Department of Natural Resources
MARYLAND GEOLOGICAL SURVEY
Kenneth N. Weaver, Director

REPORT OF INVESTIGATIONS NO. 38

HYDROGEOLOGY, DIGITAL SIMULATION, AND GEOCHEMISTRY OF THE AQUIA AND PINEY POINT-NANJEMOY AQUIFER SYSTEM IN SOUTHERN MARYLAND

by
Francis H. Chapelle
and
David D. Drummond

Prepared in cooperation with the
Geological Survey
United States Department of the Interior,
the Boards of County Commissioners of
St. Marys and Calvert Counties,
and the
Anne Arundel County Office of Planning and Zoning

1983

CONVERSION OF MEASUREMENT UNITS

The following factors may be used by readers who wish to convert inch-pound units to metric (System International or SI) units.

To convert from	Multiply by	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter (m)
foot per mile (ft/mi)	0.189	meter per kilometer (m/km)
foot per second (ft/s)	30.48	centimeter per second (cm/s)
gallon (gal)	3.785	liter (L)
gallon per day (gal/d)	3.785	liter per day (L/d)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons (Mgal)	3785	cubic meters (M^3)
million gallons per day (Mgal/d)	3785	cubic meters per day (m^3/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

NOTE REGARDING VERTICAL DATUM

The National Geodetic Vertical Datum of 1929, the reference surface to which relief features and altitude data are related, and formerly called "mean sea level," is referred to as "sea level" throughout this report.

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ABSTRACT

The hydrogeology and ground-water geochemistry of the Aquia and Piney Point-Nanjemoy aquifers in Southern Maryland have been investigated. This study was made in order to evaluate the availability and chemical quality of water from this aquifer system.

The Aquia aquifer is Paleocene in age and is a medium- to fine- grained quartz sand. It is highly glauconitic and contains abundant carbonate shell material. The transmissivity of the Aquia ranges from 200 to 2,000 feet squared per day and tends to increase to the northeast along strike. The Aquia is overlain by the Marlboro Clay and lower Nanjemoy Formation which together act as a confining bed. This confining bed ranges from 100 to 250 feet thick and exhibits vertical hydraulic conductivities that range from 10^{-7} to 10^{-10} feet per second. In 1980, approximately 6 million gallons of water per day was produced from the Aquia aquifer in Southern Maryland. Several cones of depression ranging from 20 to 80 feet below sea level have developed in response to this pumping stress.

The Piney Point-Nanjemoy aquifer is Eocene in age and is a coarse- to fine-grained glauconitic quartz sand which contains abundant carbonate shell material. The transmissivity of the Piney Point-Nanjemoy aquifer ranges from 100 to 500 feet squared per day. The Piney Point-Nanjemoy is overlain by Chesapeake Group sediments which act as a confining bed. This confining bed ranges from 150 to 250 feet thick and exhibits vertical hydraulic conductivities which range from 10^{-7} to 10^{-10} feet per second. In 1980, approximately 2 million gallons of water per day was produced from the Piney Point-Nanjemoy aquifer in Southern Maryland.

Hydrogeologic information including water levels, altitude of top, thickness, and transmissivity of the Aquia and Piney Point-Nanjemoy aquifer system is presented as a series of maps. Hydrogeologic information such as thickness, vertical hydraulic conductivity, and specific storage of confining beds is also presented. This information combined with geologic cross sections obtained during bridge construction across the Chesapeake Bay and the Patuxent River demonstrate that Pleistocene river channels have in places truncated aquifers and confining beds. This erosional truncation is a major control on the natural head distribution of the Aquia and Piney Point-Nanjemoy aquifer system.

A quasi three-dimensional digital model of this aquifer system was constructed. The Aquia and Piney Point-Nanjemoy aquifers were modeled as confined aquifers separated by semipermeable confining material. Recharge to these aquifers was considered to occur by leakage from the overlying Pleistocene water-table aquifer. The pumping history of the aquifer system was simulated from 1890 to 1980 during model calibration. The model was calibrated by adjusting the vertical hydraulic conductivity of confining beds and matching calculated water levels to measured water levels. Recharge rates to the aquifer system during the simulated pumping history varied from 0.22 to 0.57 inches per year. Simulations with the calibrated model indicate that the aquifer system can sustain the 1980 rates of pumpage to the year 2000 with water-level declines of about 0.5 feet per year in the Aquia aquifer. Simulations that increase pumpage according to projected population growth predict water-level declines on the order of 1.5 feet per year in the Aquia aquifer to the year 2000. A simulation which assumes that all holders of Gound-water Appropriation Permits pump their maximum allocation for 10 years predicts water-level declines of 8 feet per year near Lexington Park and Piney Point in southern St. Marys County, Maryland.

The principles of equilibrium chemistry were utilized to investigate the ground-water geochemistry of the Aquia and Piney Point-Nanjemoy aquifers. Trends of calcium, magnesium, sodium, and bicarbonate concentrations plotted versus distance along the flowpath delineate three regions in the aquifers where different patterns of concentration changes occur. Chemical models were constructed and tested for each region to account for the observed changes in water chemistry. Mass balance calculations based on the verified models suggest that observed calcite cementation of the Aquia aquifer is post-depositional and has resulted from the reaction of ground water with aquifer material.

INTRODUCTION

Purpose and Scope

An adequate supply of fresh water for use in households, industry, and agriculture is an important factor in the economic well being of all communities. Many regions in the United States rely on surface-water reservoirs such as natural lakes, artificial lakes, or rivers for fresh-water supplies. In Southern Maryland, the extensive use of surface water is not feasible due to the brackish nature of most surface-water bodies. Southern Maryland, therefore, has come to rely on ground water for most of its water needs. The Aquia and Piney Point-Nanjemoy aquifers of Paleocene and Eocene age respectively are two major sources of fresh ground water. The Aquia aquifer is used in conjunction with deeper Cretaceous aquifers in Anne Arundel, Prince Georges, and Charles Counties. In St. Marys and Calvert Counties, the Aquia and Piney Point-Nanjemoy aquifers are the principal sources of potable water.

Since the first artesian wells were drilled in Southern Maryland at the end of the 19th century, the use of ground water has increased rapidly. This increased pumpage has caused widespread declines of water levels in many aquifers. Proper management of ground-water resources in future years will require an adequate understanding of available aquifers. The purpose of this report is to provide county planners, elected officials, builders, contractors, engineers, well drillers, and individual citizens with information on the availability and chemical quality of ground water from the Aquia and Piney Point-Nanjemoy aquifers.

The first section of this report deals with the physical geology and hydrogeology of the Aquia and Piney Point-Nanjemoy aquifer system. Information on aquifer and confining-bed stratigraphic relationships, thickness, depth, areal distribution, lithology, and water levels has been assembled and presented. This information will be useful to engineers, geologists, and well drillers interested in the practical aspects of siting and constructing wells. This section includes information on the Aquia and Piney Point-Nanjemoy aquifers which has previously been scattered among many reports.

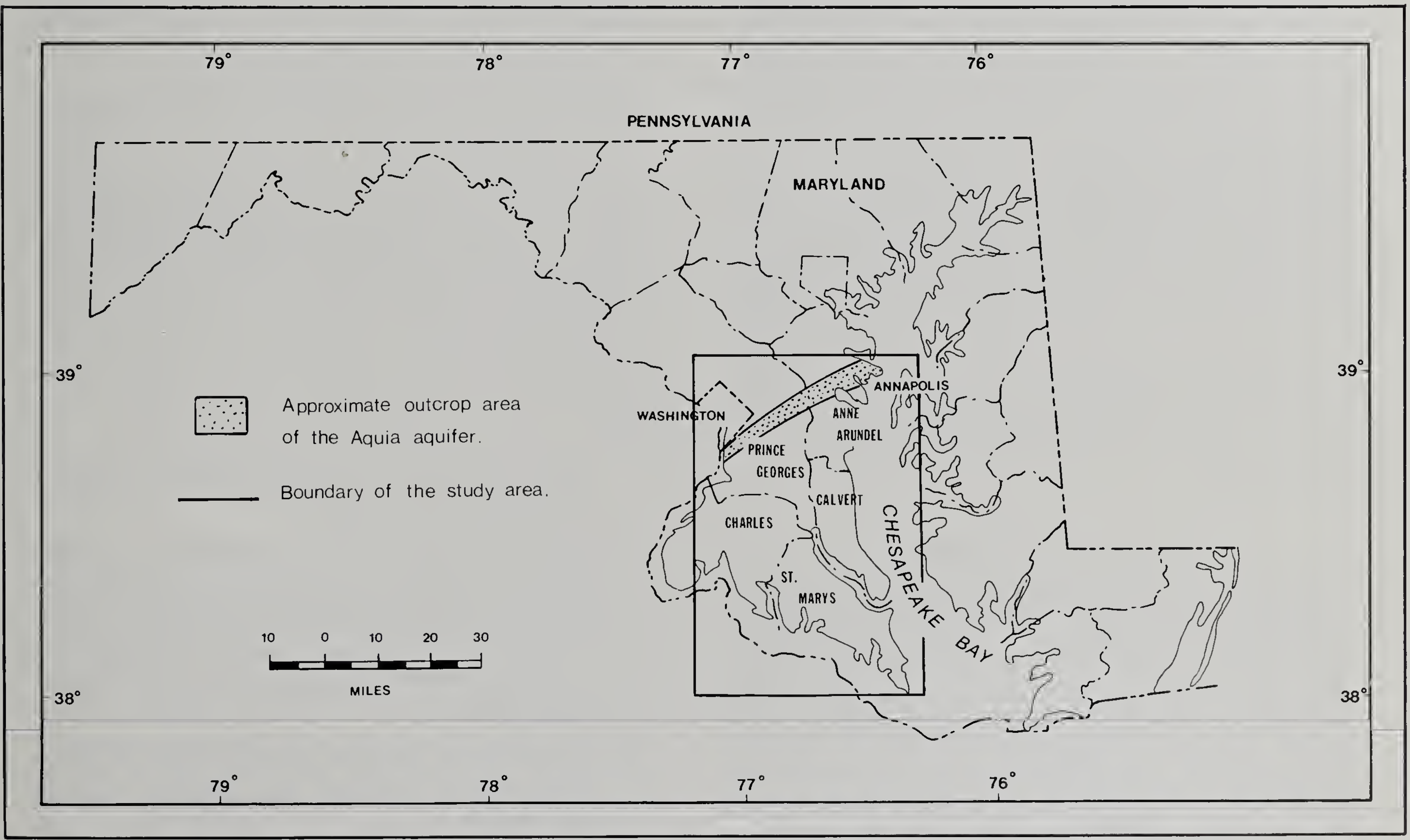


Figure 1.—Location of study area and boundary of modeled area.

The second section describes a quantitative evaluation of the future availability of water from the Aquia and Piney Point-Nanjemoy aquifers in Southern Maryland, using a three-dimensional digital model. This technique was chosen because it has been shown that a properly calibrated digital model can predict the water-level response of an aquifer system to expected rates of future pumpage with a fair degree of accuracy. These predictions can be of great value to water planners in deciding on future sources of water.

The third section describes the ground-water geochemistry of the Aquia and Piney Point-Nanjemoy aquifers. The chemical quality of ground water is an important consideration in the management of an aquifer system. This chemical quality results from the chemical reaction of recharge water with gases and minerals in the aquifer. An understanding of these chemical processes will aid in the management of the aquifers and contribute to an understanding of the system as a whole.

Location and Extent of the Study Area

Southern Maryland lies within the Atlantic Coastal Plain physiographic province. This province, which extends from South Carolina to New York, is characterized by generally low topography. The Atlantic Coastal Plain is underlain by predominantly unconsolidated clastic sediments of Lower Cretaceous to recent age, which thicken to the southeast.

The project area is shown in figure 1. The area includes the southern half of Anne Arundel County and all of Calvert and St. Marys Counties. The boundary of the digital model is also shown in figure 1. The area modeled was considerably larger than the project area in order to simulate the lateral extent and distant boundaries of the Aquia and Piney Point-Nanjemoy aquifers. Included in the model are Anne Arundel, Prince Georges, Charles, St. Marys, Calvert, Dorchester, Talbot, Caroline and Queen Annes Counties.

Methods of Investigation

The first phase of this study was to define the hydrogeologic framework of the Aquia and Piney Point-Nanjemoy aquifer system in Southern Maryland. Data were collected for the topography and stratigraphy of Southern Maryland and the Eastern Shore; depth to top, thickness, physical boundaries, and historical water levels of the aquifers; and areal distribution and thickness of the confining beds.

Some of this information was available from previously published reports. However, much had to be gathered in the field. This fieldwork consisted of:

1. Establishing an observation-well network in Southern Maryland and on the Eastern Shore for both the Aquia and Piney Point-Nanjemoy aquifers. This network included a total of 160 wells. Fifteen observation wells were drilled for this project where water levels were not otherwise available.
2. Obtaining geologists' logs and geophysical logs of 15 new observation wells.
3. Obtaining undisturbed cores of confining-bed material for laboratory determination of confining-bed vertical hydraulic conductivity.
4. Obtaining aquifer-test data.
5. Obtaining pumpage information from users of greater than 5,000 gal/d.

The second phase was to construct and calibrate a three-dimensional digital model of the Aquia and Piney Point-Nanjemoy aquifer system in Southern Maryland. This was done by:

1. Developing a finite-difference grid.
2. Collecting information on the areal extent, transmissivity, and storage coefficient of the Aquia and Piney Point-Nanjemoy aquifers.
3. Translating potentiometric, transmissivity, and confining-bed thickness maps into computer-manipulatable data sets.
4. Calibrating the digital model using historical pumpage and water levels.

The calibrated model was then utilized to predict water-level changes resulting from several senarios of future pumpage. These pumping senarios are designed to aid water planners in making water-management decisions.

The third phase was to describe the ground-water geochemistry of the Aquia and Piney Point-Nanjemoy aquifers. Methods used included:

1. Collecting available chemical data on the Aquia and Piney Point-Nanjemoy aquifers from published sources.
2. Graphing sodium (Na^+), calcium (Ca^{2+}) and magnesium (Mg^{2+}), and bicarbonate (HCO_3^-) concentrations versus distance along the flowpath. These plots illustrate water chemistry changes as water moves down the hydrologic gradient.
3. Constructing chemical models based on simplified aquifer lithology and idealized mineral composition.
4. Testing the chemical models by matching model predictions to observed data.

Previous Investigations

The Paleocene-Eocene aquifers in Maryland were first described by Darton (1891), who considered them to be a thick undivided unit called the "Pamunkey Formation." The Pamunkey was later elevated to Group status and subdivided to include the Aquia Formation, the Nanjemoy Formation and the Marlboro Clay Formation (Clark and Martin, 1901). The water resources of these formations were discussed in detail for each county in Southern Maryland by Dryden and Overbeck (1948), Bennion and Brookhart (1949), Cook and others (1952), and Martin and Ferguson (1953). The ground-water resources of Southern Maryland were described by Otton (1955), who first applied the name "Piney Point Formation" to the coarse sands of Eocene age that overly the Nanjemoy Formation in Southern Maryland. Back (1966) described the regional ground-water geochemistry of the Aquia and Nanjemoy aquifers. Glaser (1968,1971) provided a comprehensive discussion of the geology of the Coastal Plain sediments in Southern Maryland. Weigle and others (1970) constructed several hydrologic maps of Southern Maryland. Mack and others (1971) discussed the Aquia and Piney Point aquifers on the Eastern Shore of Maryland. Hansen (1972) contributed a guide to the aquifers of Maryland's Coastal Plain with emphasis on the practical use of these aquifers. Hansen (1974) interpreted the depositional environments of the Aquia Formation. Kapple and Hansen (1976) constructed a two-dimensional digital flow model of the Aquia Formation in Southern Maryland. Mack (1976) collected geohydrologic data on the Aquia Formation from several wells drilled at Chalk Point in Prince Georges County. Lucas (1976) collected well data for Anne Arundel County. Similar data were compiled for Calvert and St. Marys Counties by Weigle and Webb (1970) and Drummond (in preparation). Hansen (1977) catalogued data from two core holes in Prince Georges County and Queen Annes County. Woll (1978) provided many chemical analyses of water for Maryland. Williams (1979) constructed a two-dimensional digital fow model of the Piney Point aquifer in Southern Maryland and on the Eastern Shore of Maryland.

Acknowledgments

Financial support for this project was provided by the Maryland Geological Survey, St. Marys County, Calvert County, and Anne Arundel County in cooperation with the U.S. Geological Survey.

The authors wish to thank the officials of the Patuxent Naval Air Test Station and the St. Marys County Metropolitan Commission for their aid and full cooperation in this project. Thanks are also extended to the planning departments of St. Marys, Calvert, and Anne Arundel Counties for their cooperation.

Special thanks are extended to Joe Gribble and Paul Kanarr of the Calvert Well Drilling Company for informative discussions on drilling and completing wells. The authors also wish to acknowledge the help and support of Harry J. Hansen of the Maryland Geological Survey, and LeRoy L. Knobel of the U.S. Geological Survey. Tracey M. Curley of the U.S. Geological Survey helped extensively with the preparation of the illustrations for this report and her efforts are greatly appreciated. This report was typed and edited by Sheryl Protani. Her thoroughness and patience are gratefully acknowledged.

GEOLOGY

Regional Geologic and Stratigraphic Framework

The sediments that make up the Coastal Plain physiographic province in Southern Maryland consist of unconsolidated clay, silt, sand, and gravel beds, which dip gently to the southeast. These sediments crop out in a concentric band that lies parallel to the Fall Line. The Fall Line marks the western boundary of the Coastal Plain. The Coastal Plain sediments are underlain by Precambrian and Paleozoic gneiss, schist, and gabbroic rocks, which are usually referred to as "basement" rocks. The surface of the basement rocks underlying Southern Maryland has been downwarped into a structure termed the "Salisbury Embayment" (Richards, 1948).

The Salisbury Embayment is part of a much larger regional basement structure called the Chesapeake-Delaware Embayment (Murray, 1961). This structure, which is prominent in the basement rocks, loses form in the younger Coastal Plain sediments. Southern Maryland occupies a south-central position on the Chesapeake-Delaware Embayment.

Table 1.—Generalized stratigraphy of Southern Maryland

System	Series	Stratigraphic unit		Thickness (feet)	Dominant lithologic character	Water-bearing properties
Quaternary and Tertiary (?)	Holocene Pleistocene Pliocene (?)	Lowland and upland deposits		0-190	Sand, gravel, and silt; tan to rusty orange; predominantly quartz.	Yields small to moderate amounts of water to wells. Utilized primarily as a water source for shallow, domestic, and farm wells. The upper recharging water-table aquifer to the Aquia and Piney Point-Nanjemoy aquifers in southern Maryland.
Tertiary	Miocene	Chesapeake Group	St. Marys Formation	0-80	Clay, sandy, silty; greenish-blue to yellow; fossiliferous.	Functions as a confining bed.
			Choptank Formation	0-60	Clay, silty; olive-green to gray; fossiliferous.	Functions as a confining bed.
			Calvert Formation	0-180	Clay, silty; olive-green to gray; fossiliferous; lower member is diatomaceous and contains phosphatic pebbles.	Functions as a confining bed.
	Eocene	Piney Point Formation		0-80	Sand; grayish-green to grayish-white; medium- to coarse-grained; quartz is most common mineral; glauconitic; calcite-cemented shell beds common.	Important source of water in southern Calvert and St. Marys Counties. Hydraulically connected to the upper sandy portion of the Nanjemoy Formation.
		Nanjemoy Formation		0-250	Sand, silt, clay; blackish-green to gray; quartz most common mineral; glauconitic; the upper portion of formation is predominantly sand; the lower portion is predominantly silt and clay.	The upper sandy portion is an important source of water in Calvert and St. Marys Counties and is hydraulically connected to the overlying Piney Point Formation. The lower portion of the formation functions as a confining bed.
	Paleocene	Marlboro Clay Formation		0-35	Clay, pinkish-red to silvery-gray; very plastic; thin lenses of pale gray silt.	Functions as a confining bed.
		Aquia Formation		0-230	Sand, greenish-black; quartz most common mineral; glauconitic; lenses of silty-clay and shell beds common; calcite cementation common.	A primary source of water in southern Anne Arundel County and in St. Marys and Calvert Counties. An important source of water in southern Charles and Prince Georges Counties.
		Brightseat Formation		0-40	Silt, clayey; gray to dark gray; micaceous.	Functions as a confining bed.
Cretaceous	Upper Cretaceous	Severn and Magothy Formations, undifferentiated		350-1,700	Silt, sand, clay, interbedded.	Magothy is a primary water source in northern Anne Arundel County, but is not present in southern Calvert or St. Marys Counties. Severn and Matawan function as confining beds.
	Lower Cretaceous	Patapsco, Arundel, and Patuxent Formations, undifferentiated		300-2,500	Silt, sand, clay, gravel interbedded.	Yields large amounts of water in Charles, Prince Georges, and northern Anne Arundel Counties. Untested in southern Calvert and St. Marys Counties.
Paleozoic and Precambrian		Crystalline rocks (basement)		Unknown	Complex assemblage of schists, granites, gneisses, and gabbros.	Untested.

The wedge of sediments that make up the Coastal Plain of Maryland consists of beds ranging from Jurassic(?) to Holocene in age. This report is directed primarily to those sediments that range in age from Paleocene to Quaternary.

Plates 1 and 2 show cross sections of the idealized lithology, thickness, and distribution of the major Tertiary and Quaternary hydrogeologic units in Southern Maryland. The generalized stratigraphy of Southern Maryland is shown in table 1.

Topography

Southern Maryland is characterized by hilly, terraced upland areas which contrast markedly with the low flat-lying areas of Maryland's Eastern Shore. Where upland areas have been dissected by streams, valley walls are often steep and local relief of 100 ft is common. The valleys of major streams, such as the Patuxent and Potomac Rivers, are characterized by a system of well-marked gravel and loam-covered terraces which have been studied by Hack (1955). As these major rivers approach the Chesapeake Bay, their valleys tend to become broader and there is a general lowering of topographic relief.

The distinctive upland topography of Southern Maryland has developed in response to the repeated steepening and flattening of stream gradients which has accompanied fluctuations in sea level (Glaser, 1968). Hack (1957) has shown that a river system existed during Pleistocene time which approached equilibrium with a sea level 300 to 400 ft below the present sea level. At the close of Pleistocene time, the rising sea submerged much of this river system creating the Chesapeake Bay estuary.

Aquia Formation

Lithology

The Aquia Formation in the subsurface consists of a medium-to coarse-grained, medium-to well-sorted glauconitic-quartz sand. Carbonate shell debris is abundant and, in places, makes up approximately 20 percent of the aquifer material. The usual percentage of shell material, however, is between 1 and 5 percent. Quartz sand grains, which make up 50 to 75 percent of the aquifer material, are often angular to subangular and frequently exhibit goethite staining. Some grains are also characterized by a high polish. Glauconite, a hydrous iron-bearing aluminum silicate, typically makes up 20 to 40 percent of the aquifer material. Glauconite occurs in sand-sized grains that are usually fine to medium in size. Subspherical grains or botryoidal masses of subspherical grains are also commonly observed.

Although the Aquia is predominantly sand, some zones occur which contain significant quantities of clay and silt-sized particles. X-ray defraction analyses of this fine-grained fraction show that the clay mineralogy is mostly of the mixed-layer type (Hansen, 1977).

The heavy mineral suite identified in the Aquia includes hornblende, tourmaline, epidote, andalusite, sillimanite, garnet, zircon, ilmenite, and magnetite. Ilmenite and magnetite are the most commonly observed heavy minerals.

The lithologic character of the Aquia Formation in outcrop differs markedly from that of the subsurface. In outcrop, the Aquia appears rusty or orange-red as opposed to a dark green in the subsurface. Shell material in outcrops is severely leached and ledges of goethite-cemented sand are common. Wolff (1967) presents a detailed X-ray analysis of these goethite ledges and nodules in Anne Arundel County near Annapolis, Md., and concludes that they result from the weathering of glauconite.

Stratigraphy

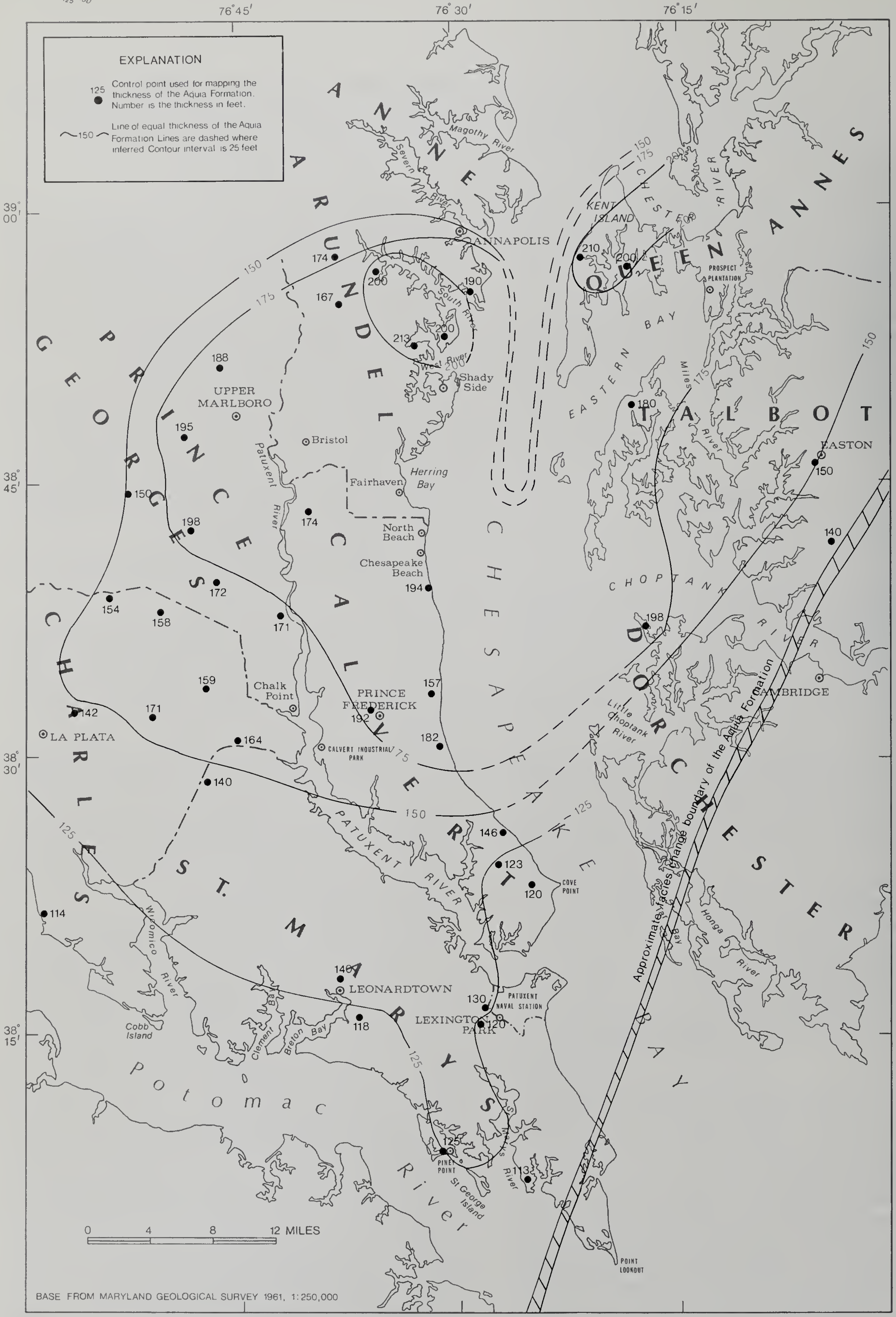
The Aquia Formation crops out in a band extending from the Potomac River near Washington, D.C., through Anne Arundel County near the Chesapeake Bay Bridge. This outcrop (fig. 4), which is often mantled by younger Pleistocene sediments, ranges in width from about 2 mi near the Potomac River to 9 mi in southern Prince Georges County.

The Aquia Formation has been interpreted by Glaser (1968) and Hansen (1974) as having been deposited in a regressive marine environment. The basal sediments are typically fine-grained suggesting deposition in the sublittoral zone (about 300 ft of water). The upper sections are considerably coarser reflecting sand deposition in a higher-energy, shallower environment.

The Aquia Formation near the Potomac River unconformably overlies the Upper Cretaceous Severn Formation. To the east, however, it overlies the Brightseat Formation of Paleocene age either conformably or with a minor unconformity (Glaser, 1968). The Aquia is overlain conformably throughout Southern Maryland by the Marlboro Clay Formation.

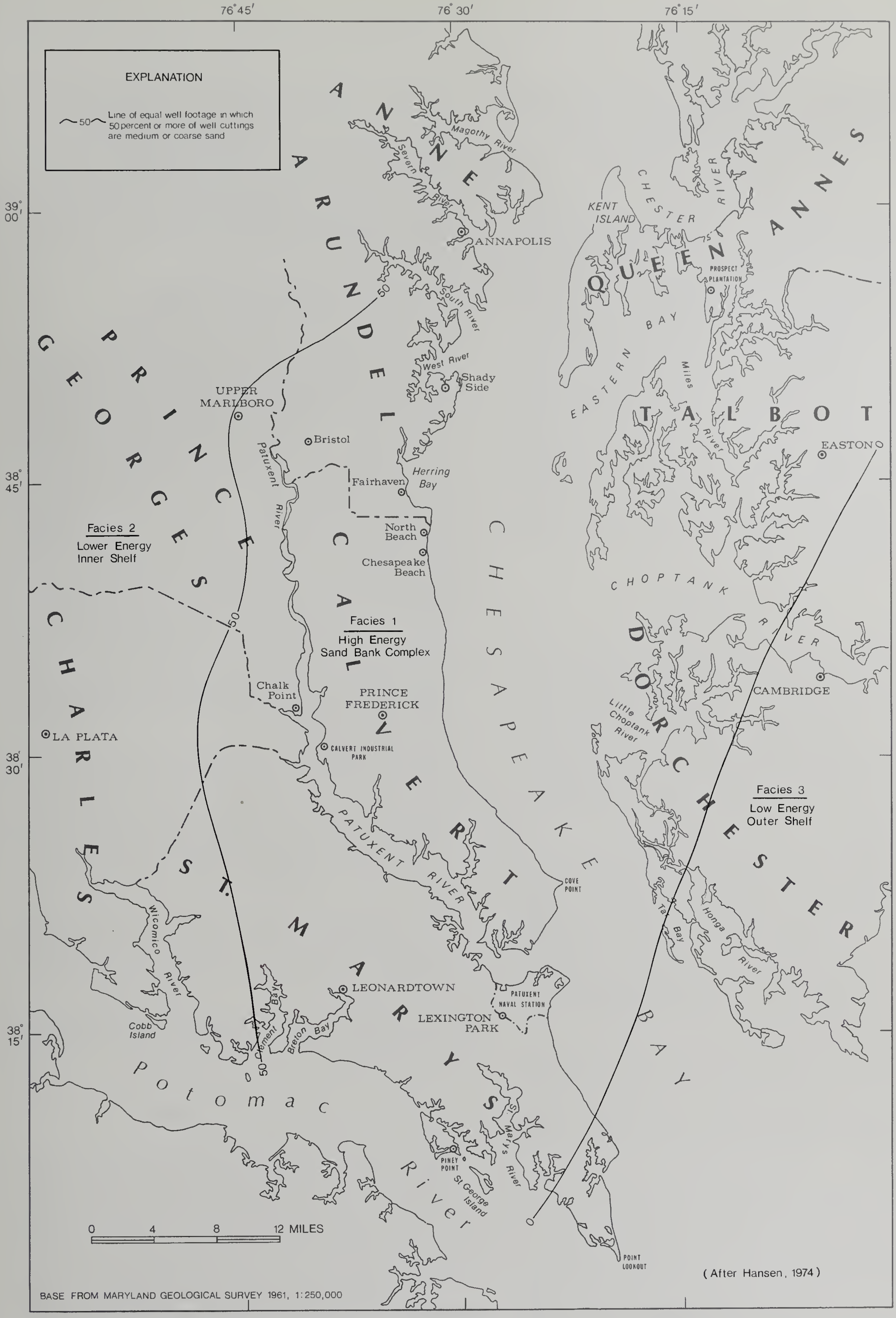
In outcrop, the thickness of the Aquia ranges from 90 ft near the Potomac River to approximately 150 ft in Anne Arundel County. The subsurface thickness of the Aquia as defined by well logs shows a similar pattern of increasing thickness to the northeast and thinning to the southwest. The thickness of the Aquia Formation in Southern Maryland is shown in figure 2.

