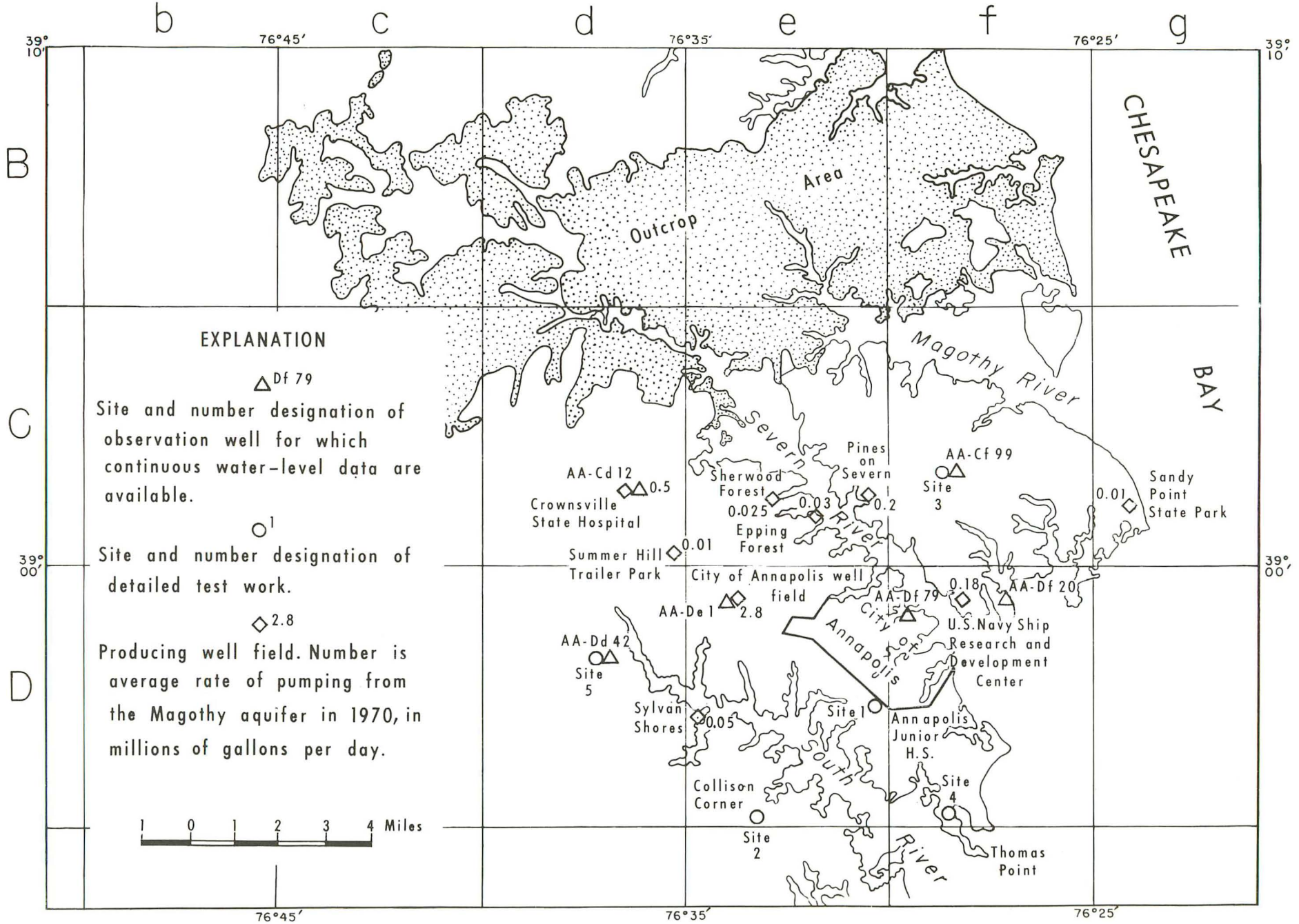

Figure 6.—Map showing location of larger well fields, sites of detailed test work, and observation wells for which continuous water-level records are available.

digital model indicates the way pumping of the aquifer affects adjacent confining layers and shows how the confining layers impede the vertical movement of water to the aquifer. This is a critical factor in evaluating the hazard of saline-water movement from Chesapeake Bay to the aquifer.

Once the models were verified, they were ready for "predictive use" to estimate the effect real well fields would have if developed in the real aquifer. Additional details on the development of the models is given in the appendix of this report.

HYDROGEOLOGY

Geologic conditions in the Annapolis area, to a large extent, control the amount of water that can be taken from the Magothy aquifer, the rate at which individual wells can be pumped, and the depth to which wells must be drilled.

COASTAL-PLAIN GEOLOGY OF THE ANNAPOLIS AREA

Anne Arundel County is underlain by a wedge-shaped mass of unconsolidated sedimentary deposits that overlie older consolidated crystalline rocks of Precambrian or Early Cambrian age. The unconsolidated deposits are stratified layers of sand, gravel, silt, and clay. The sand and gravel strata constitute the major water-bearing rocks.

The crystalline rocks consist of gabbro, diorite, and other igneous and metamorphic rocks. The surface of these rocks dips gently toward the southeast (fig. 8). Just north of the Howard County line, the crystalline rocks crop out at an altitude of 200 to 300 feet above sea level (fig. 7). They underlie Anne Arundel County at depths ranging from less than 100 feet in the northwest to 2,000 feet in the southeast. Because they are buried at great depths throughout most of the county, the crystalline rocks are seldom penetrated by drilling, and almost no information is available regarding them.

Generally the unconsolidated deposits are easy to drill and, where exposed, are soft enough to be worked with a shovel. Because the layers of sand, gravel, and clay composing these deposits crop out, they have been studied and described in detail. Figure 7 is a generalized geologic map showing the outcrop of the rock units. Figure 8, a geologic section across the county, shows that:(1)The depth to crystalline rock increases progressively toward the southeast; (2) the unconsolidated layers lap upon one another and the youngest (uppermost) formations are exposed progressively to the east; and (3) the formations thicken to the east. Little information is available regarding the unconsolidated deposits at depths greater than 1,000 feet in the project area. Table 2 summarizes the thickness and character of the geologic units. Figure 9 shows the thickness of the Magothy aquifer.

The characteristics of the Coastal Plain sediments in and near the Annapolis area are the dominant factors controlling the availability of water from the Magothy aquifer. Knowledge of the hydrologic character of all the sediments is needed to understand the source and direction of movement of the water both under non-pumping conditions and under conditions of stress caused by pumping.

Each lithologic type of sediment plays a special role in the functioning of the hydrologic system. Clean sand layers of sufficient thickness have the capability of yielding large quantities of water to individual wells and, thus are important in the development of large water supplies. Clay layers cannot yield significant quantities of water to individual wells, but they strongly influence the movement of water within the hydrologic system by impeding the vertical flow of water between aquifers. Clay layers also serve as sources of recharge, both by (1) furnishing water stored within them and (2) by functioning as conduits for leakage from other sources. Their effectiveness in these functions depends on their thickness, hydraulic conductivity, and lateral extent.

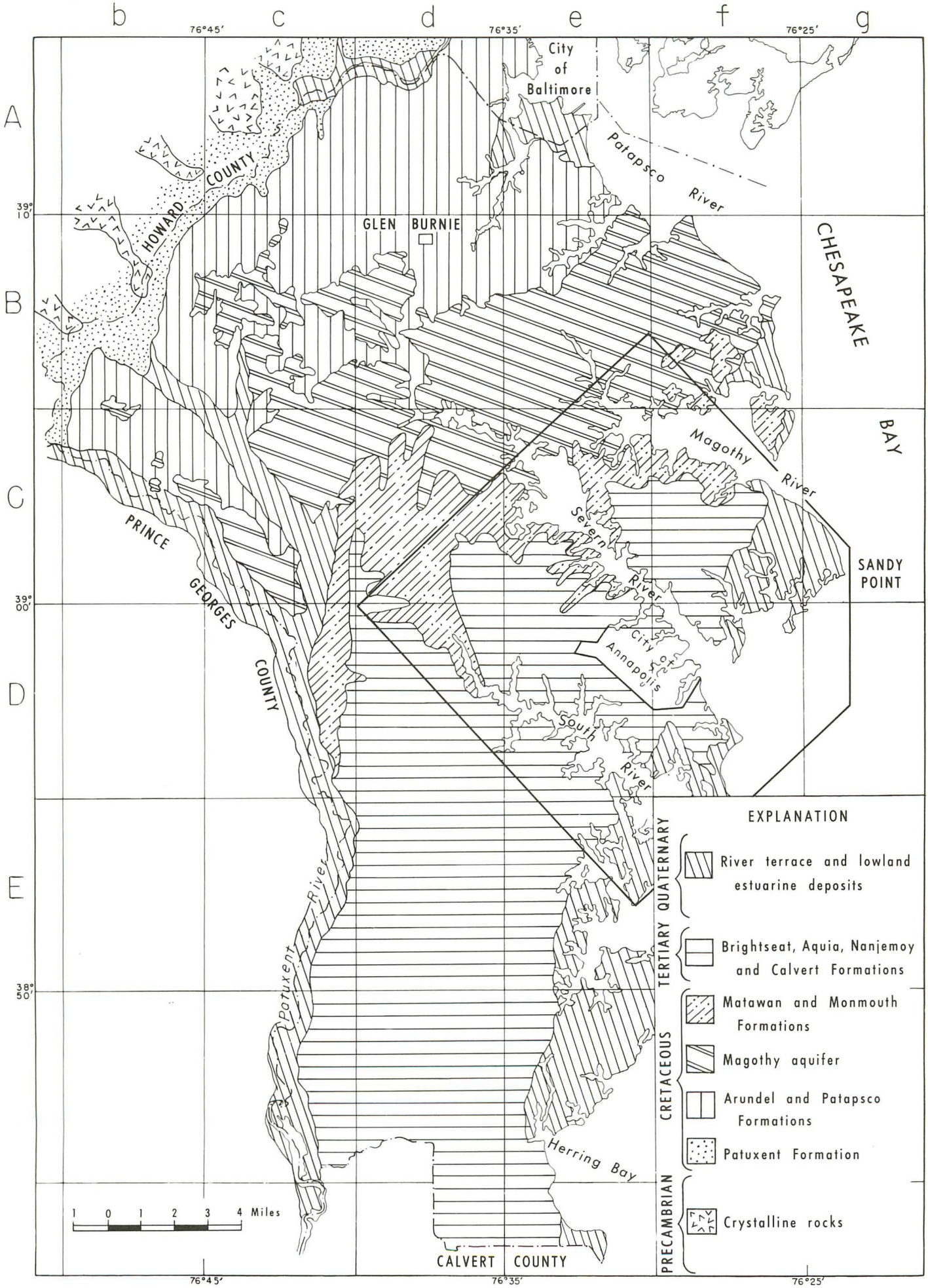

Figure 7.—Geologic map of Anne Arundel County.

MAGOTHY AQUIFER

The term "Magothy aquifer," as used in this report includes those layers of light-gray sand, interbedded with relatively thin layers of clay, that occur in the geologic section above the tough reddish clay layers of the Patapsco Formation and below the rather tough dark-gray to black layers of clayey silt and sand of the Matawan Formation. The term "Magothy aquifer," therefore, includes some of the layers of fine to coarse sand and light-gray clay considered to be the Raritan Formation in earlier publications (Clark, 1916; Brookhart, 1949; Otton, 1955).

The character of the aquifer--the thickness, hydraulic conductivity, and depth--explains its potential for yielding large quantities of water. As shown in figure 9, thickness of the aquifer ranges from 100 to 300 feet in the project area. The thickness map (fig. 9) is based on data from 17 wells that completely penetrate the aquifer.

Table 2.—Stratigraphy and hydrologic and lithologic characteristics of geologic formations in the Annapolis area.

System	Series	Group	Formation	Average thickness (feet)	Lithology	Hydrologic character	General character
Quaternary	Holocene and Pleistocene			30		Confining bed in most places. Poor aquifer in some places.	Sand, gravel, silt, and clay.
Tertiary	Eocene	Pamunkey	Nanjemoy	80		Confining bed	Sand, with clayey layers, glauconitic.
			Marlboro Clay 1/	30		Confining bed	Clay, plastic, pale-red
	Paleocene		Aquia	100		Aquifer	Glauconitic, greenish to brown sand with indurated or "rock" layers in middle and basal parts.
			Brightseat	40		Confining bed in most places. Poor aquifer in some places.	Sand, silt, and clay, olive gray to black, glauconitic.
Cretaceous	Upper Cretaceous		Monmouth	90		Poor aquifer in places	Sand, silty to fine, with some glauconite.
			Matawan	30		Confining bed	Silt and fine sand, clayey, dark gray to black, glauconitic.
			Magothy	175		Aquifer	Sand, light gray to white, with interbedded thin layers of organic black clay. Contains pyrite and lignite. Lower part composed of interbedded layers of sand and white to light gray clay. Layers of coarse sand and gravel near the base.
	Lower Cretaceous	Potomac	Patapsco	500		Confining bed Aquifer Confining bed Aquifer Confining bed Aquifer	Sand layers interbedded with thick clay layers. Color variegated but chiefly hues of red and yellow.
			Arundel Clay	250 ?		Confining bed	Clay, red brown, and gray, contains some ironstone nodules and plant remains.
			Patuxent	250 ?		Aquifer ? Confining bed Aquifer ?	Sand, gray and yellow, with interbedded clay; kaolinized feldspar and lignite common. Locally clay layers predominate.
Precambrian or Early Cambrian				Unknown		Confining bed	Probably gneiss, granite, gabbro, metagabbro, quartz diorite and granitized schist.

1/ The term Marlboro Clay is used in this report in accordance with usage proposed by Glaser (1971). The term does not conform to the stratigraphic nomenclature of the U.S. Geological Survey.

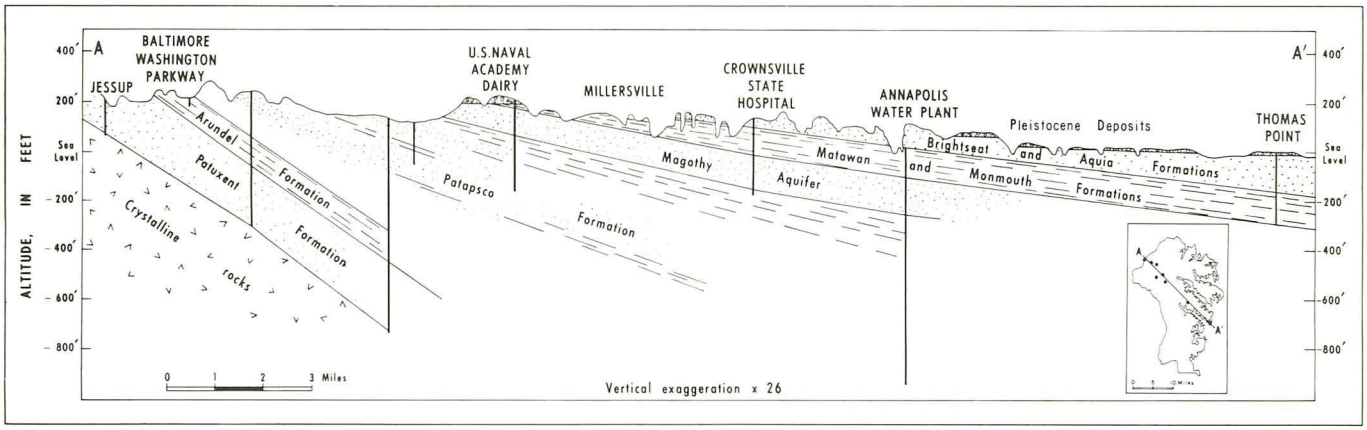

Figure 8.—Geologic section A-A' across Anne Arundel County.

In the vicinity of Annapolis and the lower part of the Severn River, the Magothy ranges in thickness from 130 to 150 feet. There seems to be a long narrow prong over 300 feet thick extending southward from the upper part of the Severn River past the headwaters of the South River.

The hydraulic conductivity of the Magothy aquifer varies considerably in the horizontal direction from place to place within the project area. Inspection of geophysical logs in figures 29 through 33 shows that the coarse sand beds of the formation are interbedded with layers of clay. This interbedding causes the hydraulic conductivity to be much greater in the horizontal direction than in the vertical direction. In many parts of the area, there is a clayey layer 10 to 20 feet thick separating the upper 60 feet of the aquifer from the lower part.

Pumping tests were made at two sites where observation wells were screened above and below this clayey layer. Short-term pumping of the sand below the clayey layer had a significant effect on water levels above it, indicating that the clayey layer is not laterally extensive. These clayey layers are probably lens-shaped and relatively thin, and extend over only relatively short distances. Figure 11A, is a particle-size analysis of a sample from an interbedded clay layer in well AA-De 104 at Collison Corner. The analysis shows that about 55 percent of the sample was composed of sediment of clay size or smaller.

Particle-size analyses made of six samples of sand from the Magothy aquifer (figs. 10 and 11) show that the median grain size is medium for three samples and fine sand, coarse sand, and fine gravel for each of the other three samples.

UPPER CONFINING BEDS

The thickness of confining beds overlying the Magothy aquifer increases progressively southeastward from the area of outcrop. Two of the layers in the sequence of beds, the Matawan Formation and the Marlboro Clay, have especially low coefficients of hydraulic conductivity. These units effectively control the vertical movement of water to the Magothy aquifer in those parts of the project area in which they occur. Other layers of clay, sandy clay, or partly cemented sand beds occur within the upper confining beds, as may be seen in the geophysical logs in figures 29-33. Glaser (see appendix) in his description of cores from test hole AA-De 100, has mentioned parts of the Aquia Formation as having a "calcareous matrix,""sand, patchily cemented," and "sand with patchy interstitial chalky carbonate." The Matawan Formation functions as the most effective confining bed for the Magothy aquifer because it occurs in all parts of the area where the aquifer is under artesian conditions. The Marlboro Clay described by Glaser (1971) seems to have a lower hydraulic conductivity but it occurs only in the southeastern part of the project area. As withdrawals of water from the Magothy aquifer increase, the roles of the confining beds will become more critical.

Laboratory determinations were made of the vertical hydraulic conductivity of five core samples of the Matawan Formation and one sample of the Marlboro. (See table 3) Determinations were made by two methods for each sample; one was the constant-flow method, and the other used a consolidation test for soils (Wolff, 1970). The procedures give values for

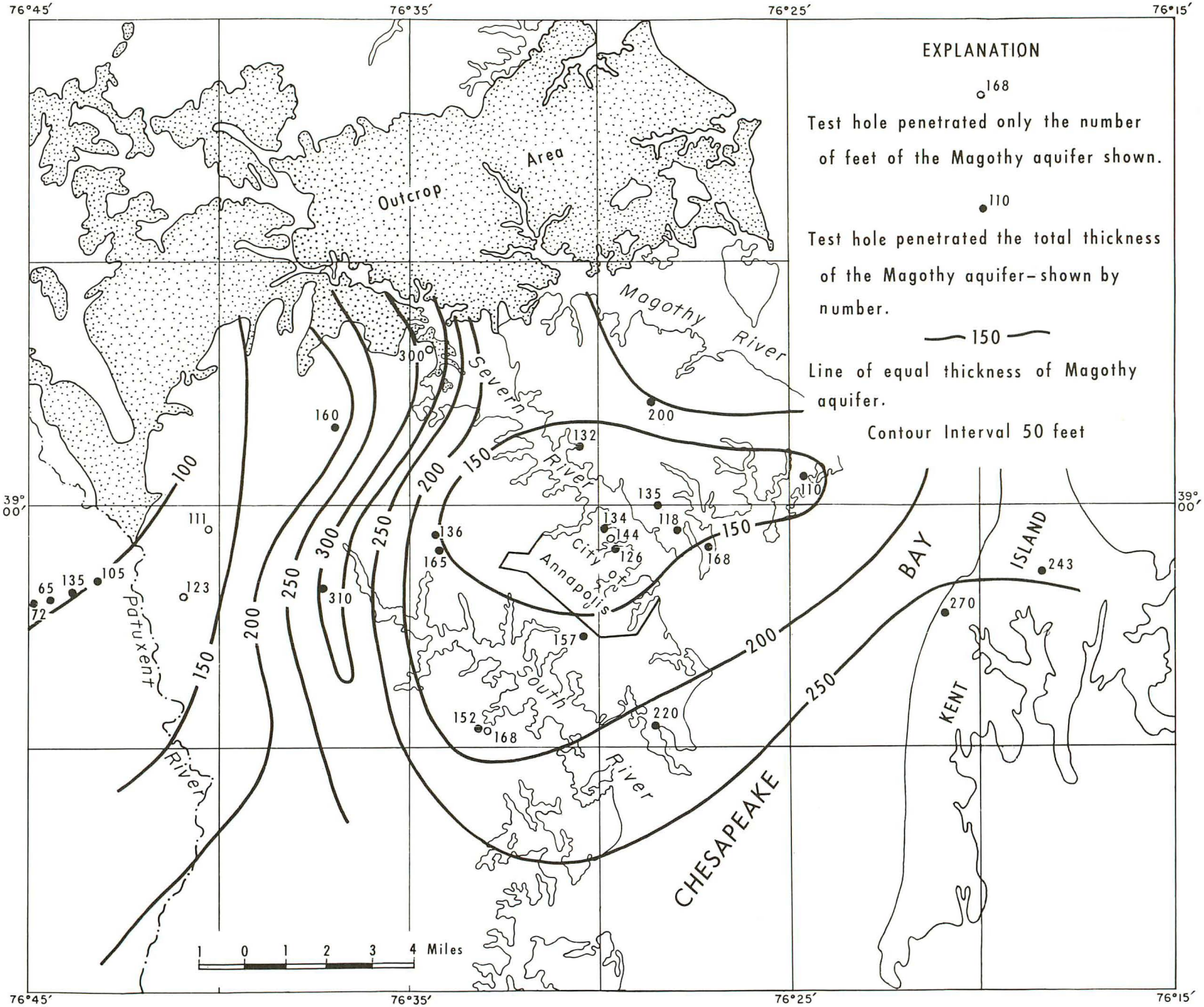

Figure 9.—Map showing thickness of the Magothy aquifer.

the hydraulic conductivity under a series of increasing loads, making it possible to select values for the hydraulic conductivity that are representative of the natural overburden load. The values obtained are consistent with values obtained for similar sediments from other areas.

The value used for the hydraulic conductivity of the confining layers in the models, 5.3×10^{-8} cm/sec (centimeters per second) or 1.5×10^{-4} ft/day (feet per day), was obtained from the value for leakance (defined by DeWiest, 1965) that best coordinated with other data and parameters to verify the model.

Geophysical logs made of 50 wells in the project area show the Matawan to be present at all sites. It is assumed on the basis of these logs that the formation is laterally continuous throughout the area. Geophysical logs (figs. 29-33) and particle-size data from test holes (fig. 12) indicate that, in much of the project area, the formation has three rather distinct lithologic facies. The upper part is generally a highly compacted layer of clayey, sandy silt about 10 feet thick, the middle layer is a coarser grained silty sand up to 20 feet thick, and the lower part is a well-compacted layer of clayey silt about 20 feet thick.

Particle-size analysis of core samples from the Matawan Formation are shown in figure 12. Although most of the samples are sand size, the clay-sized particles fill the pore spaces between the sand grains to effectively reduce the hydraulic conductivity of the formation and cause it to function as a confining bed.

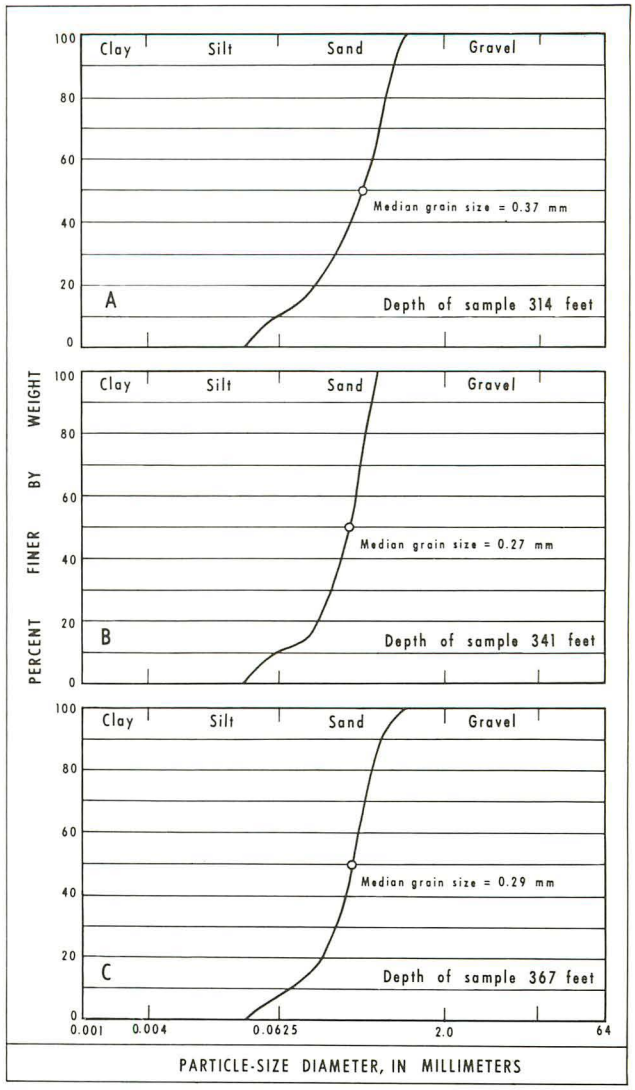

Figure 10.—Graphs showing particle-size distribution in core samples from the Magothy aquifer at well AA-Cf 101 on Broadneck Peninsula.

LOWER CONFINING BEDS

The Magothy aquifer in the Annapolis area is underlain by 1,000 to 1,300 feet of Coastal-Plain sediments of Cretaceous age (table 2). Water is currently being produced from two separate aquifers within the Patapsco Formation. The two deeper formations, the Patuxent and Arundel, have not been explored in the project area. However, the Patuxent is known to be a good aquifer at Crofton, about 6 miles updip (northwest) from the city of Annapolis well field. The base of the Patuxent (top of crystalline rock) is probably about 1,350 feet below sea level at the city well field. The criterion used during this project for picking the contact between the base of the Magothy aquifer and the top of the Patapsco Formation was the first occurrence of tough, thick (20 feet or more) reddish-brown clay. The reader is referred to Glaser (1969) for a detailed discussion of the geology of the Patuxent, Arundel, and Patapsco Formations.

The particle-size curves for three core samples of the Patapsco Formation are given in figure 13. The clay fraction of each is at least 50 percent of the total sample by weight. Table 3 shows that the vertical hydraulic conductivity of a Patapsco sample was found to be 1×10^{-5} ft/day (3.8×10^{-9} cm/sec) by the consolidation method and 7.4×10^{-6} ft/day (2.6×10^{-9} cm/sec) by the constant flow method. Little data are available to indicate how well these samples represent the full lateral extent of the lower confining beds.