Hansen (1974) identified three sedimentary facies in the subsurface of the Aquia on the basis of coarse and medium sand percentage of the formation. These facies are shown in figure 3. Facies 1 is a coarse sand that extends from Kent County to the Potomac River. Facies 2 is a fine silty sand which occurs primarily in Charles and eastern Prince Georges County. Facies 3 is a thin predominantly clay-silt facies that underlies the extreme southern tip of St. Marys County and extends to the northwest across the Chesapeake Bay. It is not clear which facies of the Aquia are present across the Potomac River in the Northern Neck Peninsula of Virginia. However, the best available information (Teifke, 1973) suggests that the Aquia in eastern part of Northern Neck is the equivalent of facies 3. In the vicinity of the Aquia Formation type section in Virginia, the formation is a fine, poorly sorted, silty sand (Drobnyk, 1965).



BASE FROM MARYLAND GEOLOGICAL SURVEY 1961, 1:250,000

Figure 2.—Thickness of the Aquia Formation.



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(After Hansen, 1974)

Figure 3.—Sedimentary facies of the Aquia Formation.

The subsurface relationships of the Aquia Formation to other Tertiary and Quaternary sediments in Southern Maryland are shown on plates 1 and 2.

Structure

The subsurface structure of the Aquia Formation in Maryland is shown in figure 4. The distinctive bend along a northwest-trending axis in southern Calvert County has been interpreted by Hansen (1974) as reflecting the deeper basinal patterns of the Chesapeake-Delaware Embayment. The dip of the Aquia ranges from approximately 10 ft/mi in St. Marys County to 20 ft/mi in Queen Annes County.

Hansen (1974) has pointed out an oblique structural relationship between the outcrop belt and several lithofacies trends in the Aquia. He suggests that the present structural strike of the Aquia Formation is different from the structural strike during Aquia deposition. This may indicate some slight post-depositional tilting.

Marlboro Clay

The Marlboro Clay, which overlies the Aquia Formation, is a pink to silver-gray plastic clay. X-ray analyses show that it is composed predominantly of kaolinite and mixed-layer clays with minor amounts of montmorillonite (Hansen, 1977). Thin lenses of silt generally less than an inch thick are common in the Marlboro. Lignite and thin lenses of glauconite sand have been reported from some localities (Glaser, 1968).

The Marlboro Clay has been interpreted as representing a very shallow, probably brackish water environment which followed the marine regression of Aquia time (Glaser, 1968). Burrows and other shallow-water features are commonly observed in the Marlboro and these are consistent with that interpretation. Microfossil data from the Marlboro indicate that it is Paleocene in age (Reinhardt and others, 1980).

The Marlboro Clay ranges in thickness from about 30 ft in Prince Georges and Anne Arundel Counties to less than 5 ft in parts of southern St. Marys County and southern Charles County. The Marlboro Clay has not been identified on the Eastern Shore of Maryland.

Darton (1948), who originally named the Marlboro Clay, assigned it as a member of the Nanjemoy Formation. Glaser (1968) pointed out that the Marlboro is lithologically distinct from overlying and underlying sediments, that it is thick enough to be mapped, and that it is areally extensive. For these reasons, Glaser (1968) proposed formational status for the Marlboro Clay. Reinhardt and others (1980), in agreement with Glaser (1968), have also given formational status to the Marlboro Clay. This report, therefore, will follow that convention.

The subsurface relationships of the Marlboro Clay Formation with other Tertiary and Quaternary sediments in Southern Maryland are shown on plates 1 and 2.

Nanjemoy Formation

The Nanjemoy Formation overlies the Marlboro Clay throughout Southern Maryland. The lower part of the Nanjemoy is an olive-green glauconitic silty clay. Some thin beds of glauconitic quartz sand 1 to 5 ft thick occur in the lower Nanjemoy, but they do not apear to be laterally extensive. The Nanjemoy Formation tends to coarsen upward. The upper part of the Nanjemoy is commonly a glauconitic medium-sorted fine quartz sand. Glauconite typically makes up 30 to 50 percent of the formation in the upper sandy portion. The upper sandy portion of the formation tends to become thinner toward the north. In southern Anne Arundel County, sand beds cannot be distinguished in the Nanjemoy Formation by geophysical logs. It is possible that this updip thinning of the upper sandy portion is due to a partial erosional truncation during the Oligocene withdrawal of the sea.

Hansen (1972) has interpreted the Nanjemoy as representing regressive marine sedimentation during Eocene time. According to this interpretation, the lower clay and silt beds were deposited in deep water. The upper sandy portion was deposited in a progressively shallower, higher energy environment.

The Nanjemoy Formation ranges in thickness from about 100 ft in Charles County to about 250 ft in northern St. Marys County and central Calvert County.

The subsurface relationship of the Nanjemoy Formation with other Tertiary and Quaternary sediments is shown on plates 1 and 2.

Piney Point Formation

The Piney Point Formation conformably overlies the Nanjemoy Formation in much of Southern Maryland. The Piney Point is grayish-white medium to coarse slightly glauconitic quartz sand. The Piney Point is readily distinguished from the underlying sand beds of the Nanjemoy Formation by its relative coarseness and by its much lower content of glauconite. Glauconite in the Piney Point generally makes up less than 5 percent of the forma-

Figure 4.—Altitude of the top and outcrop/subcrop area of the Aquia Formation.

tion. Beds of calcite-cemented sand and shell beds are very common in the Piney Point Formation.

Hansen (1972) has interpreted the Piney Point as having been deposited during a regressive marine episode, possibly by longshore currents. Upward coarsening of the Piney Point has been noticed by many workers and is probably due to shoaling during a seaward shift of the strandline.

The Piney Point Formation has been truncated in updip areas by erosion which occurred during the Oligocene-Miocene withdrawal of the sea. Because of this truncation, the Piney Point Formation does not crop out in Southern Maryland. In the subsurface, the Piney Point is not present northwest of a line that runs from Leonardtown in St. Marys County through Prince Frederick in Calvert County. Subsequent to the Oligocene-Miocene disconformity, the Piney Point was buried by Chesapeake Group sediments during the following Miocene marine transgression.

Chesapeake Group

The Chesapeake Group in ascending order consists of the Calvert, Choptank, and St. Marys Formations of Miocene Age. The Calvert Formation is a fossiliferous, slightly sandy greenish-gray silty clay. The lower part of the Calvert is a distinctive diatomaceous earth. Dark gray phosphatic pebbles and quartz sand have been reported at its base at some localities. The Calvert disconformably overlies the Piney Point in southern Calvert and St. Marys County. In northern Calvert County, where the Piney Point Formation has been truncated, the Calvert disconformably overlies the Nanjemoy Formation. (See pls. 1 and 2.)

The Choptank Formation is a gray-green clay with some yellowish-brown sand. The Choptank is fossiliferous in places and is well exposed along the Calvert Cliffs.

The St. Marys Formation is a dense, bluish-gray clay with some fine clayey sand. This sand, where present, is frequently glauconitic. Calcite-cemented sandstone beds are common in this unit.

The total thickness of Chesapeake Group sediments varies from about 175 ft to about 275 ft. In the subsurface, it is difficult to distinguish the formations of the Chesapeake Group from each other. For this reason, these sediments will be referred to collectively as the Chesapeake Group throughout this report. The subsurface relationships of the Chesapeake Group with other Tertiary sediments are shown on plates 1 and 2.

HYDROGEOLOGY

Aquia Aquifer

Regional Extent

The Aquia Formation is extensively tapped for fresh ground water in Anne Arundel, Calvert, and St. Marys Counties. It is used to a lesser extent in Charles and Prince Georges Counties. On the Eastern Shore of Maryland, the Aquia Formation is tapped in Queen Annes, Kent, and Talbot Counties (fig.1). Across the Potomac River in Virginia, the Aquia is not widely used as a source of water.

Generally, the Aquia Formation is most productive in facies 1 (fig. 3). Facies 1 is typically a thick, medium to coarse sand and has the highest permeability. Facies 2 (fig. 3) is also tapped. However, due to the higher silt content and the finer-grained sand, it is not as productive as facies 1. Facies 3, which consists predominantly of silt and clay, is not an aquifer.

In this report, the term "Aquia aquifer" refers to those portions of the Aquia Formation that can be utilized to yield ground water. This includes facies 1 and 2, and excludes facies 3.

Transmissivity and Storage Coefficient

Transmissivity is defined as the rate at which water is transmitted through a unit width of aquifer under a unit hydraulic gradient (Lohman and others, 1972). Transmissivity is closely related to the thickness of an aquifer. Generally, the thickest part of an aquifer is the most transmissive. However, as has been pointed out by Williams (1979), local calcite cementation or other lithologic inhomogeneities make a direct correlation between aquifer thickness and transmissivity unfeasible. In practice, therefore, the transmissivity of an aquifer is often determined by analyzing pumping test information using the Theis non-equilibrium equation (Theis, 1936). Transmissivities obtained by this method, however, are subject to many assumptions and simplifications and should be considered approximations rather than exact.

Figure 5 shows the transmissivity distribution of the Aquia aquifer as determined by aquifer tests. A comparison of this transmissivity distribution (fig. 5) with aquifer thickness (fig. 2) shows that the thickest part of the aquifer is also the most trans-

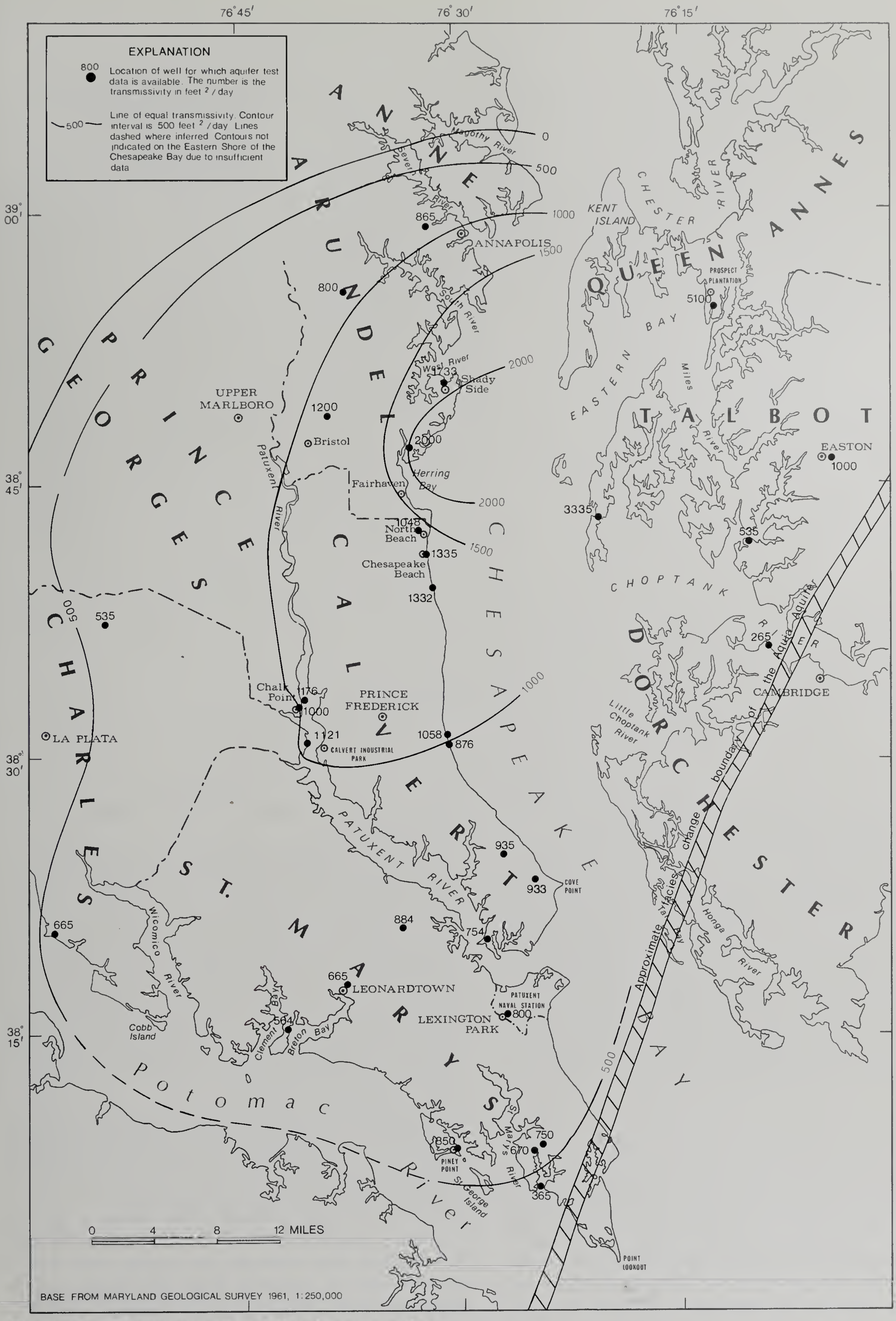

Figure 5.—Transmissivity of the Aquia aquifer.

Table 2.—Vertical hydraulic conductivities of confining beds as determined by laboratory methods

County	Geologic unit	U.S.G.S.[1] No.	Depth of sample (ft)	Hydraulic conductivity (ft/s)	Consolidation load (lb/in^2)	Permeant
St. Marys	Chesapeake Group	SM-Dd-46[3]	237-237.1	2.95×10^{-7}	90	Distilled water.
	Chesapeake Group	SM-Eg-28[3]	217-217.5	1.20×10^{-7}	1,000	Simulated formation water.
	Chesapeake Group	SM-Dd-49[2]	236	8.5×10^{-10}	236	Do.
	Marlboro Clay	SM-Dd-49[2]	458	1.1×10^{-9}	458	Do.
	Chesapeake Group	SM-Dd-50[2]	198	7.3×10^{-9}	200	Do.
Calvert	Chesapeake Group	CA-Fd-54[2]	215	6.90×10^{-10}	215	Do.
	Marlboro Clay	CA-Fd-54[2]	516	6.7×10^{-10}	516	Do.
	Chesapeake Group	CA-Cc-57[2]	197	2.3×10^{-9}	197	Do.
Prince Georges	Marlboro Clay	PG-Df-35[4]	36-38	3.13×10^{-9}	24	Do.
Queen Annes	Chesapeake Group	QA-Bg-54[4]	45-47	6.95×10^{-10}	30	Do.

1/ Location of test holes shown on plates 12 and 13.

2/ Analysis performed by TerraTek, Salt Lake City, Utah.

3/ Analysis performed by Core Laboratories, Inc., Dallas, Texas.

4/ Analysis performed by U.S. Geological Survey Hydrologic Laboratory, Denver, Colorado.

missive. Also, the most transmissive tracts of the Aquia aquifer correspond to facies 1 (fig. 3).

Storage coefficient is defined as the volume of water released from a unit surface area of aquifer per unit drop in head (Lohman and others, 1972). In confined aquifers, water derived from storage comes in part from expansion of water and compression of aquifer material. The storage coefficient is usually determined by analysis of pumping test data using the Theis non-equilibrium equation (Theis, 1936). Reported values of the storage coefficient in the Aquia aquifer, as determined by pumping tests, range from 0.0001 to 0.0004 (Hansen, 1972).

Upper and Lower Confining Beds

The clay and silt formations in the Coastal Plain sediments generally have such low permeability that they cannot be directly tapped for water. These beds are important, however, because they control the vertical leakage of water between aquifers. In addition, whereas clay and silt beds have low permeability, they commonly have high porosity, so that they may contain significant quantities of water in storage.

Leakage through a confining bed is controlled by the thickness of the bed and its hydraulic conductivity. Hydraulic conductivity is defined as the volume of water that can be transmitted in unit time under a unit hydraulic gradient (Lohman, 1972). In confining-bed materials, which are several orders of magnitude less permeable than the aquifers they confine, water movement is predominantly vertical. In general, therefore, the vertical hydraulic conductivity of a confining bed is the important parameter when evaluating leakage.

The ability of a confining bed to store water is described by its specific storage. Specific storage is defined as the volume of water released from or taken into storage per unit volume of confining bed per unit change in head (Lohman, 1972).

There is little available information on the hydraulic properties of the Brightseat and Severn Formations that underlie the Aquia. One undisturbed core of material from the Brightseat is available from Prince Georges County (Hansen, 1977). Laboratory analyses of this material in-

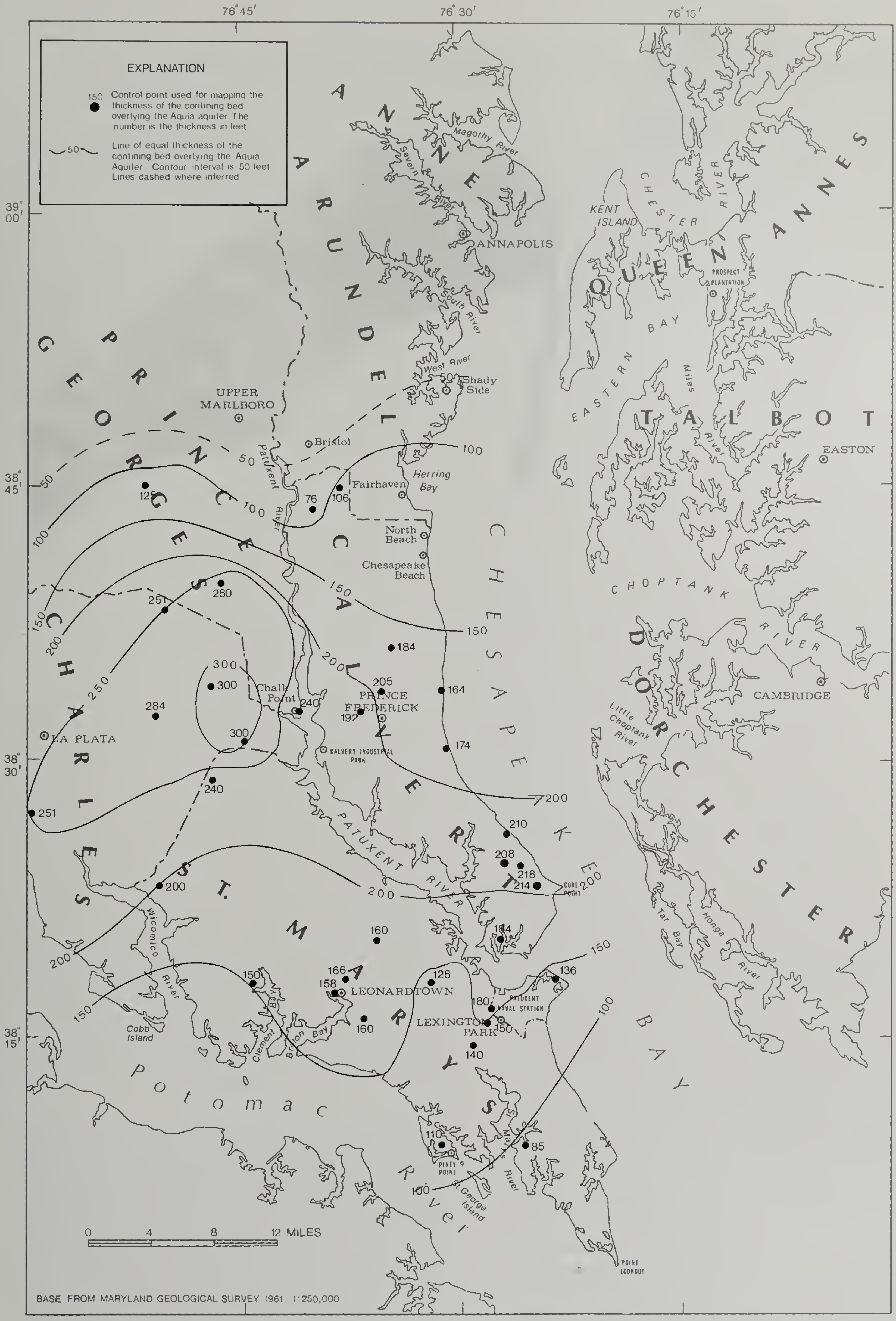

Figure 6.—Thickness of the confining bed overlying the Aquia aquifer.

Table 3.—Records of Aquia and Piney Point-Nanjemoy observation wells drilled during the project.

U.S.G.S. Well No.	State Permit No.	Nearest town	Latitude Longitude	Altitude of land surface (ft)	Date drilled	Drilled depth (ft below land surface)
SM-Dd-49	SM-73-3081	Redgate	38°16'16" 76°36'47"	115	10/20/78	617
SM-Fe-31	SM-73-3088	Piney Point	38°08'34" 76°30'35"	8	10/18/78	598
SM-Dd-50	SM-73-3082	Leonardtown	38°18'07" 76°38'00"	90	10/26/78	578
SM-Df-71	SM-73-3431	Lexington Park	38°15'27" 76°28'31"	65	7/12/79	560
SM-Bb-15	SM-73-3430	Charlotte Hall	38°28'38" 76°47'01"	170	7/18/79	460
SM-Bb-22	SM-73-3787	Charlotte Hall	38°28'38" 76°47'01"	170	6/27/80	240
SM-Dd-62	SM-73-3786	Redgate	38°16'16" 76°36'47"	115	6/30/80	382
SM-Dd-63	SM-73-3785	Redgate	38°16'15" 76°36'47"	116	7/07/80	377
CA-Cc-57	CA-73-2893	Parren	38°36'05" 76°34'46"	139	10/04/78	577
CA-Fd-54	CA-73-2892	Calvert Cliffs Park	38°21'19" 76°25'60"	129	10/11/78	698
CA-Db-47	CA-73-3304	Prince Frederick	38°32'39" 76°35'42"	142	7/26/79	570
CA-Bb-27	CA-73-3303	Dunkirk	38°43'31" 76°39'52"	130	8/03/79	320
CA-Bb-28	CA-73-3721	Dunkirk	38°43'31" 76°39'52"	130	6/25/80	199
AA-Fd-43	AA-74-1004	Tracys Landing	38°46'46" 76°35'24"	150	8/08/79	280
AA-Ed-45	AA-74-1005	Davidsonville	38°54'06" 76°38'39"	100	8/15/79	157

1/ Geophysical logs: G = gamma ray; M = multipoint electric; S = single point electric.

Well locations are given on plates 12 and 13.

dicates a vertical hydraulic conductivity of $1.0x10^{-8}$ ft/s and a specific storage of $7.4x10^{-5}ft^{-1}$.

The upper confining bed of the Aquia aquifer is the Marlboro Clay and the silty-clay portion of the Nanjemoy Formation. The thickness of this confining bed is shown in figure 6. Several undisturbed cores of this material were taken as a part of this study. The results of laboratory tests to determine the vertical hydraulic conductivity of this material are shown in table 2. The values range from 10^{-9} to 10^{-10} ft/s. Specific storage values are not available from these laboratory tests.

Water Levels

Historical water levels in the Aquia aquifer recorded by Darton (1896), Clark and others (1918), Overbeck (1948), Bennion and Brookhart (1949), Cook and others (1952), and Martin and Ferguson (1953) make possible an approximate reconstruction of the prepumping potentiometric surface (pl. 3). This reconstruction is approximate because of the lack of measured levels in much of the area. The precision of the measurements available is also uncertain; however, because many of these measure-

Construction data		Core sample (ft below land surface)	Geophysical logs 1/	Driller	Static water level (ft below land surface measured on May 1, 1981)	Aquifer	U.S.G.S. Well No.
Casing diameter (in.) upper-lower	Screen position (ft below land surface)						
4 - 2	539-617	236-236.5 458-458.5	S, G	Shannahan Artesian Well Co.	143.73	Aquia	SM-Dd-49
4 - 2	448-458	-	S, G, M	Shannahan Artesian Well Co.	37.48	Aquia	SM-Fe-31
4- 2	503-513	198-198.5	S, G	Shannahan Artesian Well Co.	124.36	Aquia	SM-Dd-50
4 - 2	550-560	-	S, G, M	Calvert Well Drilling Co.	126.66	Aquia	SM-Df-71
4 - 2	450-460	-	S, G, M	Calvert Well Drilling Co.	165.79	Aquia	SM-Bb-15
4 - 2	208-218	-	S, G, M	Calvert Well Drilling Co.	15.78	Piney Point-Nanjemoy	SM-Bb-22
4 - 2	348-358	-	S, G	Calvert Well Drilling Co.	113.60	Piney Point-Nanjemoy	SM-Dd-62
4 - 2	346-356	-	S, G	Calvert Well Drilling Co.	115.05	Piney Point-Nanjemoy	SM-Dd-63
4 - 2	511-521	-	S, G, M	Shannahan Artesian Well Co.	145.23	Aquia	CA-Cc-57
4 - 2	638-648	215-215.5 516-516.5	S, G, M	Shannahan Artesian Well Co.	156.31	Aquia	CA-Fd-54
4 - 2	560-570	-	S, G, M	Calvert Well Drilling Co.	152.90	Aquia	CA-Db-47
4 - 2	310-320	-	S, G, M	Calvert Well Drilling Co.	138.59	Aquia	CA-Bb-27
4 - 2	160-170	-	S, G, M	Calvert Well Drilling Co.	82.56	Piney Point-Nanjemoy	CA-Bb-28
4 - 2	270-280	-	S, G, M	Calvert Well Drilling Co.	146.62	Aquia	AA-Fd-43
4	147-157	-	S, G, M	Calvert Well Drilling Co.	66.21	Aquia	AA-Ed-45

ments are consistent with each other, it seems probable that the measurements are accurate within about 5 ft. The most notable features of plate 3 are the potentiometric highs, which correspond to topographically high areas, and the potentiometric lows, which correspond to low areas near the Potomac and Patuxent Rivers and the Chesapeake Bay.

Otton (1955) prepared the first potentiometric map of the Aquia in Southern Maryland. This map (pl. 4) shows cones of depression near the towns of Lexington Park and Leonardtown in St. Marys County in approximately 1952.

The cone of depression in the Lexington Park area remained nearly constant from 1952 to 1967, when the potentiometric surface was again measured by Weigle (1970). However, water-levels declined from 10 to 20 ft near Prince Frederick in Calvert County. In St. Marys County, the water level declined about 20 ft near Leonardtown because of increased municipal pumpage.

From 1967 to 1980, there were general water-level declines in the Aquia throughout Southern Maryland. The potentiometric surface of the Aquia was measured May 19-23, 1980 (pl. 5). The most significant water-level declines in this period were in the Lexington Park area and near Cove Point and Prince Frederick in Calvert County. The general declines in water levels were probably caused by growth of large cones of depression and increasing domestic and industrial pumpage.

Eleven observation wells were drilled during this project to monitor water levels in the Aquia aquifer. Records of these wells are listed in table 3 and their locations are shown on plate 12.

Pumpage

It is not known exactly when the first water wells were drilled into the Aquia. Darton (1896) lists wells in Nanjemoy and Oakley drilled into the Aquia aquifer. As these were flowing wells, however, it is unlikely that they were equipped with pumps. Clark and others (1918) list many more wells drilled into the Aquia aquifer. A few of these were equipped with suction pumps, but most relied on natural artesian pressure to produce water. Because most of these wells flowed at only 2 to 5 gal/min, total yield from the Aquia at this time was probably less than 200,000 gal/d in Southern Maryland.

Large scale pumping of the Aquia aquifer began during World War II when the U.S. Navy built several training facilities in St. Marys County near Lexington Park and in southern Calvert County. From 1941 to 1943, pumpage from the Aquia increased to 0.54 Mgal/d. By 1945, pumpage increased to 1.8 Mgal/d. After World War II, Aquia pumpage from the Naval facilities declined to 0.87 Mgal/d by 1951. From 1951 to 1966, pumpage from the Aquia increased gradually. Much of this increase came from domestic pumpage. From 1966 to 1980, municipal and domestic use of Aquia water increased rapidly.

Table 4 summarizes the pumpage history of the Aquia aquifer from 1941 to 1980. This table lists documented Aquia pumpage from well fields that use more than 5,000 gal/d. The locations of these well fields are shown in figure 7. Also shown are the county planning districts of St. Marys, Calvert, and Anne Arundel Counties where Aquia pumpage has been documented. Included with table 4 are estimates of domestic and small industrial pumpage organized by county planning district. The procedure used to estimate this pumpage was similar to the method employed by Williams (1976). First, the approximate number of domestic wells for each county was determined from the State of Maryland Water Resources Administration fact sheets WS001-WS004. The total number of wells in use was then divided among each county planning district. Each domestic well was considered to pump an average of 250 gal/d. Finally, the approximate domestic pumpage was calculated by multiplying the number of domestic wells in each planning district by the average daily usage.