Table 3.—Values for vertical hydraulic conductivity (K') of confining layers determined by laboratory methods

Well number	Depth of sample (ft)	Formation	Vertical hydraulic conductivity (K')				Percent clay size or finer (0.004 mm)	Median-grain size Grain size at 50% of volume by weight	Determinations by
			Values from consolidation tests		Values from constant flow tests				
			cm/sec	ft/day	cm/sec	ft/day			
AA-									
Cf 101	144	Matawan	1.1×10^{-7}	3.11×10^{-4}	1.5×10^{-6} [1]	4.26×10^{-3}	28.1	0.047	Michael Sorey U.S.G.S.
	171	Matawan	2.0×10^{-8}	5.68×10^{-5}	5.0×10^{-8} [1]	1.42×10^{-4}	44.0	0.0135	Michael Sorey U.S.G.S.
De 100	214	Matawan	1.7×10^{-7}	4.83×10^{-4}	1.3×10^{-6}	3.68×10^{-3}	18.0	0.2	Roger Wolff U.S.G.S.
	228 (naturally cemented)	Matawan	-----	-----	9.0×10^{-9}	2.56×10^{-5}	-----	-----	Hydrologic laboratory Denver, Colorado
	242	Matawan	4.1×10^{-8}	1.16×10^{-4}	7.3×10^{-8}	2.07×10^{-4}	54.2	0.0013	Roger Wolff
	432	Patapsco	3.8×10^{-9}	1.08×10^{-5}	2.6×10^{-9}	7.36×10^{-6}	63.8	0.0019	Roger Wolff
De 116	12	Marlboro Clay	-----	-----	1.2×10^{-8}	3.41×10^{-5}	-----	-----	Roger Wolff
De 104	24	Marlboro Clay	-----	-----	-----	-----	60.0	0.0028	Roger Wolff

[1] No load

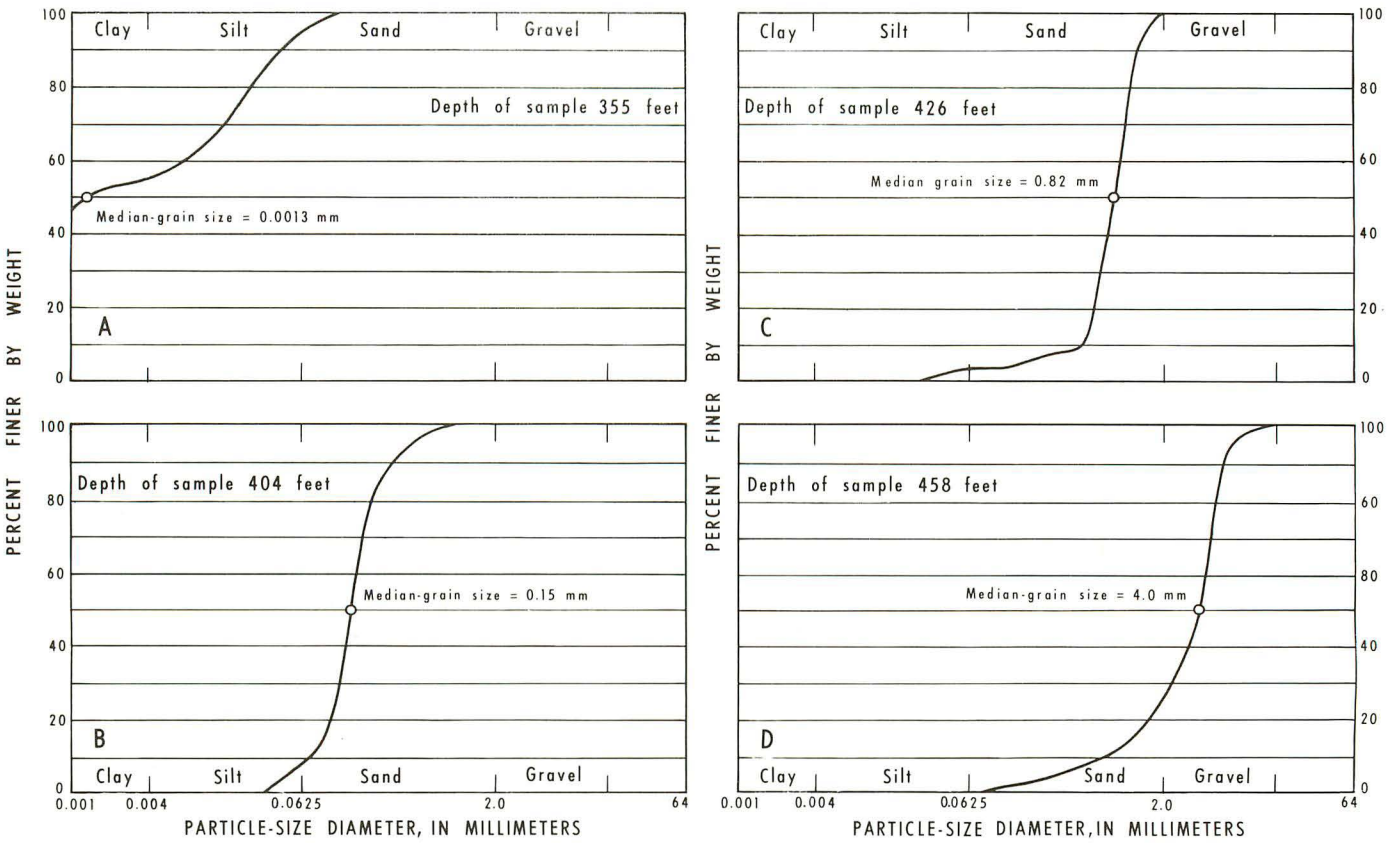

Figure 11.—Graphs showing particle-size distribution in core samples from the Magothy aquifer at well AA-De 104 at Collison Corner.

FACTORS IN PLANNING DEVELOPMENT OF THE AQUIFER

Studies to date have shown that large quantities of water can be developed from the Magothy aquifer in the Annapolis area for long periods of time. However, there would be some side effects resulting from heavy pumping. Good planning will require knowledge of both the water-yielding characteristics of the aquifer and of the impact the heavy pumping would have on both the aquifer itself and its environment. The diagrams in figure 14 show the many factors affecting the availability of water from the Magothy aquifer and give an indication of ways in which some factors are interrelated.

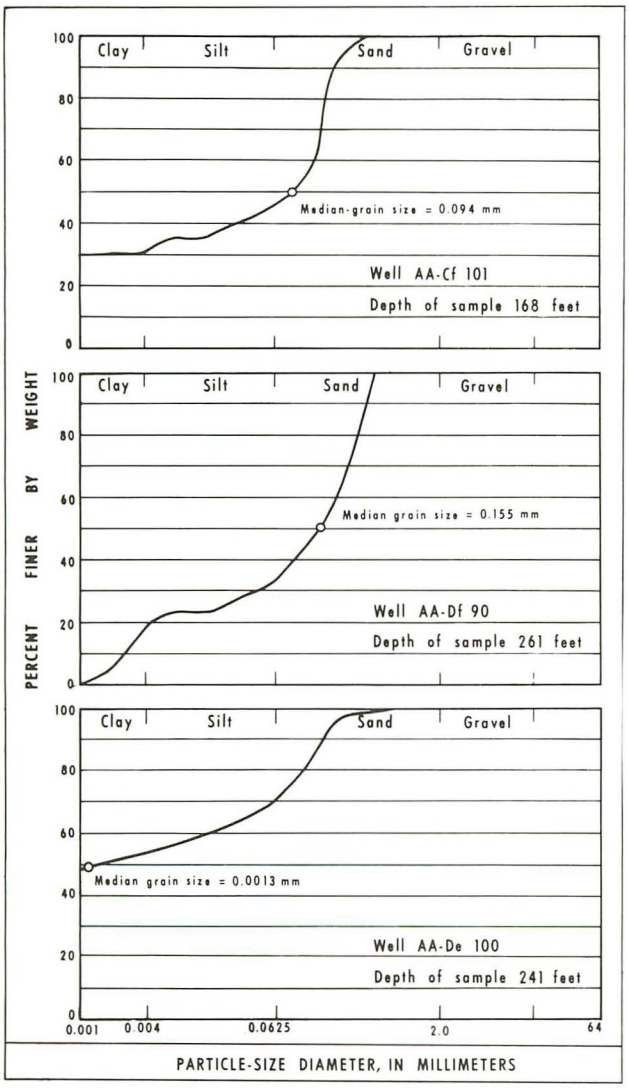

Figure 12.—Graphs showing particle-size distribution in core samples from the Matawan Formation.

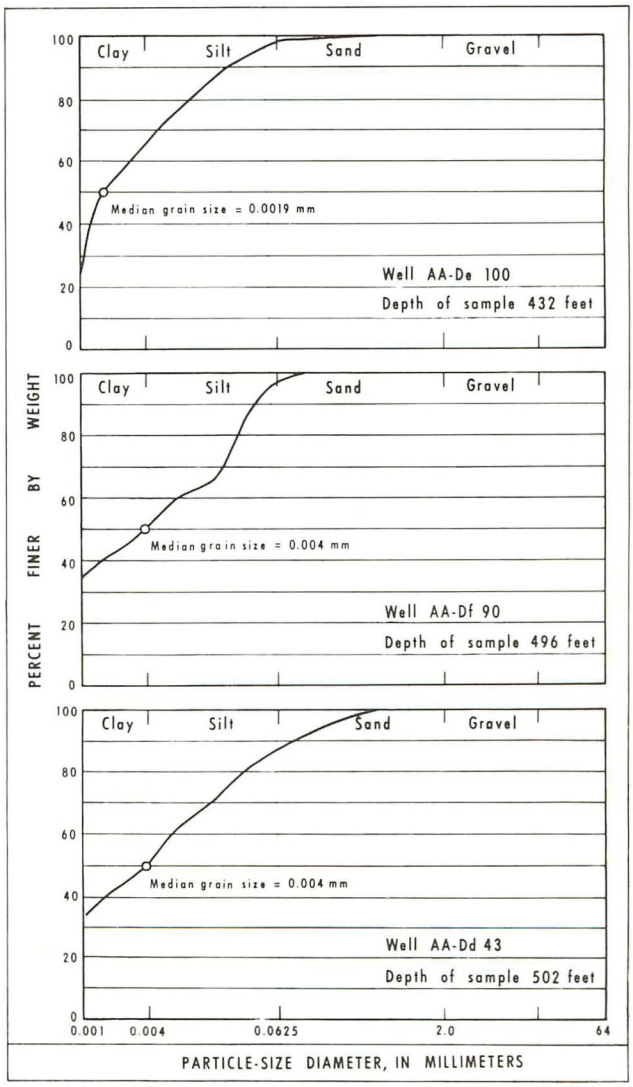

Figure 13.—Graphs showing particle-size distribution in core samples from the Patapsco Formation.

WATER-YIELDING POTENTIAL

The water-yielding potential of the Magothy aquifer varies from site to site and depends upon the source of the available water, the aquifer characteristics (such as the coefficient of transmissivity), and the available hydraulic heads.

The total amount of water to be taken from the Magothy aquifer in future years will be derived from two sources: (1) water stored in the ground-water reservoir, which would be available for a time even if there were never again any precipitation, and (2) water captured from precipitation and other sources, which would be available on a continuous basis to replenish the ground-water reservoir. Therefore, to estimate the amount of water available from the aquifer, estimates were made of the amount of water in storage and of the rates at which water taken from the aquifer could be replaced.

Large quantities of water are stored in the Magothy aquifer and the formations adjacent to it. About 4 trillion gallons of water are contained in the 20-mile-square wedge of sediments of Magothy age or younger that underlies the Annapolis area. A large percentage of the water occurs in sediments capable of supplying comparatively few gallons per minute to individual wells. However, there may be as much as 2 trillion gallons available from sand beds thick enough and permeable enough to yield water at high rates. Obviously, this figure for water storage seems high, and it would be misleading if it were considered to represent the amount that could be obtained with the ease and low cost per gallon of water pumped in 1970.

Under pre-pumping conditions, the Magothy aquifer was recharged in highland areas at

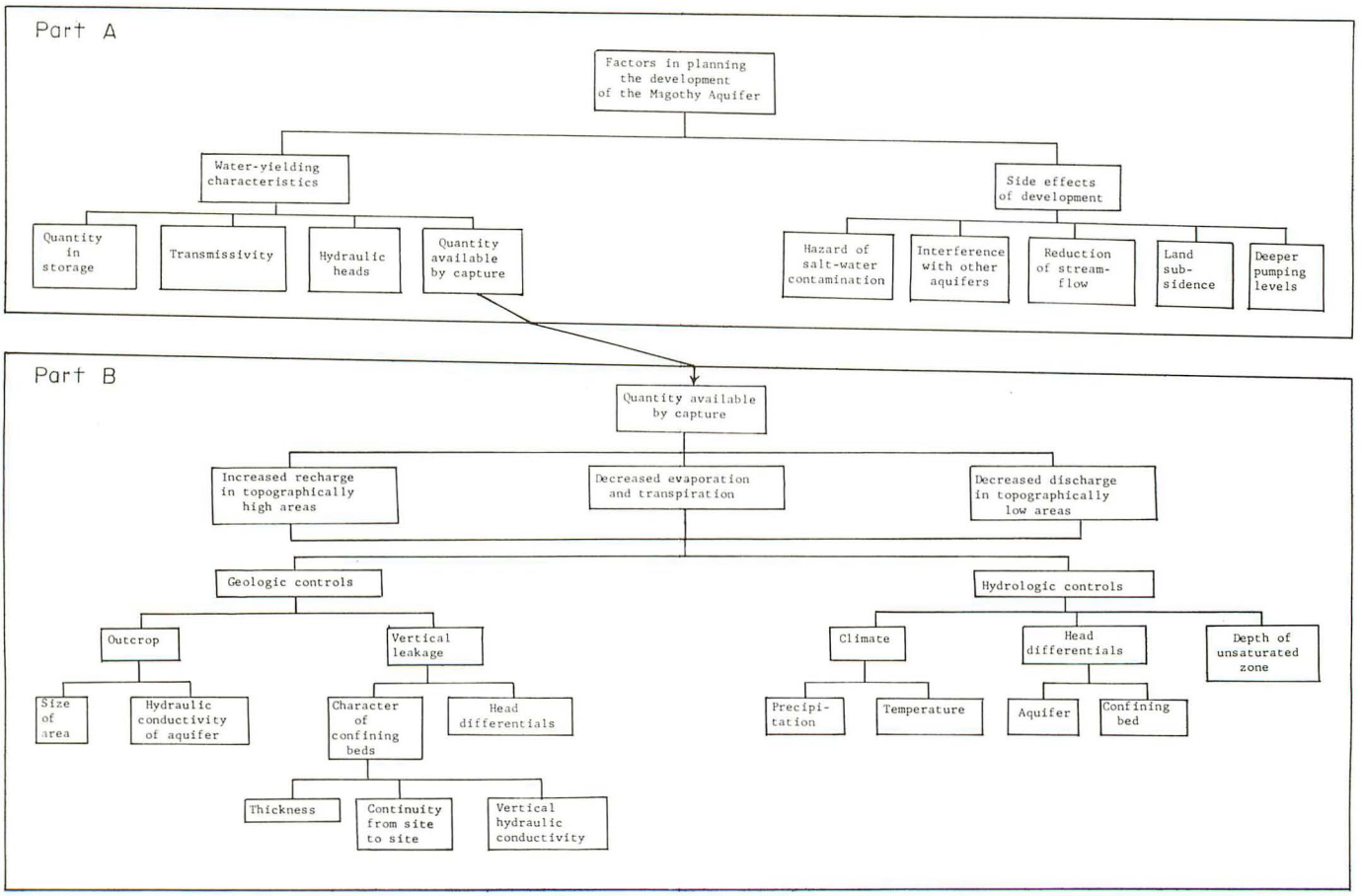

Figure 14.—Charts showing factors in planning the development of the Magothy aquifer.

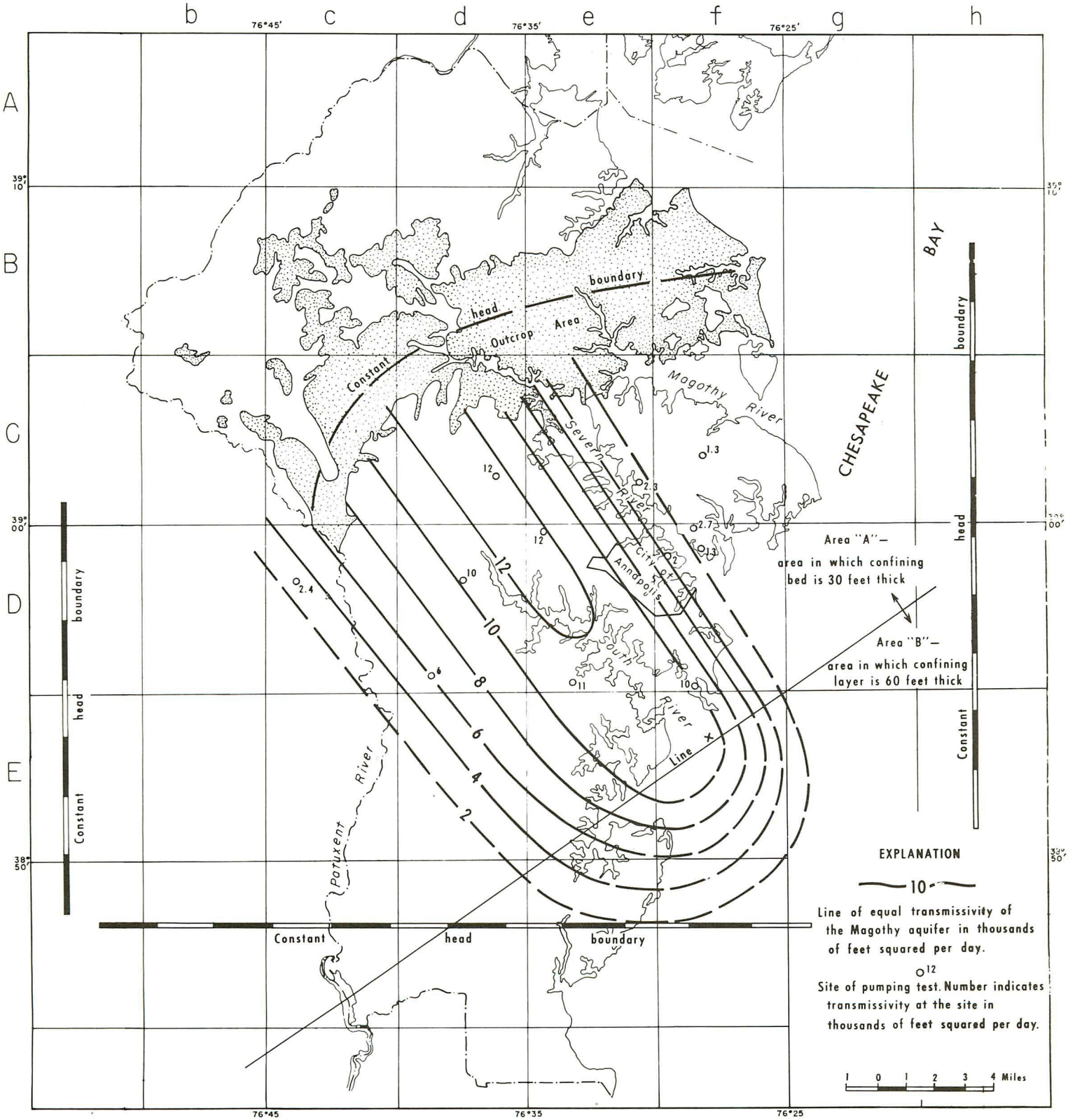

Figure 15.—Map showing the transmissivity of the Magothy aquifer in the Annapolis area and the location of the constant-head boundaries used in the analog model.

rates adequate to balance and satisfy the rate of discharge in lowlying areas. Part B of figure 14 shows that the rate at which the Magothy aquifer is recharged depends on both geologic and hydrologic controls. Recharge from precipitation in the outcrop area, where the aquifer is under water-table conditions, occurs at rates limited by the extent of the outcrop area, rate of precipitation, soil saturation, and the hydraulic conductivity of the aquifer. Recharge also occurs by leakage from overlying beds where the aquifer is confined. The quantity of water recharging by leakage is controlled by the hydraulic gradient from the overlying aquifer toward the Magothy aquifer and by the geologic characteristics of the confining layer, such as its thickness, hydraulic conductivity, and lateral extent.

Hydrologic controls on the rate of recharge include climatic factors, head differentials, and depth of the unsaturated zone. Climatic factors include adequate precipitation to replace the water discharged, and temperature conditions that control the quantities of water evaporated and transpired. Head differentials between the Magothy aquifer and the overlying aquifers differ from one part of the area to another. The head on the overlying aquifer is generally higher than the head on the Magothy aquifer in highland areas, such as the Crownsville area (fig. 16 B), whereas the head on the Magothy is generally higher than the head on the shallow aquifer in lowland areas near sea level (fig. 16 D). The depth of the unsaturated zone exerts some control on the rate of recharge because larger percentages of precipitation from

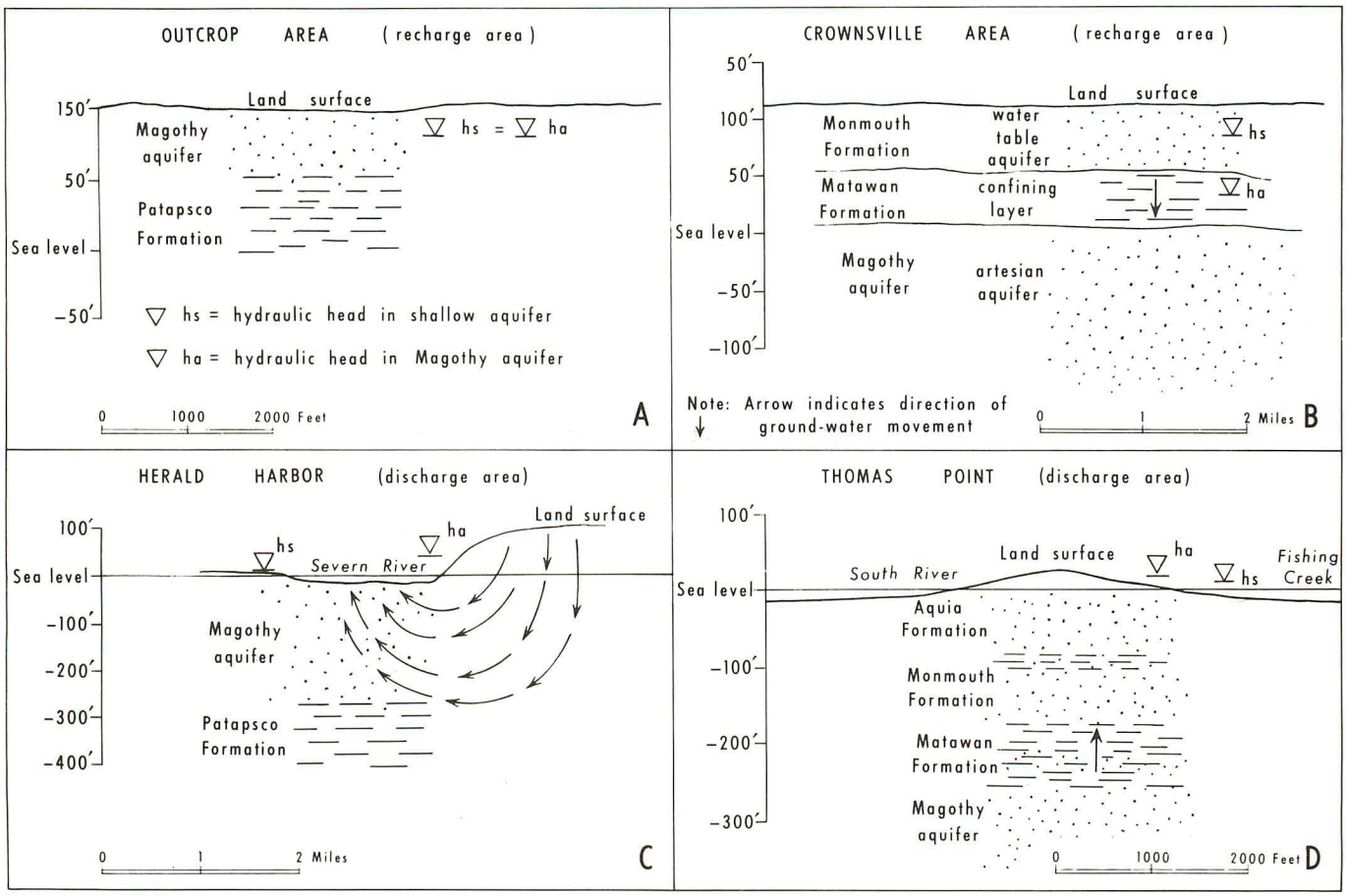

Figure 16.—Sketches of four sites within the hydrologic system showing variations of head differentials between the shallow aquifer and the Magothy aquifer, and the resulting differences in the direction of water movement.

individual rainfalls can be absorbed by the soils where the water table is deeper. Where the water table is shallow, only scant reservoir space is available to accept water that periodically becomes available from precipitation. Thus, where the zone of saturation quickly rises to the land surface, smaller percentages of precipitation can be absorbed by the ground, and larger percentages of precipitation become runoff to streams.

The coefficient of transmissivity is the rate of flow of water, in cubic feet per day, through a vertical section of the aquifer 1 foot wide extending the full saturated thickness of the aquifer under a hydraulic gradient of 1 foot per foot. Thus, the coefficient of transmissivity is the product of the thickness and hydraulic conductivity of the aquifer (transmissivity = thickness x hydraulic conductivity).

Values used to prepare the map of transmissivity in figure 15 were obtained from pumping tests made at 12 sites. Because the hydraulic conductivity is so variable from place to place, the thickest sections of the aquifer do not necessarily have the highest transmissivity. Comparison of geophysical logs from well AA-De 101 (fig. 30) and AA-Cf 100 (fig. 31) indicate the aquifer has about the same thickness at the two sites. However, because the sand beds of the aquifer at well AA-De 101 have a much higher hydraulic conductivity, the transmissivity at that site is about 10,600 ft^2/day (square feet per day) compared with about 1,300 ft^2/day at AA-Cf 100.

Hydraulic heads usually vary from place to place in the same aquifer. Water moves, in response to differences in hydraulic head, from points of high head to points of lower head. Hydraulic head in an aquifer is generally determined by measuring the water level in a well. Where these measurements are available from several wells tapping the same aquifer, a potentiometric (or hydraulic head) map may be constructed. Such a map can be used to show the direction of movement of ground water and to determine recharge and discharge areas.

In sloping or dipping aquifers of uniform transmissivity, greater drawdown in wells is available in the downdip direction. The increased available drawdown permits significantly greater yields per well.

Although large quantities of water are stored in the ground and large additional quantities can be captured from other sources, ground water is often obtained only with difficulty because aquifers release water to wells at rates that depend on aquifer transmissivity, hydraulic gradients, and methods of well construction. In some situations, water can be pumped from the ground at rates greater than the rate of recharge. In other situations, water can recharge the aquifers at rates equal to or greater than the rate at which the water can be released by the aquifers to wells.

Water can be pumped from individual wells at rates that depend on: (1) the amount of drawdown available in the well and (2) the specific capacity of the well. The drawdown available in wells in Coastal-Plain aquifers is generally considered to be the number of feet of head between static water level and the top of the water-bearing formation. Thus, in an area where the static water level stands 20 feet above sea level and the top of the formation is 80 feet below sea level, there is 100 feet of drawdown available in a well. The specific capacity of a well is the number of gallons per minute of water that may be obtained for each foot of drawdown. For example, some of the better wells in the project area yield 25 gallons per minute of water for every foot of drawdown.

The theoretical maximum rate of withdrawal (Q_W) from a single well, therefore, is the number of feet of drawdown available times the specific capacity; for example:

Maximum rate of withdrawal

$$Q_W = \text{ft. of drawdown available x specific capacity}$$

$$Q_W = 100 \text{ ft. x } 25 \text{ gpm per ft.} = 2500 \text{ gpm}$$

Note that in using this formula a maximum figure for a fixed period of pumping will be obtained. This figure will be reduced in actual practice by factors such as well-screen losses and slow declines in drawdown during extended periods of pumping.

Well fields are designed generally to obtain a specific quantity of water by the most economical method. Hydrologic and geologic data for the proposed sites are essential to the proper design of such fields. Consideration is given to factors, such as: (1) the available drawdown and specific capacity of individual wells in each aquifer, and (2) proper spacing required between wells screened in the same aquifer in order to reduce the interference between wells.

Where water-bearing sands are relatively shallow, the available drawdown is often small, and much more water can be obtained from several properly spaced wells than from a single well. On the other hand, the available drawdown is great enough in deep sand beds to increase

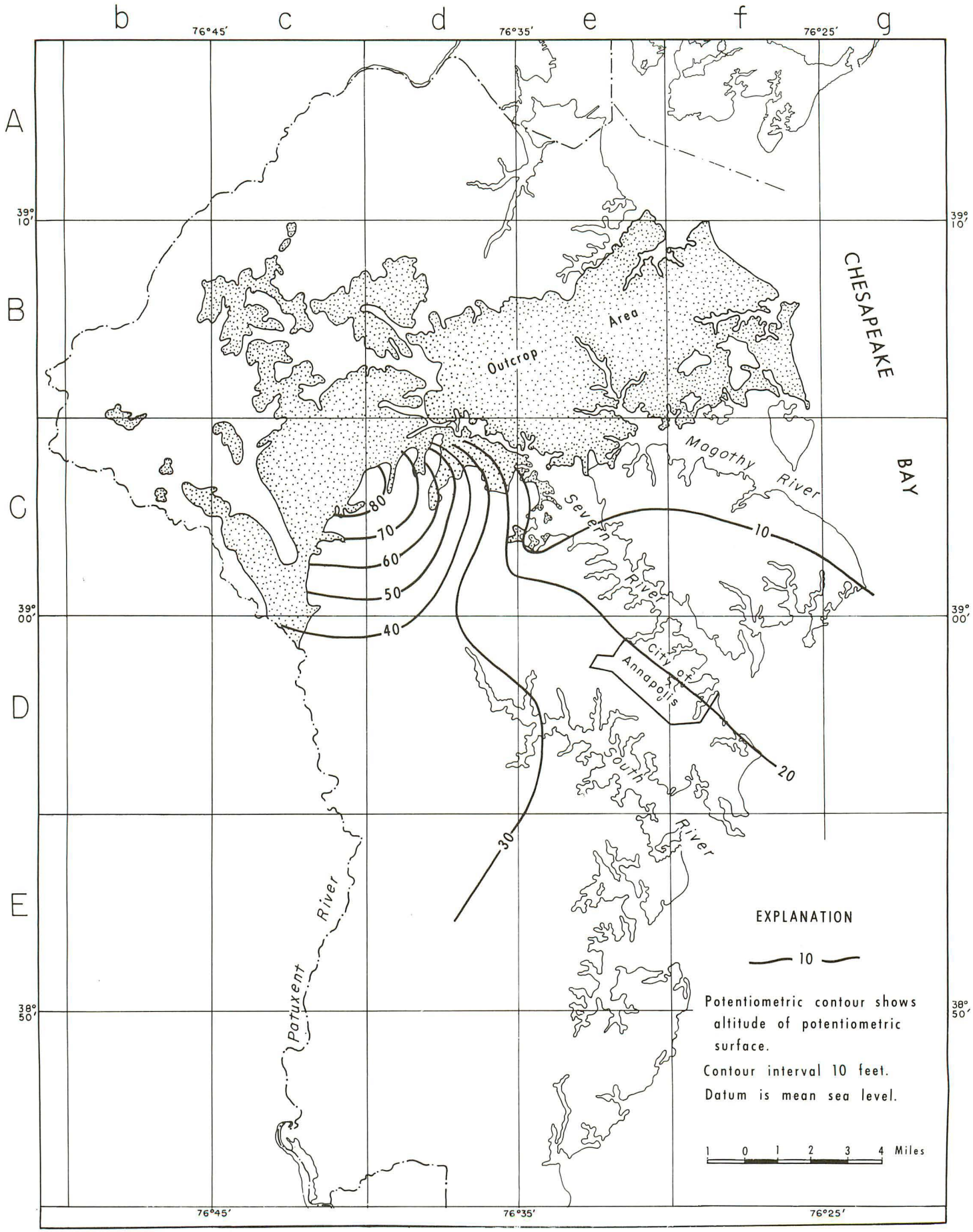

Figure 17.—Map showing the estimated potentiometric surface of the Magothy aquifer before pumping.

the yield per well and, thus, to reduce the number of wells per field. Drawdown of water levels due to heavy pumping at individual well fields tends to reduce the quantity of water available at adjacent sites because it reduces the amount of available drawdown.

CHANGING HYDROLOGIC SYSTEMS

The direction and rate of ground-water movement within hydrologic systems change in response to new pumping stresses. In order to gain a better understanding of the hydraulics of the Magothy aquifer and its potential for yielding large quantities of water, studies were made of the systems that have operated or would operate under the following three conditions:

1. Prepumping—Estimates were made of the characteristics of the hydrologic system before there was any pumping.
2. Present—Measurements have been made of the system as it is operating today.
3. Future—Models have been developed to predict some of the ways in which the system would respond to certain hypothetical conditions of heavy pumping.

Potentiometric maps are important tools in the understanding of changes within hydrologic systems. Essential to the interpretation of the potentiometric maps is the concept of "pumpage - drawdown" relationships. The concept is useful in explaining the way in which pumpage at one point in an aquifer causes a decline of water level, or interference in surrounding areas. Withdrawal of water from an aquifer creates a cone of depression centered at the point of discharge. The amount of drawdown at any particular point is controlled by the characteristics of the aquifer, the distance from the point of discharge, characteristics of the confining beds, and the pumping rate. Thus, by studying the potentiometric surface produced by a certain pattern of pumping, a basis is developed for predicting the effect to be expected by much greater withdrawals or different patterns of pumping.

The Magothy aquifer was part of a dynamic hydrologic system operating within the Coastal-Plain sediments of Maryland long before pumping began. The aquifer was recharged in high areas and discharged into low areas. To a large extent, the present hydrologic system operates in the same manner as the prepumping system. The Magothy is recharged by infiltrating precipitation in topographically high areas where it crops out (sketch A of figure 16). It is also recharged to some extent by leakage in high areas from younger overlying formations (sketch B of figure 16). Typical situations in which water discharges upward from the Magothy aquifer into low-lying water bodies, such as the Chesapeake Bay and its estuaries, are illustrated in sketches C and D of figure 16.

The estimated potentiometric surface of the Magothy aquifer before pumping is shown in figure 17. The map was prepared by adding drawdowns, computed by the model using historical records, to the present (1970) potentiometric map (fig. 18).

The Magothy aquifer is currently (1972) the primary source of large water supplies in the Annapolis area and yields an average of 4 mgd.[1] The potentiometric surface in 1970, shown in figure 18, is slightly modified from the prepumping surface (fig. 17) especially near the larger well fields. It is still from 10 to 80 feet above sea level in most of the project area and is below sea level in only a few areas near larger well fields. Therefore, the direction of water movement in topographically low areas is upward from the Magothy aquifer into discharge areas such as Chesapeake Bay and its tributaries. The pumpage of 4 mgd has undoubtedly decreased the amount of water that would naturally discharge from the aquifer under nonpumping conditions.

The locations of the nine individual well fields taking water from the Magothy aquifer in 1970 are shown in figure 6, and quantities of water pumped from them since 1950 are listed in table 4. Records for most of the individual wells in the well fields have been published in earlier reports (Brookhart, 1949; Mack, 1962). Data for the newest wells will be included in a basic-data report being prepared for Anne Arundel County.

Models were developed to predict some of the ways in which the system would respond to conceivable future heavy pumping. Specific details of the development and testing of the models--one electric analog and one digital--are given in the appendix of this report.

With the electric-analog model, the quantity of water that could be taken from the Magothy aquifer was predicted by adjusting the pumping rates and locations of hypothetical wells in order to lower the potentiometric

[1] The Aquia and Patapsco Formations supply an additional 4 mgd to users in the project area.

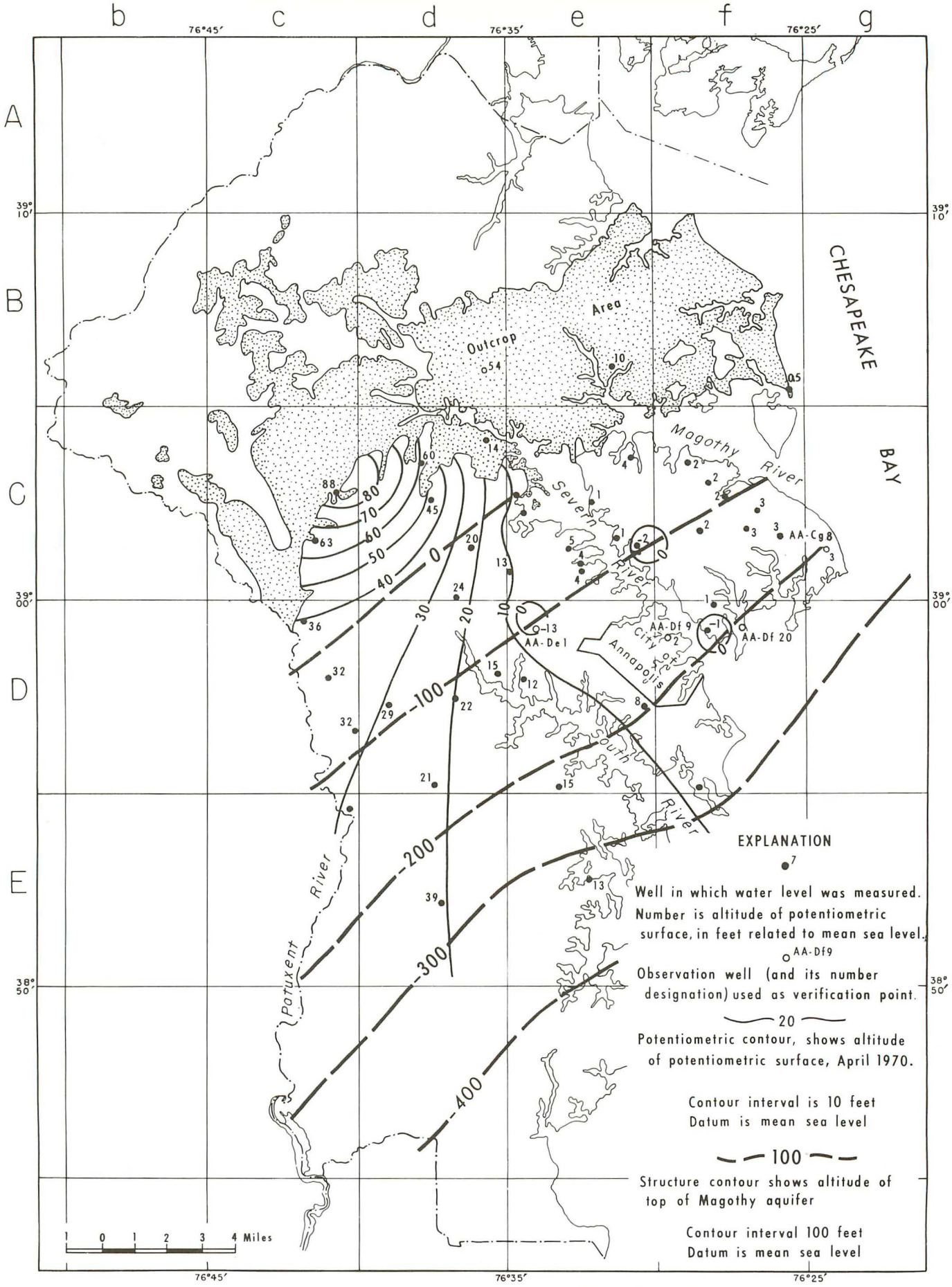

Figure 18.—Map showing the outcrop area, potentiometric surface of April 1970, and the altitude of the top of the Magothy aquifer.

surface of the aquifer to levels near the top of the aquifer. Figure 19 shows the locations of the hypothetical pumping wells and the drawdown resulting from pumping them at a combined rate of 60 mgd for 30 years. The figure also lists the pumping rate, available drawdown, and predicted drawdown for each of the wells in the hypothetical well field. The hydrologic system would be approaching a steady-state condition at the end of 30 years, so continued pumping after that would require relatively little additional lowering of the potentiometric surface. It was assumed that heads in the overlying source aquifers were not affected by the pumping. Computed drawdown values would have been greater if the model had allowed heads in the source aquifers to be affected.

The drawdowns resulting from a withdrawal of 60 mgd from the Magothy aquifer would result in a cone of depression that would be considerably below sea level in large parts of the Annapolis area. Parts of the area that have been discharge areas for the aquifer would become recharge areas. Leakage from and through confining layers overlying the Magothy aquifer would be the source of a large proportion of the water pumped. Some of the water might eventually come from Chesapeake Bay and its estuaries, which contain water with a chloride content ranging from 5,000 to 10,000 mg/l (milligrams per liter). Several aspects of the problems associated with the possible downward movement of salt water to the Magothy aquifer are considered in the next section of this report.

Characteristics of confining layers, such as vertical hydraulic conductivity, thickness, and effectiveness as an ion-selective membrane, would strongly affect the rate of recharge to the aquifer and the length of time necessary for salty water to reach the well fields.

SIDE EFFECTS OF HEAVY PUMPING

The previous section of this report showed that withdrawal of water from the Magothy aquifer causes lowering of water levels throughout the aquifer and that the amount of the lowering varies directly with the quantities of water withdrawn. The lowering of water levels requires a readjustment of the hydrologic system to the new conditions. Experience in

Table 4.—Well fields and pumpage from the Magothy aquifer from 1950-1970.

	Average pumpage, in millions of gallons per day, for the indicated period			
Name of Well field	1950-1955	1955-1960	1960-1965	1965-1970
City of Annapolis	2.3	2.3	2.6	3.1
Pines-on-Severn	.025	.025	.036	.036
U. S. Naval Ship Research and Development Center	.17	.17	.185	.185
Providence	-----	-----	-----	.005
Crownsville State Hospital	.37	.37	.3	.4
Summer Hill Trailer Park	-----	-----	.006	.02
Epping Forest	.025	.025	.025	.025
Sherwood Forest	.025	.025	.025	.025
Sylvan Shores	-----	.05	.05	.05
Sandy Point State Park	-----	.01	.01	.01
Total	2.915	2.975	3.237	3.856

other areas has shown that the readjustment may cause some side effects, such as salt-water contamination. This part of this report describes the salt-water problem and mentions other effects that may result from heavy pumping for extended periods.

Salt-Water Contamination

Salt-water contamination has long been a cause of much concern to water managers and, in some places, of great loss to users in coastal areas. Several valuable aquifers have been contaminated by saline waters (Bennett and Meyer, 1952; and Perlmutter and Geraghty,

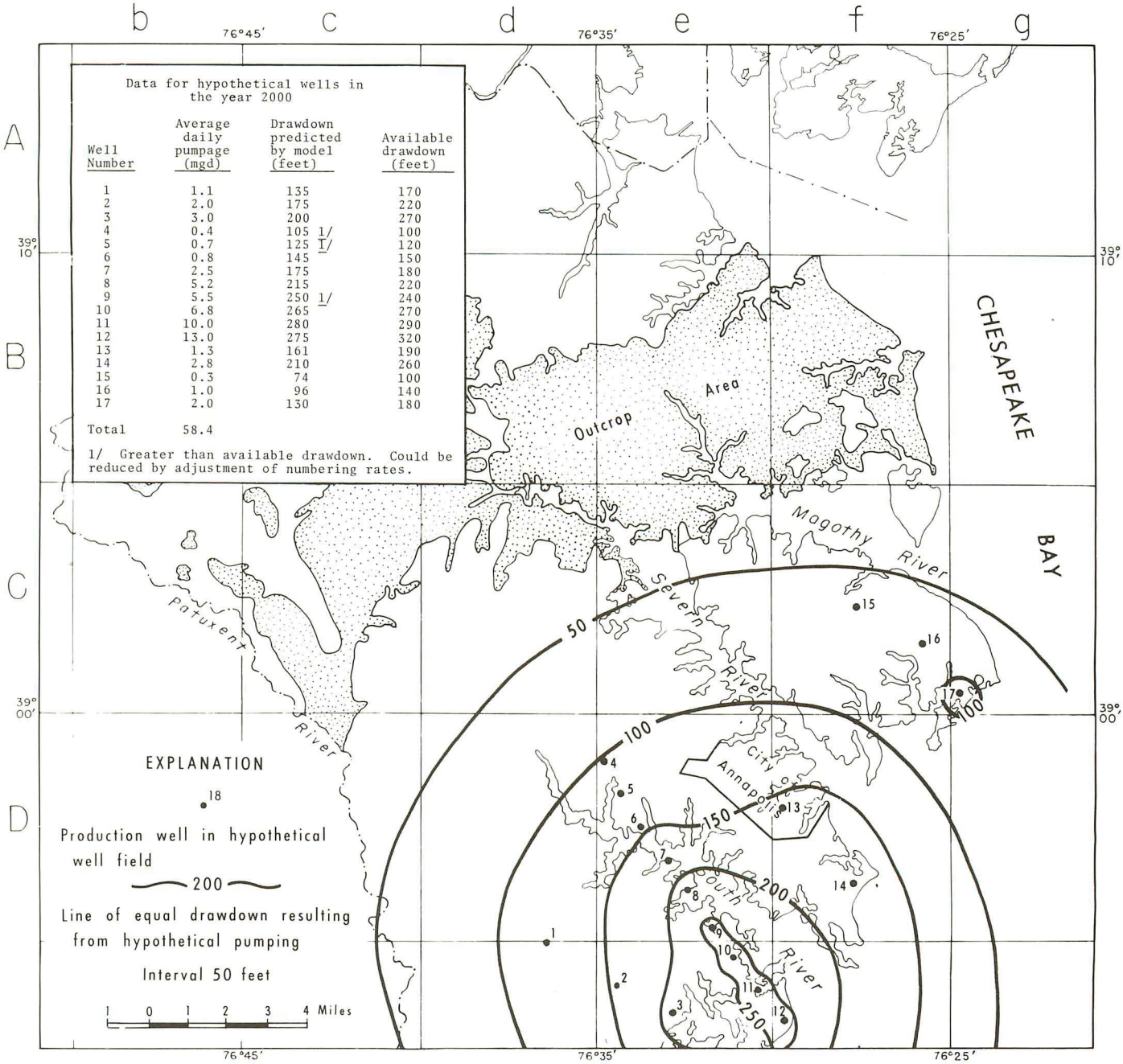

Figure 19.—Map showing drawdown predicted by the analog model as a result of pumping hypothetical wells at a combined rate of 58.4 mgd from year 1970 to 2000.

1963). The proximity of the salt water in Chesapeake Bay and its tributaries is a threat to the fresh ground-water supply of the Annapolis area.

Sources, direction, and rate of movement of salt water: Four common means by which salt water has contaminated well fields are presented on the chart in figure 20. One of these, movement of water updip from saline parts of artesian aquifers near the ocean, is considered to be extremely unlikely in the project area. The Eastern Shore cities of Cambridge and Easton are currently taking fresh water from the Magothy aquifer. Consequently, salt water encroaching from that direction must travel at least 36 miles before reaching the Annapolis area.

The amount of salt water that may move to the Magothy aquifer through abandoned wells is probably not too great. This type of contamination can occur only in areas where the head on the Magothy is below sea level. Because there are still few places where the head is below sea level, the problem has been negligible. Maximum development of the aquifer, however, would lower water levels below sea level in much of the area. Records available do not indicate that many wells exist to contribute to this problem. Where they exist, they tend to become sealed by fine-grained sediments.

Because the other means of contamination shown in the chart in figure 20 may be more serious in the project area, they are discussed in considerable detail below.

Search for evidence to indicate how long the Magothy aquifer could be pumped at high rates (for example 60 mgd) without concern about salt-water leakage through confining beds has produced information about many pertinent factors. Some of the factors tend to inhibit and some tend to induce such contamination. There is no doubt that maximum development of the aquifer will enlarge the recharge areas to include areas of salt water. Thus, it seems certain that pumping at high rates would eventually draw some water from salty sources into the well fields. The problem, then, is reduced to the development of estimates of (1) the length of time that will be required for salt water to reach the well fields, and (2) the character of the water after the salt water has been diluted with water from fresh-water sources.

Several of the factors influencing the movement of salt water toward the well fields are variable from place to place but are constants with respect to time because they define the geologic character of the sediments underlying the project area. The hydraulic characteristics of the Magothy aquifer, as well

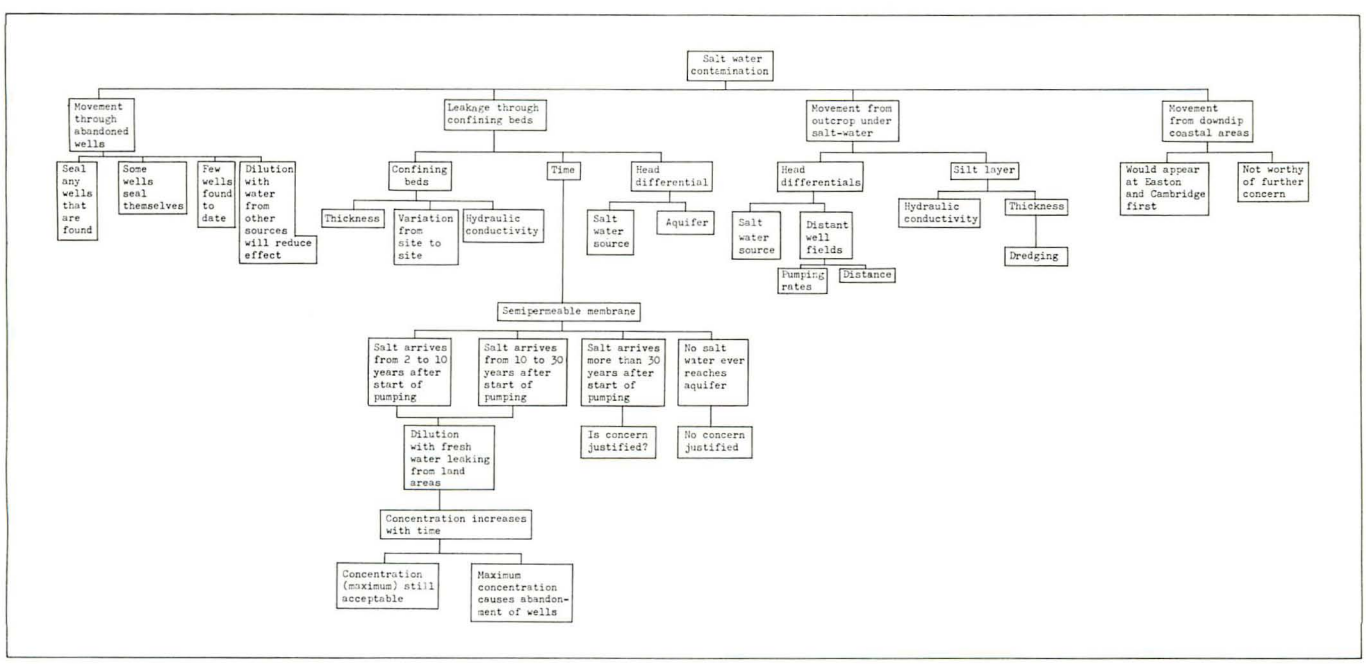

Figure 20.—Chart showing interrelationship of factors in evaluating the salt-water problem.

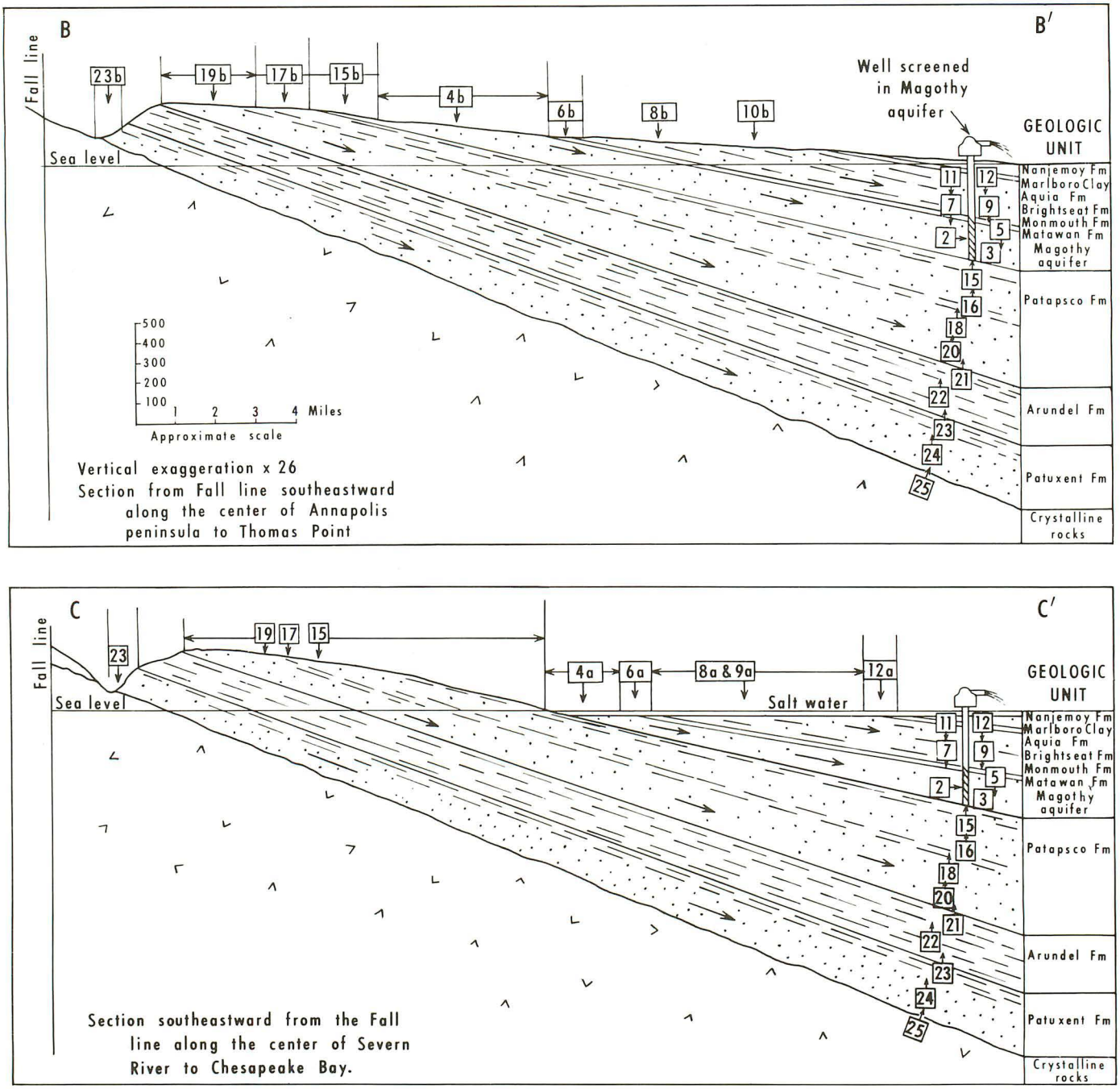

Figure 21A.—Section used for speculating about the sources, paths, and events involved in movement of water due to heavy pumping of the Magothy aquifer.

as the thickness and lateral extent of the overlying and underlying confining layers, are examples of these constants. Other factors, such as the pumping rates and the location and number of wells, can be adjusted to control the shape and depth of the cone of depression.