Table 4.—Major users of the Aquia aquifer and their pumping rates

Location No. from figure 7	Owner or Name	County water service area[2]	Groundwater Appropriation Permit (GAP) No.	U.S.G.S. Well No.	Amount appropriated (gal/d)		Amount pumped (gal/d average over 10-year period)			
					Average	Maximum	1941-50	1951-60	1961-70	1971-80
				ANNE ARUNDEL COUNTY						
1	South Down Shores, Inc.	6	AA-58-GAP-008	AA-De- 68	20,000	40,000	0	3,000	13,000	19,000
				De-119	(1)	(1)	(1)	(1)	(1)	(1)
		(Annapolis)		De-120	(1)	(1)	(1)	(1)	(1)	(1)
				De-121	(1)	(1)	(1)	(1)	(1)	(1)
2	Woodfield Fish and Oyster Company	8 (Rural)	AA-54-GAP-003	Ee- 28	144,000	150,000	0	30,000	38,000	52,000
				Ee- 61	(1)	(1)	(1)	(1)	(1)	(1)
3	Wayson's Trailer Park	8 (Rural)	AA-60-GAP-008	Fc- 20	50,000	75,000	0	0	32,000	50,000
				Fc- 21	(1)	(1)	(1)	(1)	(1)	(1)
				Fc- 27	(1)	(1)	(1)	(1)	(1)	(1)
4	Broadwater Sewage Treatment Plant	8 (Rural)	AA-71-GAP-020	Fe- 26	128,000	196,000	0	0	0	13,475
	Domestic and Small Industrial	8 (Rural)	-	-	-	-	90,000	170,000	300,000	550,000

1/ Pumpage included in the above value.

2/ Water planning district from the Anne Arundel County master plan for water supply and sewerage systems. July 1976. Plate W.

Table 4.—continued

Location No. from figure 7	Owner or Name	County planning area [3]	Groundwater Appropriation Permit (GAP) No.	U.S.G.S. Well No.	Amount appropriated (gal/d)		Amount pumped (gal/d average over 10-year period)			
					Average	Maximum	1941-50	1951-60	1961-70	1971-80
				CALVERT COUNTY						
5	U.S. Navy - Solomons Test Facility	A	Ca-32-GAP-1	Ca-Gd-36 Fd- 1	65,000 (1)	150,000 (1)	750,000 (1)	500,000 (1)	100,000 (1)	80,900 (1)
6	U.S. Navy - Randel Cliffs	C	Ca-32-GAP-2	Cc-40 Cc-41	-	-	60,000 (1)	62,800 (1)	95,900 (1)	75,900 (1)
7	Calvert County Hospital	B	Ca-52-GAP-1	Db-21 Db-46	44,000 (1)	66,000 (1)	0 (1)	4,400 (1)	5,500 (1)	8,800 (1)
8	Scientists Cliffs Water Company	A	Ca-53-GAP-2	Dc-29	42,000	60,000	0	0	6,600	10,300
9	Cassel Utility Company	B	Ca-59-GAP-2	Dc-34 Dc-37	91,500 (1)	152,000 (1)	0 (1)	0 (1)	8,800 (1)	28,000 (1)
10	Chesapeake Ranch	A	Ca-60-GAP-2	Fd-39 Fe-18	125,000 (1)	200,000 (1)	0 (1)	0 (1)	27,100 (1)	60,600 (1)
11	Long Beach	A	Ca-62-GAP-1	Ed-12	80,000	170,000	0	27,400	21,400	25,100
12	Calvert County Vocation Center	B	Ca-70-GAP-5	Db-45	11,000	15,000	0	0	0	4,500
13	Chesapeake Beach	C	Ca-72-GAP-3	Bc- 3 Bc- 4 Bc- 5 Bc-31	150,000 (1) (1) (1)	225,000 (1) (1) (1)	5,000 (1) (1) (1)	10,000 (1) (1) (1)	30,000 (1) (1) (1)	33,500 (1) (1) (1)
14	Calvert High School	B	Ca-73-GAP-8	Db-26	5,500	8,000	0	0	6,300	6,200
15	Paris Oaks	C	Ca-73-GAP-13	Bc-32	15,000	25,000	0	0	0	5,900
16	Columbia Corporation	A	Ca-73-GAP-14	Fe-19 Fe-20 Fe-21	32,500 (1) (1)	57,000 (1) (1)	0 (1) (1)	0 (1) (1)	0 (1) (1)	8,500 (1) (1)
17	Prince Frederick	B	Ca-74-GAP-5	Db-41 Db-44	216,000 (1)	288,000 (1)	0 (1)	0 (1)	9,000 (1)	90,400 (1)
18	Baltimore Gas and Electric Company (Calvert Cliffs Nuclear Power Plant)	A	Ca-69-GAP-10	Ed-23 Ed-24	600,000 (1)	865,000 (1)	0 (1)	0 (1)	5,000 (1)	159,000 (1)
	Domestic and Small Industrial	A	-	-	-	-	30,000	40,000	50,000	185,000
		B	-	-	-	-	50,000	50,000	80,000	100,000
		C	-	-	-	-	50,000	100,000	300,000	500,000

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[1] Pumpage included in the above value.
[3] Population planning area from the Calvert County comprehensive water and sewerage plan. 1978 update, Figure 5.

Table 4.—continued

Location No. from figure 7	Owner or Name	County Sanitary District[4/]	Groundwater Appropriation Permit (GAP) No.	U.S.G.S. Well No.	Amount appropriated (gal/d)		Amount pumped (gal/d average over 10-year period)			
					Average	Maximum	1941-50	1951-60	1961-70	1971-80
				ST. MARYS COUNTY						
19	St. Marys Metropolitan Commission, Birch Manor	Manor Run	STM-74-GAP-35	STM-Cc-15 Cc-16	25,000 (1)	42,000 (1)	0 (1)	0 (1)	0 (1)	9,300 (1)
20	St. Marys Metropolitan Commission, Fenwick Manor	Pine Hill Run	STM-74-GAP-43	Ce-34 Ce-35	6,500 (1)	11,000 (1)	0 (1)	0 (1)	0 (1)	3,400 (1)
21	St. Marys Metropolitan Commission, Country Lakes	Luckland Run	STM-76-GAP-3	Cb-18 Cb-19	25,000 (1)	42,000 (1)	0 (1)	0 (1)	0 (1)	7,300 (1)
22	St. Marys Metropolitan Commission, Industrial Park	Pine Hill Run	STM-76-GAP-4	De-44	34,300	49,500	0	0	0	<5,000
23	St. Marys Metropolitan Commission, Wildwood	Pine Hill Run	STM-76-GAP-14	De-36	12,500	21,000	0	0	0	6,000
24	Breton Bay	Flood Creek	STM-76-GAP-24	Dd-47	40,000	60,000	0	0	0	14,700
25	Lundeburg School of Seamanship	Piney Point	STM-70-GAP-10	Fe- 1 Fe- 2 Fe-21	-	-	96,440 (1) (1)	96,400 (1) (1)	96,400 (1) (1)	96,400 (1) (1)
26	County Metropolitan Commission, Lexington Park	Pine Hill Run	STM-46-GAP-1	Df-22 Df-42 Df-62 Df-76 Df-78	1,200,000 (1) (1) (1) (1)	1,600,000 (1) (1) (1) (1)	0 (1) (1) (1) (1)	257,500 (1) (1) (1) (1)	556,200 (1) (1) (1) (1)	659,300 (1) (1) (1) (1)
27	Stuart Petroleum Company	Piney Point	STM-50-GAP-2	Fe-23 Fe-24 Fe-36	25,000 (1) (1)	700,000 (1) (1)	0 (1) (1)	19,200 (1) (1)	19,200 (1) (1)	19,500 (1) (1)
28	Leonardtown Laundry	Leonardtown	STM-55-GAP-2	Dd-64	7,500	8,000	0	4,900	8,200	<5,000
29	St. Marys Metropolitan Commission, Cedar Cove	Pine Hill Run	STM-73-GAP-3	Df-80 Dg-10	45,000 (1)	70,000 (1)	0 (1)	0 (1)	10,000 (1)	52,000 (1)
30	St. Marys Metropolitan Commission, Tubman Douglas	Pine Hill Run	STM-74-GAP-2	Df-73	30,000	45,000	0	0	0	21,900
31	U.S. Department of the Navy Patuxent Naval Air Test Station	Pine Hill Run	STM-74-GAP-18	Df- 1 Df- 2 Df- 3 Df- 4 Df- 5 Df- 7 Df-10 Df-11 Df-12 Dg- 1 Dg- 3 Dg- 5 Dg- 6 Dg- 9	186,000 (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)	186,000 (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)	919,700 (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)	1,283,300 (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)	932,000 (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)	798,300 (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1) (1)

Table 4.—continued

Location No. from figure 7	Owner or Name	County Sanitary District[4]	Groundwater Appropriation Permit (GAP) No.	U.S.G.S. Well No.	Amount appropriated (gal/d)		Amount pumped (gal/d average over 10-year period)			
					Average	Maximum	1941-50	1951-60	1961-70	1971-80
				ST. MARYS COUNTY--Continued						
32	Easy Wash	Indian Creek	STM-66-GAP-6	Bb-18 Bb-19	10,000 (1)	13,000 (1)	0 (1)	0 (1)	0 (1)	1,600 (1)
33	St. Marys County Vocational Center	Leonardtown	STM-67-GAP-9	Dd-41	57,800	65,000	0	0	1,200	5,100
34	St. Marys College	Pine Hill Run	STM-69-GAP-1	Ef-69	63,000	84,000	0	0	28,000	40,000
35	Cherry Cove Water Company	Dukeharts Creek	STM-60-GAP-17	Dd-33 Dd-44	250,000 (1)	400,000 (1)	0 (1)	0 (1)	46,800 (1)	51,600 (1)
36	St. Marys Metropolitan Commission, King and Kennedy	Manor Run	STM-71-GAP-4	Cc-18 Cc-19	20,000 (1)	33,000 (1)	0 (1)	0 (1)	0 (1)	11,200 (1)
37	St. Clement's Shores	Dukeharts Creek	STM-65-GAP-2	Dc-58	75,000	175,000	0	0	<5,000	26,000
38	Mt. Pleasant Water Company	Dukeharts Creek	STM-72-GAP-4	Dc-59 Dc-60	60,000 (1)	85,000 (1)	0 (1)	0 (1)	0 (1)	<5,000 (1)
39	Leonardtown	Leonardtown	STM-67-GAP-3	Dd- 1 Dd- 3 Dd-39	150,000 (1) (1)	200,000 (1) (1)	13,700 (1) (1)	32,900 (1) (1)	117,800 (1) (1)	232,400 (1) (1)
40	Aqua Foods, Inc.	Piney Point	STM-79-GAP-10	-	100,000	120,000	0	0	0	-
41	St. Marys County Metropolitan Commission Rolling Acres	Indian Creek	STM-74-GAP-25	Bc-20 Bc-30	15,000 (1)	25,000 (1)	0 (1)	0 (1)	0 (1)	7,000 (1)
	Domestic and Small Industrial	Pine Hill Run	-	-	-	-	<5,000	<5,000	10,000	20,000
		Leonardtown	-	-	-	-	<5,000	<5,000	8,000	10,000
		Luckland Run	-	-	-	-	<5,000	<5,000	50,000	149,000
		Dukeharts Creek	-	-	-	-	<5,000	<5,000	<5,000	5,300
		Flood Creek	-	-	-	-	<5,000	<5,000	<5,000	5,100
		Piney Point	-	-	-	-	<5,000	<5,000	<5,000	<5,000
		Lake Canoy	-	-	-	-	10,000	20,000	40,000	78,000
		Carrol Pond	-	-	-	-	<5,000	<5,000	<5,000	<5,000
		Manor Run	-	-	-	-	<5,000	<5,000	10,000	16,800
		Indian Creek	-	-	-	-	<5,000	<5,000	30,000	130,000

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[1] Pumpage included in the above value.
[4] Sanitary districts from the St. Marys County comprehensive water and sewerage plan; 1977 update, Map 7.

Piney Point-Nanjemoy Aquifer

Nomenclature

The Piney Point Formation in Southern Maryland is lithologically and paleontologically distinct from the underlying Nanjemoy Formation (Otton, 1955). However, as has been pointed out by Weigle (1970) and Williams (1979), the upper sands of the Nanjemoy Formation are directly overlain by Piney Point Formation sands in many places. This suggests that the two formations are hydraulically connected and function as a single aquifer. In view of this, Weigle (1970) proposed the name "Piney Point-Nanjemoy hydraulic unit" for use in Southern Maryland. This report will follow that convention. Where it is used, the term "Piney Point-Nanjemoy aquifer" is synonymous with the term "Piney Point-Nanjemoy hydraulic unit."

Regional Extent

The Piney Point-Nanjemoy aquifer is used as a source of ground water in Calvert and St. Marys Counties. On the Eastern Shore of Maryland, the Nanjemoy Formation is predominantly clay and the term "Piney Point-Nanjemoy aquifer" does not apply.

Figure 8 shows the altitude of the top of the Piney Point-Nanjemoy aquifer. Its thickness is shown in figure 9. In northern Calvert and northern St. Marys Counties, the aquifer is relatively thin and unproductive. The aquifer thickens rapidly to the southeast and becomes correspondingly more productive. Southeast of Leonardtown in St. Marys County, wells screened in the Piney Point-Nanjemoy commonly yield more than 60 gal/min.

Transmissivity and Storage Coefficient

Because the Piney Point-Nanjemoy aquifer is utilized mainly by homeowners (Hansen, 1972), aquifer tests are not commonly performed on newly drilled wells. For small-capacity wells, drillers are usually concerned only to produce a short-term yield of about 20 gal/min and pumping tests to determine the long-term yield potential are deemed unnecessary. Faced with these difficulties, Williams (1979) constructed a transmissivity map of the Piney Point-Nanjemoy aquifer in Southern Maryland based upon the few available single-well aquifer tests and specific capacities of wells as reported by drillers. The portion of the transmissivity map which covers the project area of this report is shown in figure 10.

Only a few storage coefficient values have been determined for the Piney Point-Nanjemoy aquifer. These have been tabulated by Hansen (1972) and range from 0.0003 to 0.0004. A multiple-well pumping test of the Piney Point-Nanjemoy aquifer near Leonardtown in St. Marys County indicated a storage coefficient of 0.0004.

Upper and Lower Confining Beds

The Piney Point-Nanjemoy aquifer is overlain throughout Southern Maryland by silt and clay of the Chesapeake Group. These sediments act as an upper confining bed to the Piney Point-Nanjemoy aquifer. The thickness of this confing bed is shown in figure 11. In general, the Chesapeake Group sediments are thickest in the upland areas of St. Marys, Charles, and Calvert Counties and are thinnest in the valley of the Patuxent River. This suggests some post-deposition erosional influence on their thickness.

The vertical hydraulic conductivity of the Chesapeake Group has been determined in a few locations by laboratory methods. These values are shown in table 2.

The specific storage of the Chesapeake Group sediments has been determined in only one location in Southern Maryland. This is at the Old Leeland Road test well in Prince Georges County (Hansen, 1977) where specific storage is 10^{-5} ft.$^{-1}$.

The lower confining beds of the Piney Point-Nanjemoy aquifer are the silty clay beds of the Nanjemoy Formation and the Marlboro Clay. The hydraulic properties of these beds are discussed in the section on the upper confining bed of the Aquia aquifer.

Water Levels

Water levels in the Piney Point-Nanjemoy aquifer show a similar history to the water levels of the Aquia aquifer. The prepumping potentiometric map (pl. 6), as determined from historical water levels (Darton, 1896; Clark and others, 1918; Overbeck, 1948; and Otton, 1952), shows potentiometric highs in upland areas and potentiometric lows conform with the topographic lows in river valleys.

The Piney Point-Nanjemoy was developed in the early 1900's. Its relative shallowness, combined with the fact that many of the early wells flowed, made the Piney Point-Nanjemoy aquifer attractive to many users. Use of this aquifer increased rapidly during World War II. Water levels in the Lexington Park and Solomons area declined, and many artesian wells ceased flowing. During the late 1940's, the Navy reduced its pumpage of the Piney Point-

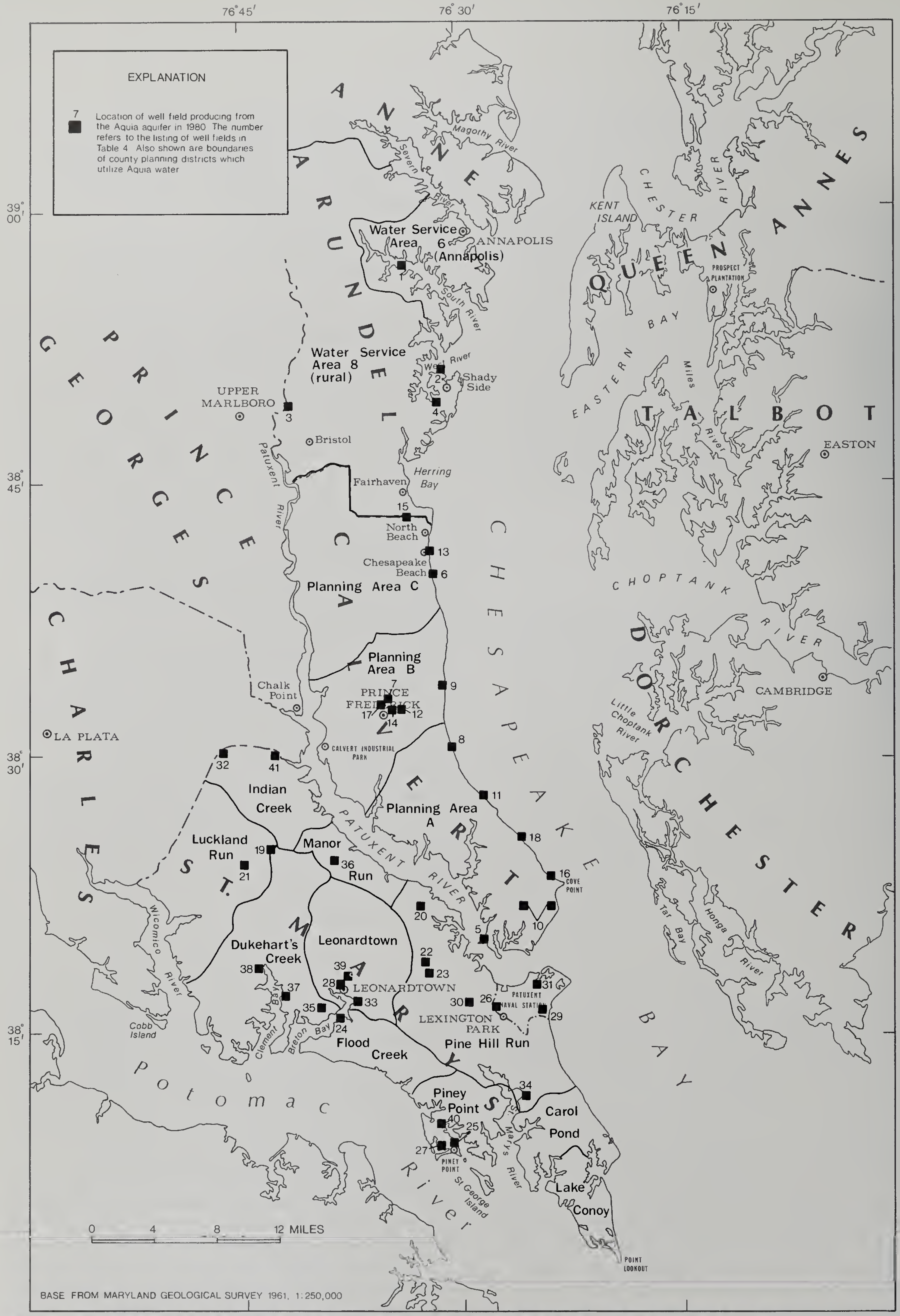

Figure 7.—Locations of well fields pumping more than 5,000 gal/d from the Aquia aquifer and boundaries of county planning districts.

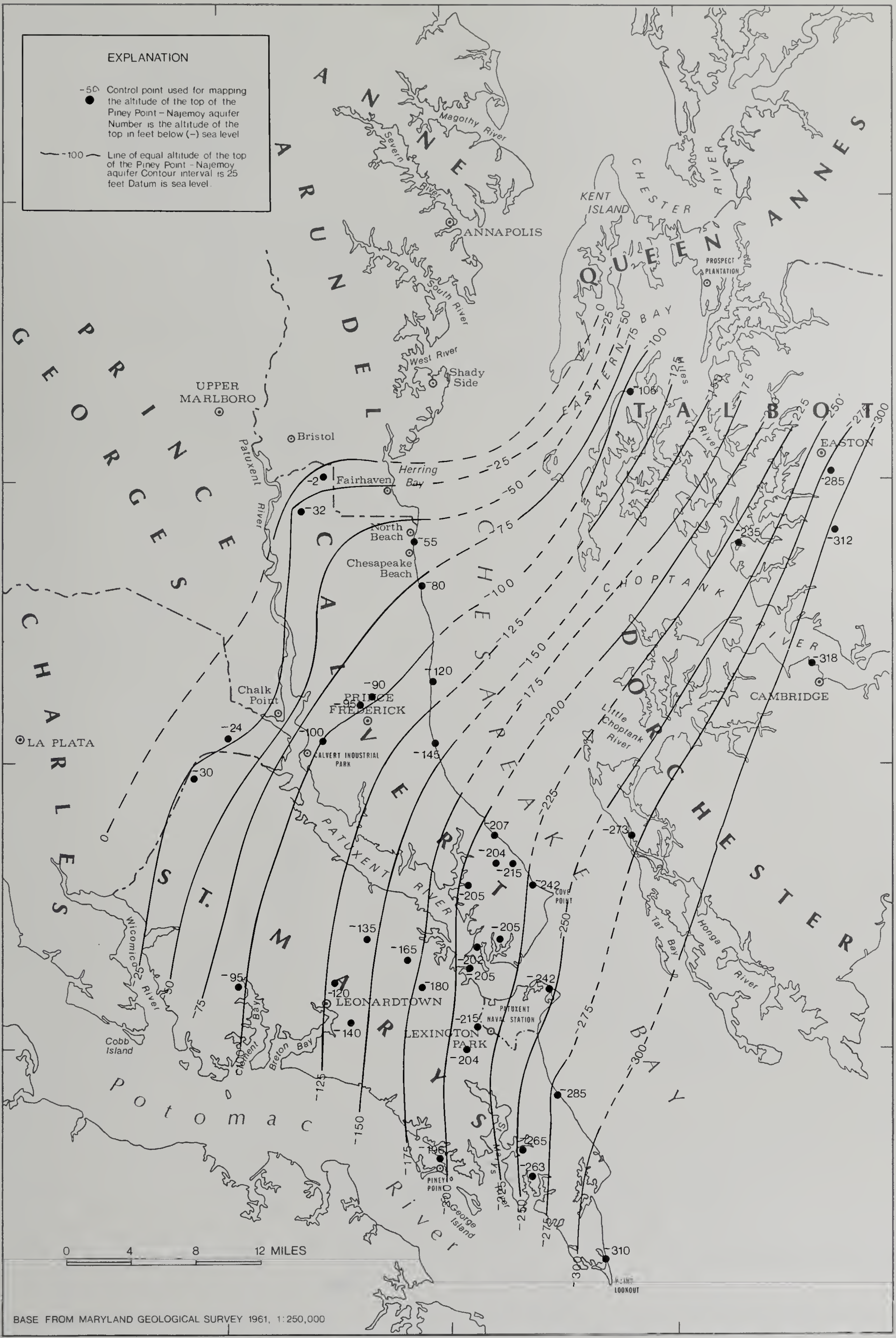

Figure 8.—Altitude of the top of the Piney Point-Nanjemoy aquifer.

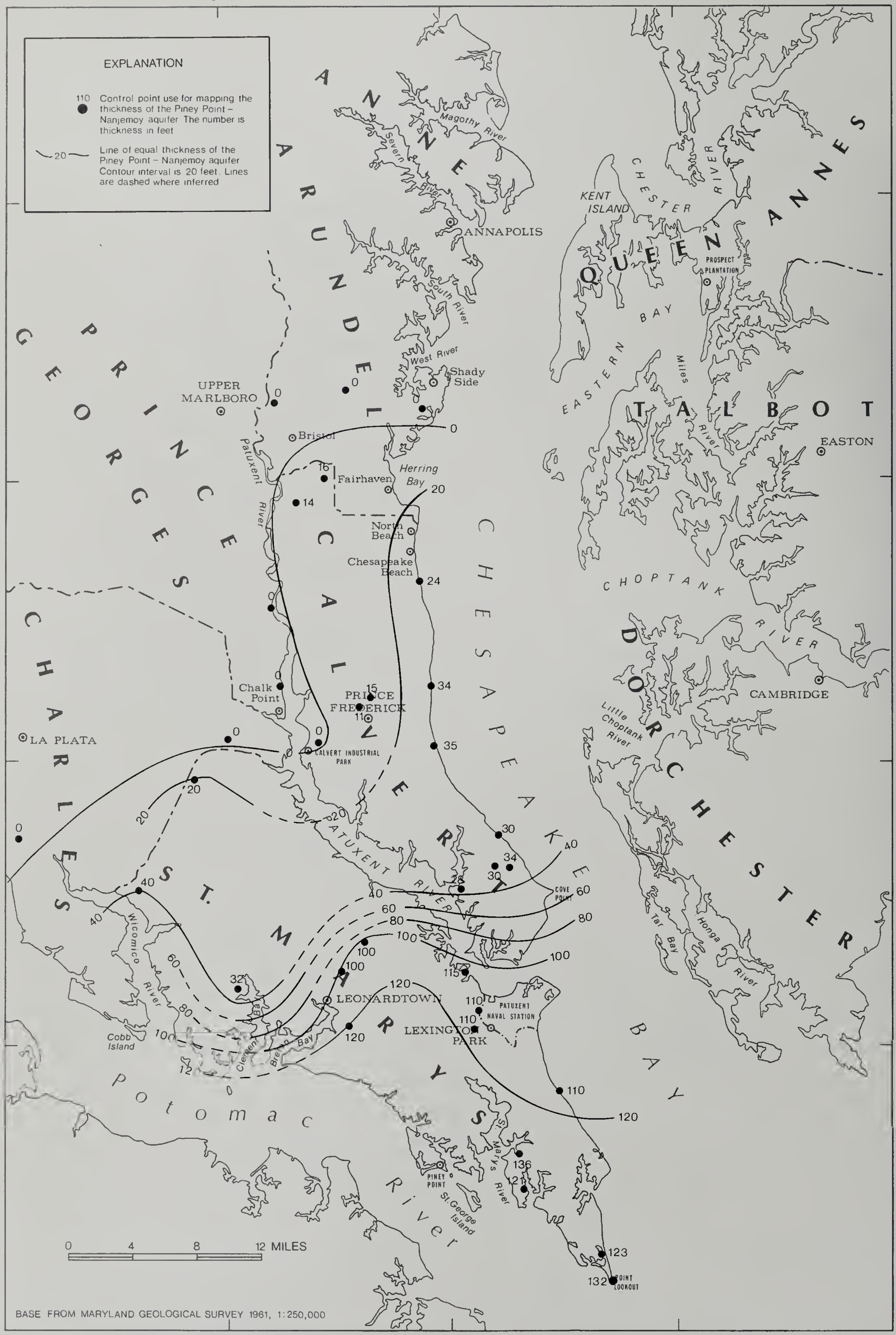

Figure 9.—Thickness of the Piney Point-Nanjemoy aquifer.

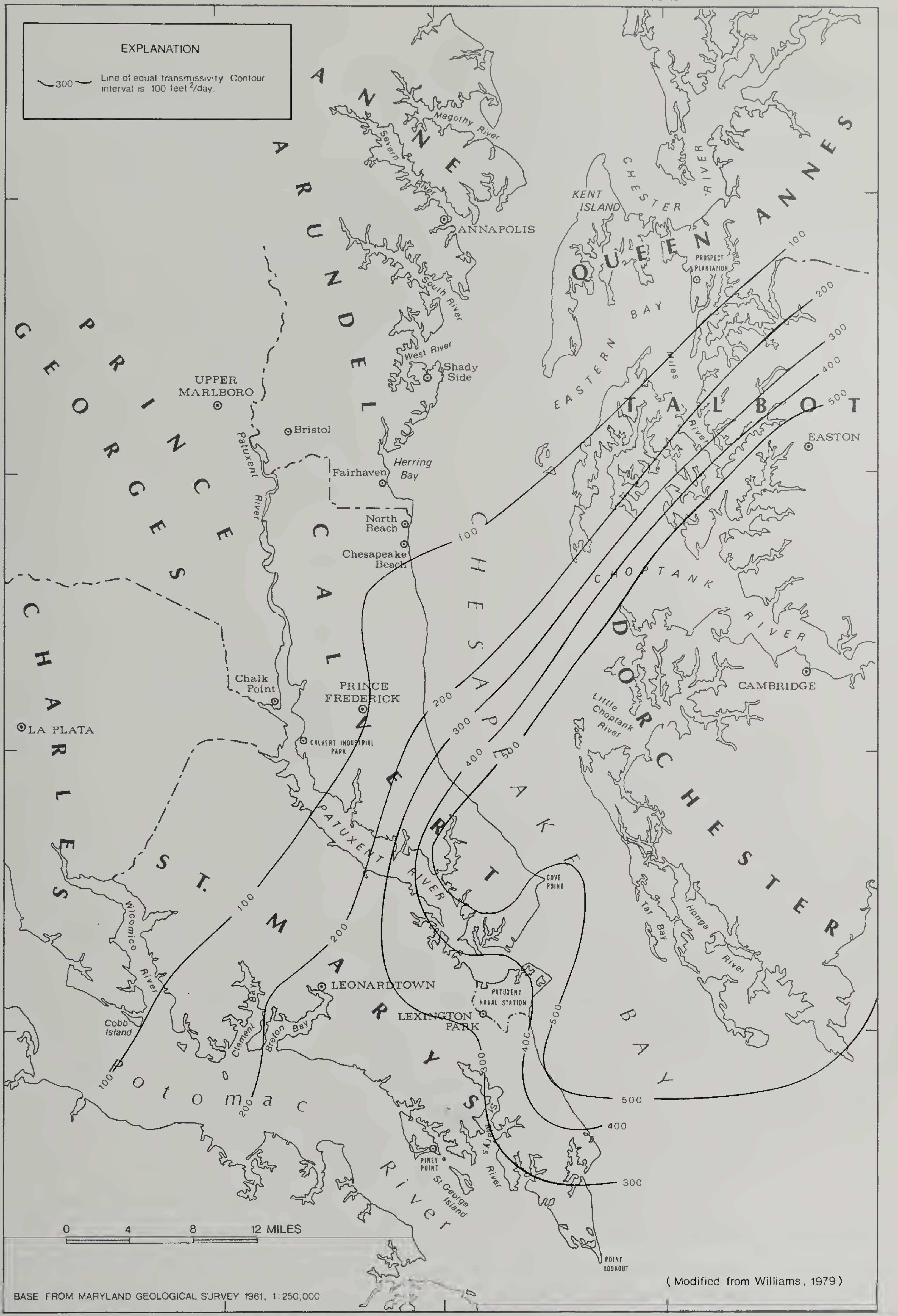

Figure 10.—Transmissivity of the Piney Point-Nanjemoy aquifer.