The geologic sections and flow diagrams in figure 21 are useful in examining the several sources of water for the Magothy aquifer and the routes by which the water would have to move to reach high-yielding wells. Two geologic sections are used to illustrate that two very different hydrologic conditions exist because of differences in topographic setting. Section B-B' represents a section through the Annapolis peninsula of the Coastal Plain from the Fall Line southeastward to Thomas Point, a section containing no salt-water sources. Section C-C', from the Fall Line southeastward along the middle of the Severn River to Chesapeake Bay, represents a source of salt water. Using the sections and the flow chart together, it may be seen that pumping from the aquifer will at first cause a sudden decrease in pressure in the

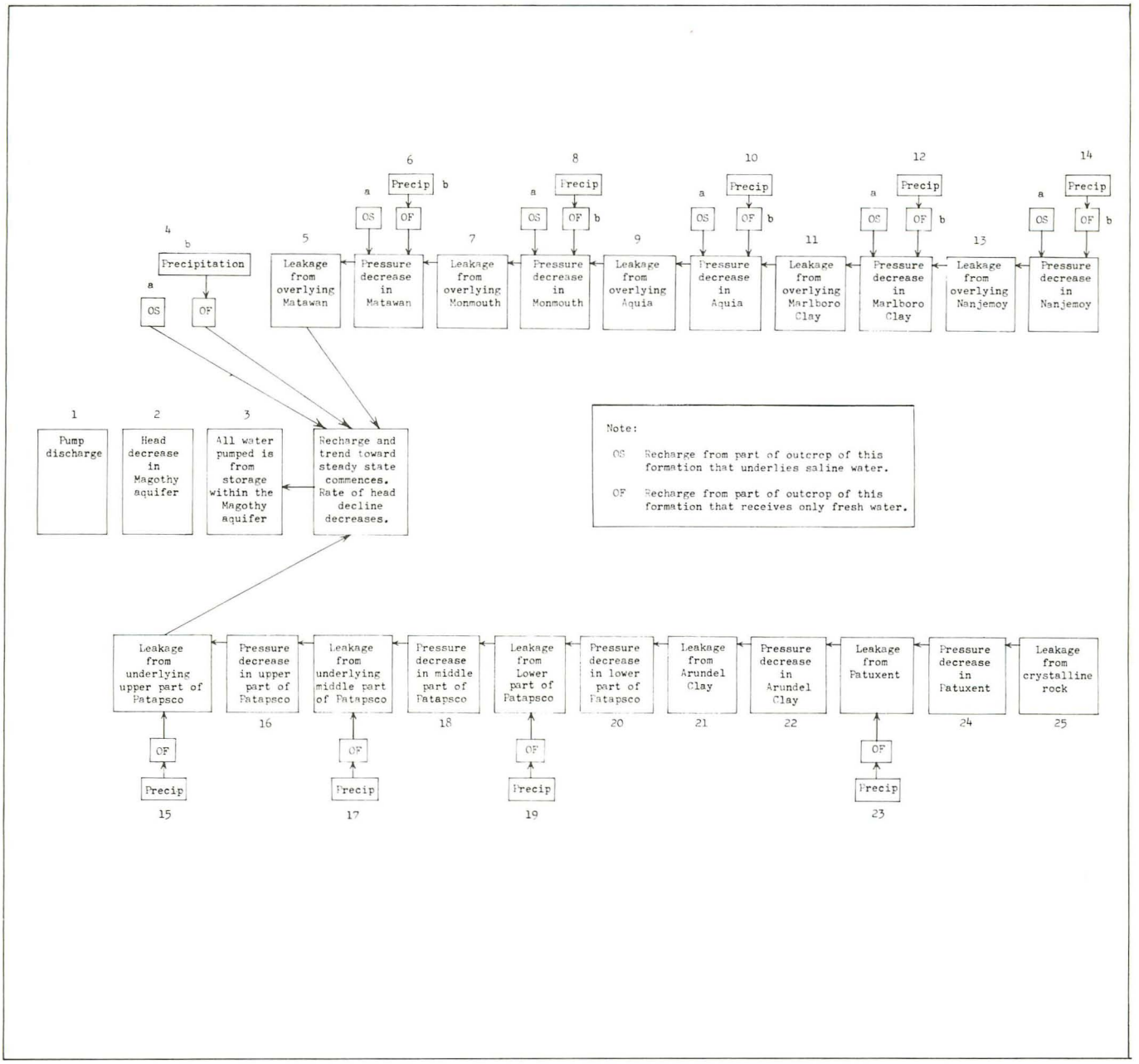

Figure 21B.—Diagram used for speculating about the sources, paths, and events involved in movement of water due to heavy pumping of the Magothy aquifer.

vicinity of the well field. The water pumped during the first few minutes will be water derived entirely from storage in the aquifer. With continued pumping, water from storage within the aquifer will be supplemented by water slowly drained from the overlying Matawan Formation and the underlying Patapsco Formation (depending on the relative heads in the Matawan and Patapsco Formations and the Magothy aquifer). It is difficult to assign values for the quantity of water to be contributed by each source or to predict the length of time needed for its arrival from each source at the well fields. As pumping continues, the area of pressure reduction will expand outward at rates dependent on the hydraulic characteristics of the aquifer and sources of recharge.

Thus, time is an important factor in development of the resource. Water managers might be willing to invest large sums of money in developing ground-water supplies if they were assured that no significant quantities of salt water would reach the well fields for 40 to 50 years.

Heavy localized stressing of the aquifer by pumping large quantities of water would lower the potentiometric surface to near the top of the aquifer in some areas. Reduction of the pressure would cause water to move toward the well field from updip in the Magothy aquifer, downward by leakage through overlying confining beds, and upward by leakage from the Patapsco Formation. Such reduction of pressures would reduce, or possibly eliminate, natural discharge from the Magothy.

1. Leakage from overlying beds: Two parallel sets of blocks are used in the flow diagram in figure 21 to represent the sources of leakage, the upper set representing leakage from above the Magothy aquifer and the lower set representing leakage from the underlying Patapsco Formation. Downdip from the outcrop of the Magothy aquifer, beneath the estuaries, several sedimentary layers combine to form a buffer between the salty water and the Magothy aquifer (section C-C'; fig. 21). Geologic studies indicate the Matawan Formation exerts the strongest control over vertical leakage because it has the lowest vertical hydraulic conductivity and greatest lateral extent of the several beds overlying the Magothy aquifer. Special studies were made of the Matawan to appraise its lateral extent, thickness, and vertical hydraulic conductivity. Because all geophysical logs from the project area show the Matawan Formation to be present at each site tested, it has been assumed for the purpose of modeling the aquifer that the formation exists as a continuous sheet with the same characteristics throughout the area. The Marlboro Clay which is much younger and higher in the geologic section than the Matawan Formation, exerts much control over vertical leakage in the southeastern part of the project area.

A digital model of the two main overlying confining layers, the Matawan Formation and the Marlboro Clay was developed by assuming the potentiometric surface was lowered to near the top of the Magothy aquifer. The hydraulic conductivity is 1.5×10^{-4} ft/day, and the thickness of the confining layers is 30 feet for the Matawan alone and 60 feet for the combined Matawan and Marlboro layers. The model was used to estimate the time required for water to move through the confining layers when the differentials between the shallow water body and the Magothy aquifer are equal to those that would be caused by a pumping rate of 60 mgd. Figure 22 shows how water droplets at the top of the confining bed at zero time progress downward in response to the drawdown caused by the hypothetical pumping. The upper three

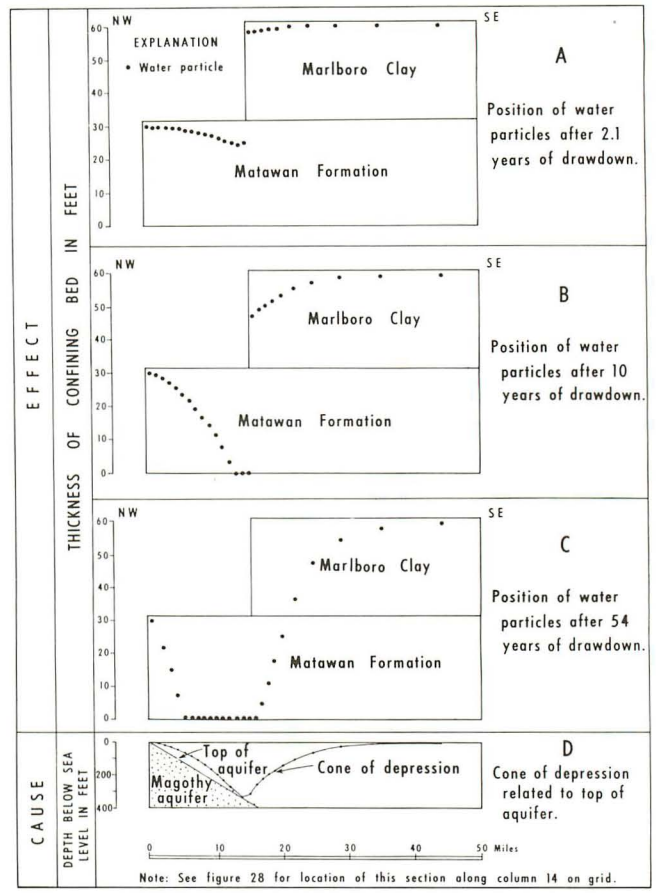

Figure 22.—Sections showing progress of water through the confining layer.

blocks in figure 22 represent the combined thicknesses of the Matawan Formation and the Marlboro Clay at three increasingly large time steps after pumping begins. Combining the two confining layers is an oversimplification of the real situation but it facilitates the computation. Because the intervening Aquia and Monmouth Formations have fairly high vertical conductivities, water would move through them more quickly. The Marlboro Clay was omitted from the northwest end of the section because it occurs only in the part of the project area southeast of Thomas Point.

Section A shows the progress of the water particles after 2.1 years of pumping; Section B, after 10 years (when the first particles are just arriving at the top of the underlying aquifer), and section C, after 54 years, when water from above the confining bed is reaching the aquifer across an area 11 miles in length. Section D

represents a cross section of the cone of depression of the aquifer resulting from the hypothetical pumping.

This model shows that 10 years would be required for a droplet of water to move through the 30-foot-thick Matawan Formation if the head differential between water in the aquifer and water in overlying beds at the interface above the Magothy aquifer were 325 feet. The maximum amount of drawdown available for the Magothy aquifer in the project area is about 325 feet. The maximum velocity of a droplet in the Matawan is, therefore:

$$\text{Velocity} = \frac{\text{Distance}}{\text{Time}} = \frac{\text{thickness of confining bed, in feet}}{\text{time for droplet to move through the confining layer}}$$

$$\text{Velocity} = \frac{30 \text{ feet}}{10 \text{ years}} = 3 \text{ feet per year}$$

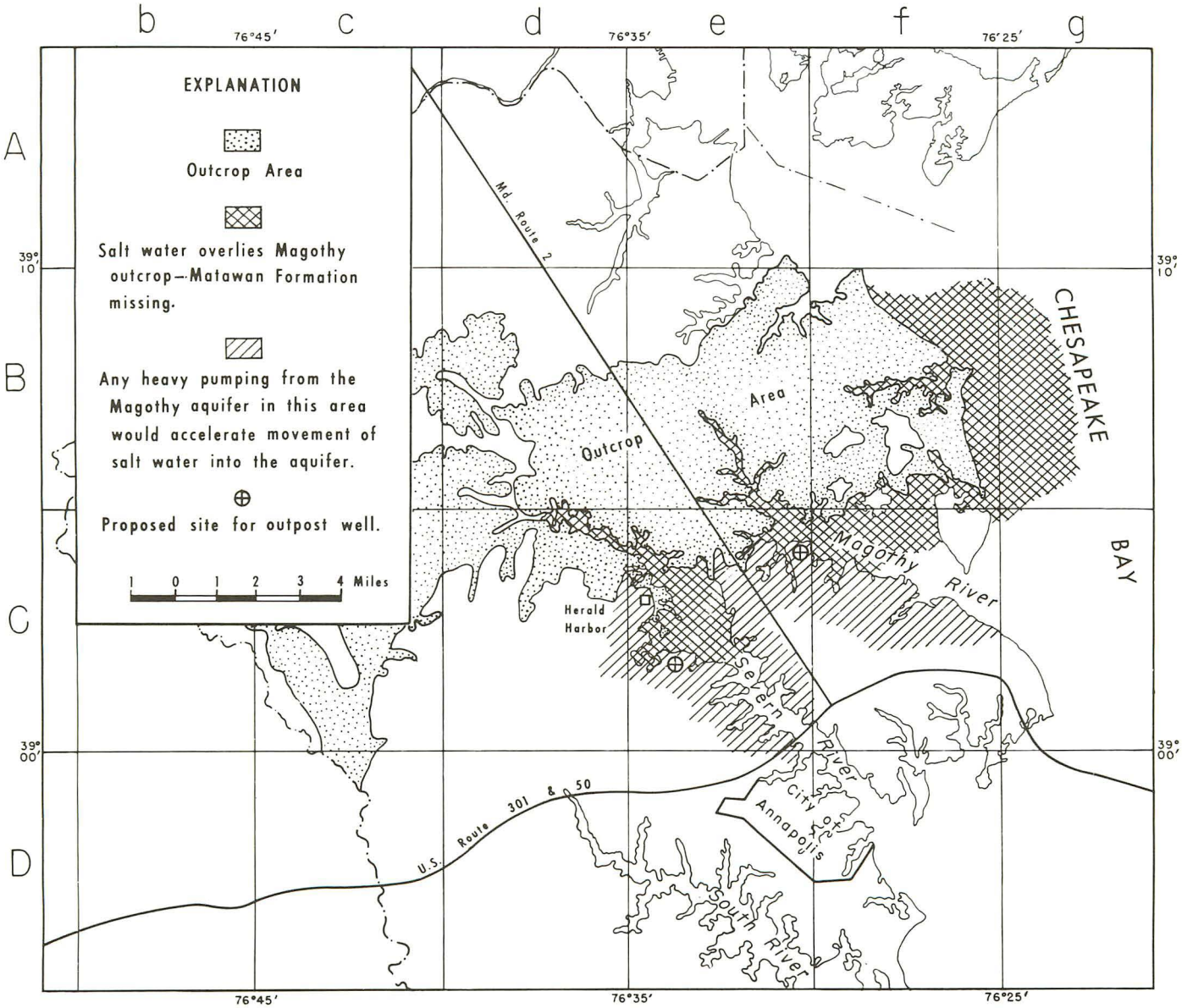

Figure 23.—Map showing areas where salt water overlies the outcropping Magothy aquifer and areas in which heavy pumping will accelerate movement of salt water into the aquifer.

Therefore, the Matawan Formation serves to restrict the rate of vertical flow to no more than 3 feet per year. The salt water of the estuaries would have to move a vertical distance of at least 300 feet through a buffer zone to reach the aquifer in areas where the head differential is 325 feet. The buffer zone is the thickness of the sediments saturated with fresh water separating the top of the aquifer from the bottom of the estuary.

$$\text{Time for droplet to move through the buffer zone} = \frac{\text{Thickness of the buffer zone}}{\text{Velocity}} = \frac{300 \text{ feet}}{3 \text{ ft. per year}} = 100 \text{ years}$$

Because the ratio between the thickness of the buffer zone and the value for the head differential is about one to one at this site and is much the same for areas toward the northwest, where the buffer zone is thinner, the time required for a droplet to move through the buffer zone would be much the same in all areas. However, in those parts of the estuaries that are about 20 feet deep and near the outcrop area, the ratio is less, and the time is calculated to be as low as 65 years. In areas where the buffer zone is thick, other factors would tend to increase the length of time of vertical movement beyond 100 years. Several other layers of low hydraulic conductivity are known to occur in the formation overlying the Matawan Formation. Each such bed would tend to decrease the rate of vertical movement and increase the time of travel. Leakage into the aquifer from underlying beds may be considerable, and its effect will also be to reduce the rate of movement through overlying formations.

The thickness and hydraulic conductivity of Holocene (recent) bottom sediments in salt-water bodies will exert some control over the downward movement of salt water. The character of the Holocene bottom sediments in

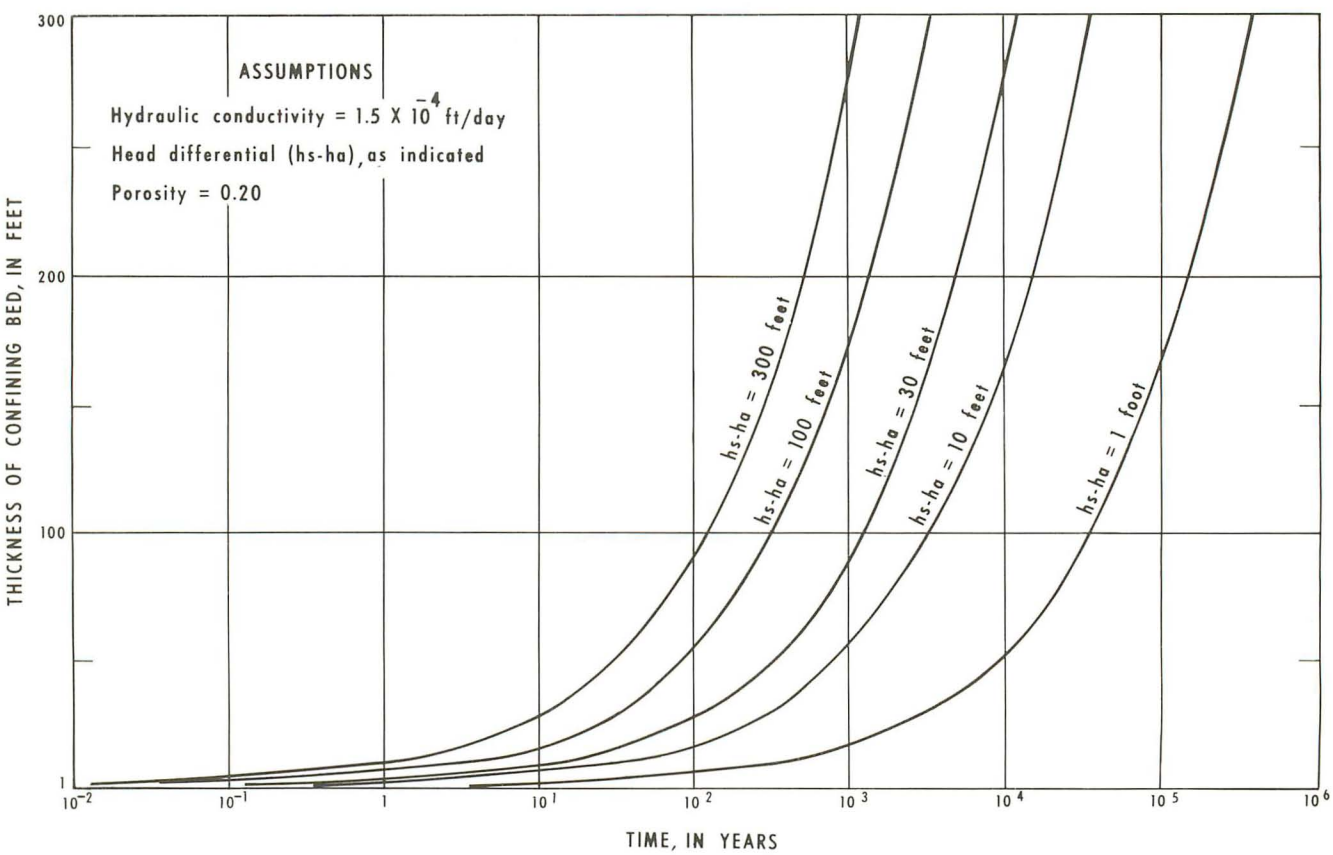

Figure 24.—Graph showing the relationship between the thickness of a confining bed and the time for water to move through it.

the salt-water bodies has not yet been mapped. Layers with low hydraulic conductivities are probably thick in some parts of these bodies, but it is also likely that the bottom sediments have been scoured away in other areas.

2. Leakage from underlying beds: Verification of the electric-analog model by balancing the historical pumpage against historical water levels required that considerable leakage be built into the model. The model gave a gross value for leakage but did not differentiate between leakage from above or below. However, the ratio of leakage from the two sources has much significance. The greater the percentage of the leakage moving from below, the greater the time required for salt water to move vertically downward through the overlying confining beds (the computations used to develop figure 22 assume all leakage occurs through the overlying beds). The Patapsco Formation is composed of lenses of sand, silt, and clay. It is probable that some of the lower sand beds of the hydrologic unit considered to be the Magothy aquifer in this report are actually of Patapsco age. The degree of interconnection between these probable Patapsco sand beds and deeper sand beds of the Patapsco Formation is difficult to determine. If the interconnection is great, a large proportion of leakage reaching the Magothy aquifer may be from below. This type of interconnection may exist if the Magothy unconformably overlies truncated, steeper dipping sand beds of the Patapsco Formation. If the sand beds of the Patapsco are conformable with the Magothy and poorly connected with deeper Patapsco sand beds, leakage from below would be fairly small.

A leaky confining bed directly below the Magothy aquifer would leak water either upward or downward, depending on the relative

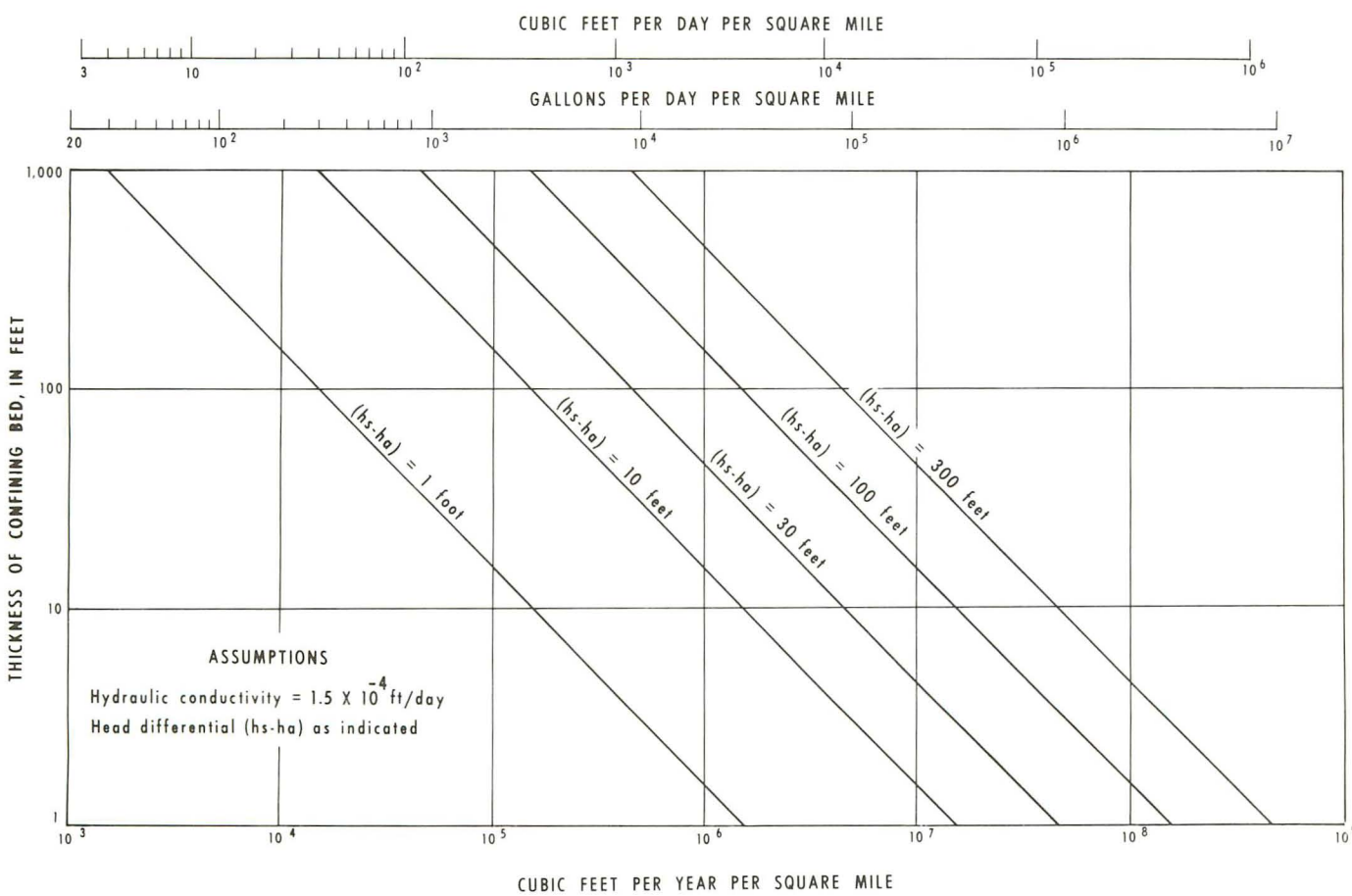

Figure 25.—Graph showing the relationship between the thickness of the confining bed and the quantity of leakage.

heads in the separated aquifers. It is conceivable, therefore, that heavy pumping of the Patapsco Formation might reduce the head on water in the Patapsco enough to cause water to leak from the Magothy to the Patapsco Formation. Thus, what had earlier been considered a source of recharge would become an area of discharge, and the total quantity of water available from the Magothy would be reduced.