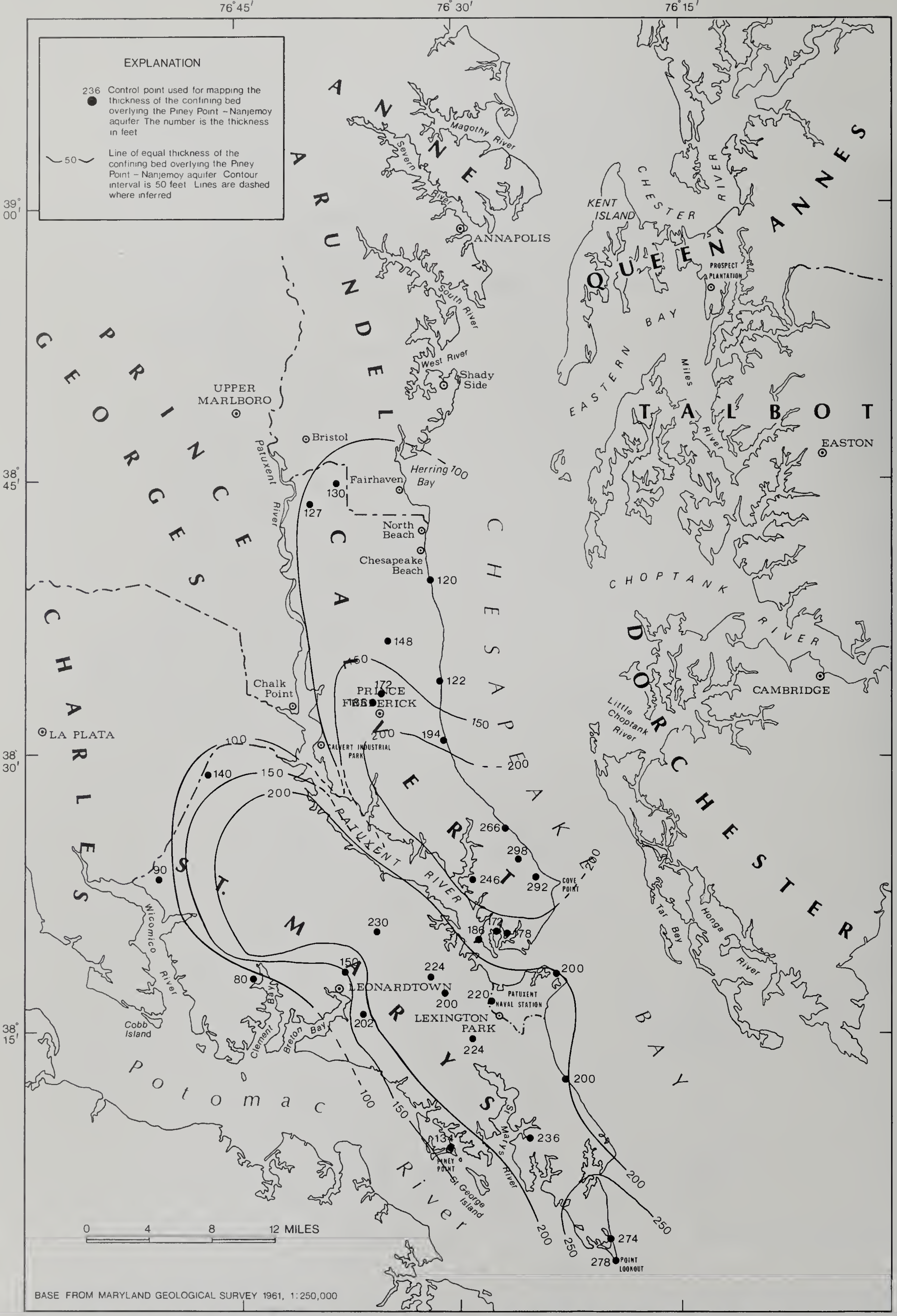

Figure 11.—Thickness of the confining bed overlying the Piney Point-Nanjemoy aquifer.

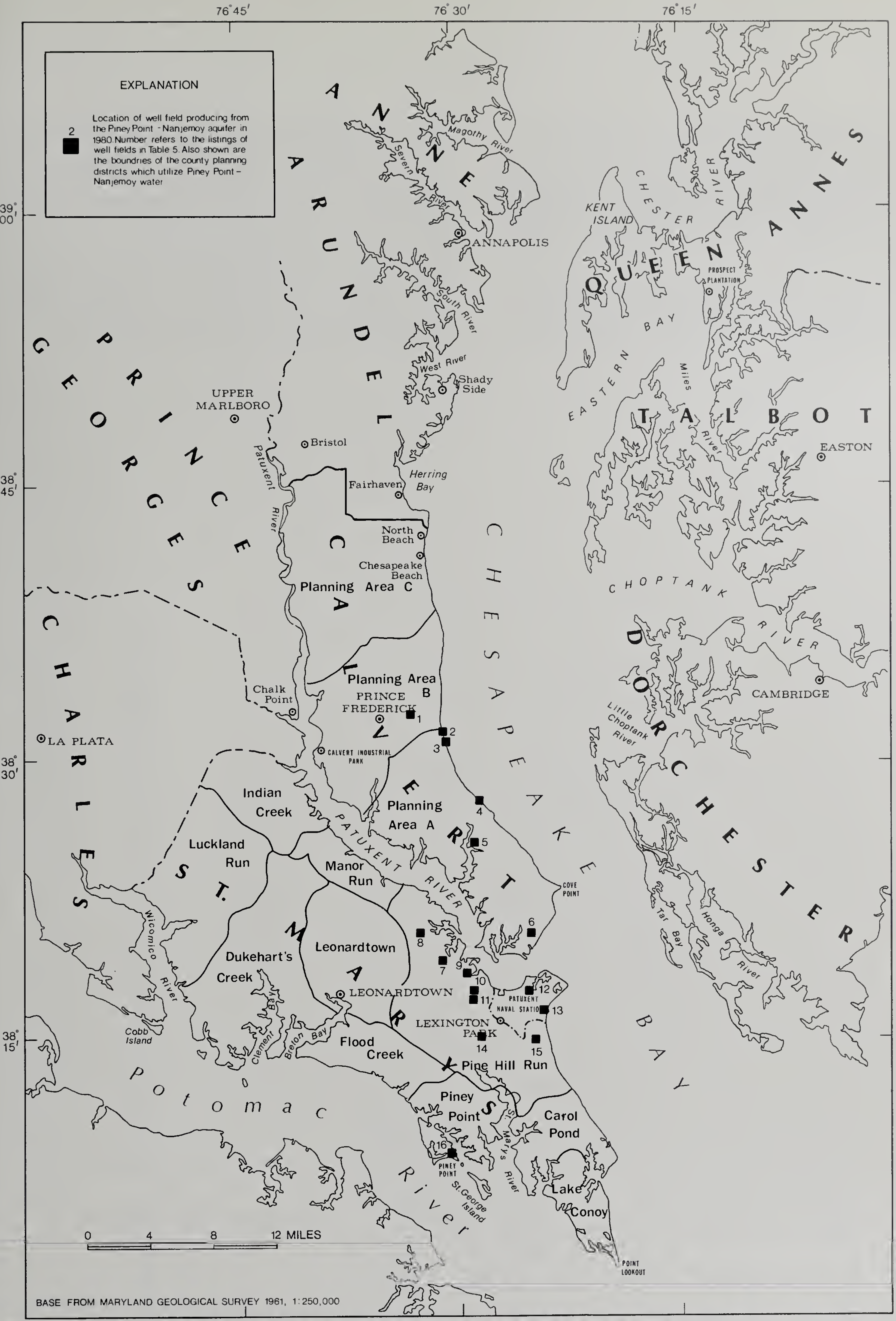

Figure 12.—Location of well fields pumping more than 5,000 gal/d from the Piney Point-Nanjemoy aquifer and boundaries of county planning districts.

Nanjemoy aquifer in response to citizens' complaints about declining water levels. Some pumping was continued, however, and by 1952 a cone of depression about 20 ft below sea level had developed around Patuxent Naval Air Training Station (PNATS). The 1952 potentiometric surface is shown on plate 7.

From 1952 to 1980, pumping from the Piney Point-Nanjemoy aquifer increased. Much of this pumpage came from homes and other small-capacity wells. The 1980 potentiometric surface of the Piney Point-Nanjemoy aquifer is shown on plate 8. The pumpage history of the Piney Point-Nanjemoy aquifer from 1941 to 1980 is summarized in table 5. The locations of well fields producing more than 5,000 gal/d are shown in figure 12.

Four Piney Point-Nanjemoy observation wells were drilled during this project to observe water levels. Records of these wells are listed in table 3 and the well locations are shown on plate 13.

Table 5.—Major users of the Piney Point-Nanjemoy aquifer and their pumping rates

Location No. from figure 12	Owner or Name	County planning area [2]	Groundwater Appropriation Permit (GAP) No.	U.S.G.S. Well No.	Amount appropriated (gal/d)		Amount pumped (gal/d average over 10-year period)			
					Average	Maximum	1941-50	1951-60	1961-70	1971-80
				CALVERT COUNTY						
1	Calvert County Commissioners (Prince Frederick Wastewater Treatment Plant)	B	Ca-73-GAP-15	CA-Dc-47	<5,000	10,000	0	0	0	6,900
2	Scientists Cliffs Water Company	A	Ca-53-GAP-2	Dc-15 Dc-16	42,000 (1)	60,000 (1)	<5,000 (1)	21,400 (1)	24,700 (1)	26,800 (1)
3	Kenwood Beach	A	Ca-68-GAP-9	Ec-27	20,000	72,000	0	0	<5,000	14,000
4	Long Beach	A	Ca-62-GAP-1	Ed-19 Ed-20 Ed-43	80,000 (1) (1)	170,000 (1) (1)	0 (1) (1)	0 (1) (1)	15,900 (1) (1)	36,000 (1) (1)
5	White Sands	A	Ca-56-GAP-2	Dc-17 Dc-32	10,500 (1)	12,000 (1)	0 (1)	<5,000 (1)	11,800 (1)	10,090 (1)
6	Chesapeake Ranch	A	Ca-60-GAP-2	Fd-38	125,000	200,000	0	0	23,800	18,300
	Domestic and Small Industrial	A	-	-	-	-	50,000	52,000	114,000	170,000
		B	-	-	-	-	10,000	20,000	40,000	100,000
		C	-	-	-	-	50,000	60,000	85,000	175,000

[1] Pumpage included in the above value.

[2] Population planning area from the Calvert County comprehensive water and sewerage plan; 1978 update; Figure 5.

Table 5.—continued

Location No. from figure 12	Owner or Name	County Sanitary District[3]	Groundwater Appropriation Permit (GAP) No.	U.S.G.S. Well No.	Amount appropriated (gal/d)		Amount pumped (gal/d average over 10-year period)			
					Average	Maximum	1941-50	1951-60	1961-70	1971-80
				ST. MARYS COUNTY						
7	Charles County Concrete Company	Pine Hill Run	STM-67-GAP-2	STM-De-32	< 5,000	6,000	0	0	1,600	5,200
8	Town Creek Water Company (Hollywood)	Pine Hill Run	STM-76-GAP-10	Ce-36 Ce-37	10,000 (1)	15,000 (1)	0 (1)	2,700 (1)	3,400 (1)	7,000 (1)
9	Town Creek Water Company	Pine Hill Run	STM-52-GAP-4	Df-49 Df-50 Df-54 Df-67 Df-68 Df-69 Df-70	200,000 (1) (1) (1) (1) (1) (1)	250,000 (1) (1) (1) (1) (1) (1)	0 (1) (1) (1) (1) (1) (1)	65,700 (1) (1) (1) (1) (1) (1)	82,200 (1) (1) (1) (1) (1) (1)	113,200 (1) (1) (1) (1) (1) (1)
10	Greenview Knolls	Pine Hill Run	STM-67-GAP-1	Df-53 Df-60	25,000 (1)	40,000 (1)	0 (1)	2,200 (1)	24,700 (1)	45,300 (1)
11	Chance Water Company	Pine Hill Run	STM-56-GAP-6	Df-82 Df-83	12,000 (1)	19,000 (1)	0 (1)	4,400 (1)	5,500 (1)	10,000 (1)
12	U.S. Department of the Navy Patuxent Naval Air Test Station	Pine Hill Run	STM-74-GAP-18	Df- 6 Df- 8 Df- 9 Df-13 Df-14 Df-38 Df-39 Dg- 2	186,000 (1) (1) (1) (1) (1) (1) (1)	186,000 (1) (1) (1) (1) (1) (1) (1)	124,400 (1) (1) (1) (1) (1) (1) (1)	216,900 (1) (1) (1) (1) (1) (1) (1)	180,300 (1) (1) (1) (1) (1) (1) (1)	111,200 (1) (1) (1) (1) (1) (1) (1)
13	U.S. Department of the Navy Patuxent Naval Air Test Station	Pine Hill Run	STM-74-GAP-18	Dg- 4 Dg- 8	(1) (1)	(1) (1)	(1) (1)	(1) (1)	(1) (1)	(1) (1)
14	Hills Trailer Park	Pine Hill Run	STM-52-GAP-2	Ef- 3 Ef-13 Ef-65 Ef-66	100,000 (1) (1) (1)	150,000 (1) (1) (1)	0 (1) (1) (1)	39,000 (1) (1) (1)	49,000 (1) (1) (1)	46,000 (1) (1) (1)
15	Friendly Manor Trailer Park	Pine Hill Run	STM-66-GAP-3	Eg-29	1,000	-	0	0	1,600	8,200
16	Puchetti Trailer Park	Piney Point	STM-67-GAP-7	Fe-27	9,000	12,500	0	0	1,400	5,200
	Domestic and Small Industrial	Pine Hill Run	-	-	-	-	150,000	160,000	180,000	200,000
		Leonardtown	-	-	-	-	< 5,000	< 5,000	< 5,000	< 5,000
		Luckland Run	-	-	-	-	< 5,000	< 5,000	< 5,000	< 5,000
		Dukeharts Creek	-	-	-	-	< 5,000	< 5,000	< 5,000	< 5,000
		Flood Creek	-	-	-	-	10,000	12,000	15,000	18,150
		Piney Point	-	-	-	-	15,000	25,000	30,000	42,400
		Lake Canoy	-	-	-	-	45,000	50,000	60,000	78,000
		Carrol Pond	-	-	-	-	65,000	70,000	80,000	90,000
		Manor Run	-	-	-	-	< 5,000	< 5,000	< 5,000	9,000
		Indian Creek	-	-	-	-	< 5,000	< 5,000	< 5,000	< 5,000

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[1] Pumpage included in the above value.

Hydrologic Effects of Pleistocene Erosion in Southern Maryland

Pleistocene Erosion

The worldwide lowering of sea level during Pleistocene time and the consequent development of a river system approaching equilibrium with that sea level has had a strong influence on the present topography and drainage system of Southern Maryland. Hack (1955, 1957) has shown that the Chesapeake Bay Estuary is a drowned Pleistocene river system and that this river system approached equilibrium with a sea level 300 to 400 ft below present sea level. In the process of approaching this dynamic equilibrium with the lower sea level, there was considerable downward erosion of river channels. In many areas of Southern Maryland, these river channels have eroded through sediments of Miocene, Eocene, and Paleocene age.

The effects of this erosion can clearly be observed at some locations. One such location is at the Chesapeake Bay Bridge. Figure 13 shows a geologic cross section at this site that was constructed from bore hole data gathered during bridge construction. This figure shows a buried channel that has a base about 200 ft below sea level. Hack (1957) has interpreted this channel as representing the Pleistocene Susquehanna River. The channel of this ancient river has completely cut through the Aquia aquifer at this location.

Other examples of the effects of Pleistocene erosion can be observed near Benedict, Md. (fig. 14), and near Solomons, Md. (fig. 15). Bore hole data gathered at these sites show that Chesapeake Group sediments have been eroded and buried by sediments of Pleistocene age.

Areal Distribution of Pleistocene Erosional Channels

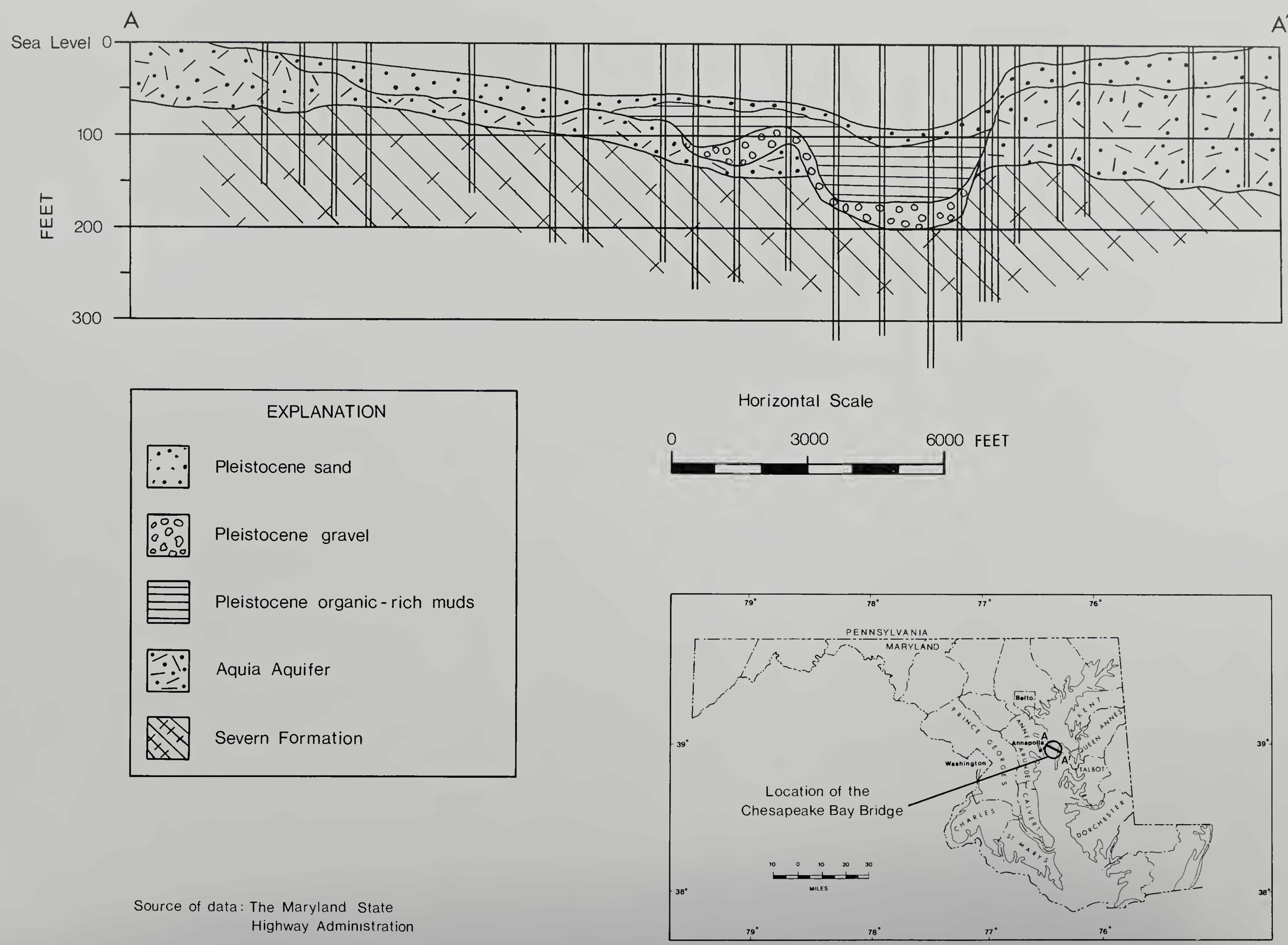
To evaluate the effects that Pleistocene erosional channels have on the hydrogeology of the Aquia and Piney Point-Nanjemoy aquifers, it is necessary to determine where these aquifers or their confining beds have been disturbed. Hack (1957) estimates the longitudinal profiles of the Pleistocene Susquehanna River and some of its major tributaries. Figue 16 shows the approximate locations and approximate depths of these Pleistocene channels, which are assumed to coincide with the present day deep channel of the Chesapeake Bay. The information of figure 16 combined with a knowledge of the areal distribution, altitude of top, and thickness of geologic formations makes possible an estimate of where these formations have been eroded by Pleistocene channels.

Schubel and Zabawa (1972) have identified at least one other channel in the Chesapeake Bay region using continuous seismic reflection profiling. It is possible, therefore, that the truncation of Tertiary sediments is more extensive in the Bay region than can be inferred from figure 16, which considers only those channels identified by Hack (1957).

Hydrogeologic Effects of Pleistocene Erosional Channels

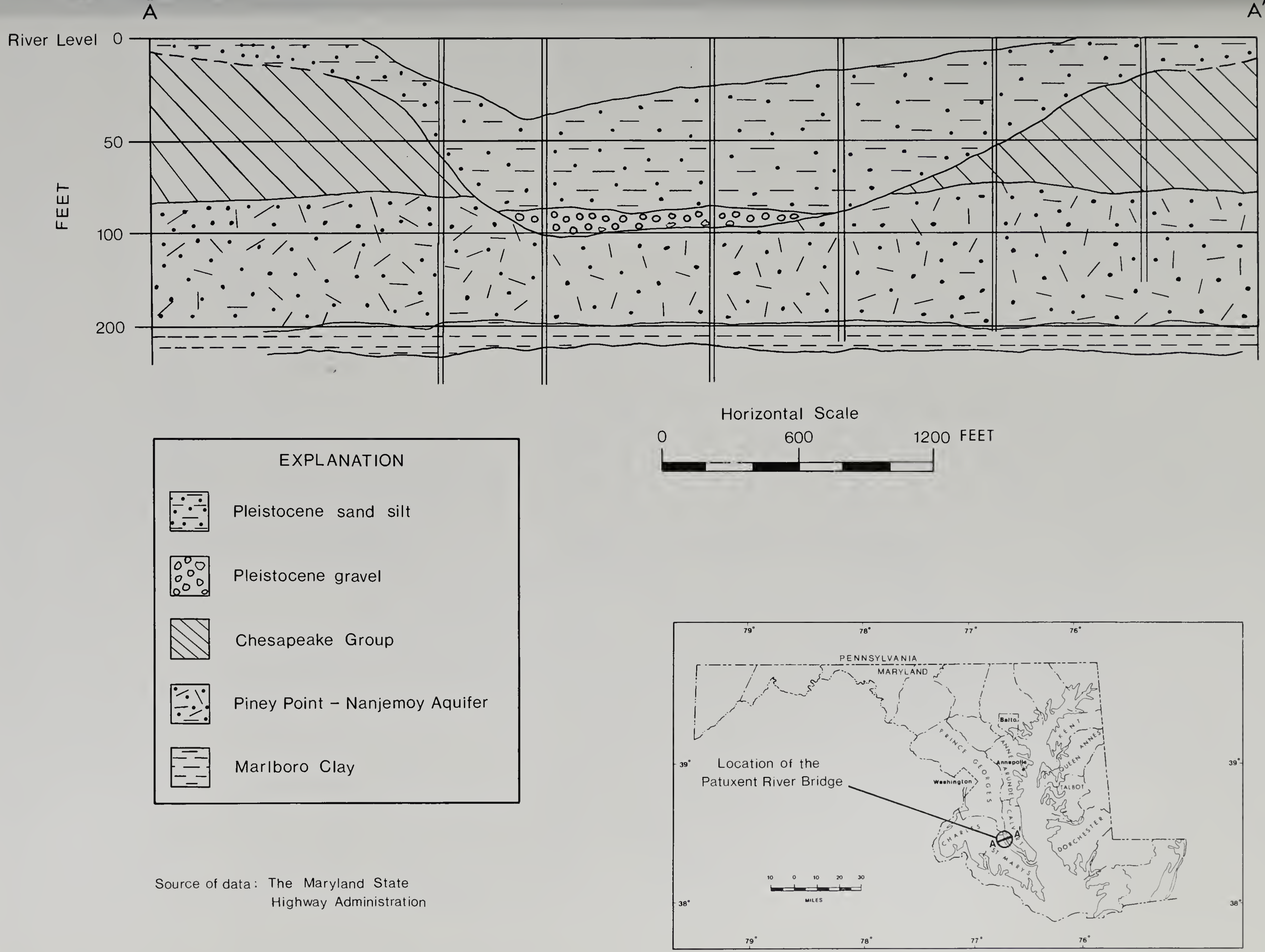
Disruption of aquifers and confining beds by Pleistocene erosional channels appears to have a significant effect on head distributions in the Aquia and Piney Point-Nanjemoy aquifers. Where aquifers have been breached by erosional channels, aquifer water levels will tend to approach the river water level by leakage into or out of the aquifer. Similarly, where confining beds have been breached, increased leakage into or out of the aquifer will cause a head distribution adjustment. This reasoning is consistent with the observed prepumping potentiometric surfaces of the Aquia and Piney Point-Nanjemoy aquifers. A comparison of figure 16 with plates 3 and 6 shows that potentiometric lows correspond to areas in river channels where erosion has disturbed either the aquifers or their confining beds. This process appears to be one of the major controls on the natural head distribution of the Aquia and Piney Point-Nanjemoy aquifers in Southern Maryland.

In some areas close to the Chesapeake Bay, Pleistocene erosion has increased the potential for salt-water intrusion into aquifers. For example, figure 13 shows that at the Chesapeake Bay Bridge, Pleistocene river sands have been deposited on an erosional surface which truncates the Aquia aquifer. If the potentiometric surface of the Aquia aquifer drops significantly below sea level near this area, intrusion of brackish water into the Aquia is possible. Future water-supply decisions in these areas should consider this potential for contamination.



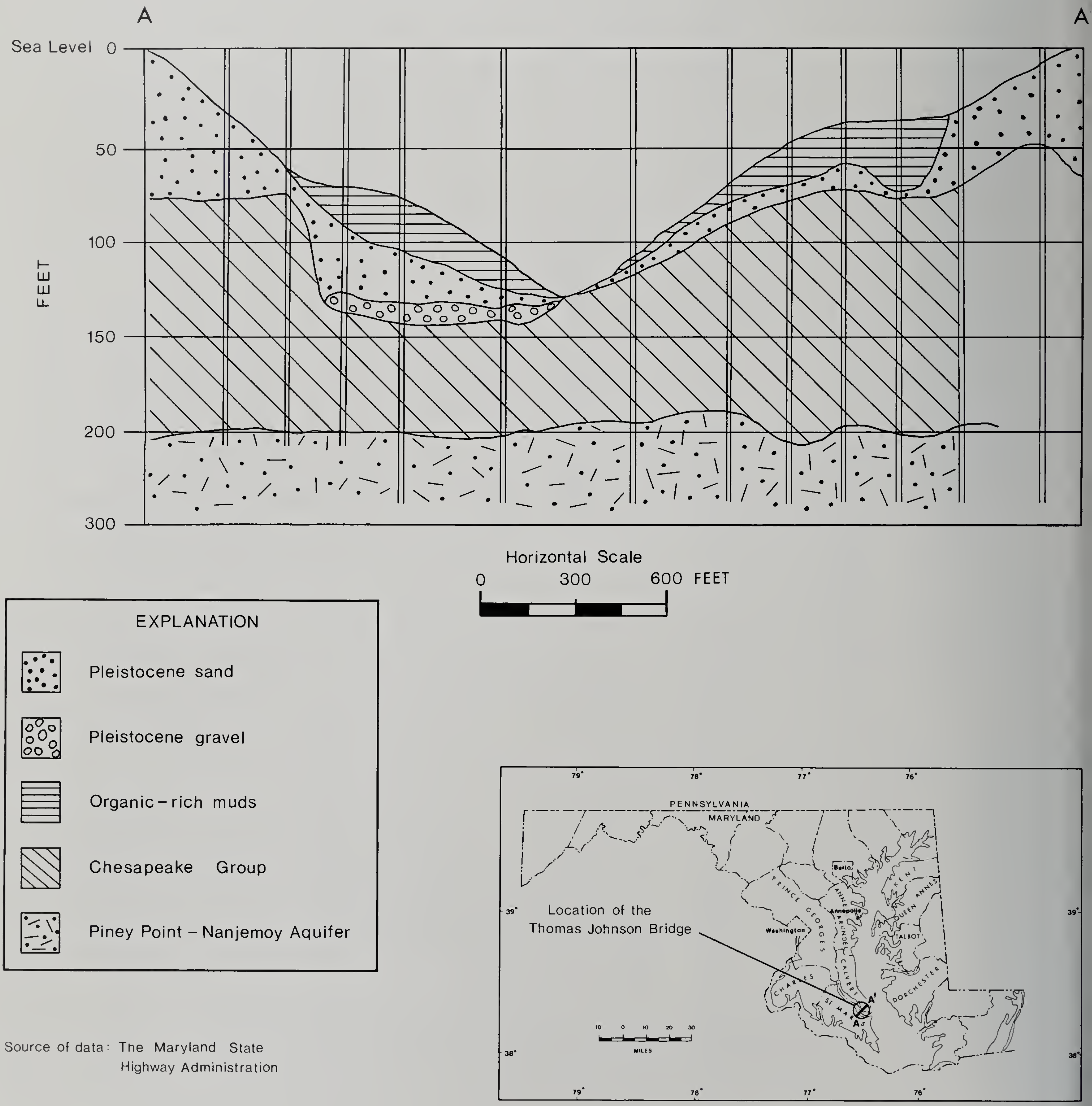
Source of data: The Maryland State Highway Administration

Figure 13.—Geologic cross section at the Chesapeake Bay Bridge.



Source of data: The Maryland State Highway Administration

Figure 14.—Geologic cross section at the Patuxent River Bridge.



Source of data: The Maryland State Highway Administration

Figure 15.—Geologic cross section at the Thomas Johnson Bridge.

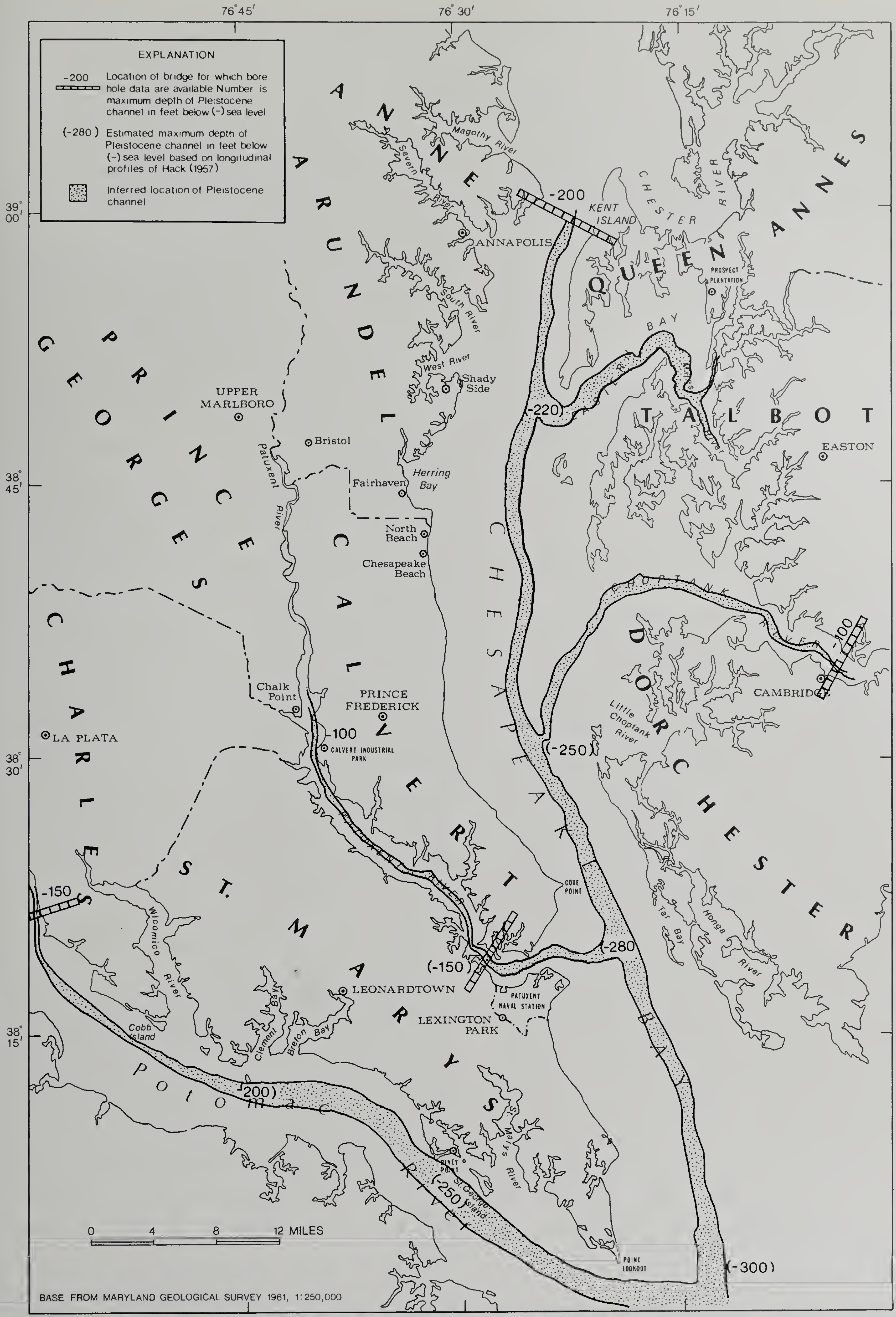


Figure 16.—Approximate locations and depths of Pleistocene channels.

Theory of Modeling Gound-Water Flow

The flow of ground water in a heterogeneous and anisotropic medium can be described mathematically as

$$\frac{\partial}{\partial x}(T_{xx}\frac{\partial h}{\partial x}) + \frac{\partial}{\partial y}(T_{yy}\frac{\partial h}{\partial y}) + \frac{\partial}{\partial z}(bK_{zz}\frac{\partial h}{\partial z}) = S'\frac{\partial h}{\partial t} + bW(x,y,z,t)$$

in which

T_{xx} = principal transmissivity tensor in the x direction (L^2T^{-1});
T_{yy} = principal transmissivity tensor in the y direction (L^2T^{-1});
K_{zz} = hydraulic conductivity tensor in the z direction (LT^{-1});
h = hydraulic head (L);
S′ = storage coefficient (dimensionless);
b = thickness of hydraulic unit (L);
t = time (T);
x, y, z = space coordinates (L);
W(x, y, z, t) = volumetric flux per unit volume (T^{-1}) (Trescott, 1975).

The volumetric flux term W(x, y, z, t) allows the model to adjust calculated head values to different rates of pumpage and leakage across confining beds.

Equation 1 can be solved by subdividing the region into blocks where the medium properties are assumed to be uniform. The continuous derivatives are replaced by finite-difference approximations at a point in the center of each block. The result is N algebraic equations in N unknowns, where N is the number of blocks representing the porous medium. The finite-difference approximation of equation 1 can be written as

$$\begin{aligned}
&\frac{1}{\Delta x_j}\{[T_{xx(i,j+\frac{1}{2},k)}\frac{(h_{i,j+1,k} - h_{i,j,k})}{\Delta x_{j+\frac{1}{2}}}] - [T_{xx(i,j-\frac{1}{2},k)}\frac{(h_{i,j,k} - h_{i,j-1,k})}{\Delta x_{j-\frac{1}{2}}}]\} \\
&+ \frac{1}{\Delta y_j}\{[T_{yy(i+\frac{1}{2},j,k)}\frac{(h_{i+1,j,k} - h_{i,j,k})}{\Delta y_{i+\frac{1}{2}}}] - [T_{yy(i-\frac{1}{2},j,k)}\frac{(h_{i,j,k} - h_{i-1,j,k})}{\Delta y_{i-\frac{1}{2}}}]\} \\
&+ \frac{1}{\Delta z_k}\{[(bK_{zz})_{i,j,k+\frac{1}{2}}\frac{(h_{i,j,k+1} - h_{i,j,k})}{\Delta z_{k+\frac{1}{2}}}] - [(bK_{zz})_{i,j,k-\frac{1}{2}}\frac{(h_{i,j,k} - h_{i,j,k-1})}{\Delta z_{k-\frac{1}{2}}}]\} \\
&= \frac{S'_{i,j,k}}{\Delta t}(h_{i,j,k} - \hat{h}_{i,j,k}) + bW_{i,j,k}
\end{aligned}$$

in which

Δx_j = space increment in the x direction for column j (L);
Δy_i = space increment in the y direction for row i (L);
Δz_k = space increment in the z direction for layer k (L);
Δt = time increment (T);
i = index in the y dimension;
j = index in the x dimension;
k = index in the z dimension;
h = hydraulic head (L);
S′ = storage coefficient (dimensionless);
b = thickness of hydraulic unit (L);
T_{xx} = principal transmissivity tensor in the x direction (L^2T^{-1});
T_{yy} = principal transmissivity tensor in the y direction (L^2T^{-1});
K_{zz} = hydraulic conductivity tensor in the z direction (LT^{-1}).

This set of algebraic equations can be solved with a digital computer.

The digital model program used in this study was developed by Trescott and Larson (1976). In this program, the Strongly Implicit Procedure (SIP) numerical technique is used to solve equation 2. The derivation of the SIP algorithm is given in Weinstein and others (1969). The program incorporates a transient leakage calculation, developed and documented by Posson and others (1980), to simulate the effects of confining-bed storage. For this study, the quasi three-dimensional approach was used. This approach incorporates the effects of vertical flow through confining beds in the vertical components of hydraulic conductivity of adjacent aquifers (Trescott, 1975). This is justified if the ratio of aquifer hydraulic conductivity to the confining bed's hydraulic conductivity is greater than 100:1. In the aquifer system of Southern Maryland, it is estimated that this ratio is greater than 1,000:1.

Description of the Model

Conceptual Model

A digital ground-water flow model is a mathematical representation of an aquifer system and is constructed by (1) quantifying the physical characteristics of an aquifer system, and (2) translating these characteristics into a form which can be manipulated by a computer. Most natural ground-water flow systems, however, are far too complex to be precisely represented in this manner. As a practical matter, therefore, digital flow models are constructed from idealized and simplified representations of aquifer systems. These simplified versions of the natural systems are called conceptual models.

Figure 17 shows schematically the conceptual model which was used to construct the digital model described in this report as interpreted from geologic and hydrologic information previously discussed.

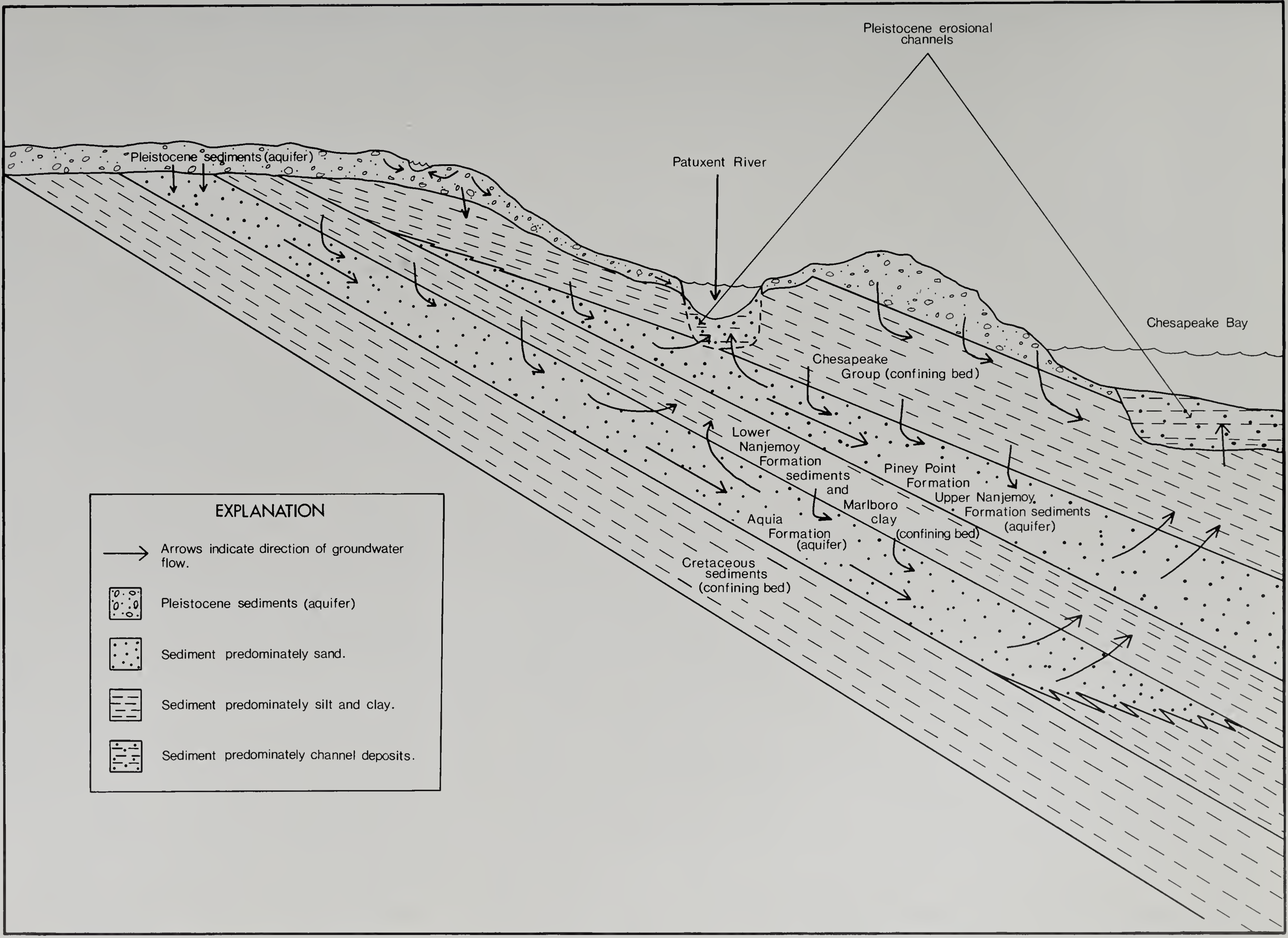


Figure 17.—Schematic diagram showing the conceptual model used in constructing the digital model.

The project area is conceived to be covered by a mantle of Pleistocene sediments which acts as a water-table aquifer. This water-table aquifer is recharged directly from precipitation. Most of the water in this aquifer is ultimately discharged into streams or by evapotranspiration. A small amount of water, however, percolates vertically and recharges the Aquia and Piney Point-Nanjemoy aquifers. Where the Aquia aquifer is directly overlain by Pleistocene sediments (for example, the outcrop-subcrop area), this vertical leakage is greater than where the Aquia is overlain by confining-bed material. Because of the subsurface truncation of the Piney Point Formation and the upper sands of the Nanjemoy Formation, the Piney Point-Nanjemoy aquifer does not have an outcrop area. Discharge from the Aquia and Piney Point-Nanjemoy aquifers occurs as upward leakage through confining beds in downgradient areas. Additional discharge occurs in major river valleys, such as the Patuxent River, where confining-bed material has been eroded by Pleistocene channels.

This conceptual model is consistent with the main features of the natural flow system as shown on plates 3 and 6. It is also consistent with the distribution and lithology of the Tertiary sediments as shown on plates 1 and 2. It should be remembered, however, that this conceptual model represents a simplification of the natural system. It therefore introduces the possibility of error in areas where the simplifications may not be good approximations. Future studies with more complete data will possibly add refinements to the conceptual model used in this report.

Grid Design

The model area was divided into a rectangular grid having 3 layers, 28 rows, and 55 columns. A variable grid spacing was used so that the smallest grid blocks coincide with areas where greater accuracy was needed. A multiplication factor of 1.5 was used to expand the block size outside the area of interest. The smallest block in plan view was 1 mi^2 and the largest was 25 mi^2. By convention, the point at the center of each block is called the node. The layer-row-column system (I,J,K) was used to label each node. For example, the index for the node (1,5,8) refers to the center of the block which is located in layer 1, row 5, column 8. For the model in this report, layer 1 represents the Aquia aquifer, layer 2 represents the Piney Point-Nanjemoy aquifer, and layer 3 represents the Pleistocene water table aquifer. *Each input value (transmissivity, vertical hydraulic conductivity, and so forth) assigned to a node is considered to be the average value over the entire block. Similarly, each output value (hydraulic head, drawdown) is also an average value for that block.* The grid design used for this study is shown in figure 18.

Model Boundaries

The first step in translating the conceptual model of the Aquia and Piney Point-Nanjemoy aquifer system into a digital model was to select appropriate boundaries. These boundaries were placed so that they were consistent with the hydrogeologic framework of the aquifer system. Because natural aquifer boundaries in Southern Maryland do not coincide with the study area, the area modeled was considerably larger than the project area.

The Aquia aquifer has several natural boundaries which were utilized in the modeling process. The eastern boundary of this aquifer coincides with the change from facies I to facies III (fig. 4) and was modeled as no-flow. The western boundary coincides with the Aquia outcrop-subcrop area and was modeled as a no-flow boundary. The boundary to the north, where the Aquia aquifer extends through Queen Annes County to Delaware, was assumed to be no-flow and was placed far enough away from the study area to have minimal effect on model results. Although the Aquia Formation extends to the south into Virginia, its lithology changes to a poorly sorted fine silty sand (Drobnyk, 1965) that is not generally utilized as an aquifer. No data on the yield characteristics of the Aquia are available for this area of Virginia. However, based on the lithology, it is assumed that the transmissivity is relatively low. It was judged that this area of low transmissivity could be best simulated by treating it as a no-flow boundary. The location of simulated no-flow boundaries for the Aquia aquifer are shown on figure 18.

The Piney Point-Nanjemoy aquifer also has natural boundaries which were utilized in the modeling process. The western boundary, which was modeled as no-flow, approximates the subsurface truncation of the Piney Point-Nanjemoy aquifer. The southern boundary borders an area of low transmissivity and is also modeled as no-flow (Williams, 1979). The northeastern and eastern boundaries are artificial since the Piney Point Formation extends in this direction up to New Jersey. However, no-flow boundaries in this direction were placed far enough away so that they would have little or no effect on model results in the project area. The location of simulated no-flow boundaries for the Piney Point-Nanjemoy aquifer are shown in figure 18.

The lower boundary, which separates the base of the Aquia aquifer from the underlying Cretaceous sediments, was modeled as a no-flow boundary.

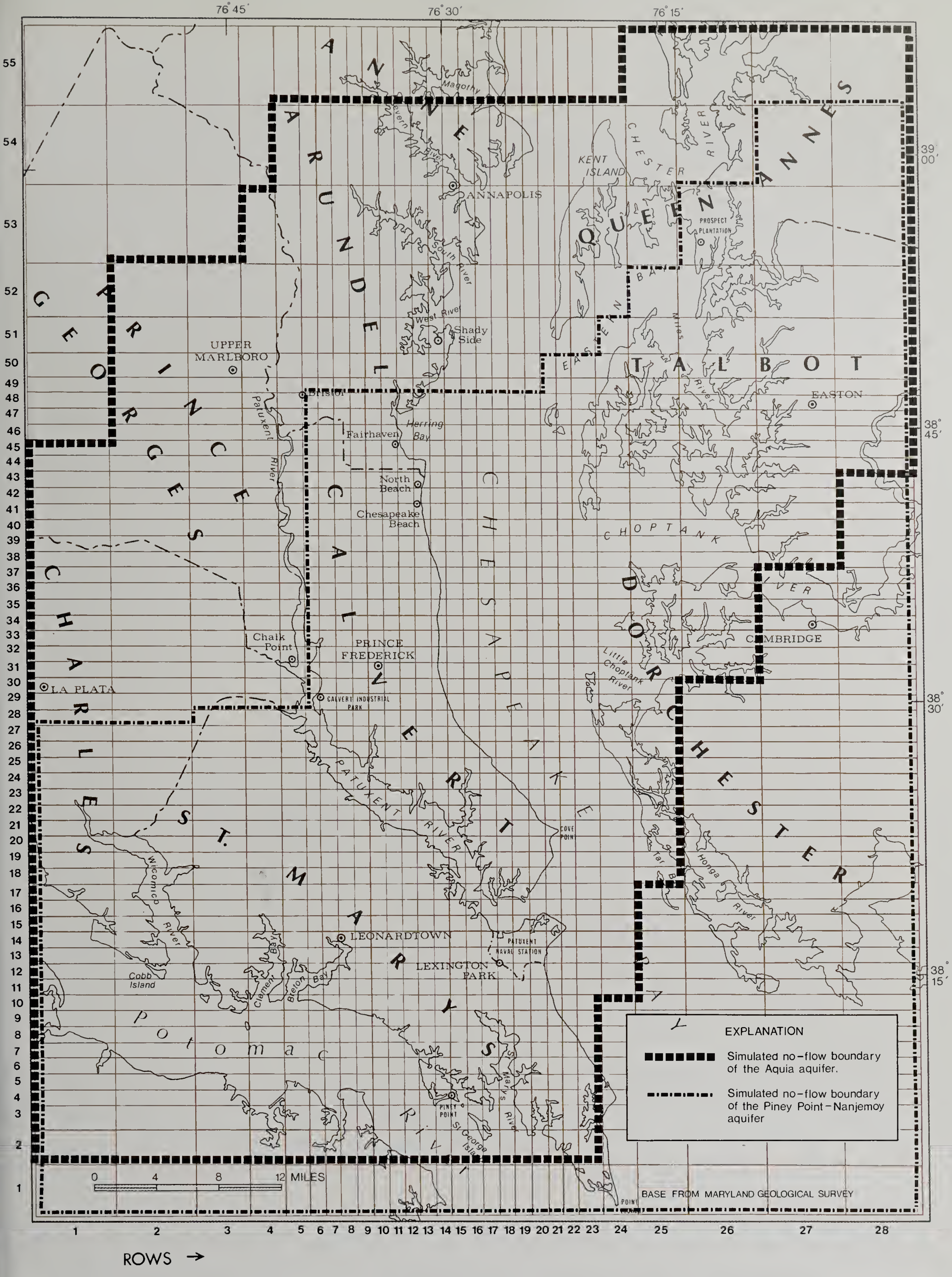
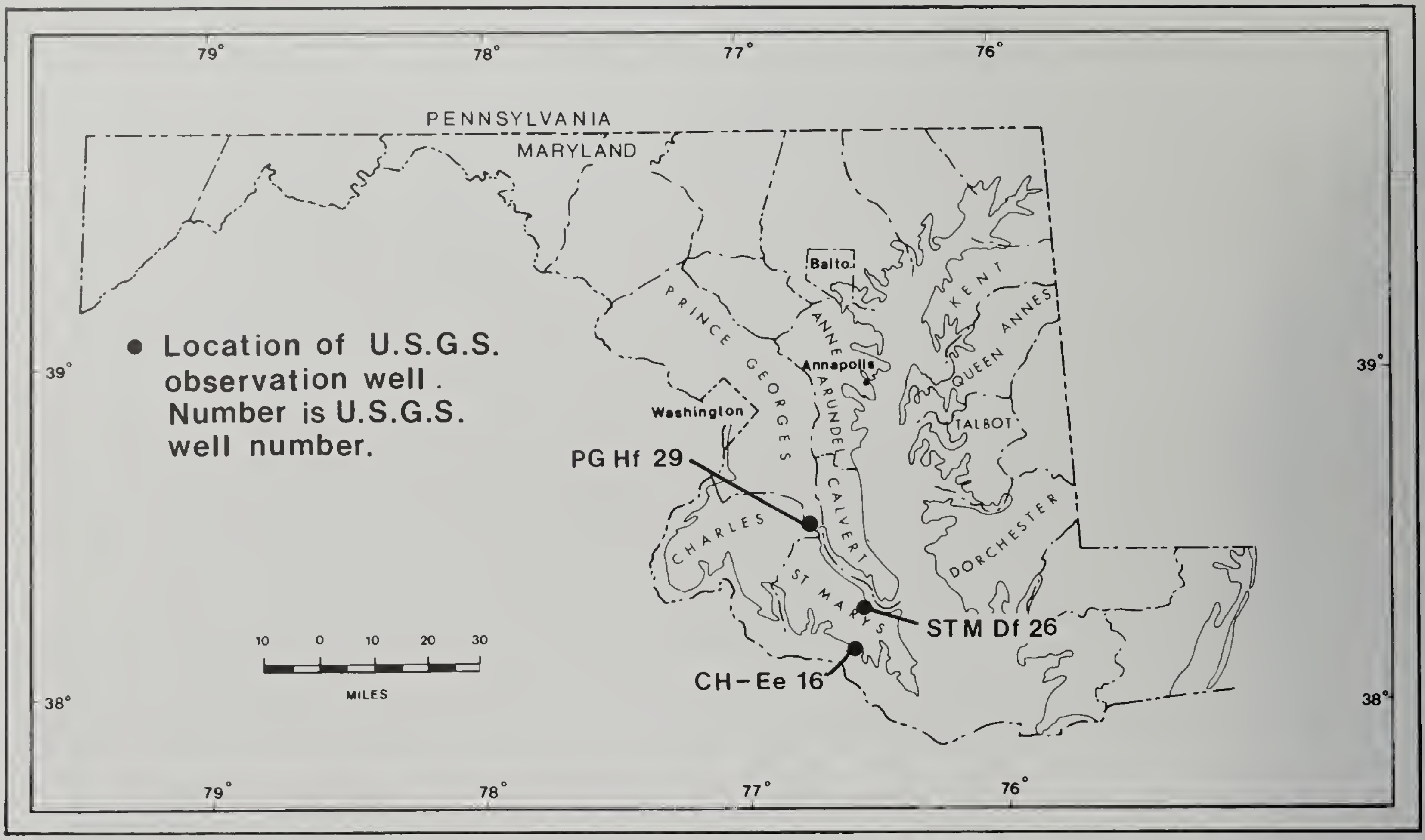


Figure 18.—Finite difference grid and simulated no-flow boundaries of the digital model.



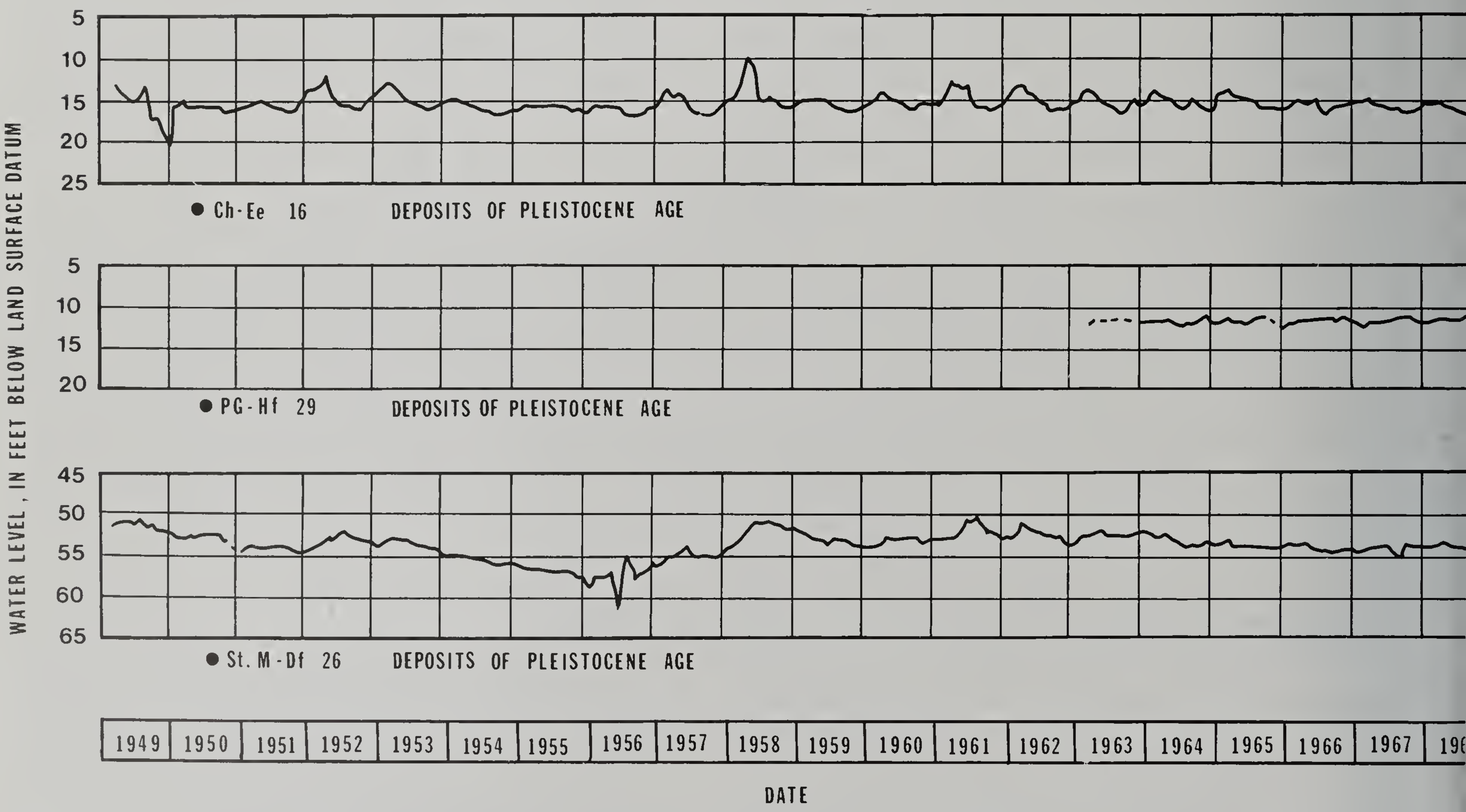


Figure 19.—Hydrographs of observation wells in the Pleistocene water-table aquifer.

Some vertical leakage might exist between the Aquia aquifer and the underlying Magothy aquifer. However, the thick clay layers of the Severn Formation that separates the Aquia and Magothy aquifers are believed to restrict leakage through the lower boundary.

The upper boundary of the aquifer system was modeled as a constant-head boundary. Conceptually, the upper boundary simulates the Pleistocene water-table aquifer in Southern Maryland. The water-table aquifer recharges the underlying confined aquifer system by vertical leakage. The rate of vertical leakage depends on the head gradient across, the thickness, and vertical hydraulic conductivity of the confining beds. An assumption implicit in this treatment of the upper boundary is that heads in the Pleistocene water-table aquifer remain relatively constant. Figure 19 shows three hydrographs of water-table wells in Southern Maryland. The hydrographs indicate that although short-term variations occur, the long-term water-level trend is relatively constant. This long-term trend indicates that the constant-head assumption for the upper boundary of the model is reasonable.

Figure 20 summarizes the boundary conditions used in the digital model. The upper Pleistocene aquifer (layer 3) is modeled as a constant-head boundary. The subsurface truncation of the Piney Point-Nanjemoy aquifer (layer 2) is modeled as a no-flow boundary. Areas of layer 2 overlying the Aquia aquifer (layer 1) northwest of the subsurface truncation were modeled as a constant-head boundary in order to simulate the Pleistocene water-table aquifer in areas where the Piney Point-Nanjemoy aquifer is absent. In areas where Pleistocene sands directly overlie Aquia sands, a thin (1 ft) confining bed was considered to separate layers 1 and 2 of the model. The subsurface facies change of the Aquia aquifer was modeled as a no-flow boundary.

Transmissivity and Storage Coefficient

Values of transmissivity and storage coefficient for the Aquia and Piney Point-Nanjemoy aquifers are discussed in the Hydrogeology section. The transmissivity distributions of the Aquia and Piney Point-Nanjemoy aquifers are shown in figures 5 and 10, respectively.

Average transmissivity values for the Aquia and Piney Point-Nanjemoy aquifers were estimated from figures 5 and 10 for each block of the model grid. These values were then entered into the model

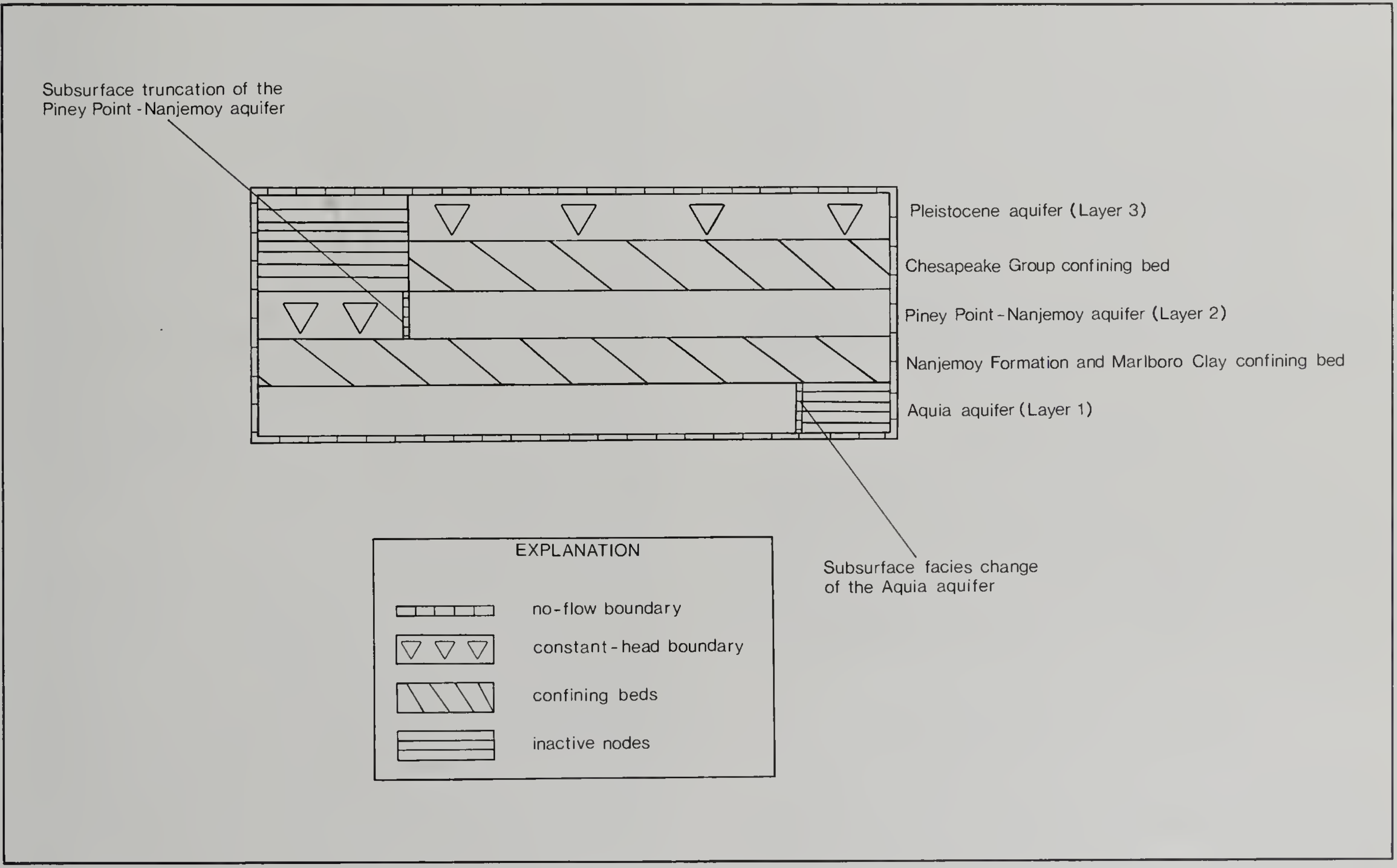


Figure 20.—Schematic diagram showing boundary conditions used in the digital model.

as a matrix. The value of 1×10^{-4} is a representative value of storage coefficient for the confined portions of the Aquia aquifer and was used throughout the modeled area. A value of 3×10^{-4} is a representative storage coefficient value for the Piney Point-Nanjemoy aquifer and was used throughout the modeled area.