3. Movement from outcrop: Zone 4a of section C-C' in figure 21 represents the areas in the upper parts of the Severn and Magothy Rivers where the Magothy aquifer is protected from salt water only by Holocene silt deposits and the hydraulic gradients toward the rivers. Several forms of evidence suggest that salty water from the estuaries does not yet exist below the river bottoms. To date, there has been no indication that any of the wells along the shoreline have encountered salt water. Scuba divers have reported seeing underwater springs, and swimmers have described "cold spots" near the river bottoms. However, those areas shown in figure 23 are the areas most susceptible to salt-water intrusion and are possible sources of contamination. The time required for water to move from this source to areas of pumping under conditions of maximum stress can be estimated by using the hydraulic gradient predicted by the model when the aquifer was pumped at 60 mgd by the hypothetical well field. Using a gradient of 150 feet in 4 miles and assuming a hydraulic conductivity of 100 ft/day (feet per day) and an effective porosity of 30 percent, the formula below shows that 23 years would be required for water to move the 4 miles from Round Bay to the nearest well in the hypothetical well field shown in figure 19.

$$V = \frac{(K)\,(I)}{p}$$

$$V = \frac{100 \text{ ft/day} \times 150 \text{ ft/ } 21{,}120 \text{ ft}}{.30} = 2.4 \text{ feet per day}$$

Where: V = velocity of water movement in feet per day

K = hydraulic conductivity in ft/day

I = hydraulic gradient

p = effective porosity of the aquifer

4. Buffer effects of shallow aquifers: The hydrologic character of the Aquia Formation or other shallow aquifers will control, in part, the quantity of water leaking from the bottom of the salt-water estuaries. Although good potentiometric maps for the shallow aquifers are not available, it is assumed that, as in the case of the Magothy aquifer, the heads on water in the shallow aquifers are several feet above sea level in most areas. These heads cause upward ground-water movement adjacent to and beneath the estuaries. In these areas, the shallow aquifer acts as a buffer to protect deeper aquifers. If heads on the Magothy were to be greatly reduced by pumping, the large quantities of water that would leak from the Matawan Formation into the Magothy aquifer would be replaced by water from the overlying Monmouth Formation. This water would, in turn, have to be replaced by water from the Aquia Formation. The effectiveness of the Aquia as a buffer between the salt-water estuaries and the Magothy aquifer will be determined by its ability to maintain a sufficiently high potentiometric surface despite downward leakage of water into deeper formations.

If water should leak through the bottom of the Aquia Formation at a rate higher than the rate at which the Aquia is recharged, water levels in it would decline, gradients would probably be reversed, and it is probable that the Aquia would also become contaminated in some areas by salt water.

5. Thickness of confining beds as a control: The thickness of the confining layer is an important factor in controlling the rate of leakage, as shown in the graphs in figures 24 and 25. If it is assumed that the confining bed has a uniform vertical hydraulic conductivity of 1.5×10^{-4} ft/day (5.3×10^{-8} cm/sec) and the maximum head differential is that created by pumping the aquifer at 60 mgd, the time required for water to move across beds with thicknesses of 1, 30, and 100 feet would be 5 days, 10 years, and 122 years, respectively. Figure 25 shows that, under the same conditions, the quantities of water per square mile leaking through confining beds with thicknesses 1, 30, 100 feet would be 9.2 mgd, 0.3 mgd, and 0.092 mgd, respectively. In the development of the models, it was assumed that the Matawan Formation has a uniform thickness of 30 feet and a vertical hydraulic conductivity of 1.5×10^{-4} ft/day.

6. Dispersion effects: The effects that dispersion may have on the movement of a solute (principally sodium chloride in this case) through porous media have been studied extensively. These studies have been summarized and cited by DeWiest (1969, pp. 41-45). Dispersion would tend to cause low concentrations of salty water to move through confining layers faster than by conventional flow. The concentration would gradually increase, as illustrated by the breakthrough curve presented by DeWiest (1969, p. 44), reaching about half the eventual concentration at a time equivalent to the time of arrival if there was no dispersion. The concentration would gradually increase for a period similar to that of attainment of half concentration and then, depending on osmotic effects, would level off at a concentration somewhat lower than it would have had if there was no osmotic effect. Laboratory determinations are to be made of the coefficient of dispersion of a sample from the Matawan Formation in order to estimate the role dispersion and osmosis might be expected to have in the movement of salt water in the project area. Recent studies of chemico-osmotic diffusion related to confining layers at Oxnard Plain, California, have been described by Witherspoon and others (1971).

Dilution effects: As had been shown above, many factors would interplay to determine the time required for saline water to move from salt-water sources to the well fields. While it is moving, the saline water would undoubtly be mixed with water from several fresh-water sources. The relative percentages of water from the various sources and the effects of dispersion and osmosis would determine the character of the water that reaches the well fields. Fresh water may dilute the salt water to such an extent that the chemical quality of the mixture may be suitable for a water supply. A mixture of 20 parts of fresh water with 1 part of salt water, having a chloride concentration of 5,000 mg/l, would result in an acceptable mixture, having approximately 250 mg/l.

Figure 26 is a diagram showing three ways in which the quality of the water may be affected after the well fields have been pumped for extended periods of time. Of the three, number one is the most desirable, but, to be realistic, the other possibilities are considered.

Further examination of figure 26 raises the question of the value "n", the number of years for the salt water to reach the wells. Data given previously indicate that at least 100 years would be required for a drop of water to reach the aquifer by moving vertically through the confining bed and that the time for movement downdip from the outcrop area may be almost that long if development of the ground water is properly managed. This seems to be a conservative estimate of the minimum time for salt water to reach the wells (n_3 and n_5 in figure 26). The actual minimum time for arrival of salt water may be several times greater than the periods indicated because of unevaluated factors, such as:

1. the effectiveness of the Aquia Formation in recharging the water lost by downward leakage;
2. the effectiveness of the underlying Patapsco in supplying recharge by upward leakage;
3. the probability that some confining layers, in addition to those built into the models, will inhibit the vertical flow of salt water; and
4. the effectiveness of Holocene sediments on the bottoms of the estuaries in inhibiting the downward flow of salty water.

The time required for the concentration of salt to either stabilize at an acceptable level (n_3) or increase to an unacceptable level (n_5) cannot be determined with the data presently available.

OTHER SIDE EFFECTS

The cone of depression that must develop to obtain 60 mgd from the Magothy aquifer will have certain effects worthy of consideration.

1. At present, fresh water is being discharged naturally from the Magothy aquifer, either directly into Chesapeake Bay and its estuaries or into streams that discharge into these saline bodies. Lowering of the potentiometric head in the aquifer would reduce the quantity of water discharging from it, thereby salvaging fresh water that is now being lost. Reduction of the natural discharge from the aquifer will reduce the flow of streams, such as Severn Run, and will increase salinity of the water in the estuaries.
2. Creation of a large cone of depression in the potentiometric surface of the Magothy aquifer would draw water from the overlying and underlying formations and would thus, reduce the quantities of water available from them.
3. Subsidence of the land surface would be possible by developing an extensive cone of depression. Poland and Davis (1969) have described land subsidence caused by removal of fluids from

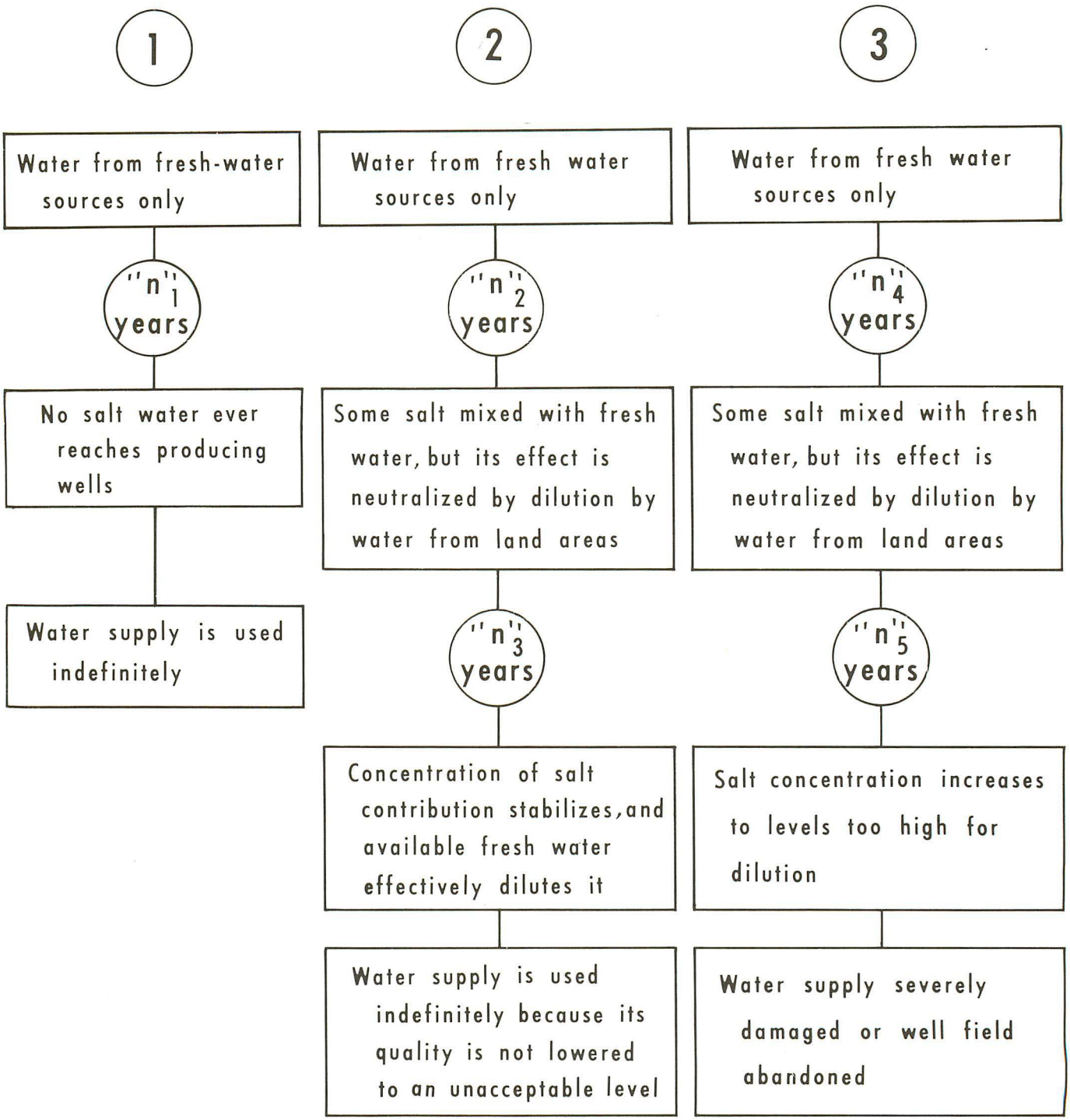

Figure 26.—Conceivable changes in the quality of water after long-term pumping from the Magothy aquifer.

geologic formations in other areas. Geologic formations in the Annapolis area have been well consolidated naturally, and the possibility of a significant amount of subsidence is rather remote. Nevertheless, monitoring devices for detecting early indications of subsidence could be installed.

4. As water levels decline, the cost of obtaining water would increase because of the added power needed to lift the water.

GUIDELINES FOR DEVELOPMENT OF THE MAGOTHY AQUIFER

The Magothy aquifer has a hydraulic head several feet higher than sea level. As long as that head is maintained, the possibility of salt water reaching the fresh water in the aquifer is small. However, the quantitative studies showed that in order to obtain the maximum ground-water yield (60 mgd) from the Magothy aquifer, heads would have to be drawn down to almost 300 feet below sea level in some areas. Thus, water management is faced with a dilemma. If the resource is developed to anywhere near its full potential, the natural safeguard is destroyed; if the safeguard is preserved, the full benefit of the resource cannot be realized.

The Magothy aquifer is in direct contact with salty water in two parts of the project area, beneath the upper parts of the Severn and Magothy Rivers (fig. 23). Probably only the presence of fine-grained bottom sediments and thin silt layers within the aquifer would inhibit the movement of salty water toward wells if pumping reverses the present upward gradient by lowering the potentiometric head on the Magothy aquifer. These areas are particularly susceptible to salt-water contamination that might render them unusable for long periods of time. Consideration of the problem may produce a scheme that would make it possible to keep the potentiometric head in these areas above sea level. Artificial recharge to the aquifer might be one way to accomplish that end. New water supplies being developed in these areas, ideally, would be completed only in aquifers that are deep enough to be overlain by significant thicknesses of clay. Wells for monitoring the chloride content of the water could be established downgradient from sensitive areas. Two possible sites for such wells are shown in figure 23.

Static water levels at two well fields close to salt-water bodies are currently a few feet below sea level--the Pines-on-Severn field and the field of the U.S. Naval Ship Research and Development Center. Because the full thickness of the Matawan confining layer overlies the Magothy aquifer at these sites and the downward hydraulic gradient is small, many years of pumping would probably be required for any salt water to reach the Magothy; nevertheless, the chloride content of water from the Magothy wells in these fields could be monitored.

Time is an important factor in the development of the resource. The investment of large funds in well fields might be justified if the well water were to remain salt-free for 40 to 50 years. Pumping rates can be regulated to control the development of the cone of depression and, thus, control the head differential across the confining layers. Figure 27 is a graph relating the pumping rate to the length of time required for water to move across a confining bed with the characteristics used in the aquifer models. It shows that the time for water to move across the confining beds is much greater when rates of withdrawal are low. Thus, the water manager can exert some control over the time of arrival of the salt water by regulating pumping rates and by designing well fields to keep individual wells as far from salt-water bodies as possible.

CONCLUSIONS

The Magothy aquifer is currently yielding water at a rate of 3 to 4 mgd in the Annapolis area. The cone of depression created by this pumping is relatively shallow, and the potentiometric surface for the aquifer is above sea level in all but a few places near larger well fields. Because the potentiometric surface of the Magothy aquifer is above sea level, the hydraulic gradient is currently upward into low-lying areas, such as the estuaries of Chesapeake Bay, and salt-water contamination is not likely.

Studies with the electric-analog model indicate that at least 60 mgd could be pumped from the Magothy aquifer. However, salt-water contamination and other deleterious side effects

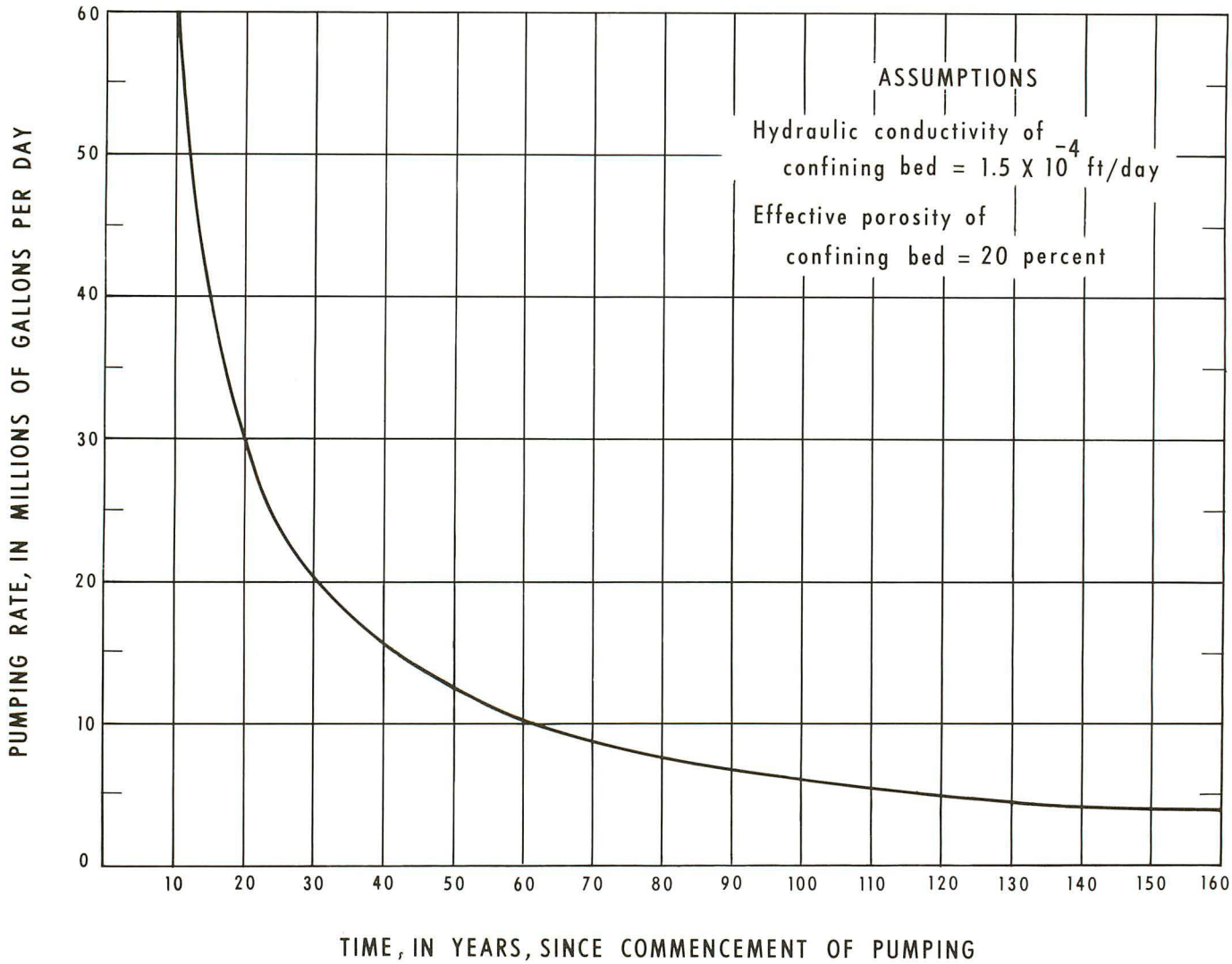

Figure 27.—Graph showing the relationship between the pumping rate and the time for water to move through the confining layer.

at the site of withdrawal are possible. The heavy pumping required to develop such supplies would deepen the cone of depression and reverse the natural hydraulic gradient. The enlarged area of recharge would include, in addition to large land areas, extensive areas of Chesapeake Bay and its estuaries. The chloride content of the bay water and of the bay's estuaries ranges from 5,000 to 10,000 mg/l.

The position of salt-water bodies above the aquifer will always be a factor in the development of new well fields in this area. The lowering of the potentiometric surface by heavy pumping would tend to induce salt water toward wells by two different paths. One path would entail vertical downward movement through the confining layers, and the other would entail movement downdip from the aquifer outcrops directly beneath the upper parts of the Severn and Magothy Rivers. However, available data indicate that the Matawan Formation alone would probably impede the downward flow of water enough to require at least 100 years for the salt water to reach the aquifer by the first path, but salt water might cause costly contamination of parts of the Aquia Formation. Movement of salt water along the other path, downgradient from the outcrops in the upper parts of the Severn and Magothy Rivers, would be faster, depending on the distance to and pumping rates of the well fields. Because the outcrops are fairly well defined and relatively small, techniques could possibly be devised to monitor and confine downgradient movement.

Dilution would reduce the harmful effects of salt water that might eventually reach the well fields. Most water recharging the aquifer during heavy pumping would be from

fresh-water sources. However, because the concentration of chloride averages about 6,000 mg/l in water of the Bay and its estuaries, 24 parts of fresh water would be required to dilute each part of salt water to give a concentration of 250 mg/l. The quantities of water from the various sources and the dispersion and osmotic coefficients of the confining beds would determine the character of the water that reaches the well fields.

Studies with the analog and digital models indicate that under conditions of maximum development, most of the water that could be pumped from the Magothy aquifer would be derived by leakage from the overlying and underlying geologic formations. Such leakage would, in time, reduce the quantity of water available from the other aquifers. It would have a beneficial effect in salvaging some water currently discharging to waste into the bottom of the bay and its estuaries. Conversely, withdrawal of large quantities of water from adjacent formations would reduce the quantity of water available from the Magothy. Thus, the Magothy aquifer can be viewed as a large collecting gallery that has the capability of yielding several thousand gallons per minute to each of several individual wells while drawing large percentages of its recharge from adjacent formations. It becomes obvious that the Magothy aquifer is a part of a larger hydrologic system, not an isolated source of water.

This project has produced a relatively detailed knowledge of the geologic and hydrologic character of the Magothy aquifer. It was a first step toward determining the availability of water from the Magothy aquifer throughout the entire Coastal Plain of Maryland and has yielded much data needed for estimating the total amount of water available from the Annapolis area.

Many broad assumptions had to be made in the preparation of the models of the aquifer; the models, therefore, could be made more accurate by updating and verification, as new data become available.

Detailed knowledge of the total thickness of the Coastal-Plain sediments in the Annapolis area will be needed to make reliable estimates of the ultimate availability of water from the aquifers. Additional information will be needed concerning the leakage characteristics of the confining layers separating the several aquifers.

Future projects might include a detailed study of the hydrologic interrelationships between the several aquifers. Preparation of a multilayer model integrating the hydrologic characteristics of each of the geologic formations would permit far better estimates of the availability of ground water, of interference or leakage between aquifers, and of the hazard of salt-water intrusion. Such a model would require expansion of the current system of collection of water-level and pumpage data from the Magothy aquifer to include collection of similar data for the Patapsco and Aquia Formations.

The character of Holocene bottom sediments in the Severn and Magothy Rivers is an important factor. Detailed information regarding the thickness and hydraulic conductivity of these sediments would aid in estimating the time required for salt water to move from the surface bodies to the aquifers.

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APPENDIXES

The construction and development of models representing parts of the hydrologic system were an important part of this project. Descriptions of their development and values for parameters used are given in this part of this report. (Appendix A)

Detailed geologic, geophysical, and hydrologic field data collected at each of five test sites have been summarized in figures 29-33 and in table 7 (Appendixes B, C). Lithologic and petrologic studies of core samples from test hole AA-De 100 were made by John Glaser of the Maryland Geological Survey (Appendix D). Spore and pollen studies by Gilbert Brenner of several samples from test hole AA-De 100 were used in conjunction with the work of Glaser in preparing a stratigraphic classification for the site (Appendix E). This classification was used as a reference point for the correlation of geologic data from other parts of the project area.

APPENDIX A

MODEL DEVELOPMENT

Models of parts of the hydrologic system in which the Magothy aquifer is situated have been prepared and used to develop a better understanding of the problems associated with optimum development of the aquifer. Development of the models required that all known pertinent geologic and hydrologic data for the area be brought together to construct and verify a physical entity representing the shape, size, and characteristics of the Magothy aquifer. An analog model of the aquifer was developed by the U. S. Geological Survey in Phoenix, Arizona, by using input data from the Maryland District Office. Results of this study have been presented in an open-file report (Mack, 1971).

A digital model of the aquifer has also been developed by using the same input data used for the analog model. Comparison of the output of the two types of model was very satisfactory. A second digital model was prepared to explore the rate of movement of water across the confining bed. These models are described briefly in the following section.

Electric-Analog Model

The following geologic and hydrologic data were used in the design of the model:

Storage coefficient in artesian area . . 0.0003

Storage coefficient in the outcrop area . . 0.2

Transmissivity as shown in figure 15.

Vertical hydraulic conductivity of confining layers in area A shown in figure 15 is 1.5 x 10^{-4} ft/day or 5.3 x 10^{-8} cm/sec.

Vertical hydraulic conductivity of confining layer in area B shown in figure 15 is 7.5 x 10^{-5} ft/day or 2.6 x 10^{-8} cm/sec.

Thickness of confining layer is 30 feet.

Leakage from beneath aquifer is zero.

Boundaries are as shown in figure 15.

Node spacing is 2000 feet.

Verification tests were made by stressing the electric model with the appropriate historical pumpage and comparing the simulated drawdowns with actual water-level drawdowns measured in the aquifer. Comparative data are given in table 5.

Table 5.—Results of verification trials of the electric-analog model.

Well number	Owner or location	Actual drawdown from 1950-1970 (feet)	Drawdown according to model (feet)
AA-Cg 8	Sandy Point State Park	4.6	2.8
AA-De 1	City of Annapolis well field	30 to 35[1]	31
AA-Df 9	U. S. Naval Academy	14	12
AA-Df 20	U. S. Naval Academy	10	8.5

[1] Because this well is in the well field of the city of Annapolis, water levels fluctuate rapidly, causing difficulty in selecting a water level representative of 1970 pumping levels.

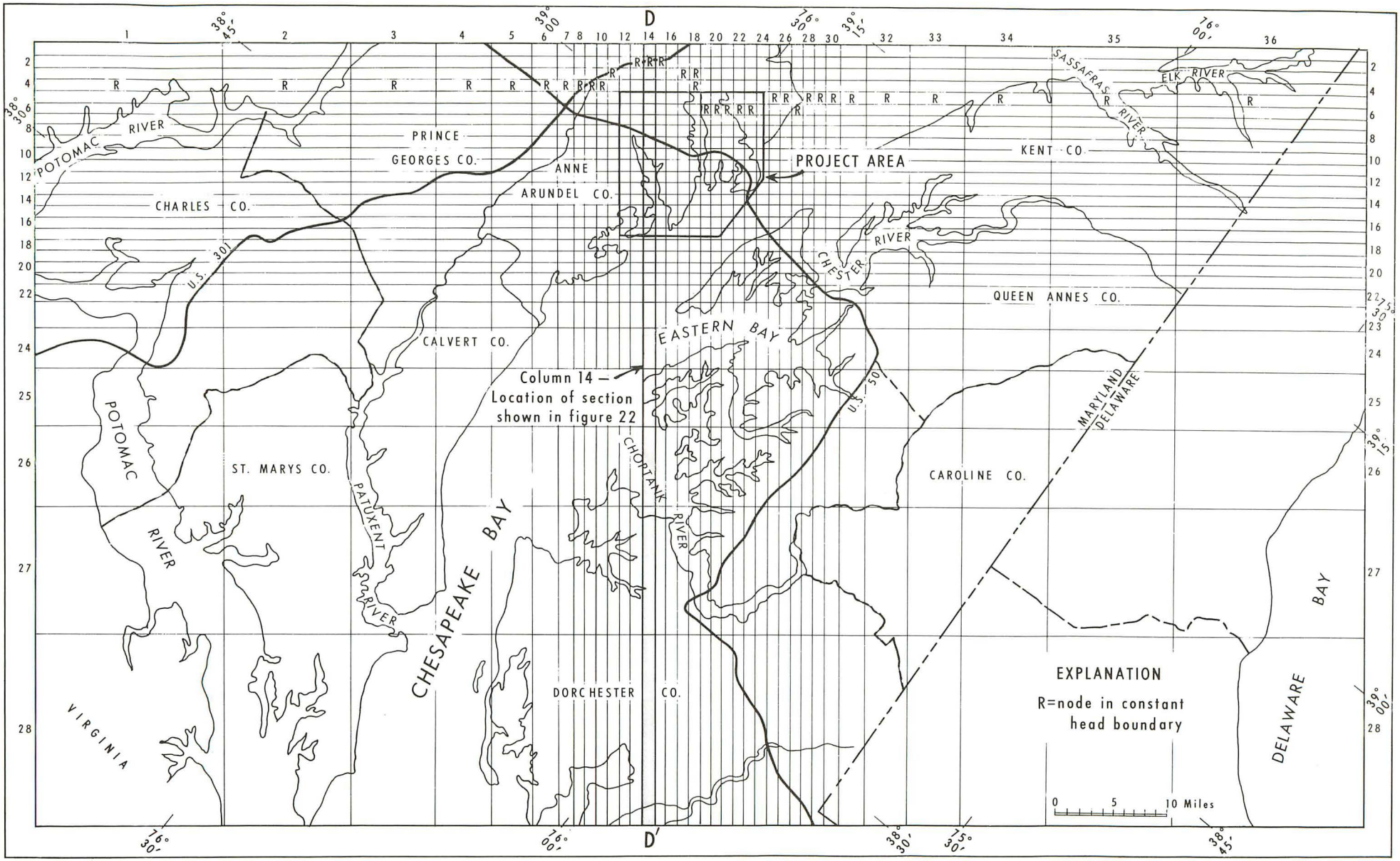


Figure 28.—Map showing area and grid spacing used in the digital model of the Magothy aquifer.

Preferably, verification of the model would be based on maps showing the difference in potentiometric surfaces between 1950 and 1970. However, because water levels in 1950 are known at only the four wells shown in table 5, the verification data are far from ideal. Continued search may produce historical water levels at a few additional points.

The first trial made with the model made no provision for leakage and the predicted drawdowns obtained at the verification points were greatly in excess of real drawdowns. On the second trial, a value for leakage from the overlying formations was built into the model. Although the value used, 1.5 $x10^{-3}$ ft/ day, was based on laboratory measurements of the hydraulic conductivity of samples from test wells, drawdown values were not great enough at the verification points. The value for hydraulic conductivity was, therefore, arbitrarily reduced by one order of magnitude to 1.5 x 10^{-4} ft/day. This value, although fairly low, is within the range of values determined by the laboratory measurements (table 3). Drawdowns obtained using the reduced values for hydraulic conductivity then compared favorably with drawdowns observed at the verification points.

Because the verification trial indicated the model was responding appropriately to imposed historical stresses, several trials were made to predict the quantities of water that could be pumped to the year 2000. A major limitation on the amount of stress that can be applied to an aquifer is the amount of drawdown available under artesian conditions (the distance, in feet, between the top of the aquifer and its potentiometric surface). Figure 18 shows, by means of contours, that the top of the Magothy Formation slopes to the southeast at about 28 feet per mile. The potentiometric surface for the aquifer in April 1970 is also shown in figure 18. As much as 320 feet of drawdown is available at the southeast ends of the peninsulas extending into the Chesapeake Bay.

Figure 19 shows the location of hypothetical well fields and the predicted water-level declines by the year 2000. The pumping (stress) used in the model for each well field is shown in the included table. The predicted and available drawdowns at each of the well fields are also shown in the table.

The model indicates that at a pumping rate of about 60 mgd, for a period of 30 years, a total quantity of more 657 billion gallons of water, could be obtained from the simulated aquifer without drawing water levels below its upper surface, exclusive of the area of outcrop. The sources of water pumped from the hypothetical wells, as indicated by the model, are as shown in table 6.

Table 6.—Predicted quantities of water derived from storage, leakage, and boundary sources after pumping the hypothetical well field 30 years.

Source	Percent of total	Billions of gallons
Storage	16	105
Leakage	64	421
Boundaries	20	131
Total	100	657

DIGITAL MODELS

Aquifer Model

Peter Trescott and Roger Wolff of the U. S. Geological Survey developed a digital model of the Magothy aquifer based on the program developed by Pinder and Bredehoeft (1968). The input data were the same as those used in the electric-analog model. Figure 28 shows the area covered by the model and the grid spacing used for the nodes. The grid spacing in the project area is 1 mile between nodes. An increased spacing is used beyond the project area in order to include the effect of distant areas.

The geographical area represented by the digital model is much greater than the area represented by the analog model. The digital model includes the full extent of the Magothy to the southwest, where it pinches out in Charles County, Maryland, and extends to the southeast beyond Cambridge, in Dorchester County, Maryland, and to the northeast as far as Newark, Delaware. By enlarging the area studied, the model better simulates the boundaries of the real aquifer. The drawdown values computed with this model compare favorably with drawdown values from the electric-analog model.

Hydrologically, the digital model differs from the electric-analog model in the treatment of the recharge boundary. In the digital model, the recharging constant-head boundary is located along the southeast edge of the outcrop area rather than in the middle of the band-shaped outcrop area. Thus, the digital model assumes that drawdown is zero in the outcrop area.

Confining-Bed Model

A finite-difference model of the confining layers was developed by Peter Trescott by utilizing the program of Pinder and Bredehoeft (1968). This model provides an understanding of the effectiveness of the least permeable confining layers as (1) sources of water by leakage and (2) barriers to impede the vertical flow of salt water from Chesapeake Bay and its estuaries. The model computes responses in the confining beds due to the lowering of the potentiometric head in the aquifer. The computations are made at nodes along column 14 (section D-D) of figure 28 because the major part of the withdrawals in the hypothetical well fields occur along that line.

Drawdown data along column 14 of the aquifer model at each time step were used as the head differentials causing water to move downward from and through the confining layer into the aquifer. Responses of the confining bed to these stresses are complex. Pressure decreases due to the pumping of the aquifer also affect the confining beds but at a much slower rate. Pressure decreases that move outward in the aquifer for distances of miles in 1 day would need 18 days to move across the 30-foot-thick confining bed to the overlying aquifer. Thus, the first 18 days of pumping would be required for the effect of the decreasing pressure due to the pumping of the aquifer to reach the overlying aquifer. During the 18-day period, some water stored within the confining beds would drain into the aquifer but no water would move from the overlying aquifer into the confining bed. After 18 days, water would continue to move from storage within the confining bed into the aquifer, but water from the overlying aquifer would move into the confining bed to replace it. Computations were made of the rate of downward movement of water through the confining layer. Figure 22 shows the progress of the water at 2.1 years, 10 years, and 54 years. As may be seen in that figure, the model indicates the first droplets of water would arrive at the bottom of the confining layer after about 10 years of continuous pumping.

APPENDIX B
GEOLOGIC AND HYDROLOGIC DATA FROM TEST SITES

Table 7.—Data available for test sites.

Test site number	Location	Owner of property	Altitude of land surface (ft.)	Depth of probe hole (ft.)	Geophysical logs obtained				Core samples				Number of sands tested by pumping	Permanent observation wells	
									Split spoon a)	Double tube core barrel	Stationary piston sampler				
					Resistivity	Self potential	Gamma ray	Caliper	Number of cores taken	Total footage taken (ft.)	Number of cores collected	Depth sampled (feet below land surface)		Well number	Position of screens relative to sea level
1	Annapolis Junior High School	Anne Arundel County Board of Education	41	436	X X	X X	X X	X X	0	254	3	177 214 347	0	AA-De 99 AA-De 107	-55 to -65 -215 to -242
2	Collison Corner	Maryland State Roads Comm.	50	534	X	X	X	X	36	0	3	23 282 358	3	AA-De 101 AA-De 102 AA-De 103	-360 to -400 -20 to -46 -248 to -288
3	Broadneck Road & Jones Station Road	Anne Arundel County Dept. of Recreation	94	410	X	X	X	X	18	0	3	144 172 231	1	AA-Cf 98 AA-Cf 99 AA-Cf 100	+3 to -7 -116 to -126 -222 to -232
4	Thomas Point	U. S. Coast Guard	6	510					15	0	0	0	1	AA-Df 84	-294 to -304
5	South side of right-of-way of Rt. 50, 0.5 mile east of Rutland Road	Maryland State Roads Comm.	106	505	X	X	X	X	16	0	0	0	1	AA-Dd 41 AA-Dd 42	-254 to -266 -84 to -94 -119 to -129 -159 to -169

a) See figures 29-33 for depth of individual samples.

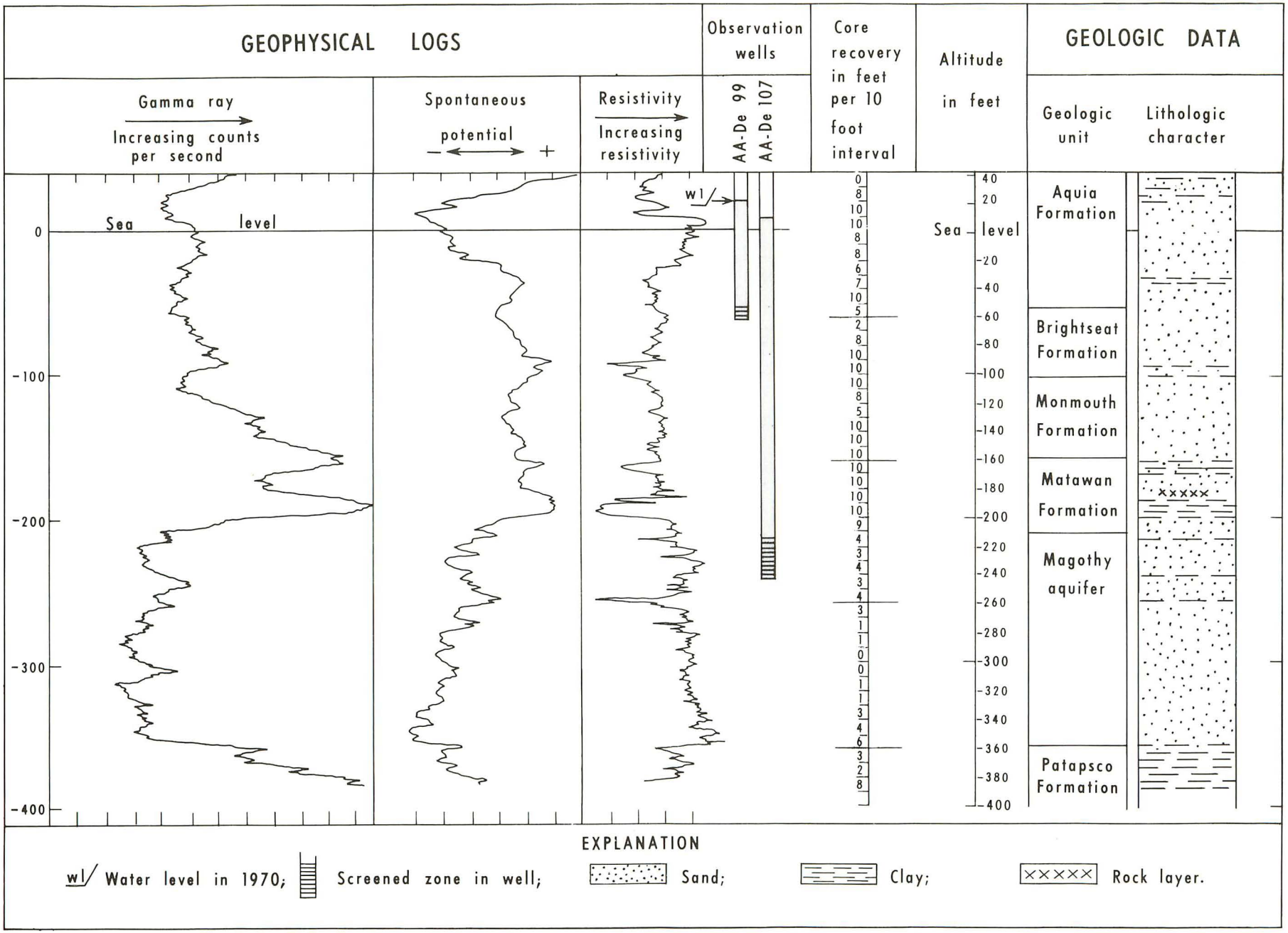
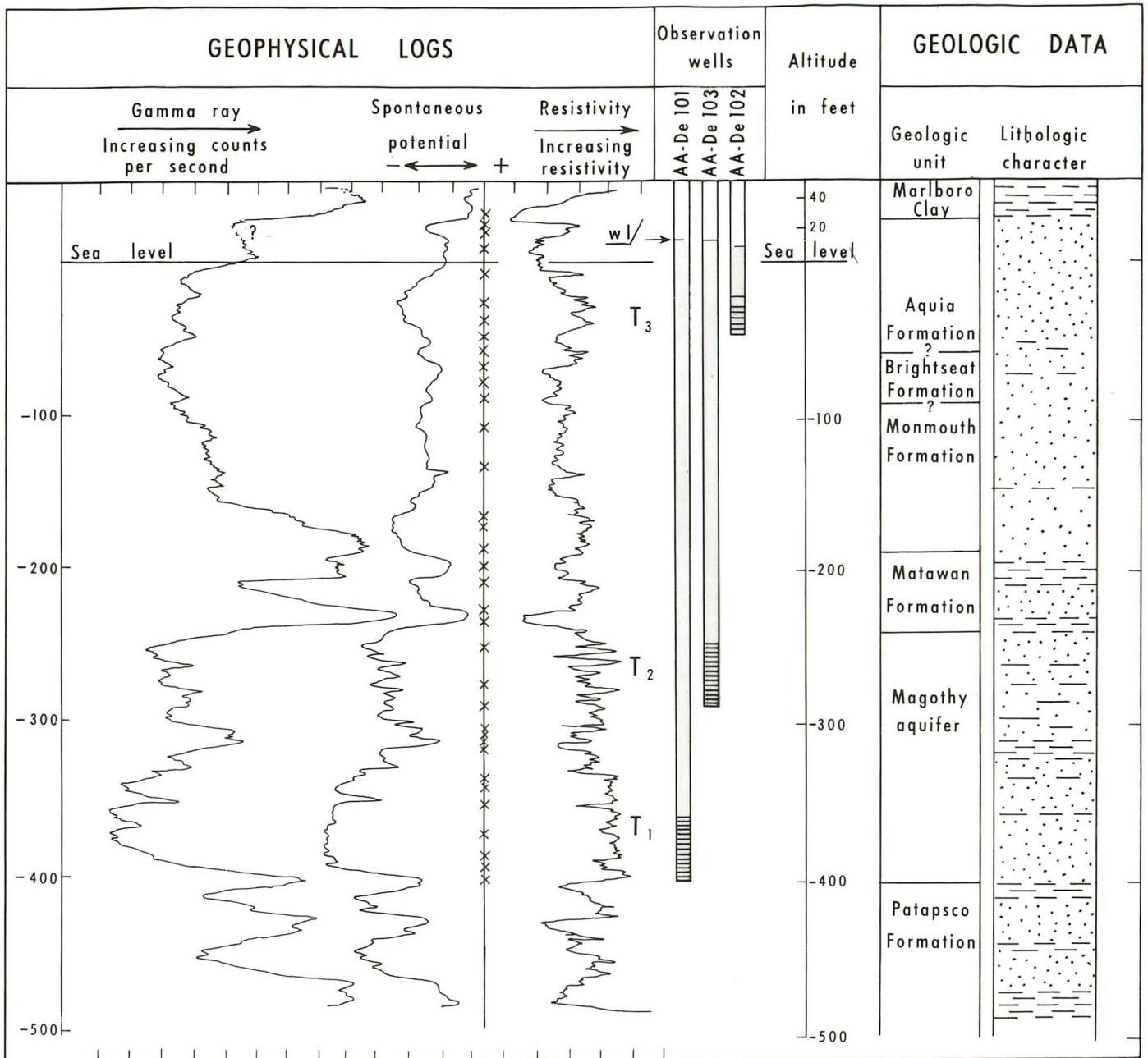


Figure 29.—Section showing geophysical, geologic, and hydrologic data for test site 1 at Annapolis Jr. High School.



EXPLANATION

Sand; Clay;

T_1 = Transmissivity equals 11,000 ft^2/day; T_2 = Transmissivity equals 1,200 ft^2/day; T_3 = Transmissivity equals 3,300 ft^2/day;

Screened zone in well; × = Zone sampled by coring; wl = Water level in 1970.

Figure 30.—Section showing geophysical, geologic, and hydrologic data for test site 2 at Collison Corner.

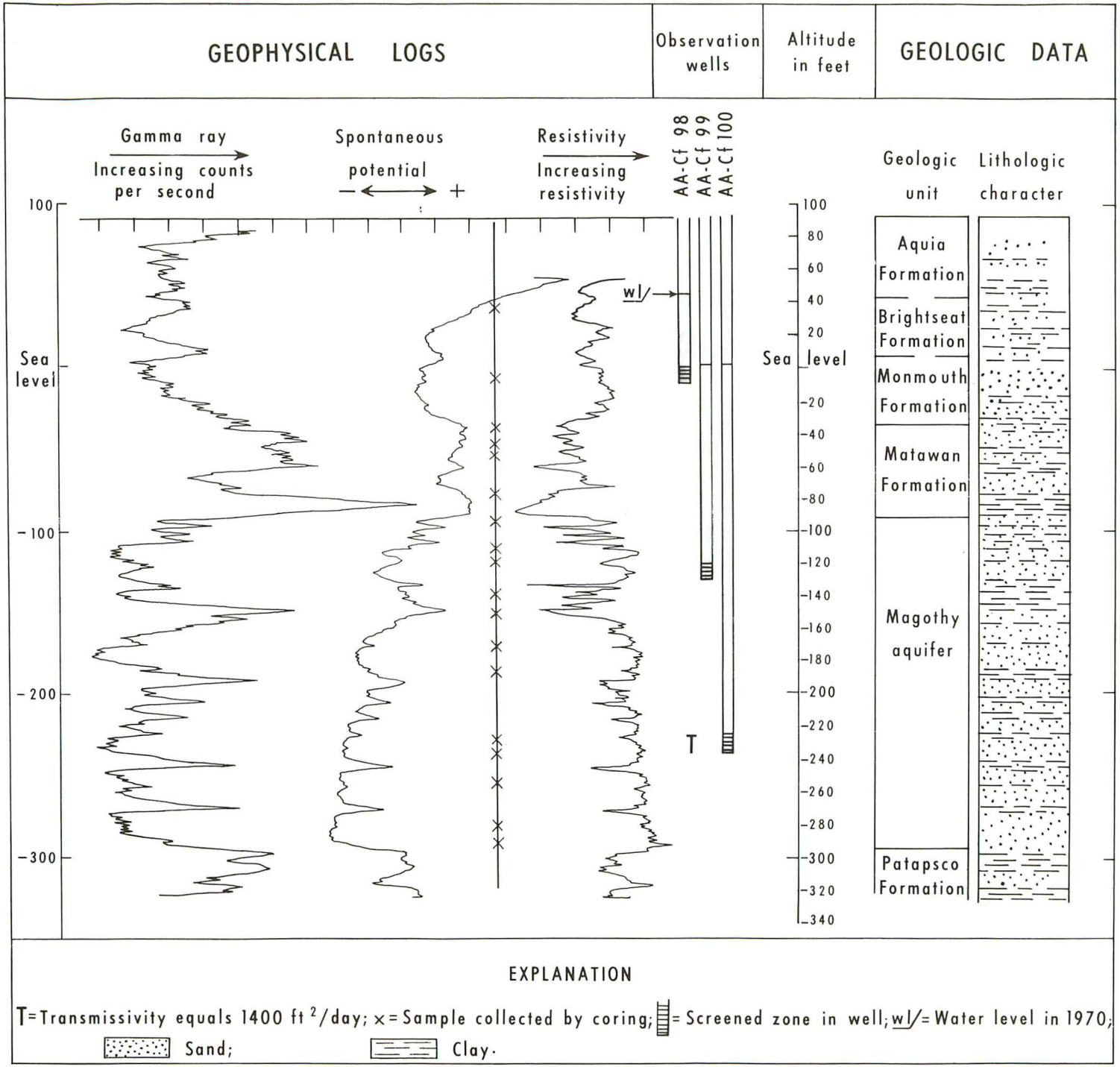


Figure 31.—Section showing geophysical, geologic, and hydrologic data for test site 3 at Broadneck Peninsula.

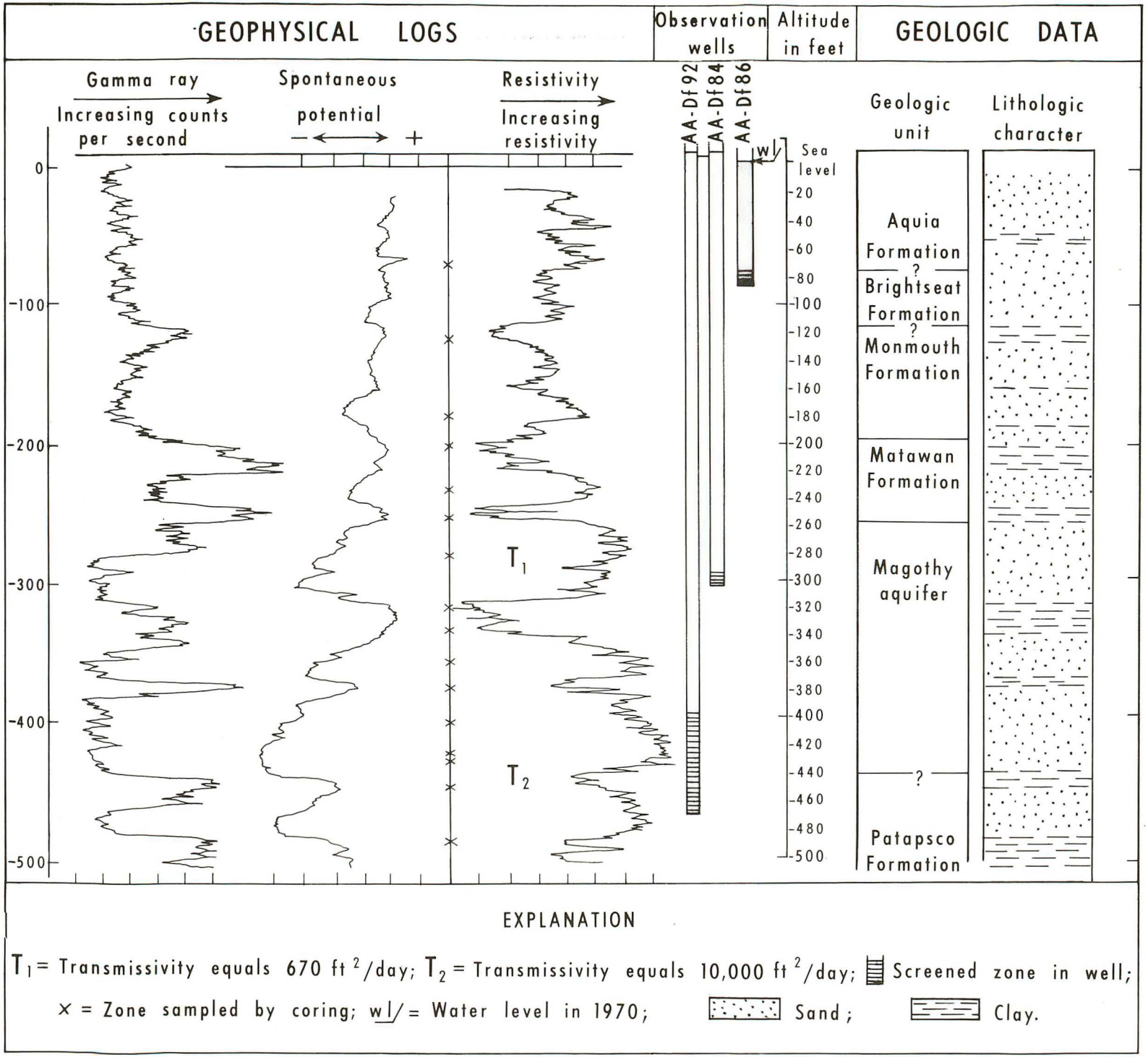


Figure 32.—Section showing geophysical, geologic, and hydrologic data for test site 4 at Thomas Point.

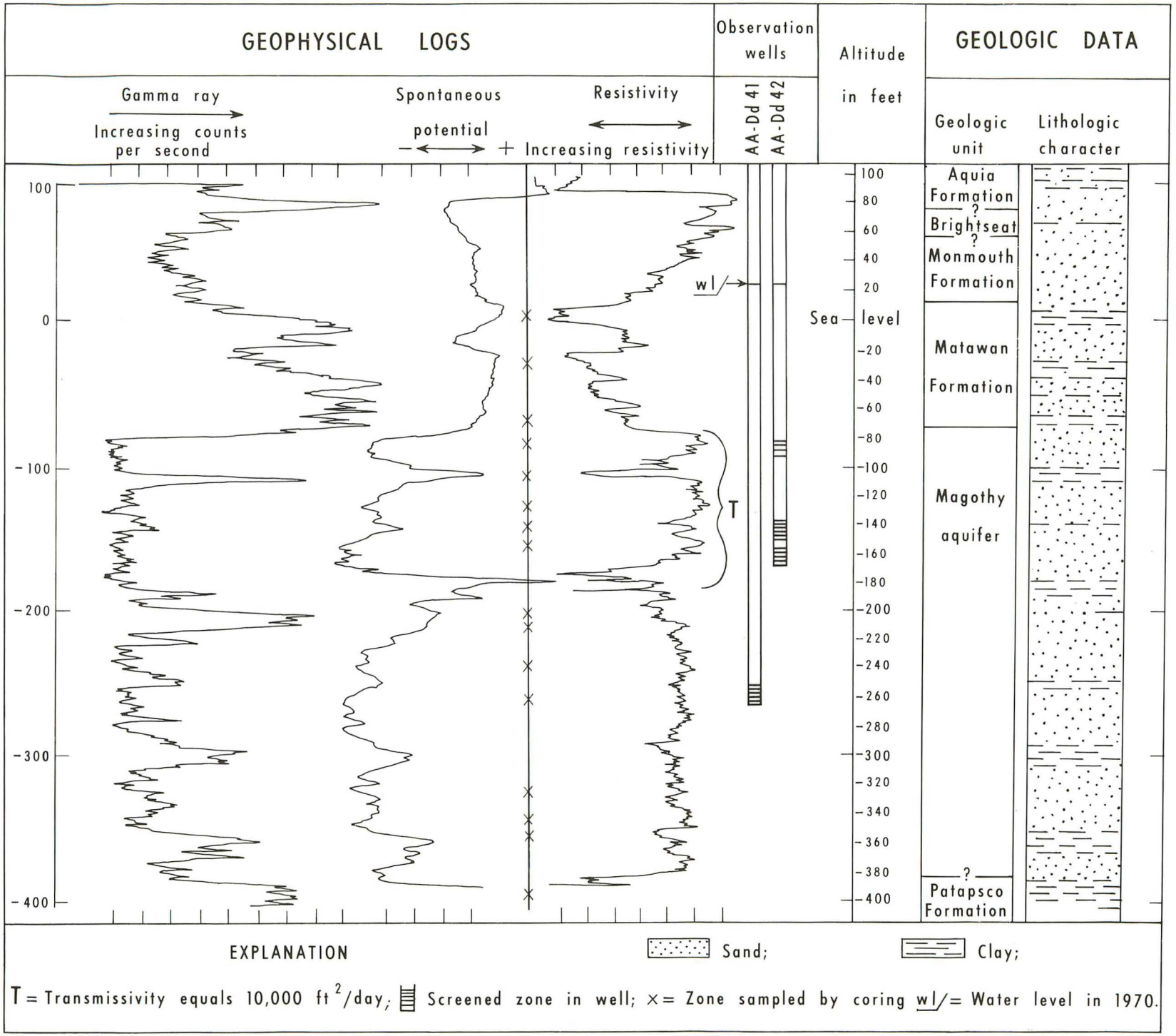


Figure 33.—Section showing geophysical, geologic, and hydrologic data for test site 5 at Rutland Road.