Starting Heads

The prepumping potentiometric surfaces of the Aquia and Piney Point-Nanjemoy aquifers were estimated on the basis of historical water levels (pls. 3 and 6). Average head values for each grid block were estimated from these figures and used as starting head values for model simulations.

The Pleistocene water-table aquifer provides recharge to the Aquia-Piney Point-Nanjemoy system in Southern Maryland. The potentiometric surface of this unit was estimated from the altitude of perennial streams that intersect the water table (pl. 9). Average head values for each grid block were entered into the model as a constant-head matrix.

Vertical Hydraulic Conductivities of Confining Beds

The upper confining beds of the Aquia aquifer are the clays and silts of the Marlboro Clay and Nanjemoy Formations. The Piney Point-Nanjemoy is confined above by the silts and clays of the Chesapeake Group. Some values of vertical hydraulic conductivity for these confining beds are available from laboratory core analyses (table 2). For the most part, however, vertical hydraulic conductivities were determined by calibration of the model. In all cases the vertical hydraulic conductivities as determined from model calibration fall within the range of experimentally determined values (10^{-9} to 10^{-10} ft/s).

Specific Storage

Very few data on the specific storage of the confining beds in Southern Maryland are available. Hansen (1977) presented the results of consolidation tests on the Marlboro Clay which shows a specific storage on the order of 10^{-5} ft^{-1}. In the absence of other data, this value was used in the model.

Thickness of Confining Beds

The thickness of the upper confining beds of the Aquia and Piney Point-Nanjemoy aquifers was estimated for each grid block from figures 6 and 11. These values were then entered into the model as a matrix.

Model Calibration

Before a model is used to predict future water levels, it is necessary to verify the ability of the model to reproduce historical water levels and water-level changes due to pumpage. Although model input represents the best available data, these parameters frequently have to be adjusted (calibrated) in order for the model to reproduce historical water levels. In calibrating the Aquia and Piney Point-Nanjemoy model, parameters that were judged to be relatively well known were not varied during calibration. The model parameters not varied during calibration were starting head of the Pleistocene water-table aquifer, thickness of confining beds, aquifer transmissivity, storage coefficient, and documented pumpage by major users. The vertical hydraulic conductivities of confining beds were varied to calibrate the model.

The method of calibrating a digital flow model is, in large measure, determined by the kinds of data available. Ideally, long-term hydrographs of observation wells and documented pumpage would be available for each grid block in the model. Such complete data, however, are rarely available. In Southern Maryland, enough water levels were recorded early in the history of aquifer development to estimate the prepumping potentiometric surfaces of the Aquia and Piney Point-Nanjemoy aquifers (pls. 3 and 6). In addition to this data, Otton (1955) published the potentiometric surfaces of the Aquia and Piney Point-Nanjemoy aquifers as they existed in approximately 1952 (pls. 4 and 7). Finally, the potentiometric surfaces of the Aquia and Piney Point-Nanjemoy aquifers were measured in 1980 as part of this study (pls. 5 and 8). A few hydrographs of water levels in the aquifers of Southern Maryland are available (Weigle, 1970; Williams, 1979). These hydrographs, however, cover only a small portion of the aquifer-development history and are available for only a few locations. It was determined, therefore, that the prepumping, 1952, and 1980 potentiometric surfaces were the best data available for calibrating the model.

The calibration of the Aquia and Piney Point-Nanjemoy model was accomplished in three steps. First, the model was adjusted so that it could reproduce the estimated steady-state (prepumping) potentiometric surfaces of the aquifers. This phase of calibration was done on a trial-and-error basis by adjusting confining-bed vertical hydraulic conductivities. It was found that relatively high values of vertical hydraulic conductivity had to be assigned to the confining beds overlying the Piney Point-Nanjemoy aquifer in major river valleys. In these areas it had been documented that Pleistocene

Table 6.—Pumpage rates used during the calibration period 1890-1980
[Average pumpage in million gallons per day]

County	Aquifer	Pumping period						
		1	2	3	4	5	6	7
		1890-1942	1942-46	1946-52	1952-66	1966-76	1976-79	1979-80
St. Marys 1/	Piney Point-Nanjemoy	0.14	0.46	0.77	0.69	0.79	0.92	0.99
	Aquia	.05	1.73	.80	1.25	2.00	2.43	2.62
Calvert 1/	Piney Point-Nanjemoy	-	.30	.15	.37	.64	.83	1.01
	Aquia	-	.15	.08	.13	.61	1.44	1.81
Anne Arundel 1/	Piney Point-Nanjemoy	-	-	-	-	-	-	-
	Aquia	-	-	.019	.032	.10	.49	.68
Charles	Piney Point-Nanjemoy	-	-	-	-	-	-	-
	Aquia	-	-	-	.05	.10	.27	.28
Prince Georges	Piney Point-Nanjemoy	-	-	-	-	-	-	-
	Aquia	-	-	-	.05	.10	.32	.34
Queen Annes	Piney point-Nanjemoy	-	-	-	-	-	-	-
	Aquia	-	-	-	-	.1	.34	.34
Talbot	Piney Point-Nanjemoy	-	-	-	-	-	-	-
	Aquia	-	-	-	-	.80	.80	.80
Dorchester	Piney Point-Nanjemoy	.20	3.91	3.91	3.91	3.91	3.91	3.91
	Aquia	-	-	-	-	-	-	-

1/ Location of pumping centers shown in figures 11 and 12.

streams had eroded channels into the confining-bed material and deposited more permeable silty sands and gravels. Because of this geologic evidence, it was judged that the higher values of vertical hydraulic conductivity in these areas were justified. This phase of calibration was considered complete when the model could reproduce the shape of the prepumping potentiometric contours (pls. 3 and 6) and calculated water levels agreed with measured water levels within 5 ft.

In order to simulate the pumping history of the Aquia and Piney Point-Nanjemoy aquifers, pumpage was divided into seven pumping periods as listed in table 6. The year 1890 was chosen to start the simulation period because little pumpage had taken place in these aquifers at that time and it is reasonable to assume near steady-state conditions. The divisions of pumping periods shown on table 6 were chosen in order to best simulate significant changes in pumping patterns. For example the heavy pumping during World War II, for the period 1942-46, was simulated as one pumping period.

The second phase of calibration was to match the computed 1952 potentiometric surfaces of the Aquia and Piney Point-Nanjemoy aquifers with the potentiometric maps published by Otton (1952). It was not necessary to change model parameters during this phase of calibration in order to obtain a match that was considered acceptable. In all cases, the calculated water levels agreed with measured water levels within 5 ft.

The last stage of calibration was to match the computed potentiometric surfaces for 1980 to the potentiometric surfaces of the aquifers as measured in 1980. Some changes in the vertical hydraulic conductivity of the Piney Point-Nanjemoy upper confining bed were necessary in order to match the computed and observed water levels within a margin of 5 ft. Therefore, after the changes were made for the last calibration period, a final calibration run was made to insure that the changes did not significantly alter the matches of the first two calibration periods. The final matches between the computed prepumping, 1952, and 1980 potentiometric surfaces and available water-level measurements for those periods are shown on plates 10 and 11.

The level of confidence placed on model predictions should be tempered by an evaluation of the model calibration. In general, the greatest amount of confidence in the model is warranted where water-level data are plentiful. Similarly, less confidence in the model calibration is warranted where water-level data are scarce. Plates 10 and 11 show the water-level control points which were used for each phase of model calibration. The area where the greatest amount of data were available for calibration is in the Lexington Park—PNATS, Leonardtown, and Piney Point areas of St. Marys County. The model calibration in these areas, therefore, should be considered the most reliable. Adequate data were also available near the Chalk Point, Benedict, Prince Frederick, North Beach, and Shady Side areas. In the areas near the subcrop zone of the Aquia, few water levels were available and the calibration should be given less confidence. Also, areas on the Eastern Shore of Maryland had few data available and the calibration should not be given a high level of confidence.

Water Budget

The water budget calculated by the digital model during the calibration period is of interest for two reasons. First, it provides a rough check on the model solution by indicating if the quantity of water flowing into and out of the aquifer system is reasonable. Secondly, it can provide estimates of the total recharge to the aquifer system. These recharge estimates are useful to water planners because they may reflect the yield potential of the aquifer system.

Table 7 summarizes the water budget of the Aquia and Piney Point-Nanjemoy aquifers (considered together) for the 90-year calibration period as calculated by the model. The main source of water (recharge) to the aquifer system is leakage from the overlying Pleistocene water-table aquifer. Additional water is derived from storage in the aquifers and confining beds. Storage is treated as a source by this model (Trescott, 1975). Water is discharged from the aquifer system by upward leakage to the overlying Pleistocene aquifer and by pumpage.

The data in table 7 show that the rate of recharge to the aquifer system varied over the calibration period from 0.22 to 0.57 in./yr. These recharge rates are consistent with rates to be expected of confined aquifer systems (Walton, 1970).

The yield potential of an aquifer system is, in part, limited by the rate that it is recharged. It is important to realize, however, that factors such as aquifer transmissivity, proximity of aquifer boundaries, and well-field spacing can also limit yield potential. Aquifer transmissivity is particularly important in this respect. If transmissivity is low, then drawdowns resulting from pumpage can be more of a limiting factor to yield than recharge rates. Another factor which complicates this type of analysis is that aquifer recharge rates are not necessarily con-

Table 7.—Model-calculated water budget of the Aquia and Piney Point-Nanjemoy aquifer system for the calibration period

Pumping period	Sources [1]				Discharges [1]				Percent difference between sources and discharges
	Leakage [2]		Storage		Leakage [3]		Pumpage		
	(in./yr)	(ft^3/s)	(gal/d)	(ft^3/s)	(in./yr)	(ft^3/s)	(gal/d)	(ft^3/s)	
1	0.22	9.72	2,160	3.33×10^{-3}	0.21	9.14	390,000	0.60	< 1
2	.41	18.1	253,600	0.390	.19	8.40	6,500,000	9.98	< 1
3	.39	17.2	33,700	.052	.19	8.40	5,800,000	8.93	< 1
4	.40	17.7	33,300	.051	.17	7.51	6,500,000	10.0	< 1
5	.45	19.9	70,400	.109	.16	7.06	9,140,000	14.1	< 1
6	.52	22.9	189,000	.292	.13	5.74	11,500,000	17.7	< 1
7	.57	25.2	230,136	.355	.12	5.30	12,960,000	20.0	< 1

[1] Sources and discharges are considered for the aquifer system as a whole.
[2] Figures assume recharge area of 600 mi^2.
[3] Figures assume discharge area of 600 mi^2.

stant. If more potential recharge (precipitation) is available to an aquifer system than is utilized, then recharge rates can increase if pumping stress is increased. Conversely, the recharge rate can decrease if pumping stress is decreased.

The complex relationship between aquifer recharge rates and aquifer yield can be illustrated with the model-calculated water budget shown in table 7. During the first pumping period, recharge to the aquifer system (leakage) was 0.22 in./yr (6.3 Mgal/d). The pumpage during this period was only 0.39 Mgal/d and, therefore, recharge greatly exceeded pumpage. In contrast, recharge to the aquifer system during the last pumping period was 0.57 in./yr (16.3 Mgal/d), while pumpage increased to about 13 Mgal/d. Therefore, in the last pumping period recharge still exceeded pumpage, but the difference was much less than in the first pumping period. It is significant that during the last pumping period, large water-level declines occurred in some places. These water-level declines, which are a function of aquifer transmissivity and proximity of aquifer boundaries, impose a practical limit on aquifer yield in certain places even though aquifer recharge remains higher than pumpage. This suggests that aquifer properties at individual pumping locations are more limiting to water production than recharge rates in this aquifer system. From a water planner's point of view, the amount of water-level drawdown considered acceptable will ultimately limit aquifer yields rather than recharge rates.

Simulated Future Water Levels

The water budget analysis provided by the model suggests that aquifer yield properties and drawdowns resulting from pumpage rather than the recharge rate to the aquifer system are the factors that will limit the quantity of available water. The next step in the model analysis, therefore, was to estimate aquifer drawdowns based upon alternative scenarios of future pumpage. The simulations consist of the following:

1. A series of simulations using estimates of future pumpage in Southern Maryland for the intervals (a) 1980-1985, (b) 1980-1990, and (c) 1980-2000.
2. A series of simulations to predict water levels in the year 2000 assuming the Aquia aquifer is pumped an average of 1.5, 2.0, 2.5, and 3.0 Mgal/d in the Lexington Park—PNATS area. These simulations include 1980 pumpage.
3. A series of simulations designed to show the effects of withdrawing 1 Mgal/d from northern St. Marys County for 10 years. Two pumping schemes were simulated: (a) 1 Mgal/d of pumpage from a single well field; and (b) 1 Mgal/d of pumpage spaced among four well fields.
4. A series of simulations designed to show drawdown in the Piney Point-Nanjemoy aquifer due to pumpage in the Aquia aquifer. Two simulations are presented that show (a) drawdown in the Piney Point-Nanjemoy due to a 1 Mgal/d withdrawal from the Aquia in the Lexington Park-PNATS area, and (b) drawdown in the Piney Point-Nanjemoy due to a 2 Mgal/d withdrawal from the Aquia in the Lexington Park-PNATS area.
5. A series of simulations designed to show drawdown effects of a hypothetical 0.5-Mgal/d well field in southern Anne Arundel County. Three different sites were simulated at this pumping rate for a period of 10 years. These sites were located near (a) Shady Side, (b) Fairhaven, and (c) Bristol.
6. A simulation of a 0.5 Mgal/d withdrawal from the Aquia aquifer at the Chalk Point Power Plant in Prince Georges County.
7. A hypothetical simulation which assumes that all appropriated users of the Aquia and Piney Point-Nanjemoy aquifers daily pump their maximum Groundwater Appropriation Permit (GAP) allocations for a period of 10 years.
8. A simulation which assumes a pumpage of 0.5 Mgal/d from the Aquia aquifer in Chesapeake Beach.

Each of these pumping scenarios was selected and simulated in response to information requests from the planning departments of St. Marys, Calvert, and Anne Arundel Counties. They are designed to illustrate the yield potential of the Aquia and Piney Point-Nanjemoy aquifers in areas where pumpage is expected to increase in the future. Because of the many simplifications made of the natural aquifer system during construction of the digital model, the drawdown and water-level predictions made should not be considered exact. Instead, they should be considered the best estimates which can be made, given the current available data and technology.

Projected Water Levels Based on Estimates of Future Withdrawal

A series of transient simulations of the Aquia and Piney Point-Nanjemoy aquifers were made using estimates of future withdrawals. These estimates (table 8) assume that future pumpage will be directly proportional to the projected population growth. For example, if the projected population increase is 10 percent, pumpage is assumed to increase 10 percent. These estimates also assumed that all in-

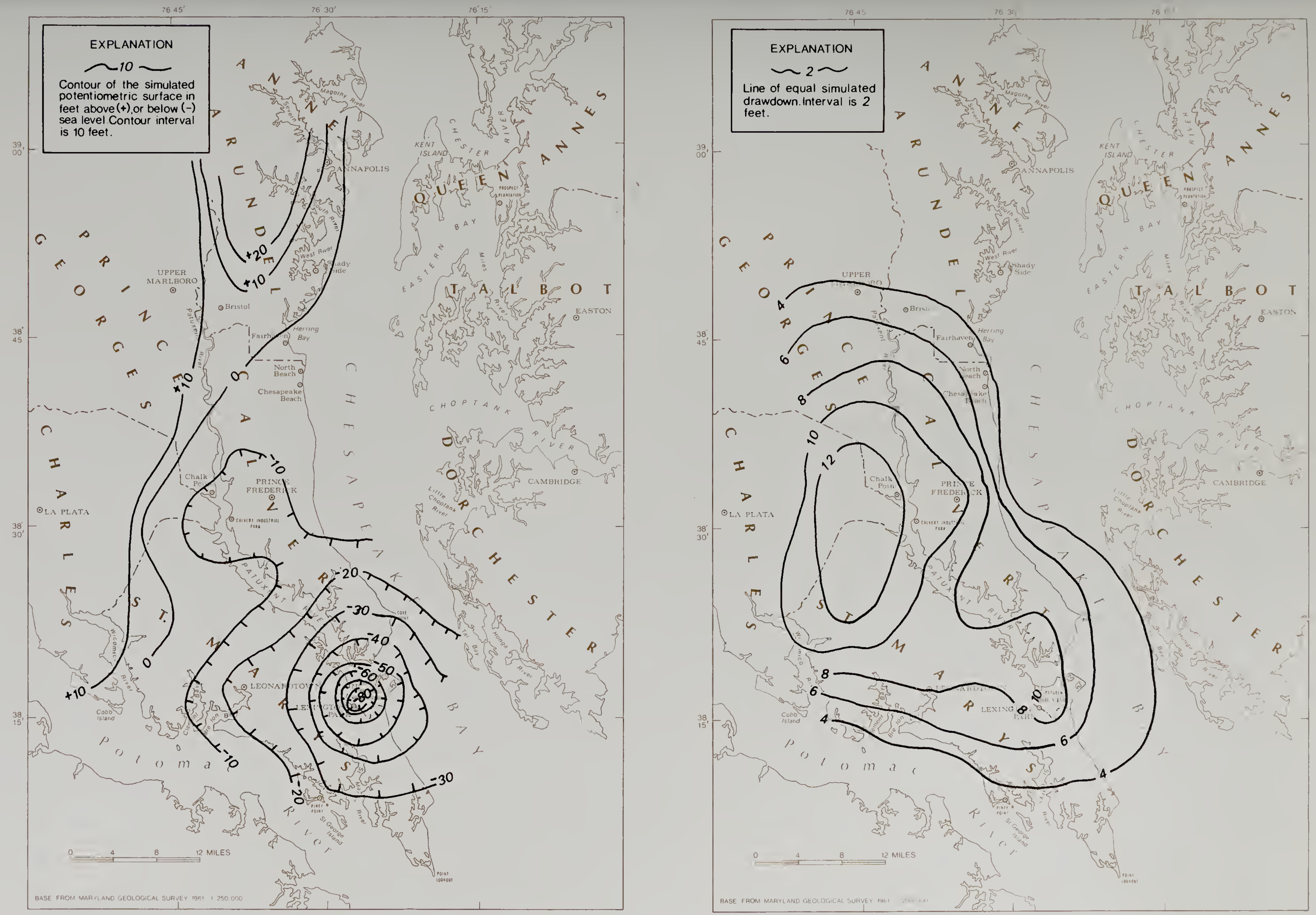
Table 8.—Projected rates of future pumpage from the Aquia and Piney Point-Nanjemoy aquifers based on county population growth estimates

County	County planning area	Projected population 1/			Aquifer	Projected pumping rates 2/ (gal/d)		
		1985	1990	2000		1985	1990	2000
St. Marys	Pine Hill Run	31,026	33,527	39,194	Aquia	1,740,000	1,890,000	1,970,000
					Piney Point-Nanjemoy	700,000	750,000	980,000
	Leonardtown	6,093	6,926	8,817	Aquia	380,000	440,000	550,000
					Piney Point-Nanjemoy	0	0	0
	Luckland Run	6,620	8,445	12,582	Aquia	310,000	390,000	590,000
					Piney Point-Nanjemoy	0	0	0
	Flood Creek	1,733	1,974	2,522	Aquia	10,000	11,000	16,000
					Piney Point-Nanjemoy	20,000	23,000	28,000
	Piney Point	3,100	3,286	3,708	Aquia	180,000	190,000	210,000
					Piney Point-Nanjemoy	62,000	66,000	74,000
	Lake Conoy	2,056	2,223	2,603	Aquia	0	0	0
					Piney Point-Nanjemoy	130,000	140,000	116,000
	Carrol Pond	1,426	1,593	1,973	Aquia	0	0	0
					Piney Point-Nanjemoy	160,000	180,000	220,000
	Manor Run	2,530	3,030	4,165	Aquia	32,000	39,000	53,000
					Piney Point-Nanjemoy	16,000	19,000	27,000
	Indian Creek	6,965	8,800	12,937	Aquia	280,000	360,000	520,000
					Piney Point-Nanjemoy	0	0	0
	Dukeharts Creek	7,871	8,880	11,170	Aquia	37,000	42,000	52,000
					Piney Point-Nanjemoy	0	0	0
Calvert	A	13,000	15,500	20,500	Aquia	684,800	729,600	854,400
					Piney Point-Nanjemoy	374,400	425,600	582,400
	B	11,150	13,100	17,300	Aquia	599,200	638,400	747,600
					Piney Point-Nanjemoy	327,600	372,400	509,600
	C	16,450	19,800	26,200	Aquia	856,000	912,000	1,068,000
					Piney Point-Nanjemoy	468,000	532,000	728,000
Anne Arundel	8 (Rural)	3/	3/	3/	Aquia	616,000	805,000	1,043,000
					Piney Point-Nanjemoy	0	0	0
	6 (Annapolis)	3/	3/	3/	Aquia	264,000	345,000	447,000
					Piney Point-Nanjemoy	0	0	0
Charles	3/	3/	3/	3/	Aquia	310,000	340,000	370,000
					Piney Point-Nanjemoy	0	0	0
Prince Georges	3/	3/	3/	3/	Aquia	410,000	490,000	590,000
					Piney Point-Nanjemoy	0	0	0

1/ Population projections from Calvert County Comprehensive Water and Sewerage Plan, 1978 update, and St. Marys County Comprehensive Water and Sewerage Plan, 1977 update.
2/ Projected pumping rate assumes that future pumpage is directly proportional to population growth.
3/ Population projections by planning district not available.

creases of future pumpage in Southern Maryland would come from the Aquia and Piney Point-Nanjemoy aquifers. Because the Maryland State Water Resources Administration has mandated that the Piney Point-Nanjemoy aquifer be reserved for domestic and small industrial users, all increases in municipal and large industrial users were assumed to come from the Aquia aquifer. The pumping centers used in this simulation are those located in figure 7 and 12.

Figures 21 and 22 show the predicted potentiometric surface of the Aquia and Piney Point-



Simulated 1985 potententiometric surface of the Aquia aquifer.

Simulated drawdown of the potentiometric surface of the Aquia aquifer from 1980 to 1985.

Figure 21.—Simulated 1985 potentiometric surface of the Aquia aquifer and simulated drawdown from 1980 based on estimates of future pumpage.

Simulated 1985 potentiometric surface of the Piney Point-Nanjemoy aquifer.

Simulated drawdown of the potentiometric surface of the Piney Point-Nanjemoy aquifer from 1980 to 1985.

Figure 22.—Simulated 1985 potentiometric surface of the Piney Point-Nanjemoy aquifer and simulated drawdown from 1980 based on estimates of future pumpage.

Nanjemoy aquifers in 1985. Also shown are the drawdowns from the 1980 potentiometric surface. The maximum head declines for the Aquia aquifer are predicted to occur in the Lexington Park—PNATS area, in northern St. Marys County, and near Prince Frederick in Calvert County. In the Lexington Park—PNATS area, declines of 8 to 10 ft are predicted. In northern St. Marys County, where presently rapid population growth is taking place, 10 to 15 ft of head decline is predicted. Near Prince Frederick, approximately 8 to 10 ft of head decline is predicted. The maximum head declines for the Piney Point-Nanjemoy aquifer are predicted to occur in the Lexington Park-PNATS area. Declines in this area are predicted to be about 6 ft for the simulated period.

Figures 23 and 24 show the Aquia and Piney Point-Nanjemoy potentiometric surfaces predicted for 1990 based on estimated future withdrawals. Also shown are the predicted water-level declines from the 1980 potentiometric surfaces. For the Aquia aquifer, the greatest drawdowns are predicted to occur in the Lexington Park-PNATS area, northern St. Marys County, and Prince Frederick. For the Piney Point-Nanjemoy aquifer, the greatest drawdowns are predicted to occur in the Lexington Park-PNATS area, near Prince Frederick, and in the North Beach area.

Figures 25 and 26 show the predicted potentiometric surfaces of the Aquia and Piney Point-Nanjemoy aquifers in the year 2000. Also shown are drawdowns from the 1980 potentiometric surfaces.

This series of simulations suggests that water levels in the Aquia and Piney Point-Nanjemoy aquifers will decline in the future in many areas. The predicted maximum rate of decline for the Aquia aquifer is approximately 1.5 ft/yr near Lexington Park. The predicted maximum rate of decline for the Piney Point-Nanjemoy aquifer is approximately 1 ft/yr near Lexington Park. The assumption that pumpage will be proportional to population growth is probably conservative and higher pumpages than the projections used in these simulations are possible. In this case, water-level declines greater than those predicted will occur.

This series of simulations predicts that by the year 2000, the potentiometric surface of the Aquia aquifer near Lexington Park will be more than 100 ft below sea level. The actual pumping levels of production wells will be much lower, probably on the order of 200 to 300 ft below sea level. These predicted low water levels may make production of water from some domestic wells in this area (which typically are designed to lift water 250 to 300 ft) impractical.

Projected Water Levels Based on Hypothetical Withdrawal Rates near Lexington Park-PNATS

The Lexington Park-PNATS area of St. Marys County is presently the heaviest user of ground water from the Aquia aquifer in Southern Maryland. It is important for planners to be able to estimate the amount of water which is available from the Aquia aquifer in this area. To aid planners in this decision-making process, a series of transient simulations was done for the Lexington Park-PNATS area that simulates different pumping rates for the period 1980-2000. Included in these simulations is the average 1980 pumpage (tables 4 and 5). The pumping center simulated is location 26 in figure 7.

The first simulation specified a total withdrawal rate of 1.5 Mgal/d in the Lexington Park-PNATS area for 20 years. The approximate pumpage rate in this area for May 1980 was 1.5 Mgal/d, so that no net increase in pumpage is simulated. Figure 27 shows the predicted drawdown from 1980 to the year 2000. According to this simulation, 1.5 Mgal/d of pumpage will result in about 10 ft of drawdown in the Lexington Park-PNATS area. The drawdown in northern St. Marys County is due to the 1980 rate of domestic pumpage.

The second simulation assumed a total withdrawal in the Lexington Park—PNATS area of 2.0 Mgal/d for 20 years, which is a net increase of 0.5 Mgal/d from 1980. Figure 28 shows the predicted drawdown from the 1980 potentiometric surface. The maximum predicted drawdown for the year 2000 is approximately 40 ft.

The third simulation in this series assumed a total withdrawal in the Lexington Park-PNATS area of 2.5 Mgal/d for 20 years, which is a net increase of 1.0 Mgal/d from 1980. Figure 29 shows the predicted drawdown from the 1980 potentiometric surface in the Aquia aquifer. This drawdown is predicted to be approximately 60 ft during the simulation period for the center of the cone of depression.

The last simulation in this series specified an average withdrawal rate of 3.0 Mgal/d from the Aquia in the Lexington Park—PNATS area, which is a net increase of 1.5 Mgal/d from 1980. The predicted drawdown from 1980 is shown in figure 30. This drawdown is predicted to be approximately 90 ft during the simulation period for the center of the cone of depression.

This series of simulations provides water planners with drawdown estimates in the Aquia aquifer for various rates of pumpage in the Lexington Park-PNATS area. These simulations are designed to help planners estimate the approximate quantity of water available in this area. The quantity of water available ultimately depends on how much draw-

Simulated 1990 potentiometric surface of the Aquia aquifer.

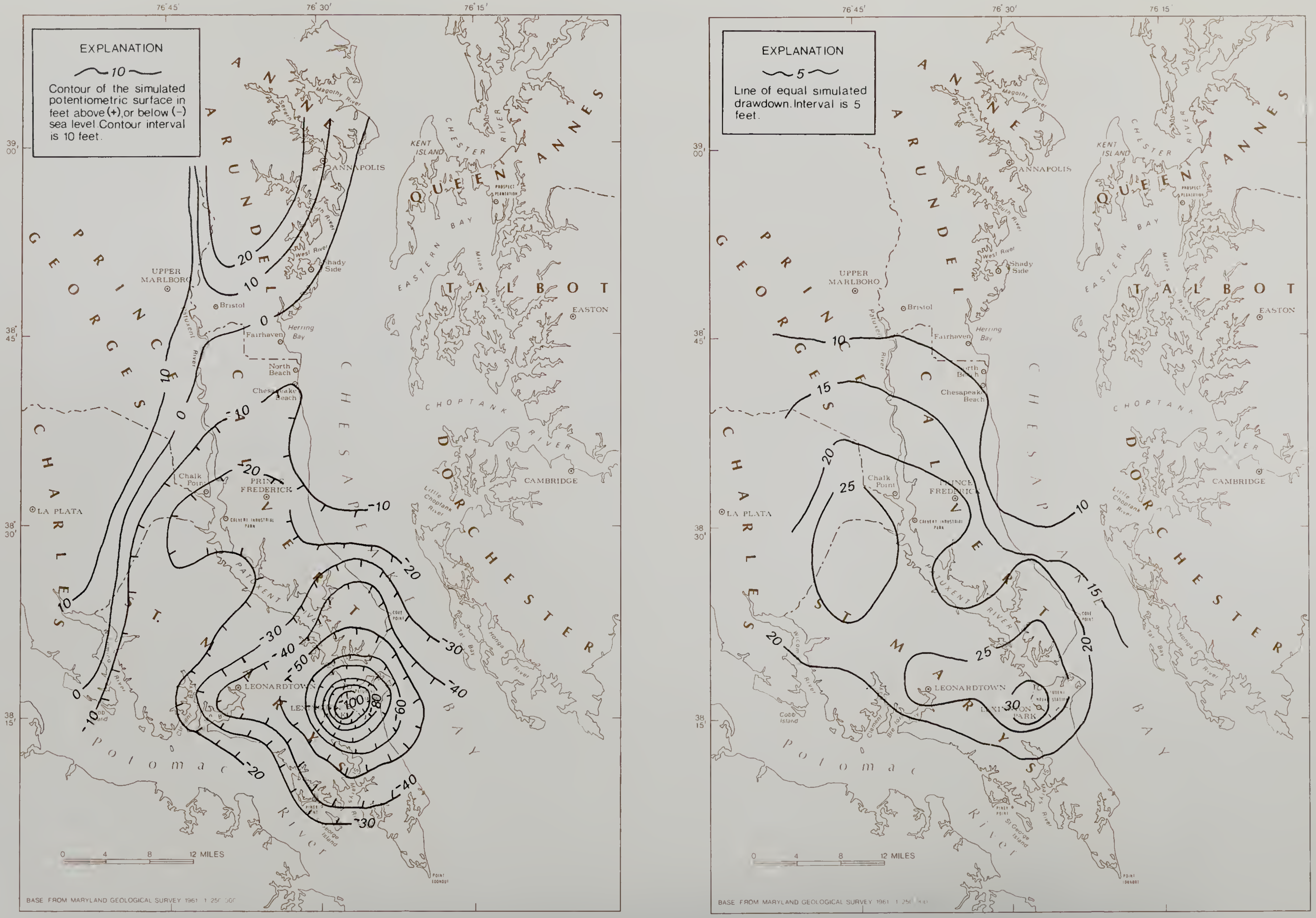
Simulated drawdown of the potentiometric surface of the Aquia aquifer.

Figure 23.—Simulated 1990 potentiometric surface of the Aquia aquifer and simulated drawdown from 1980 based on estimates of future pumpage.

Simulated 1990 potentiometric surface of the Piney Point-Nanjemoy aquifer.

Simulated drawdown of the potentiometric surface of the Piney Point-Nanjemoy aquifer from 1980 to 1990.

Figure 24.—Simulated 1990 potentiometric surface of the Piney Point-Nanjemoy aquifer and simulated drawdown from 1980 based on estimates of future pumpage.



Simulated 2000 potentiometric surface of the Aquia aquifer.

Simulated drawdown of the potentiometric surface of Aquia aquifer.

Figure 25.—Simulated 2000 potentiometric surface of the Aquia aquifer and simulated drawdown from 1980 based on estimates of future pumpage.

Simulated 2000 potentiometric surface of the Piney Point-Nanjemoy aquifer.

Simulated drawdown of the potentiometric surface of the Piney Point-Nanjemoy aquifer from 1990 to 2000.

Figure 26.—Simulated 2000 potentiometric surface of the Piney Point-Nanjemoy aquifer and simulated drawdown from 1980 based on estimates of future pumpage.

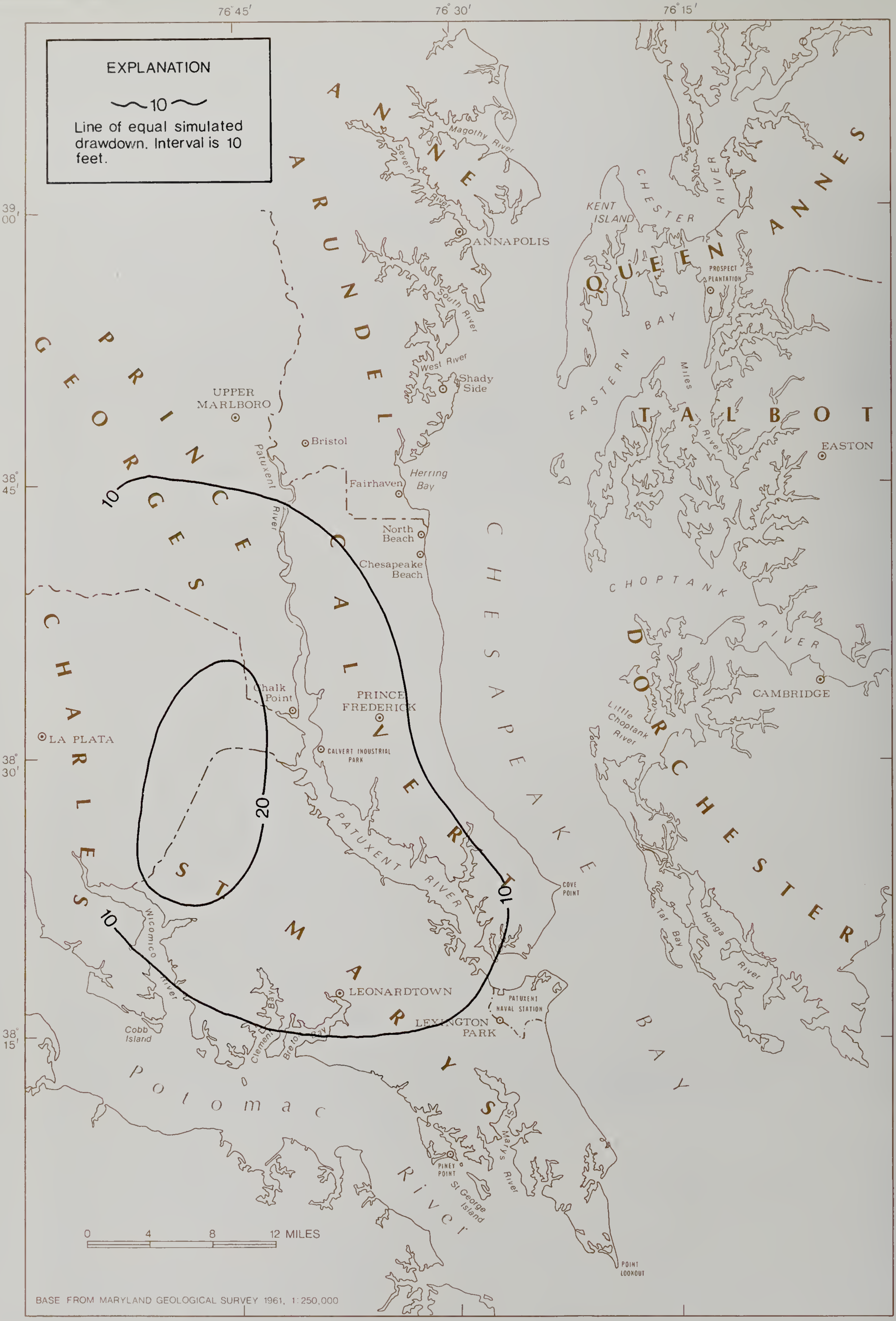


Figure 27.—Simulated drawdown from the 1980 potentiometric surface in the Aquia aquifer based on 20 years of 1.5 Mgal/d pumpage from the Lexington Park—PNATS area.

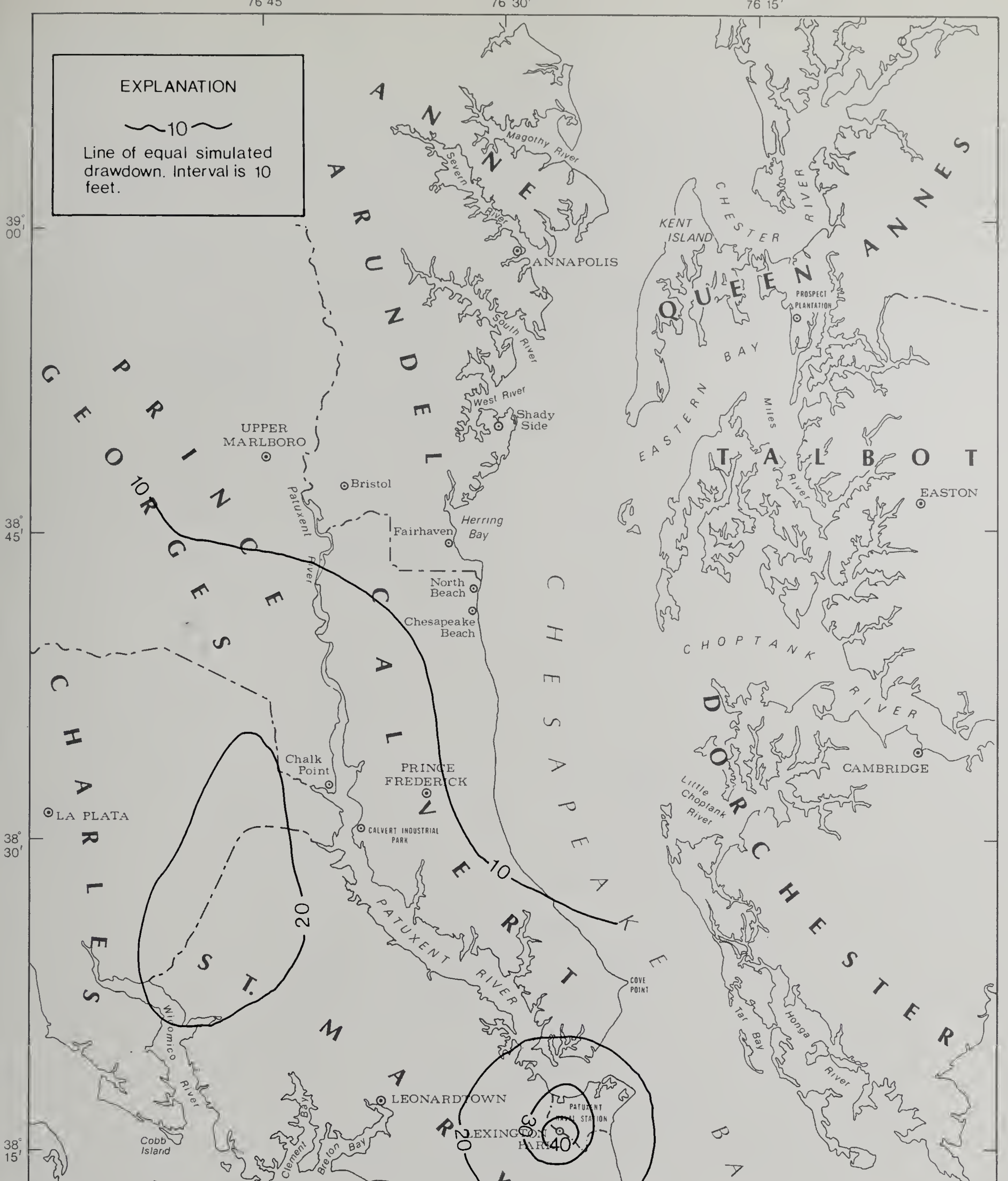


Figure 28.—Simulated drawdown from the 1980 potentiometric surface in the Aquia aquifer based on 20 years of 2.0 Mgal/d pumpage in the Lexington Park-PNATS area.

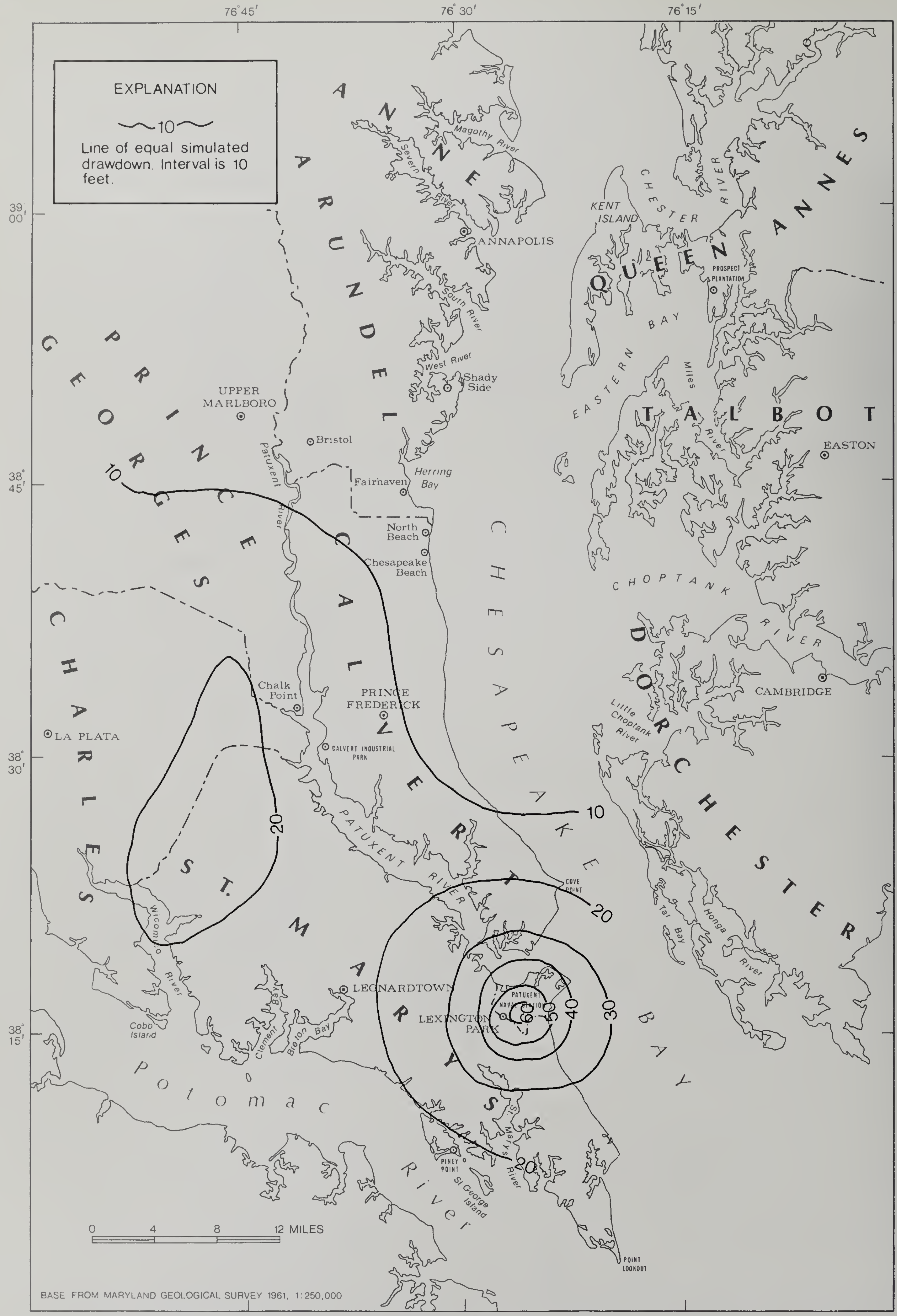


Figure 29.—Simulated drawdown from the 1980 potentiometric surface in the Aquia aquifer based on 20 years of 2.5 Mgal/d pumpage in the Lexington Park-PNATS area.

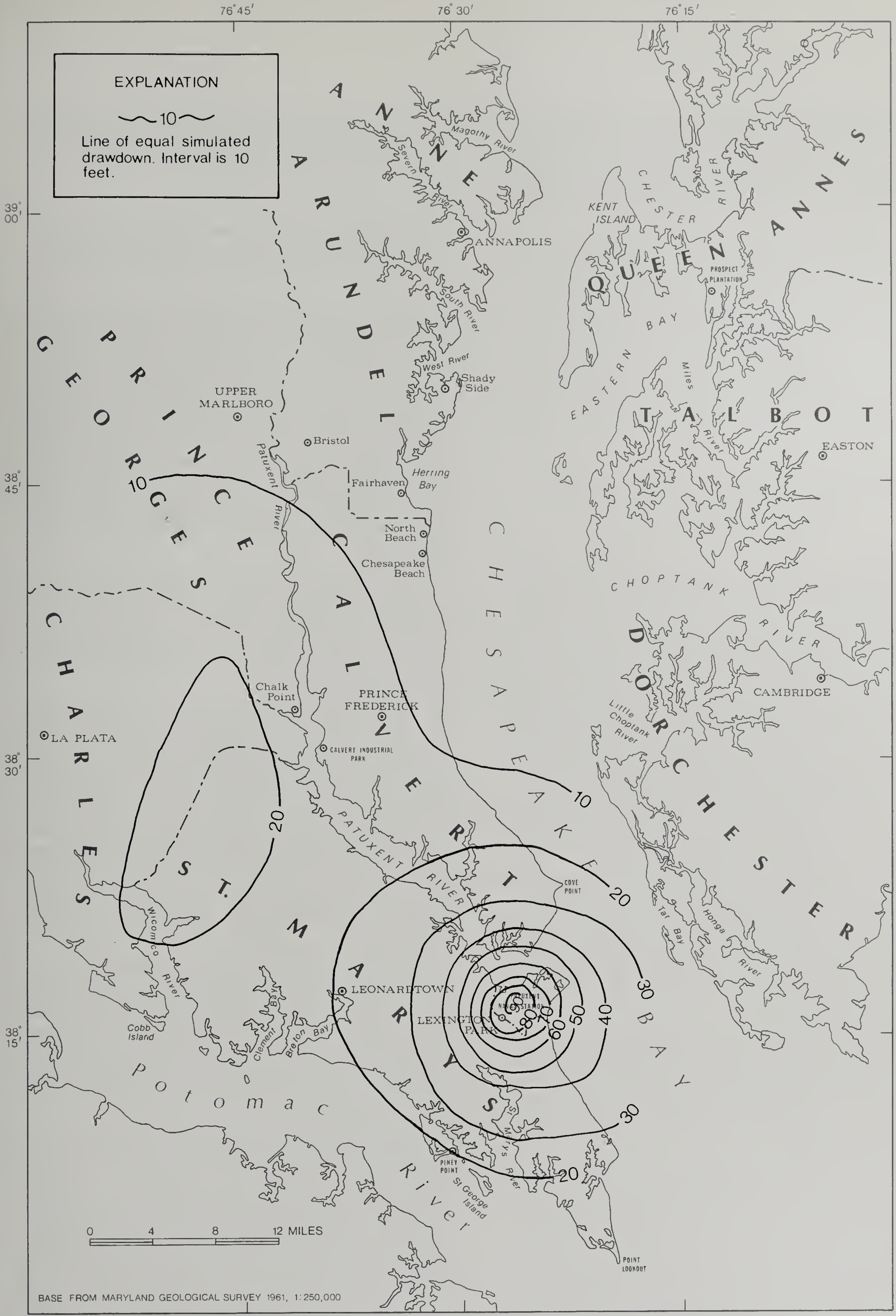


Figure 30.—Simulated drawdown from the 1980 potentiometric surface in the Aquia aquifer based on 20 years of 3.0 Mgal/d pumpage in the Lexington Park-PNATS area.

down is judged to be acceptable. If, for example, it is decided that an additional average drawdown (drawdown in a grid block) of more than 60 ft would be undesirable, the effective limit of aquifer yield would be approximately 2.0 to 2.5 Mgal/d in this area.

It should be reemphasized at this point that the model calculates average drawdowns for each grid block (1 mi^2 in the Lexington Park-PNATS area). Pumping levels in individual wells within this grid block are not calculated by the model. These individual pumping levels, which are dependent on pumping rates, well diameter, and well efficiency will be greater than the average drawdowns given by the model.

Simulation of 1 Mgal/d Withdrawal from Northern St. Marys County

Northern St. Marys County is presently a rapid-growth area. It has been estimated by county planning officials that in the next 20 years the population of this area will more than double (table 8). This increasing population will increase demands for water. The Aquia and Piney Point-Nanjemoy model was used to simulate two pumping scenarios for this region. For these simulations, it was assumed that growth in this area would result in a demand for an additional 1 Mgal/d. The first simulation placed a 1 Mgal/d well field at the present location of the St. Marys County Metropolitan Commission (METCOM) Rolling Acres (table 4, no. 41) well field in northern St. Marys County. The second scenario again simulated withdrawal of 1 Mgal/d, but spread the pumpage between the Birch Manor, Country Lakes, King and Kennedy, and Rolling Acres (table 4, nos. 19, 21, 36 and 41) well fields in northern St. Marys County. Average 1980 pumpage was also used for these simulations so that the 1 Mgal/d is an increase above 1980 pumpage.

Figure 31 shows the predicted drawdown of the Aquia aquifer based upon a 1-Mgal/d withdrawal from the METCOM Rolling Acres wells for a period of 10 years. At the end of the simulation period, the drawdown in the pumping node had declined slightly more than 100 ft.

Figure 32 shows the predicted drawdown after 10 years of pumping the Rolling Acres, Birch Manor, Country Lakes, and King and Kennedy wells at a combined rate of 1 Mgal/d. In this case, the largest predicted drawdown in one node is about 45 ft.

A comparison of figures 31 and 32 shows the effects of spreading pumpage between well fields as opposed to withdrawing all the required water from one well field. The impacts as far as decline of water level is concerned are less if pumpage is spread out. Careful spacing of well fields can minimize drawdown impacts of pumpage.

Simulation of Drawdowns in the Piney Point-Nanjemoy Aquifer due to Aquia Pumpage

In Southern Maryland, the Maryland State Water Resources Administration has mandated that the Piney Point-Nanjemoy aquifer be reserved for use by homeowners and small industries. Large industry and municipal wells therefore have been developed almost exclusively in the Aquia aquifer. One question that has arisen over this practice is what effects do drawdowns in the Aquia aquifer have on heads in the Piney Point-Nanjemoy aquifer. It has been suggested that drawdowns in the Aquia could produce drawdowns in the Piney Point-Nanjemoy.

It is possible to address this type of question with the digital model developed for this study. Transient leakage between aquifers is considered by this model and it is therefore possible to simulate pumpage in one aquifer and predict resulting drawdowns in adjacent aquifers.

A model run designed to address this question simulated a 1-Mgal/d withdrawal from the Aquia aquifer in the Lexington Park-PNATS area. The simulation was started with steady-state heads in both the Aquia and Piney Point-Nanjemoy aquifers and no other pumpage was simulated. These starting conditions were specified to eliminate drawdown effects of other pumpage and to isolate the effects of vertical leakage on the Piney Point-Nanjemoy aquifer. No pumpage was simulated in the Piney Point-Nanjemoy aquifer.

Figure 33 shows the calculated drawdowns in the Piney Point-Nanjemoy aquifer due to withdrawal of 1 Mgal/d from the Aquia for a period of 10 years. This pumpage resulted in a drawdown of about 90 ft in the Aquia for this time interval. The corresponding drawdown in the Piney Point-Nanjemoy aquifer is about 4 ft for the same time interval.

An additional simulation was made that specified a 2-Mgal/d withdrawal from the Aquia in the Lexington Park—PNATS area. Again the simulation was started under initial steady-state conditions and only withdrawal from the Aquia was specified. The simulation period was again 10 years. Figure 34 shows the drawdown in the Piney Point-Nanjemoy aquifer which results from the scenario. The Aquia shows a drawdown of about 180 ft. The corresponding drawdown in the Piney Point-Nanjemoy over the same time period is about 7 ft.

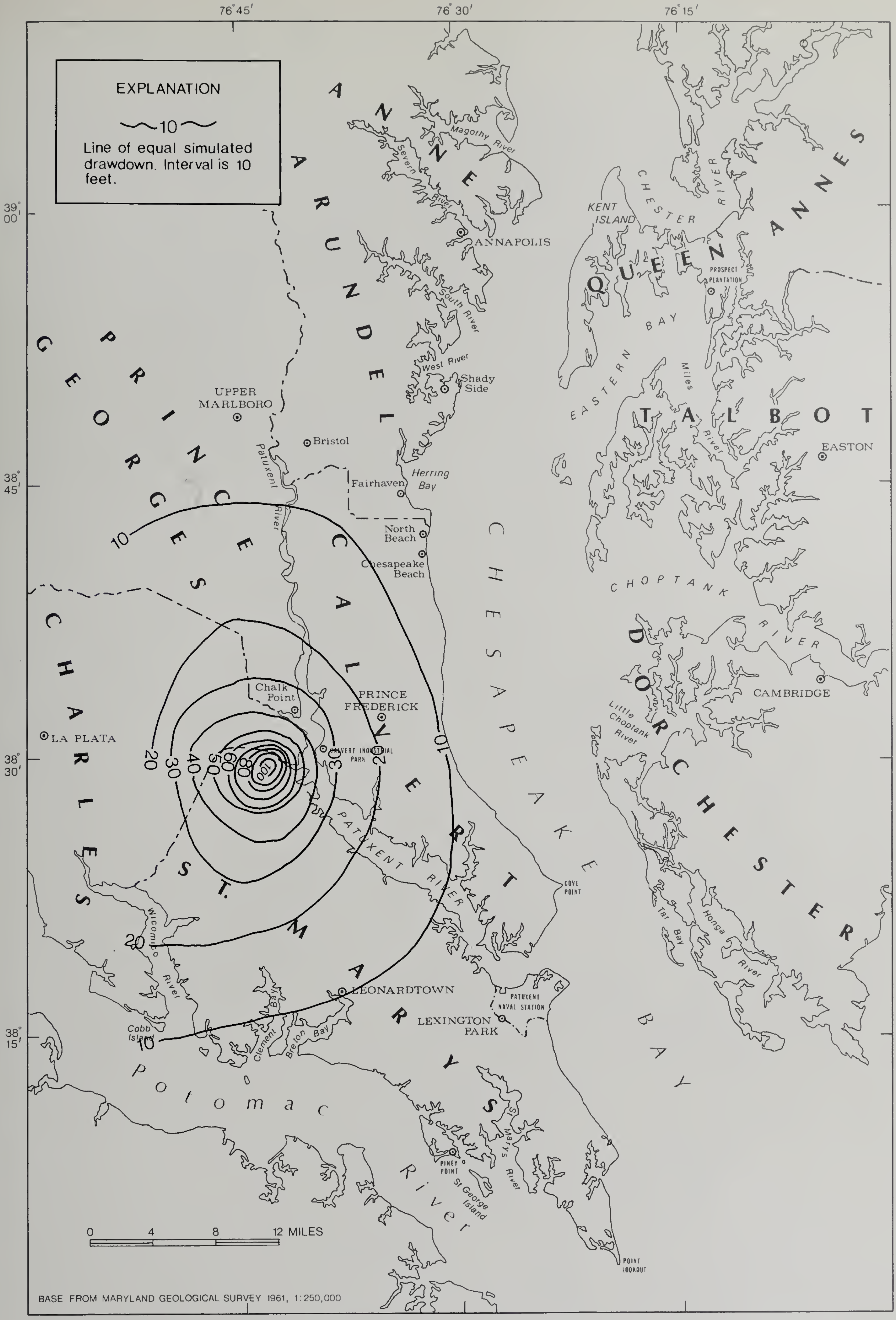


Figure 31.—Simulated drawdown from 1980 in the Aquia aquifer based on 10 years of 1.0-Mgal/d pumpage in the northern area of St. Marys County from one well field.

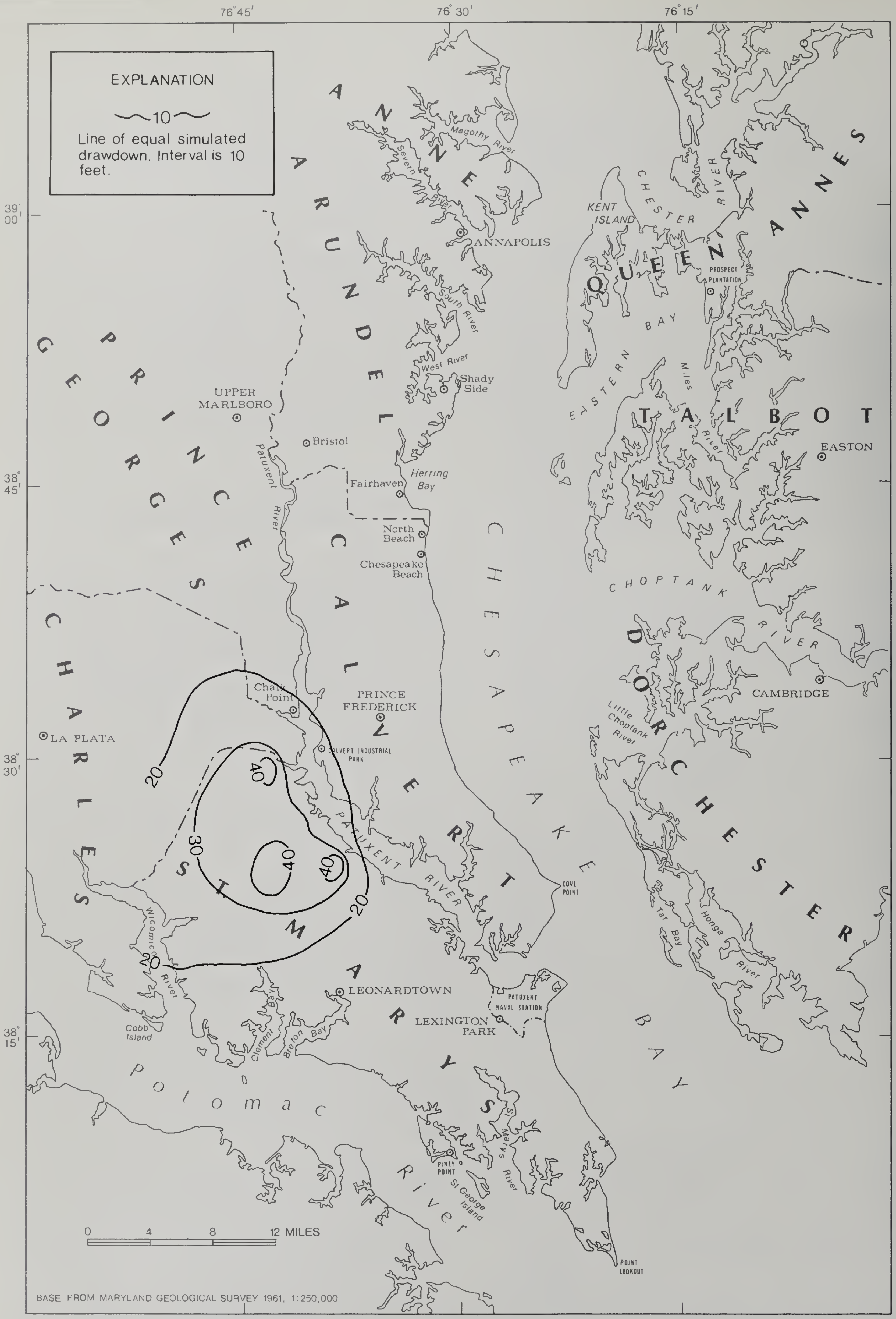


Figure 32.—Simulated drawdown from 1980 in the Aquia aquifer based on 10 years of 1.0-Mgal/d pumpage in northern St. Marys County from four well fields.