APPENDIX C
Description of Drill Cuttings From Test Holes AA-Cf 100, AA-Dd 41, AA-De 101, AA-Df 90

Description of Drill Cuttings Test Hole AA-Cf 100 Located at Anne Arundel County Department of Recreation and Parks; Broadcreek and Jones Station Roads

Altitude of land surface is 94 feet Test hole completed 9-11-69

Field Description of Cuttings	Thickness (feet)	Depth to base (feet)
Sand, fine to medium, some clay, dark yellowish brown	5	5
Clay and sand, fine, moderate yellowish brown	5	10
Clay, some sand, brown yellowish	5	15
Sand, medium, moderate brown	5	20
Sand, fine to medium, brown	5	25
Sand, fine to medium, brown, some unaltered glauconite	5	30
Sand, medium to coarse, brown, some unaltered glauconite, some altered	5	35
Sand, medium to coarse, brown; glauconite, some altered, some unaltered	5	40
Sand, medium, dark yellowish brown, most glauconite unaltered	45	85
Sand, fine to medium, pale yellowish brown, unaltered glauconite	5	90
Sand, fine, pale yellowish brown, glauconite, altered and unaltered	10	100
Sand, fine to medium, pale yellowish brown, glauconite, altered and unaltered	10	110
Sand, medium, "salt & pepper", white quartz mixed with glauconite	5	115
Sand, fine to medium, dark yellow brown, glauconite; drilling mud turned black, probable clay layer	5	120
Sand, fine to medium, dark olive gray, glauconite	5	125
Sand, medium, dark olive gray, glauconite	5	130
Sand, fine to medium, dark olive gray, glauconite	5	135
Sand, fine to medium dark gray, glauconite	5	140
Sand, fine to medium, dark green gray, glauconite	10	150
Sand, fine to coarse dark yellow brown, glauconite	10	160
Sand, fine to medium, dark gray, glauconite	5	165
Clay with some sand, dark gray	13	178
Sand, coarse, rounded quartz, some pink and violet, much white and gray grains, little wood if any	12	190
Similar to above but with more clay, some clay balls, brownish red and some greenish	5	195
Sand, uniform, medium, rounded quartz grains, some wood chips, less clay	5	200
Similar to above sample, sand, medium to coarse	5	205
Sand, medium, with wood becoming abundant and clay layers	5	210
Sand, fine to medium, clay streaks and wood	5	215
Sand, fine and lignite	5	220
Sand, fine to medium, with lignite	5	225
Sand, fine, much lignite	5	230
Sand, fine and lignite	5	235
Sand, fine with almost equal amount of lignite	5	240
Sand, fine, and lignite	5	245
Clay, some fine sand, light gray (white) with some pink	5	250
Clay, some fine sand, light gray (white)	2	252
Sand, fine, with streaks of white clay	3	255
Sand, fine, and streaks of white clay	5	260
Sand, fine with streaks of white clay	5	265
Sand, fine, uniform, light gray	5	270
Clay, white	2	272
Sand, white, coarse	5	277
Clay, sandy, white	3	280
Clay, white with sand	15	295
Sand, fine, white with streaks of white clay	10	305
Sand, white, fine with clay	10	315
Sand, fine, white	5	320
Sand, medium, white	5	325
Sand, coarse, white	3	328
Clay, white	2	330
Sand, coarse, white	10	340
Sand, coarse, white	11	351
Clay with some sand, drilling hard	4	355
Sand, coarse, white	5	360
Sand, coarse, dark gray	5	365
Sand, medium to coarse, light gray	10	375
Sand, medium to coarse, reddish brown, color due to clay layer in zone from 379-380, drill mud became reddish brown	5	380
Clay, tough, drill mud turned brown, took 18 min. to drill	5	385
Clay, tough, dark gray	10	395
Sand, fine, with clay, drilled fast	5	400
Clay, tough, dark gray, 20 minutes to drill 5 ft.	5	405
Clay, soft, reddish-brown chips	5	410

Bottom of hole 410 feet

Description of Cuttings from Test Hole AA-Dd 41 Located on south side of right-of-way of U.S. Route 50 one half mile east of Rutland Road

Altitude 106 ft. Completed 9-17-70

Field Description of Cuttings	Thickness (feet)	Depth to base (feet)
Sand and silt, fine-medium, yellow brown	5	5
Sand, glauconite, fine-medium, green-gray	5	10
Sand, fine-medium, glauconite, green-gray	5	15
Sand, fine-medium, glauconite, brown, oxidized	5	20
Sand, fine-medium, glauconitic, gray brown, oxidized	5	25
Sand, fine-medium, glauconitic, medium-brown, oxidized	40	65
Sand, fine-medium, glauconitic, gray-green	35	100
Sand, coarse, quartz grains rounded and stained glauconitic, gray-green	15	115
Sand, fine with medium, glauconitic, gray-green	60	175
Sand, medium with fine, gray-green	5	180
Sand, medium with fine, quartz, wood, light gray	5	185
Sand, medium with fine, quartz angular, wood, light gray	22	207
Clay or wood (no clay sample)	3	210
Sand, medium with fine, angular quartz, light gray	15	225
Sand, fine-medium, light gray	10	235
Sand, fine-coarse, light gray	5	240
Sand, fine-medium, light gray	20	260
Sand, fine-medium, some silt, light brown	5	265
Sand, medium-coarse, light brown	10	275
Sand, case, angular quartz, some wood,	5	280

Clay, some gravel, gray-green	5	285
Gravel, and some coarse sand, light gray	15	300
Gravel and sand, fine-coarse, some clay	5	305
Sand, fine-medium, some clay, light gray	10	315
Gravel and sand, fine-coarse, light gray	5	320
Sand, fine to gravel	10	330
Sand, fine-medium, light gray to cream color	10	340
Sand, fine-coarse, some clay	25	365
Clay	5	370
Clay, some grit	5	375
Sand, gravel, and clay, light brown	15	390
Clay, light gray	10	400
Clay, some sand, light gray	5	405
Sand, fine-medium	5	410
Sand, fine-medium, some clay, light brown	10	420
Clay and sand, fine-medium, light brown	5	425
Sand, fine-medium, light gray	5	430
Sand, medium, light gray	5	435
Sand, medium, light brown	10	445
Sand, medium-coarse, light gray	5	450
Sand, medium-coarse, light brown	5	455
Sand, fine-coarse, light gray	5	460
Clay, some grit, light gray	5	465
Sand, medium, light gray brown	15	480
Sand, fine-medium, some clay, light gray brown	5	485
Clay, silt, and fine sand, light gray brown	10	495
Clay, silt, and fine sand, light gray brown and some red	10	505

Total depth drilled 505 feet

Description of Drill Cuttings
Test Hole AA-De 101
Located near Collison Corner, at intersection of Md. 214 and Md. 253

Altitude of land surface is 50 feet — Completed 9-18-68

	Field Description of Cuttings	Thickness (feet)	Depth to base (feet)
0-6	Sand, fine to coarse, glauconite, green and white particles	6	6
----------	Top of Marlboro Clay		
6-8	Clay, light gray	2	8
8-26	Clay, dark, reddish brown	18	26
----------	Top of Aquia		
26-42	Sand, fine to medium, glauconitic	16	42
42-43	Ironstone, glauconitic	1	43
43-56	Sand, fine to coarse, some layers of cemented sand, some green clayey layers	13	56
56-56′6″	Sand, cemented zone, shell zone	½	56½
56′6″-75′	Sand, fine to coarse, glauconitic, shells abundant, several layers cemented with carbonate	18½	75
75-80	Sand, cemented with carbonate	5	80
80-100	Sand, with some layers of green clay, some cementation, fossil fragments	20	100
100-105	Sand, some cementation, some layers of green clay, glauconitic, phosphate nodules, shells	5	105
105-110	Sand, some cementation, some layers of green clay, glauconite, shells	5	110
110-115	Sand, cemented, chunky, glauconitic, shells	5	115
115-120	Sand, cemented, glauconitic shells, shark's tooth, some chunks dark gray, some light gray	5	120
120-125	Sand, cemented, green, glauconitic	5	125
----------	Top of Monmouth? -- color change --		
125-133	Sand, with clay intermixed, dark gray	8	133
133-185	Clay and sand, dark gray	52	185
185-186	Hard layer, drilled 20 minutes to penetrate, cuttings indicate hard red clayey layer	1	186
----------	Top Matawan?		
186-200	Clay, dark gray, sample is frothy	14	200
200-208	Clay with sand, dark gray	8	208
208-215	Sand, fine to medium, dark gray, glauconitic, mica, with layers of soft green clay	7	215
215-260	Clay, sandy, mostly micaceous, dark gray, with some green sand. Started to lose water between 220 and 225	45	260
260-265	Sand and clay	5	265
265-298	Clay, silt and fine sand, dark gray, chunky samples	33	298
----------	Top Magothy -- first wood appeared		
298-310	Sand, coarse, with gravel and wood, some chunks of dark gray clay	12	310
310-315	Sand, coarse to clay size, wood, dark gray	5	315
315-364	Sand, fine to coarse, dark gray, with wood	49	364
364-392	Clay, silty, with sand, dark gray	28	392
392-439	Sand, medium to fine gravel, dark gray	47	439
439-444	Sand and gravel	5	444
444-452	Sand and gravel	8	452
452-467	Clay, some light gray and some reddish brown, drilled a little harder than before	15	467
467-477	Sand, fine to medium, light gray	10	477
477-501	Clay layers, red and white, with some sand	24	501
501-517	Sand, medium, with streaks of red and white clay	16	517
517-534	Clay, hard, red and white	17	534

Total depth drilled 534 feet

Log of Well AA-Df 90
U.S. Coast Guard Station at Thomas Point

Altitude of land surface is 6 feet — Test hole completed 8-11-70

Field Description of Cuttings	Thickness (feet)	Depth to base (feet)
Top soil (no sample)	1	1
Sand, fine to medium, glauconite, dark green to dark brown	17	18
Sand, fine to coarse, glauconite, brown, some fine shell	12	30
Sand, fine to coarse, glauconite, brown and dark green, no shell	10	40
Rock or shell caused drill rods to clatter (Sample same as 30 to 40)	5	45
Sand, fine to medium, dark brown with some green glauconite. Rock or shell caused rods to clatter at 48 feet	5	50
Sand, fine to medium, fine fragments of shells; red grains are probably ironstone	5	55

Sand, fine to medium, fine fragments of shells; sample is gray-green	25	80
Sand, medium to coarse; large shell fragments; dark brown	5	85
Sand, medium, with coarse; shell fragments glauconite, dark brown and green	5	90
Sand, medium with some coarse shell fragments abundant, dark glauconite more abundant	10	100
Sand, fine to medium, some shell, dark green glauconite	5	105
Sand, fine to medium; dark green and brown glauconite; some large fragments of shell	16	121
Sand, fine to medium, dark green to black glauconite, shell not common	4	125
Sand, fine to medium, abundant black glauconite, shell common	9	134
Sand, fine to medium, abundant black glauconite, shell fragments common, some clay	6	140
Sand, silt and clay, much glauconite, some fine shell fragments, dark green	5	145
Sand, fine, silt, and some clay, much dark glauconite, some shell	5	150
Sand, silt, and clay, sample is probably more representative of coarse sizes than fine sizes, glauconite, some shell, dark gray	5	155
Sand, fine to coarse, glauconite, black, shell abundant	5	160
Sand, fine to medium, black glauconite, little shell, gray-green	10	170
Sand, silt, and clay, black glauconite, some shell	5	175
Sand, fine to coarse, black glauconite, shell common	10	185
Sand, silt, and clay, black glauconite, large shell shell fragments common	5	190
Sand, fine to medium, black glauconite, some large shell	5	195
Clay, silt, and fine sand in lumps, dark gray	5	200
Clay, silt and fine sand some shell fragments, dark gray	20	220
Clay, some silt and sand, tough, dark gray	15	235
Same with cemented sand	5	240
Clay, some silt and sand, dark gray	15	255
Same, with some cemented sand	5	260
Clay, some silt and sand with large percentage of sand, olive gray, lighter than previous sample	5	265
Clay, silt, and some sand, no shell, dark gray few fragments of cemented sand	5	270
Clay, silt and sand	5	275
Clay, silt, and little sand, dark gray	5	280
Clay, silt, and little fine sand, dark gray	8	288
Sand, silt, and clay, washed sample shows well rounded coarse, quartz grains, some wood, no shell	7	295
Sand, coarse, silt, gray, washed sample contains wood, well rounded quartz (white) some pyrite, some quartz fragments up to 2½ mm, clay may be drilling mud	15	310
Same with some fine gravel	5	315
Sand, medium to coarse, quartz grains white, subangular to rounded, wood pieces to ¾ inch	5	320
Gravel particles to 4 mm, rounded, sand, quartz, white, wood pieces to 1¼ inch, some clay lumps in washed sample	3	323
Hard layer reported by driller	1	324
Clay and silt, washed sample contained 1 mm ball of quartz particles cemented with pyrite	6	330
Clay, dark gray, tough	5	335
Clay, dark purple	5	340
Clay, dark purple, washed sample shows some pyrite-cemented quartz grains	5	345
Clay, dark purple, some grit	3	348
Silt, clay, and fine sand, light gray, washed sample contains lumps of pyrite, cemented quartz and some wood	7	355
Silt, clay, some fine sand, some wood, some pyrite black globules of glauconite?	5	360
Sand, fine, with medium, some wood, some clay chips, and some glauconite?	5	365
Sand, fine and medium, some wood, some clay chips, some glauconite?	10	375
Sand, fine and medium, some wood, some glauconite?	5	380
Sand, medium and fine, silt, and clay, some wood, some glauconite, and pyrite	10	390
Clay, white, with sand, fine to medium, some wood	5	395
Sand, fine to medium, light gray	5	400
Sand, fine and medium, some coarse, clear quartz	10	410
Sand, fine and medium with some coarse and some very coarse, some pink quartz particles	5	415
Sand, coarse, with some very coarse, medium and fine	33	448
Clay, white, no sample (cuttings were not collected because they are coarse sand from upper parts of the hole)	22	470
Sand, silt, and clay (drilled in 8 minutes)	5	475
Same (drilled in 7 minutes)	5	480
Same (drilled in 6 minutes)	5	485
Same (drilled in 6 minutes)	5	490
Clay, tough, red and white (drilled in 30 minutes)	5	495
Same (drilled in 35 minutes)	5	500
Same (drilled in 35 minutes)	5	505
Same (drilled in 50 minutes)	5	510

Drilling stopped at 510 feet

APPENDIX D
LITHOLOGIC LOG OF TEST HOLE AA-De 100

by
John Glaser
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The following tentative conclusions were drawn from data obtained from cores from test hole AA-De 100 and from the attached lithologic log (fig. 34):

1) The Aquia Formation is deeply oxidized to a depth of 70 feet; further, the intensity of oxidation increases with depth. Such deep weathering may reflect lowered Pleistocene water tables in the absence of a protective cover of later sediments.

2) The small amounts of glauconite and garnet in the upper oxidized Aquia is a probable consequence of selective removal by weathering processes rather than primary deficiencies. Both minerals are known to be chemically unstable in the zone of weathering.

3) Delineation of the Brightseat Formation is based on several lines of evidence, none conclusive. A clear, sedimentation break occurs at the base of the gravel at 95 feet (see lith. log), below which dusky blue-green colors make their first appearance. Further, garnet proportions abruptly rise as does sand angularity. These observations, supported by Brenner's placement of the interval 135-136 feet in the lowest Tertiary, suggest a Brightseat assignment for 95-136 feet. I have drawn the Brightseat-Monmouth contact at 138 feet at which point phosphate pebbles and oxidized burrow fillings suggest a second sedimentation break.

4) The Matawan Formation admits subdivision into three lithic units; an upper lignitic, sparingly glauconitic silty clay with downward increasing sand mottling; a middle, very glauconitic, interlaminated silt-clay sequence; and a lower, sparingly glauconitic sand, pebbly at the base. These subunits, however, do not appear to be lithologic correlatives of the tripartite Kent County Matawan.

5) The Magothy Formation is, generally speaking, a fining-upward sequence. Moreover, sand grain roundness, both heavy and light, increase upward through the section, and relatively unstable heavy minerals such as garnet, sillimanite, and chloritoid, species characteristic of the marine units above, are introduced in the upper twenty feet of the unit. The lower portion of the Magothy, typified by angular quartz, and with a heavy mineral assemblage dominated by angular staurolite and kyanite, reflects fluvial deposition of sands derived almost wholly from the local Piedmont Wissahickon terrain. The mineralogic and textural changes into the upper Magothy suggest a shoreline complex of sediments diluted by a longshore-drift contribution, i.e., rounded grains and unstable heavy minerals.

6) The Patapsco Formation in De 100 is analogous in gross lithology and heavy mineral assemblage to the outcropping Patapsco.

SAMPLE DESCRIPTIONS: MAGOTHY TEST WELL AA-De 100

Aquia Formation

0-6 No samples

6-15 Sand, moderate olive-brown, medium-grained with admixed coarse to very-coarse grains, sparsely glauconitic; clay-silt fraction small to moderate, increasing downward; structureless; weakly oxidized.

15-22 Sand, moderate olive-brown to grayish-olive, fine to medium-grained moderately glauconitic; structured, thin laminae of reddish-brown clayey sand alternating with much thicker beds of much less clayey olive sand; moderately oxidized, patchy.

22-29 Sand, moderate olive-brown mottled with reddish-brown, medium to coarse grained, sparsely glauconitic, clay-silt fraction small; structureless; moderately oxidized.

29-39 Sand, predominantly reddish-brown mottled olive, medium to coarse-grained, clay-silt fraction moderate, sparsely glauconitic; structureless; increasing oxidized, limonitic lumps conspicuous.

39-60 Sand, predominantly medium-grained with admixed coarse grains; structured; interlaminated clean sand and very clayey sand in 10-20 mm beds, base color olive-brown with irregularly-spaced reddish-brown, highly oxidized beds to 10 cm in thickness and with sharp boundaries, percentage of oxidized beds and limonitic crusts increases downward through interval, basal 5 ft. is 70% reddish-brown oxidized sediment, liesegang banding conspicuous.

60-70 Sand, medium-grained, wholly reddish-brown limonite-permeated, crusts and irregular lumps of limonite abundant, structureless in other respects; scattered irregularly-shaped, sharply-bounded islands of unoxidized sand, periphery limonite-cemented.

Base of oxidized zone

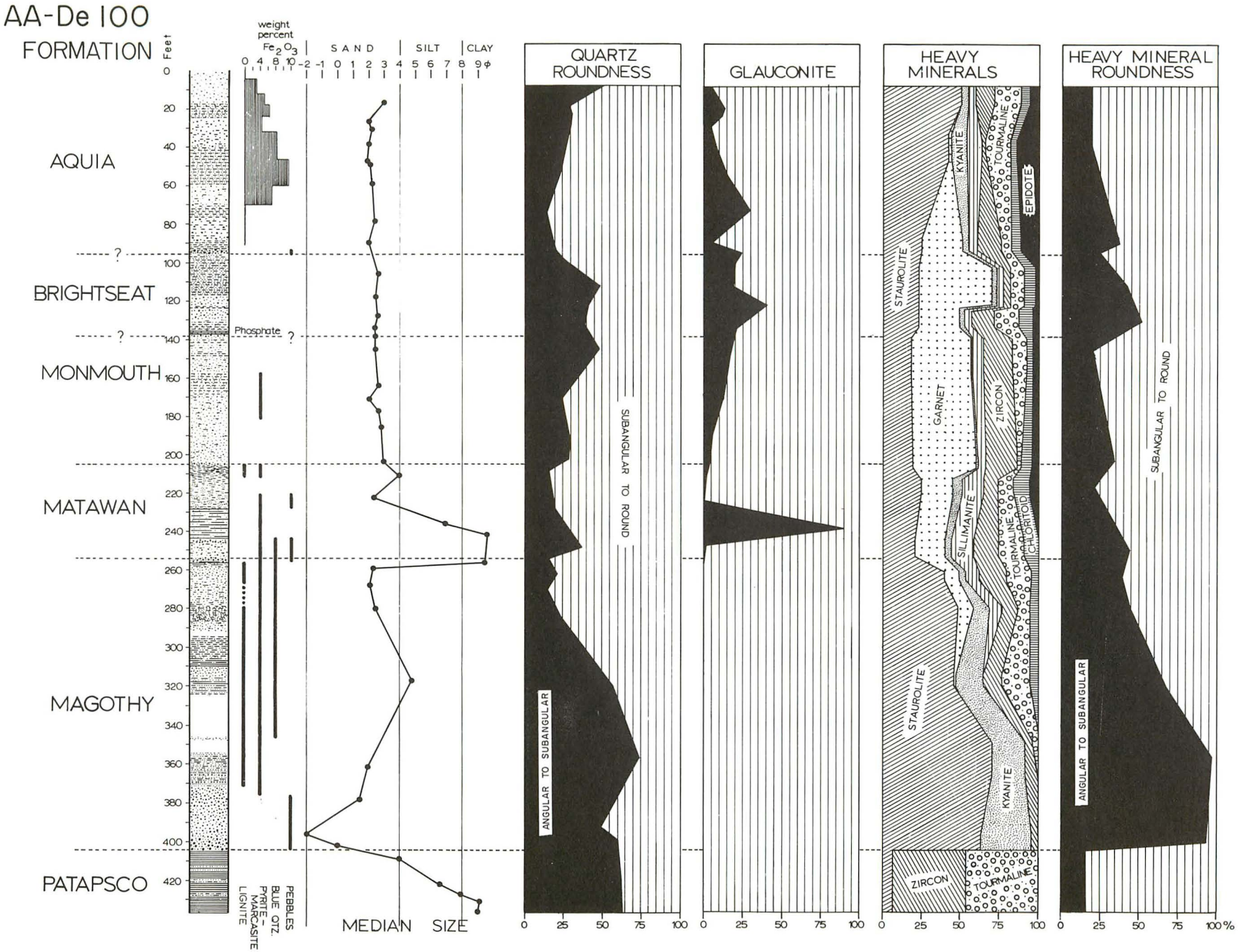

Figure 34.—Chart summarizing lithologic data from test hole AA-De 100.

70-77 Sand, olive and gray speckled, clean, medium-grained interlaminated with sandy clay, light olive, sand laminae 15-20 mm thick, clay laminae about 5 mm; laminations regular, evenly-spaced; sand with patchy interstitial chalky carbonate; upper boundary with oxidized sediment sharp, irregular; sand moderately glauconitic.

77-90 Sand, olive and gray speckled, clean, predominantly medium-grained with admixture of coarse, with sporadic olive-green clayey laminae, these becoming fewer downward through the interval; calcareous matrix sporadically distributed, sand patchily cemented; scattered molluscan molds and casts.

90-93 Sand, olive and gray speckled, clean, fine to medium-grained, regularly and closely interlaminated with clayey fine sand on a 10-20 mm scale, the latter grayish-green, slightly bluish; sparsely glauconitic.

93-95 Sand, bluish gray-green, medium to very coarse-grained with admixture of granules and small pebbles, clayey, poorly-sorted, structureless; coarsest fraction (to 16 mm) includes: vein qtz., metasiltstone, chert, phosphate, fish teeth, and bits of bone; sand moderately glauconitic.

Brightseat Formation

95-117 Sand, olive-black to olive-gray speckled, fine to medium-grained, moderately glauconitic, very clean, evenly interlaminated with very clayey fine sand, dusky blue-green; sand laminae 10-20 mm, clayey sand laminae 5-10 mm.

117-132 Sand, greenish-gray and dark-gray speckled, medium to coarse-grained, moderately glauconitic, very clean, interbedded on a variable scale with fine clayey sand, dusky blue-green; sand beds range from an inch or two to 12 in. in thickness whereas the clayey beds range from less than an inch to 6 in.; sand with patchy weak siderite cementation; scattered pelecypod fragments, these friable, indeterminate.

132-135 Sand, dark-gray to olive-black, fine to medium-grained, moderately glauconitic, with sparse, thin, more-clayey sand laminae, these weakly greenish; sand fines and becomes more clayey downward in interval; at 132-132.5 ft. and 134-134.5 ft. siderite-cemented sandstone.

135-137 Clayey silt, greenish-black, dense, conspicuously micaceous, scattered shell fragments, otherwise structureless.

137-138 Sand, olive-black, medium-grained, slightly clayey; numerous rounded phosphate clasts ranging to 20 mm in diameter; several fish teeth and bone bits; scattered brownish limonite-cemented pods with sharp rims.

Monmouth Formation

138-152 Sand, olive-black, fine to medium-grained, clean to slightly clayey, moderately glauconitic, interbedded in upper 4 ft. and lowermost 2 ft. with very clayey, fine-grained sand, dusky blue-green, laminations even and regularly spaced 5 to 10 mm apart.

152-157 Sand, grades from olive-black through olive-gray to dusky blue-green at base of interval, fine to medium-grained, clean, moderately-glauconitic; few scattered shell fragments; first definite burrows.

157-160 No recovery.

160-181 Sand, medium-gray to olive-black, fine to medium-grained, sparsely glauconitic, clean; intervals 160-167, 169-171 ft. with well-defined even laminae of dusky blue-green, more clayey fine sand; several clearly-defined burrows with sharp limonitic borders; rare pyrite-cemented aggregates.

181-205 Sand, dark-gray to olive-black, sporadically mottled greenish, fine-grained, slightly clayey, sparsely glauconitic; scattered burrow-mottling; at base several granules and bone bits.

Matawan Formation

205-224 Silty clay, tough, micaceous, plastic in part, olive-black, mottled with fine to medium sand, clayey, grayish olive-green, very sparingly glauconitic; upper contact sharp, upper several inches with sharply-defined, sand-filled, vertical burrows; sandy mottling increases downward through interval until virtually all sand at base; molluscan fragments scattered through interval; sparsely lignitic.

224-228 Sand, olive-black and gray mottled, fine to medium-grained with admixed coarser grains (coarse sand to small pebbles); burrowed; scattered shell fragments.

228-229 Sandstone, siderite-cemented, olive-black, moderately glauconitic, medium-grained; abundantly burrowed.

229-243 Silty clay, olive-black with purplish cast, tough, closely and irregularly interlaminated with very clayey sand, greenish-black; laminae very irregular (pinching, swelling, and bifurcating); micaceous; rare shell fragments; pyritic concretions common.

243-254 Sand, uniformly grayish-black, fine to medium-grained with admixed coarse material, granules and small pebbles common in lower 6 in.; at 244 ft. a 1 in. thick bed of fine gravel; very sparingly glauconitic.

Magothy Formation

254-256 Sand, medium-gray, coarse to very coarse grained, very little clay-silt; scattered pebbles to 20 mm; sparsely lignitic; pyrite-cemented aggregates to 80 mm diam.

256-257 Sand, medium-gray, medium-grained, interbedded with clay, dark-gray; moderately lignitic pyritic.

257-260 No recovery.

260-273 Sand, medium and dark-gray mottled, fine to medium-grained with some coarse admixture; variably lignitic and clayey; pyritic concretions common.

273-280 Sand, fine to medium-grained, clayey, variably lignitic; upper portion medium-gray, lower 2 ft. laminated medium and dark-gray; one thin bed dark-gray plasitc clay.

280-287 Sand, pale-gray, fine-grained, clayey, interlaminated with silty clay, dark-gray, lignitic.

287-292 Sand, light olive-gray, medium-grained, clayey.

292-294 No recovery.

294-300 Sand, light-gray, fine-grained, clayey, interlaminated with clay, plastic, dark-gray; entire interval lignitic.

300-301 Lignite bed, composed of compressed, partly pyritized, wood fragments with dark-gray silt-clay filling interstices.

301-310 Sand, light-gray, fine-grained, clayey, interlaminated with silt-clay, dark gray, lignitic; sand component decreases downward in interval.

310-315 Clay, sandy, medium-gray, lignitic, with thin lenses fine clayey sand (in part).

315-325 Sand, medium-gray, fine to medium-grained, clayey, closely interlaminated with clay, plastic, medium-gray, and silt, pale grayish orange; lignite throughout, pyritic in part; bedding irregular, lenticular (in part).

325-354 No recovery.

354-371 Sand, pale-gray to dark-gray, fine to coarse interbedded, variably clayey and lignitic, interlaminated with clayey silt, mostly dark-gray; bedding irregular and lenticular; pyrite-cemented aggregates common.

371-376 No recovery.

376-387 Sand, pale to medium-gray, coarse to very coarse, pebbly; 2 thin beds of interlaminated fine clayey sand and dark-gray silt; lignite very scarce.

387-398 No recovery (much coarse sand, granules, and small pebbles between barrels)

398-404 Sand, medium light-gray, coarse to very coarse, and fine gravel; pebbles to 25 mm, vein quartz and metaquartzite, subrounded.

Patapsco Formation

404-436 Clay, mottled dark reddish-brown, pale red, light olive-brown, medium gray, and light gray, dense, with thin irregular thin lenses and partings of very fine sand and silt, light-gray.

APPENDIX E

Palynological Analysis of the Upper Cretaceous to Lower Tertiary Section from the Magothy Test Well AA-De 100

by

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INTRODUCTION

Twenty-two core samples from 95 feet to 434 feet of well AA-De 100 have been examined for their palynological content. Fourteen samples contained plant microfossils while eight samples were barren of any sporomorphs. The following depth intervals contained plant microfossils:

1. 95-96′	8. 251-252′
2. 117-118′	9. 280-282′
3. 135-136′	10. 300-305′ Top of core
4. 143-144′	11. 300-305′ Bottom of core
5. 193-194′	12. 305-310′
6. 208-212′	13. 354-359′
7. 241-242′	14. 376-382′

The following depth intervals were found to be barren of plant microfossils:

1. 20-21′	5. 170-172′
2. 29-32′	6. 231-232′
3. 53-55′	7. 407-412′
4. 78-79′	8. 433-434′

PALYNOLOGICAL RESULTS

The zonation of this well is done only on a preliminary basis. Research on the vertical changes in the pollen record during the Upper Cretaceous of the Atlantic Coastal Plain is practically nil. I have tentatively been able to distinguish five palynological units in this well.

1. Lower Tertiary
2. Monmouth
3. Matawan
4. Upper Magothy
5. Lower "Magothy"

European stage designations have been made on the rare occurrence of some index types from European works. Further research is needed in order to corroborate these correlations.

The following stratigraphic and age determinations have been made:

Samples
95-96′
Aquia Fm. (Eocene)
117-118′

135-136′ Cretaceous-Tertiary Transition interval (Paleocene)

143-144′
Monmouth (Upper Senonian)
193-194′

208-212′
241-242′ Late Campanian Matawan (Lower Senonian)
251-252′ Early Campanian

280-282′
300-305′ (top)
Upper Magothy (Santonian)
300-305′ (bottom)
305-310′

354-359′
Lower "Magothy"? (Santonian)
376-383′

UPPER CRETACEOUS – LOWER TERTIARY BOUNDARY

Samples above 119′ contain numerous small prolate tricolporate types, with lalongate pores, similar to *Castanea* (Chestnut, plate 1, fig. 11) and several grains of alnoid or *Platycarya* pentaporate types (Plate 2, fig. 34). Typical Cretaceous acritarchs and normapolles for the most part are absent. Abundant *Castanea* types have been reported in the oldest Tertiary of Middle Europe by Krutzsch (1958), in the Eocene, London Clay (Macko, 1963), and by this writer in the Marlboro Clay of Maryland.

I have placed Sample 135-136′ in the lowest Tertiary because *Castanea* and Alnoid types are common. A single grain of *Tetrapollis*, an ulmoid form, was found in sample 135-136′. This form has previously been described from the Middle Paleocene of Central Europe. It is possible that this interval may be Upper Cretaceous as some typically Upper Cretaceous acritarchs (marine microplankton) such as *Pterospermosis ginginensis* and *Palaeotetradinium hyalodermum* occur in this sample.

Sample 143-144′ contains marine microplankton (Plate 1, figs. 4, 10-13) that I have seen to be commonly present in the Red Bank

Formation of New Jersey. I would consider this interval as the highest definitely Cretaceous sample in the core material.

The highest position of *Rugibivesiculites* (a typically Upper Cretaceous bisaccate) was found in sample 208-212′.

Twofold Division of the Marine Upper Cretaceous

It may be possible to establish palynologically an upper and lower unit of the marine Upper Cretaceous corresponding to the Monmouth and Matawan Groups, respectively. In this well the first indication of a lower unit is the increase in *Minorpollis* types, the abundance of *Rugubivesiculites* and the presence of a triporate type with annulate and subequatorial pores (Plate 2, figs. 30-32). Samples from the Navesink Formation (Maestrichian) of New Jersey examined by this author are also sparse in grains of *Rugubivesiculites* as compared to the Merchantville Formation of New Jersey.

Twofold Division of the Magothy in AA-De 100

The Magothy is recognized from core 280-282′ to core 376-383′ by the increase in normapolle types and the lack of marine microplankton.

A lower unit in the Magothy can be recognized by the introduction of small oblate triporates and tricolporates (8-12 microns) and by the presence of *Porocolpopollenites*.

There is a possibility that this unit may be some part of the Upper Raritan, but not enough information is available at this time.

PLANT MICROFOSSIL LISTS

CORE 95-96′

Age Determination: Eocene
Stratigraphic Correlation: Aquia

Plant Microfossils:	Frequency:[1]
Gymnospermae	
Abietineaepollenites sp.	C
Angiospermae	
Pseudo-alnoide type	C
Castanea crenataeformis Samig	A

Discussion:

The abundance of small *Castanea* (chestnut) type pollen and alnoid types is similar to what has been reported from various Eocene deposits of Europe. Abundant *Castanea* types have been found by the writer in samples from the Shark's River Formation (Eocene of New Jersey) and the Marlboro Clay of Maryland.

CORE 117-118′

Age Determination: Eocene
Stratigraphic Correlation: Aquia

Plant Microfossils:	Frequency:
Marine Microplankton	
Pterospermopsis ginginensis Deflandre & Cookson, 1955	R
Gymnospermae	
Tsugapollenites sp.	R
Angiospermae	
Castanea crenataeformis Samig	C

CORE 135-136′

Age Determination: (Paleocene-Danian) Lowermost Tertiary
Stratigraphic Correlation: Brightseat (?)

Plant Microfossils:	Frequency:
Marine Microplankton	
1. Acritarch Type 2 (Plate 1, figs. 12, 13)	C
2. *Palaeotetradinium hyalodermum* (Plate 1, fig. 5)	
3. *Pterospermopsis cf. ginginensis*—Deflandre & Cookson	R
Pteridophyta	
4. *Osmundacidites sp.*	R
5. *Laevigatosporites sp.*	C
6. *Cicatricosisporites sp.*	R
Angiospermae	
7. *Tricolporopollenites sp.* (Castanea type)	C
8. Pseudo-alnoide type	O
9. *Triatriopollenites sp.*	O
10. *Tetrapollis sp.* Ulmus type	R
11. *Piolencipollis cf. piolencensis* Groot & W. Kr	R

Discussion:

This sample contains both Cretaceous types like form no. 2, 3, and 11 and Eocene types - number 1 and 2.

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1 Rare (R) = Less than 1%
Occasional (O) = 1-5%
Common (C) = 6-10%
Abundant (A) = Greater than 10%

Piolencipollis cf. piolencensis was previously described from the Middle to Upper Santonian of Middle Europe (Plate 2, fig. 29).

Pterospermopsis ginginensis Deflandre and Cookson has been found in the Senonian of Western Australia.

CORE 143-144′

Age Determination: Upper Senonian

Stratigrapic Correlation: Monmouth Group

Plant Microfossils:	Frequency:
Marine Microplankton	
Hystrichosphaeridium sp. (Plate 1, fig. 7)	O
Hystrichosphaeridium tuberose type	O
Deflandre sp.	O
Microdinium sp. (Plate 1, figs. 10,11)	C
Acritarch Type 2 (plate 1, figs. 12, 13)	C
Pterospermopsis ginginensis Deflandre and Cookson	R
Pteridophyta	
Camarozonosporites sp. (Plate 2, figs. 1a, 1b)	R
Cicatricosisporites sp.	R
Deltoidospora halii Miner	C
Gymnospermae	
Podocarpidites sp.	O
Pinuspollenites sp.	C
Angiospermae	
Minorpollis sp.	C
Tricolporopollenites sp.	O

CORE 193-194′

Age Determination: Lower Senonian

Stratigraphic Correlation: Lower Matawan

Plant Microfossils:	Frequency:
Marine Microplankton	
Microdinium sp. (Plate 1, figs. 10, 11)	C
Pteridophyta	
Cicatricosisporites sp.	R
Gymnospermae	
Abietineaepollenites sp.	C
Angiospermae	
Tricolporopollenites cf. disjunctus	C
Tricolporate "reticulate type"	R

CORE 208-212′

Age Determination: Lower Senonian

Stratigraphic Correlation: Matawan Group

Plant Microfossils:	Frequency:
Marine Microplankton	
1. *Deflandre sp.*	R
Pteridophyta	
2. *Gleicheniidites sp.*	O
Gymnospermae	
3. *Rugubivesiculites reductus*	A
Angiospermae	
4. *Minorpollis sp.*	C
5. "*Protocarya*" types (plate 2, figs. 30-32)	O
6. *Tricolpopollenites sp.* (psilate)	R

Discussion:

It may be possible to establish palynologically a lower unit of the marine Upper Cretaceous which may represent the Matawan horizon. The change downwell in this sample is represented by an increase in small triporates (*Minorpollis*), the first occurrence of *Rugubivesiculites* and the presence of triporate forms (no. 4) with annulate, subequatorial pores. Only future investigations will demonstrate if this biostratigraphic change will hold horizontally.

CORE 241-242′

Age Determination: Upper Campanian

Stratigraphic Correlation: Matawan Group

Plant Microfossils:	Frequency:
Marine Microplankton	
Micrhystridium sp. (Plate 1, fig. 6)	O
Chlamydophorella cf. hyei Cookson and Eisenack, 1957 (Plate 1, figs. 8, 9)	R
Fromea amphora Cookson and Eisenack, 1958	R
Microdinium sp. (Plate 1, figs. 10, 11)	C
Pteridophyta	
Gleicheniidites sp.	R
Gymnospermae	
Abietineaepollenites microreticulatus	O
Angiospermae	
Minorpollis sp. (Plate 2, figs. 19-22)	C
"*Protocarya*" type (Plate 2 figs. 31, 32)	O
Suemegipollis triangularis Goczan, 1964	R

Discussion:

Because of the common occurrence of

Minorpollis types and the presence of "*Protocarya*" types this sample belongs in the same palynologic zone as Core 208-212', which, as stated above may be characteristic of the Matawan Group in Maryland.

A single grain of *Suemegipollis triangularis* Goczan was found in this sample. In Hungary this form is indicative of the Upper Campanian.

CORE 251-252'

Age Determination: Lower Campanian

Stratigraphic Correlation: Matawan Group

Plant Microfossils:	Frequency:
Marine Microplankton	
Palaeotetradinium hyalodermum (Plate 1, fig. 5)	A
2. *Dinogymnium cf. nelsonense* (Cookson) (Plate 1, fig. 1)	O
Microdinium sp. (Plate 1 figs. 10, 11)	C
Deflandrea sp.	R
Fromia amphora Cookson & Eisenack	
Gymnospermae	
Rugubivesiculites reductus	C
Angiospermae	
Tetracolporopollenites globosus Goczan (Plate 2, fig. 33)	R
Tricolpollenites cf. retiformis Thomson & Pflug	R
Minorpollis sp.	C
Momipites cf tenuipolus Anderson (Plate 2, figs. 23, 24)	O

Discussion:

The age of Lower Campanian is based on the presence of *Tetracolporopollenites globosus*. In Hungary this form is an index for the Lower Campanian. Dinogymnium ranges from Coniacian to Maestrichian; however, most species do not occur above the Campanian.

CORE 280-282'

Age Determination: Santonian

Stratigraphic Correlation: Magothy Fm.

Plant Microfossils:	Frequency:
Pteridophyta	
Rotaspora rugulatus Gray and Groot	R
Laevigatosporites sp.	C
Deltoidospora sp.	C
Gleicheniidites sp.	O
Gymnospermae	
Abietineaepollenites microreticulatus	C
Angiospermae	
Tricolpites sp.	O
Minorpollis sp.	O
Triatriopollenites sp.	R
Tricolporate "reticulate type"-Found in Magothy in New Jersey and Maryland (Plate 2, figs. 14, 15)-*Vitaceae*	
Intratriporopollenites sp.	R
Trudopollis sp. (Plate 2, figs. 26, 27)	O
Liliacidites sp. (Plate 2, figs. 5-7)	VA
Triorites sp. (Plate 2, fig. 25)	R
Tricolpopollenites micromumus types	C
Triporopollenites sp. 2 Groot & Penney (Magothy)	O

Discussion:

Core 280-282' is the first non-marine sample encountered. At this interval until total depth the Normapolles are more varied than above 280 feet. Many species of Normapolles belonging to such genera as *Pecakipollis, Plicapollis, Praebasopollis, Pseudoplicapollis,* and *Semioculopollis* are not found in this well. The large number of varied *Liliacidites* types suggests that perhaps we are seeing here some marginal non-marine facies of the Magothy. This sample contains the greatest variety of *Liliacidites* types.

CORE 300-305' (Top)

Age Determination: Santonian

Stratigraphic Correlation: Upper Magothy Lileaceous facies

Plant Microfossils:	Frequency:
Pteridophyta	
Cicatricosisporites sp.	R
Angiospermae	
Liliacidites sp.	C
Momipites sp.	O
Intratriporopollenites sp. (Magothy type)	R
Sporopollis pseudosporties Pflug, 1953 (Plate 2, fig. 28)	R

CORE 300-305' (Bottom)

Age Determination: Santonian

Stratigraphic Correlation: Upper Magothy

Plant Microfossils:	Frequency:
Pteridophyta	
Deltoidospora sp.	C
Zonalapollenites dampieri	O
Cicatricosisporites sp.	R
Matonisporites sp.	O
Gymnospermae	
Pinuspollenites sp.	C
Rugubivesiculites sp.	C
Abietineapollenites sp.	C
Araucariacites australis	O
Angiospermae	
Liliacidites sp.	C
Minorpollis sp.	O
Tricolpites retuculatus	C
Momipites sp.	O
Tricolpopollenites platyreticulatus Groot P & G	R
Triatriopollenites sp.	C
Sporopollis pseudosporites	R
Tricolporate "reticulate type" (Plate 2, figs. 14,15)	C
Trudopollis sp. (Plate 2, fig. 26)	R

CORE 305-310′

Age Determination: Santonian

Stratigraphic Correlation: Magothy

Plant Microfossils:	Frequency:
Pteridophyta	
Deltoidospora sp.	O
Cicatricosisporites sp.	R
Gymnospermae	
Araucariacidites sp.	C
Zonalapollenites dampieri	R
Rugubivesiculites sp.	A
Angiospermae	
Minorpollis sp.	O

CORE 354-359′

Age Determination: Santonian

Stratigraphic Correlation: Lower Magothy

Plant Microfossils:	Frequency:
Pteridophyta	
Laevigatosporites sp.	C
Gleicheniidites sp.	O
Camarozonosporites	O
Perotriletes sp.	R
Cicatricosisporites sp.	R
Gymnospermae	
Araucariacidites sp.	C
Abietineaepollenites sp.	A
Rugubivesiculites sp.	VA
Podocarpidites sp.	R
Angiospermae	
Tricolpites reticulatus	C
Many small oblate 8-12 micron *Tricolporates* and *Triporates*	C
Liliacidites sp.	O
Tricolporate "recticulate" type (Plate 2, fig. 15)	C
Porocolpopollenites sp. (Plate 2, fig. 16)	O

Discussion:

This sample and core 376-382′ can be distinguished from the Magothy levels above by the introduction of small oblate *tricolporates* and *triporates* (8-12 microns) and by the presence of *Porocolpopollenites*. At this time I am placing these two cores in the Lower Magothy.

CORE 376-382′

Age Determination: Santonian

Stratigraphic Correlation: Lower Magothy

Plant Microfossils:	Frequency:
Pteridophyta	
Aequitriradites spinulosus (Cookson & Dettmann)	R
Camarozonotriletes sp. (Plate 2, fig. 3)	O
Deltoidospora sp.	O
Sphagnumsporites sp.	R
Gymnospermae	
Araucariacites australis	R
Pinuspollenites sp.	C
Rugubivesiculites sp.	C
Angiospermae	
Tricolpites reticulatus	C
Numerous very small oblate *Tricolporates* and *Triporates*	C
Tricolporate "reticulate type" (Plate 2, figs. 14, 15)	C
?Vacuapollis sp.	R
Tricolporate sp. (Plate 2, fig. 10)	O
Porocolpopollenites orbiformis Thomson and Pflug	O

SAMPLE DESCRIPTION: Test Well AA-De 101

CORE (535′)

Age Determination: Albian

Stratigraphic Correlation: Zone II Patapsco Fm.

Appendicisporites potomacensis Brenner

Cingulatisporites sp.

Deltoidospora sp.
Granulatisporites dailyi Cookson
Ephedripites multicostatus Brenner
Classopollis torosus (Reissinger)

The pollen and spore content of this sample is very sparse; however, the presence of *Appendicisporites potomacensis* and *Ephedripites multicostatus* suggests Zone II, Patapsco Formation.

CORE MAGOTHY SAND (358-359')
Barren

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PLATE ONE

(X 1000)

Figure 1. *Dinogymnium cf. nelsonense* (Cookson) (251-252 feet)
2. *Deflandrea sp.*
3. *Pterospermopsis sp.* (135-136 feet)
4. *Pterospermopsis ginginensis* Deflandre and Cookson (117-118 feet)
5. *Paleotetradinium hyalodermum* (251-252 feet)
6. *Micrhystridium sp.* (241-242 feet)
7. *Hystrichosphaeridium sp.*
8.,9. *Chlamydophorella cf. hyei* Cookson and Eisenack, 1957
10.,11. *Microdinium sp.* (241-242 feet)
12.,13. Acritarch Type 2 (135-136 feet)

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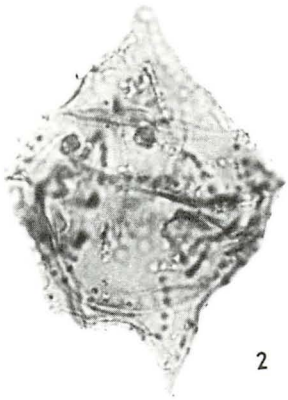
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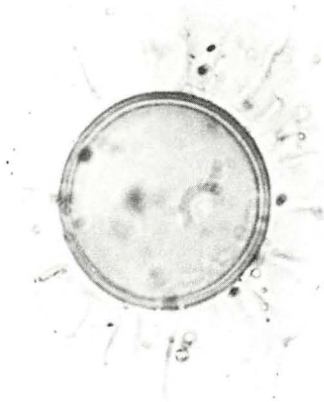
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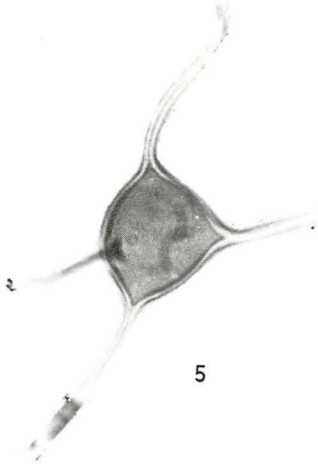
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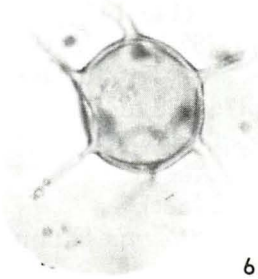
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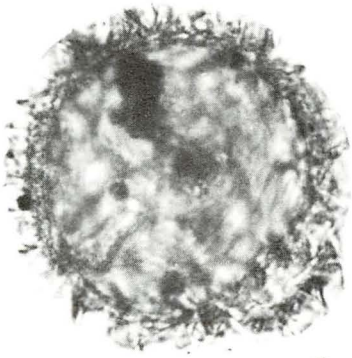
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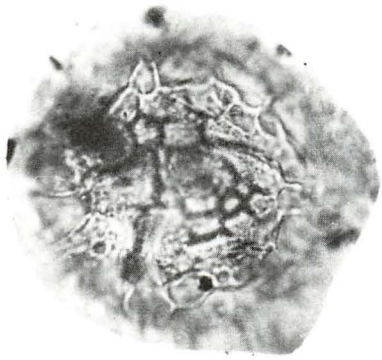
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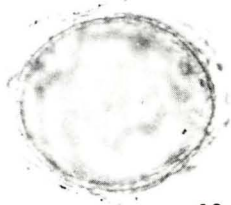
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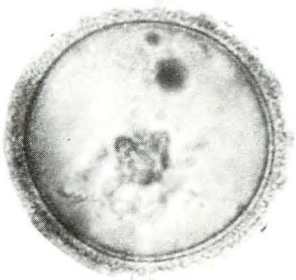
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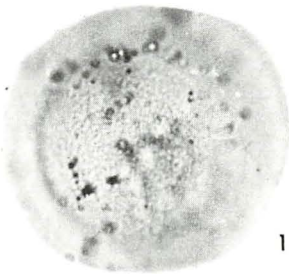
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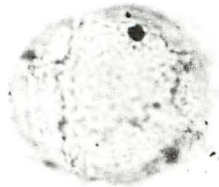
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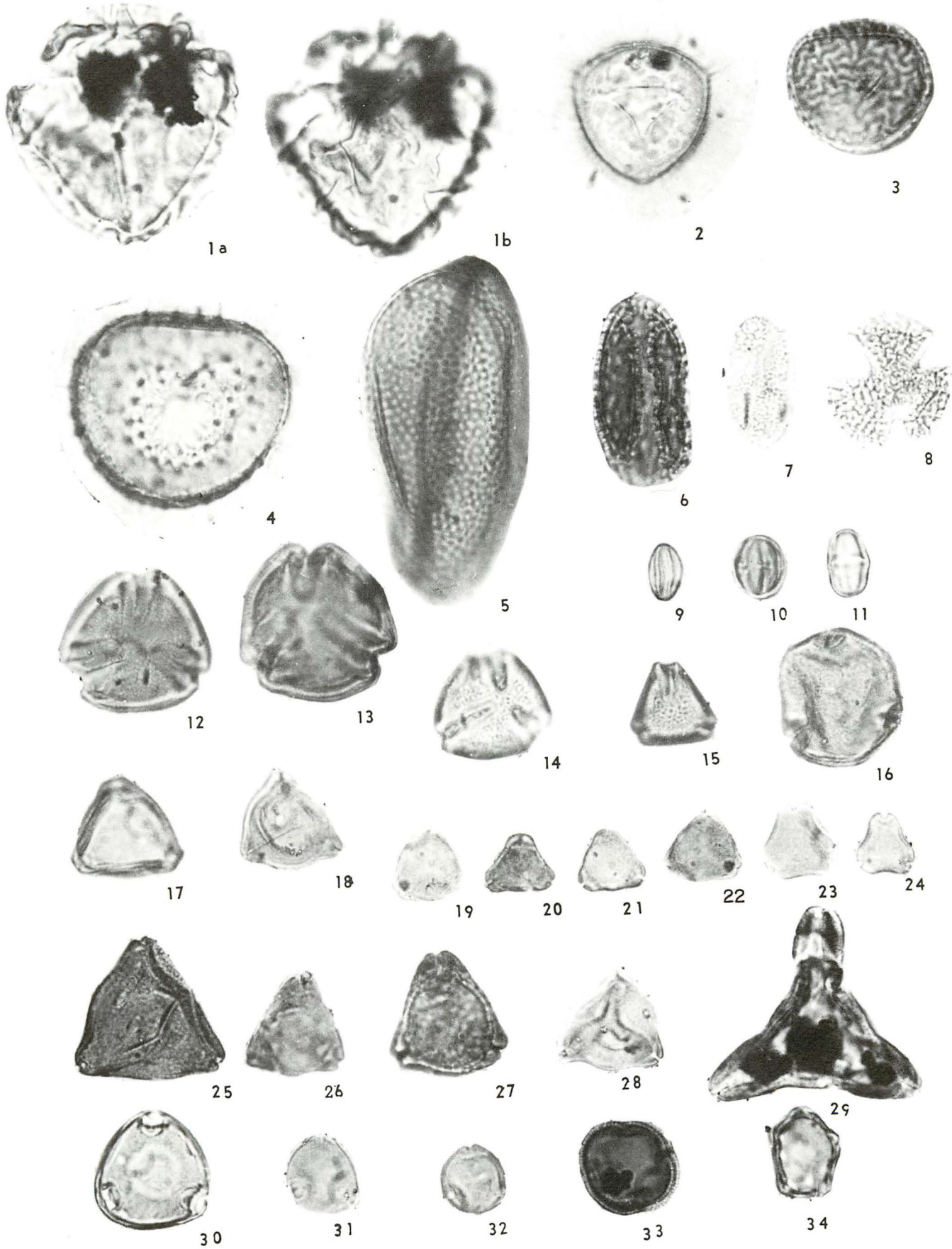
PLATE TWO

(X 1000)

Figure 1a.,1b. *Camarozonosporites sp.* (143-144 feet)
2. *Sphagnumsporites sp.* (376-382 feet)
3. *Camarozonosporites sp.* (376-382 feet)
4. *Aequitriradites sp.* (376-382 feet)
5. Iris type, *Liliacidites sp.* (354-359 feet)
6. *Liliacidites sp.* (280-282 feet)
7. *Liliacidites sp.* (280-282 feet)
8. *Tricolpopollenites cf. retiformis* Thomson and Pfulg (208-212 feet)
9. *Tricolpate sp.*
10. *Tricolporate sp.*
11. *Castanea crenataeformis* Samig (95-96 feet)
12.-15. *Tricolporate* ''reticulate type'' (376-382 feet)
16. *Porocolpopollenites sp.* (376-382 feet)
17. *Sporopollis pseudosporites* Pflug
18. *Triatriapollenites sp.*
19.-22. *Minorpollis sp.* 21, (241-242 feet)
23.,24. *Momipites cf. tenuipolus* Andersn (300-305 feet)
25. *Triorites sp.* (280-282 feet)
26.,27. *Trudopollis sp.* (280-282 feet)
28. *Sporopollis sp.*
29. *Piolencipollis piolencensis* Groot & W. Kr.
30.-32. ''Protocaryoid type'' (208-212 feet)
33. *Tetracolporopollenites globosus* Gozcan (251-252)
34. *Platycarya*-Alnoid Type (95-96 feet)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