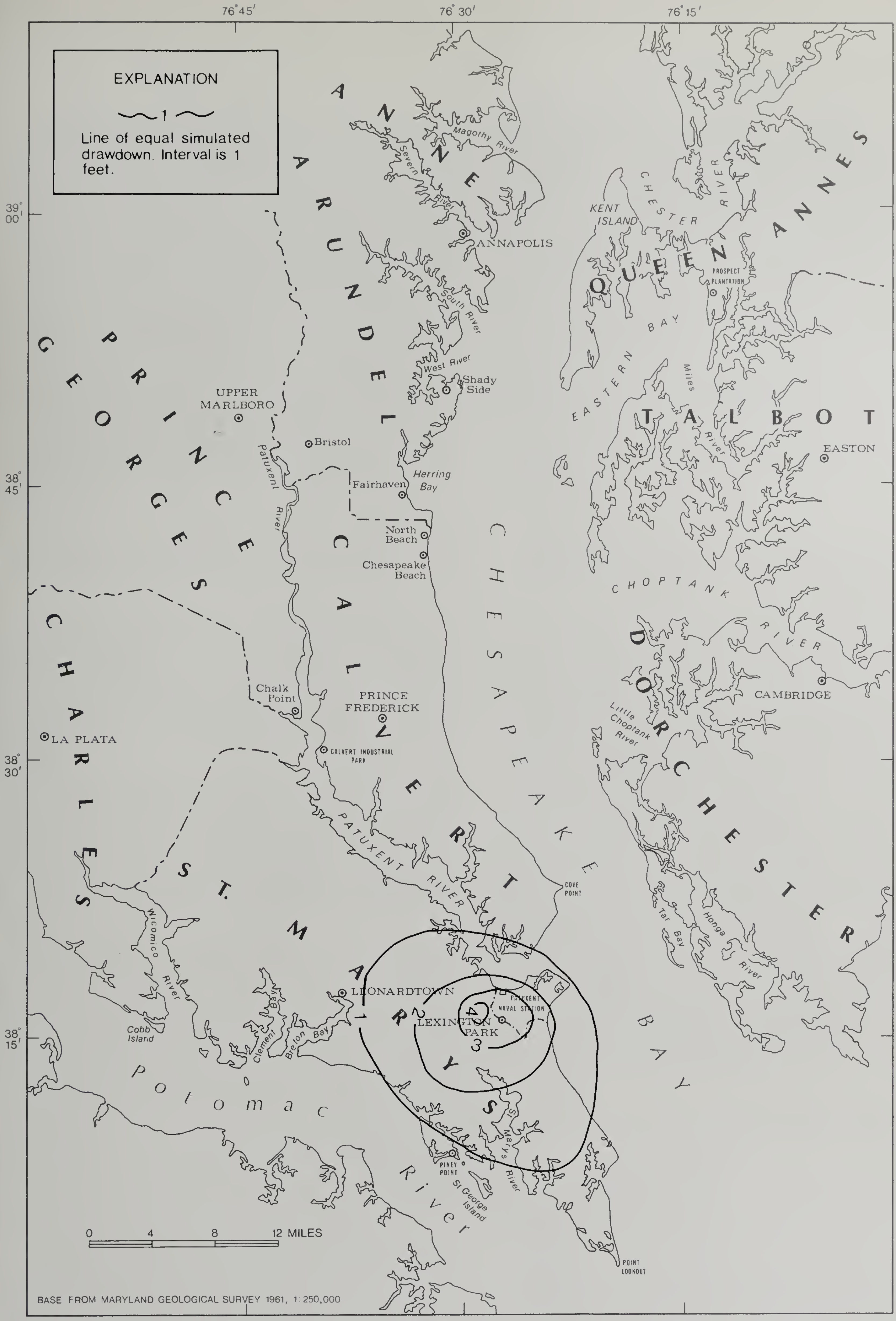


Figure 33.—Simulated drawdown from a steady-state potentiometric surface in the Piney Point-Nanjemoy aquifer based on 10 years of 1.0 Mgal/d pumpage from the Aquia aquifer near Lexington Park -PNATS.

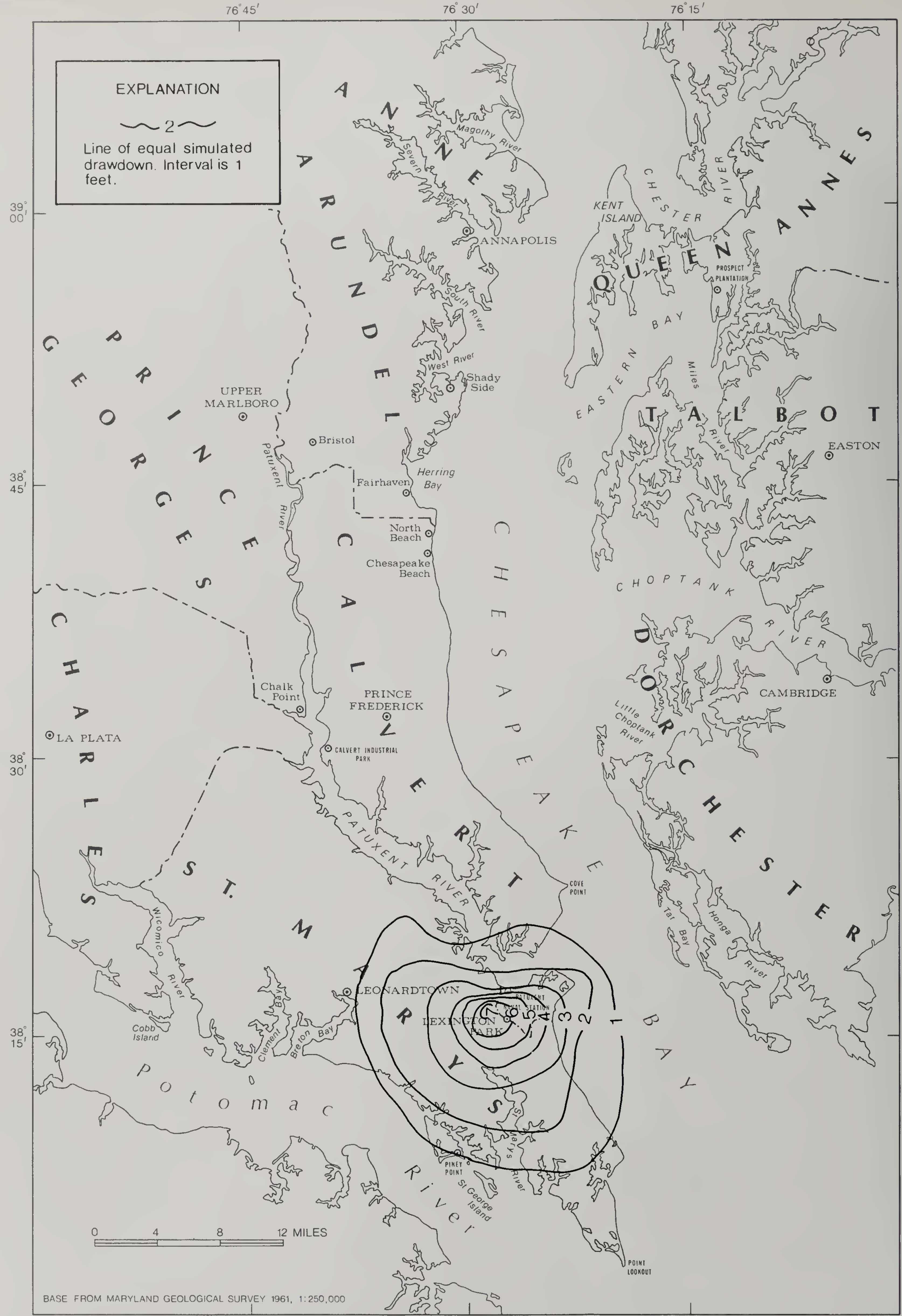


Figure 34.—Simulated drawdown from a steady-state potentiometric surface in the Piney Point-Nanjemoy aquifer based on 10 years of 2.0 Mgal/d pumpage from the Aquia aquifer near Lexington Park -PNATS.

These simulations show that major drawdowns in the Aquia can have a drawdown impact on the Piney Point-Nanjemoy aquifer. These drawdowns in the Piney Point-Nanjemoy are, however, rather small. It is not likely, therefore, that significant drawdowns in the Piney Point-Nanjemoy have been caused by Aquia pumpage. It should be noted that these simulations assume an undisturbed confining bed between the Aquia and the Piney Point-Nanjemoy aquifers and that there is no artificial connection between the two aquifers. It is possible for improperly grouted wells to provide a conduit of water between aquifers. Significant artificial connection of the Aquia and Piney Point-Nanjemoy aquifers caused by poorly grouted wells, or multiple-screened wells, could increase the drawdown impacts of one aquifer on the other.

Simulation of a Hypothetical 0.5-Mgal/d Well Field in Southern Anne Arundel County

Most of the present water usage in southern Anne Arundel County is by homeowners' wells and by small industries. The Aquia aquifer in southern Anne Arundel County is relatively shallow and is a good producer of ground water. Because of this, the majority of wells in this area are screened in the Aquia.

At the present time, there is no municipal water service planned for southern Anne Arundel County. However, such a system may become desirable sometime in the future near one or more of the population centers such as Shady Side, Fairhaven, or Bristol. For this reason, three simulations were made of hypothetical well fields near each of these towns.

Figure 35 shows the predicted drawdown for a 0.5 Mgal/d well field near Shady Side. Domestic and municipal pumpage for 1980 is included in this simulation. The calculated heads in this simulation show a drawdown of about 20 ft for the 10-year simulation period from the 1980 potentiometric surface.

Figure 36 shows the predicted drawdown from the 1980 potentiometric surface for a 0.5 Mgal/d well field near Bristol in southern Anne Arundel County. Domestic and municipal pumpage for 1980 is included in this simulation and the period simulated is 10 years. Calculated drawdowns due to the well field are about 26 ft for the simulation period.

The final simulation of pumpage in southern Anne Arundel County was near Fairhaven. Again, a 0.5 Mgal/d well field was simulated for a period of 10 years. The results of this simulation are shown in figure 37. The maximum drawdowns from the 1980 potentiometric surface are about 28 ft.

The moderate drawdowns produced by the simulated pumpage near these towns in Anne Arundel County suggest that municipal well fields in these locations are feasible. It should be noted, however, that the predicted cones of depression for the Shady Side and Fairhaven simulations may intersect the subsurface truncation of the Aquia aquifer. This introduces the possibility that chlorides may enter the Aquia aquifer due to leakage from the Chesapeake Bay. Monitoring chloride concentrations of Aquia water in these areas would be a prudent precaution. It is interesting to note that the simulated 0.5 Mgal/d simulation near Shady Side produces less drawdown than the 0.5 Mgal/d simulation near Fairhaven. This reflects the increasing transmissivity of the Aquia aquifer north of Fairhaven.

Simulation of a 0.5 Mgal/d Withdrawal at the Chalk Point Power Plant, Prince Georges County

The Chalk Point Power Plant, which is fired by fossil fuels, currently is a heavy user of Cretaceous aquifers (Mack, 1976). This heavy usage has led to large drawdowns in the Magothy aquifer in particular. The Aquia aquifer (but not the Piney Point-Nanjemoy aquifer) is present at Chalk Point and its ability to supply water to the power plant is of interest to water planners. For this reason, a model run which simulated the withdrawal of 0.5 Mgal/d from the Aquia at Chalk Point for a period of 10 years was made. The pumpage for 1980 is included in this simulation. Figure 38 shows a simulated drawdown of 45 ft from the 1980 potentiometric surface after 10 years of pumping.

This simulation indicates that 0.5 Mgal/d of Aquia pumpage from the Chalk Point Power Plant would have a relatively large impact on water levels in the area. This is partly because of the lower transmissivity in the Aquia aquifer west of Calvert County, and partly because of domestic and small industrial use in the same area.

Simulation of Maximum GAP Pumpage

The Maryland State Water Resources Administration presently has a policy that all users of ground water who pump more than 10,000 gal/d must apply for a Ground-Water Appropriation Permit (GAP). These GAP permits specify an average amount and a maximum amount of water that each user may consume. The average is defined to be the daily pumpage averaged over a year, while the maximum is the daily average for the highest use month.

In practice, ground-water users seldom pump the maximum amount of water allocated to them. However, to illustrate a high stress situation it is instructive to estimate the effects on water levels assuming each user actually did pump their maximum appropriation daily over a 10-year simulation period. This is a hypothetical situation and does not simulate the effects of presently allocated ground-water in the study area.

Figures 39 and 40 show the predicted drawdowns from the 1980 potentiometric surfaces of the Aquia and Piney Point-Nanjemoy aquifers assuming each holder of a 1980 GAP permit (tables 4 and 5) pumped their maximum allotment of ground water for a period of 10 years. Results suggest that large drawdowns would probably occur in the Aquia aquifier near Lexington Park-PNATS, Leonardtown, Piney Point, the Calvert Industrial Park, and Cove Point. In the Piney Point-Nanjemoy aquifer, there are small drawdowns caused in St. Mary's County. This simulation suggests that near Piney Point, Leonardtown, and Lexington Park, each additional appropriation of Aquia ground water should be carefully considered. In other areas of Southern Maryland, the Aquia aquifer does not appear overly stressed. The simulation of maximum GAP withdrawals in the Piney Point-Nanjemoy aquifer shows that no drawdowns greater than about 20 ft would occur. This indicates that the Piney Point-Nanjemoy aquifer is not presently over-allocated.

Simulation of a 0.5 Mgal/d Withdrawal at Chesapeake Beach, Calvert County

The community of Chesapeake Beach in Calvert County is presently evaluating the feasibility of constructing a municipal water system pumping from the Aquia aquifer. In view of this, the Calvert County Planning Department requested that a simulation be performed specifying a pumpage of 0.5 Mgal/d combined with estimated future pumpage (table 8) for a period of 5 years at Chesapeake Beach.

Figure 41 shows the drawdowns which resulted from this simulation. Approximately 20 ft of drawdown is predicted for the simulation period. It should be noted that transient flow was occurring at the end of the simulation period. This indicates that the water levels at Chesapeake Beach were still dropping at the end of the simulation period. Thus, at the end of 10 years, the drawdown would be greater than those shown in figure 38, which was for a period of 5 years. The simulation performed for Fairhaven in Anne Arundel County (5 miles from Chesapeake Beach) indicated a drawdown of 28 ft for a 0.5 Mgal/d withdrawal for 10 years. It is likely that after 10 years the drawdown at Chesapeake Beach would also be about 28 ft.

This simulation indicates that a municipal water system pumping from the Aquia aquifer at Chesapeake Beach would produce moderate drawdowns. This simulation also indicates that the edge of the drawdown cone may possibly intersect the subsurface truncation of the Aquia aquifer under the Chesapeake Bay. There is a possibility that this could result in chlorides moving into the aquifer from the Bay. The likelihood of this possibility cannot be evaluated within the scope of this project. However, it would be a reasonable precaution to monitor the Chesapeake Beach municipal system for possible chloride contamination.

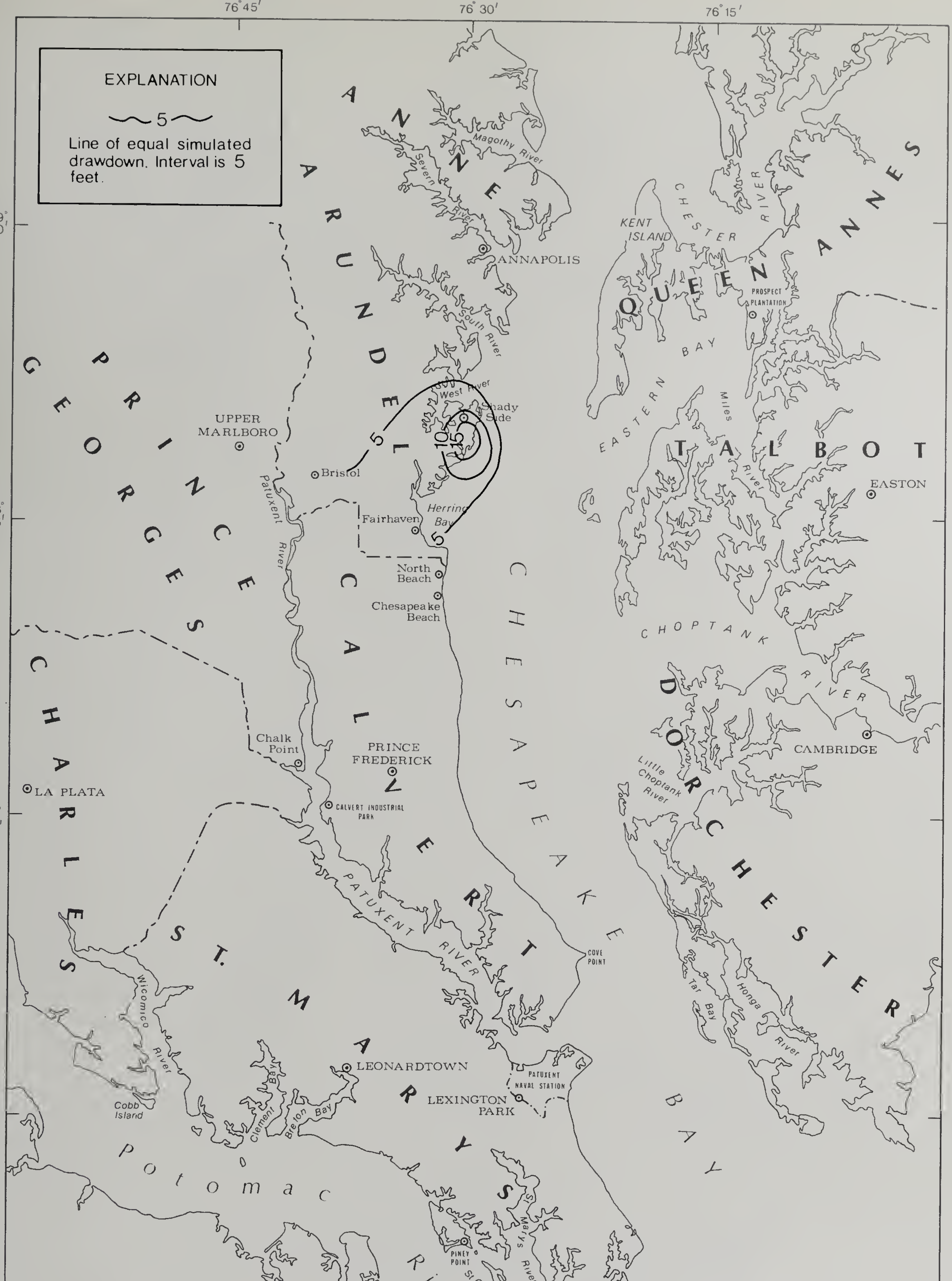


Figure 35.—Simulated drawdown from the 1980 potentiometric surface in the Aquia aquifer based on 0.5 Mgal/d pumpage for 10 years near Shady Side, Anne Arundel County.

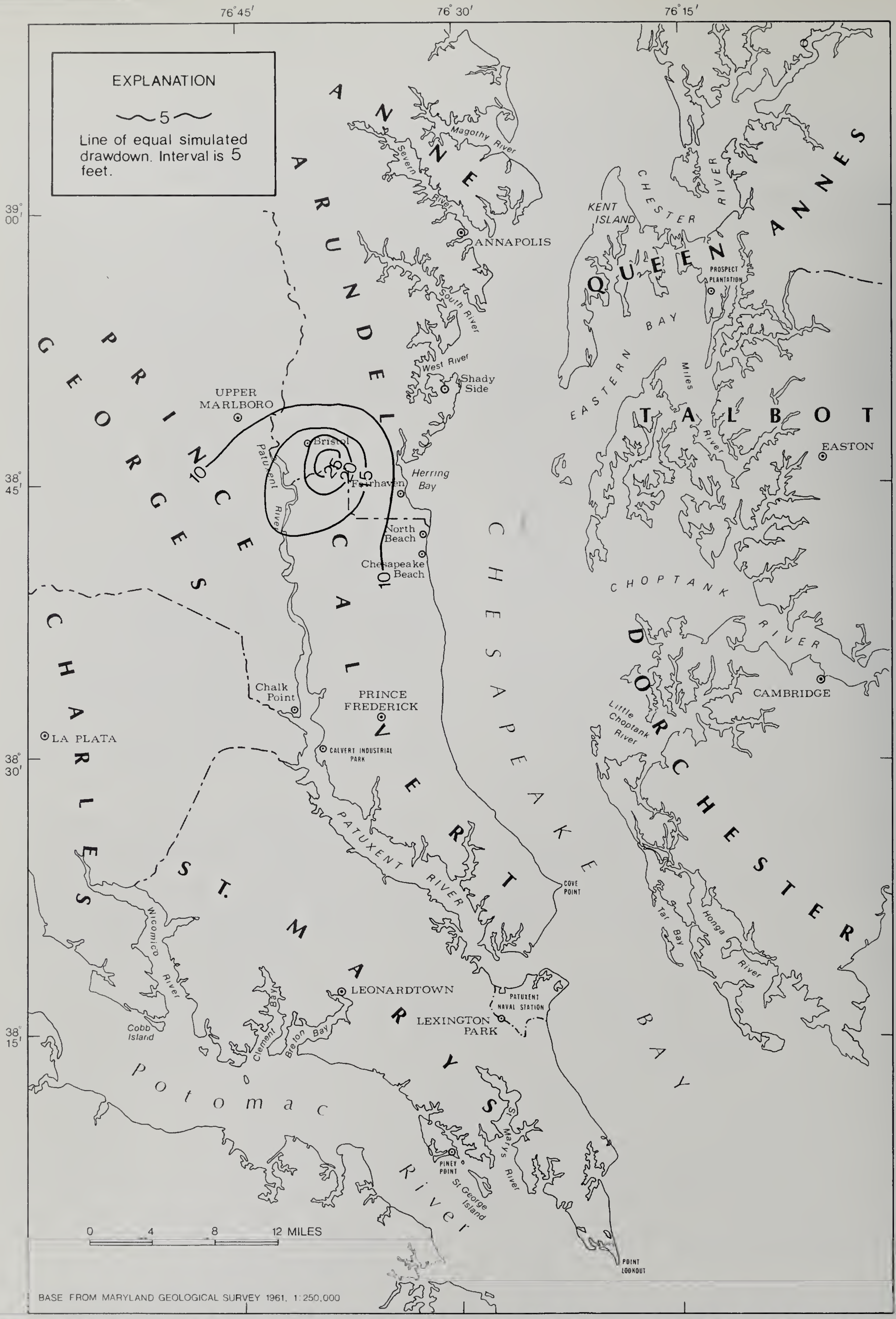


Figure 36.—Simulated drawdown from the 1980 potentiometric surface in the Aquia aquifer based on 0.5 Mgal/d pumpage for 10 years near Bristol, Anne Arundel County.

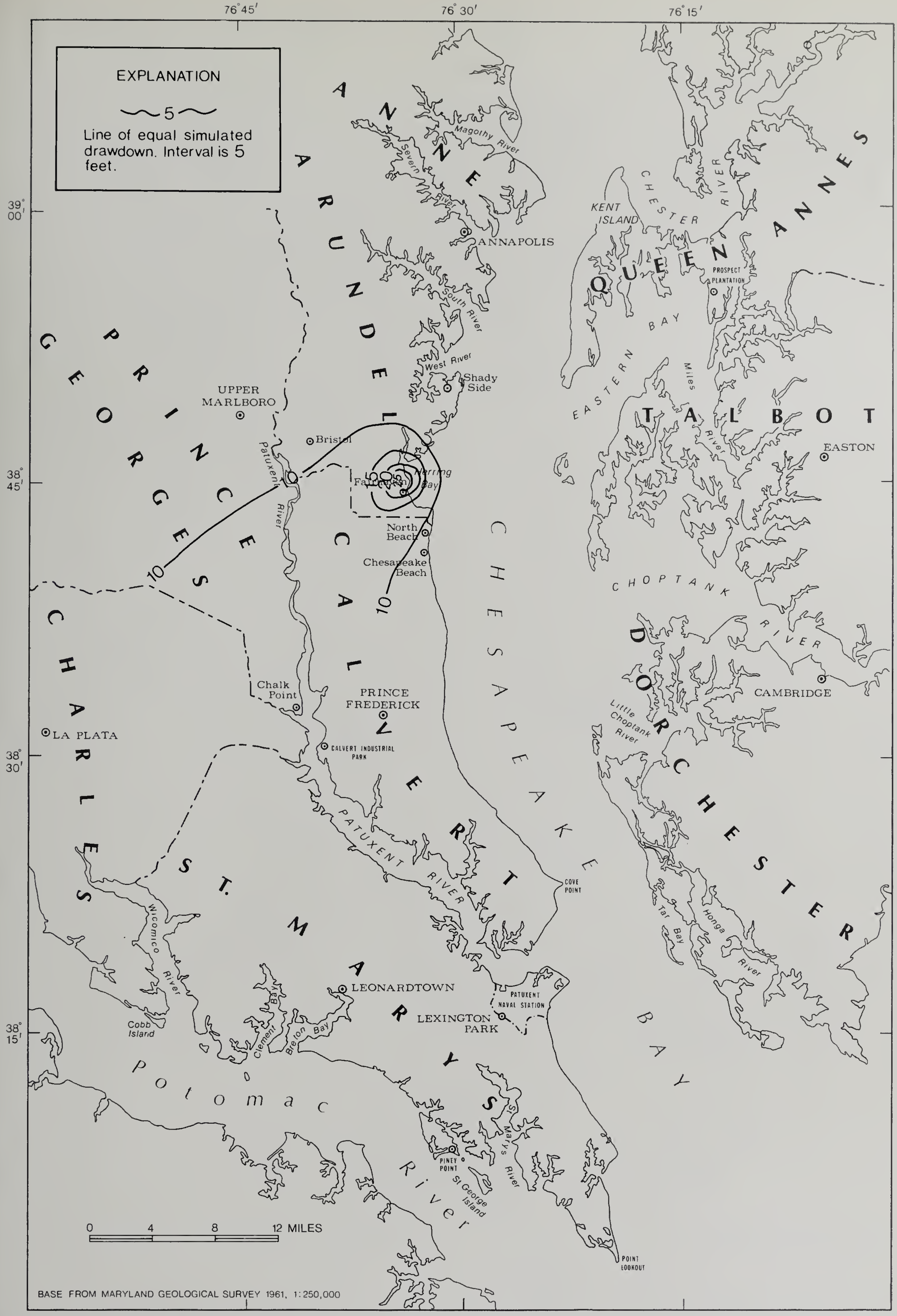


Figure 37.—Simulated drawdown from the 1980 potentiometric surface in the Aquia aquifer based on 0.5 Mgal/d pumpage for 10 years near Fairhaven, Anne Arundel County.

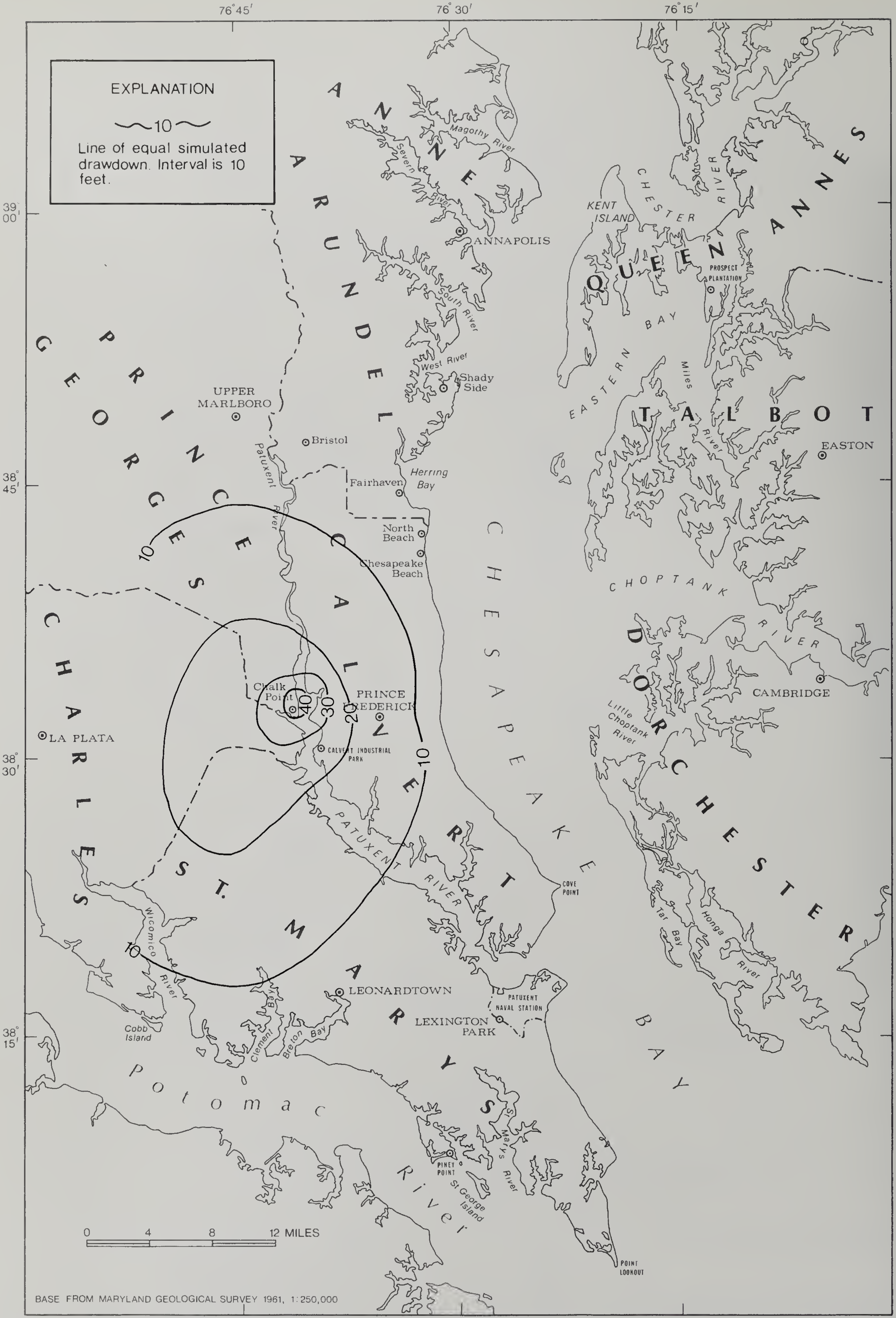


Figure 38.—Simulated drawdown from the 1980 potentiometric surface of the Aquia aquifer based on 0.5 Mgal/d pumpage for 10 years at the Chalk Point Power Plant.

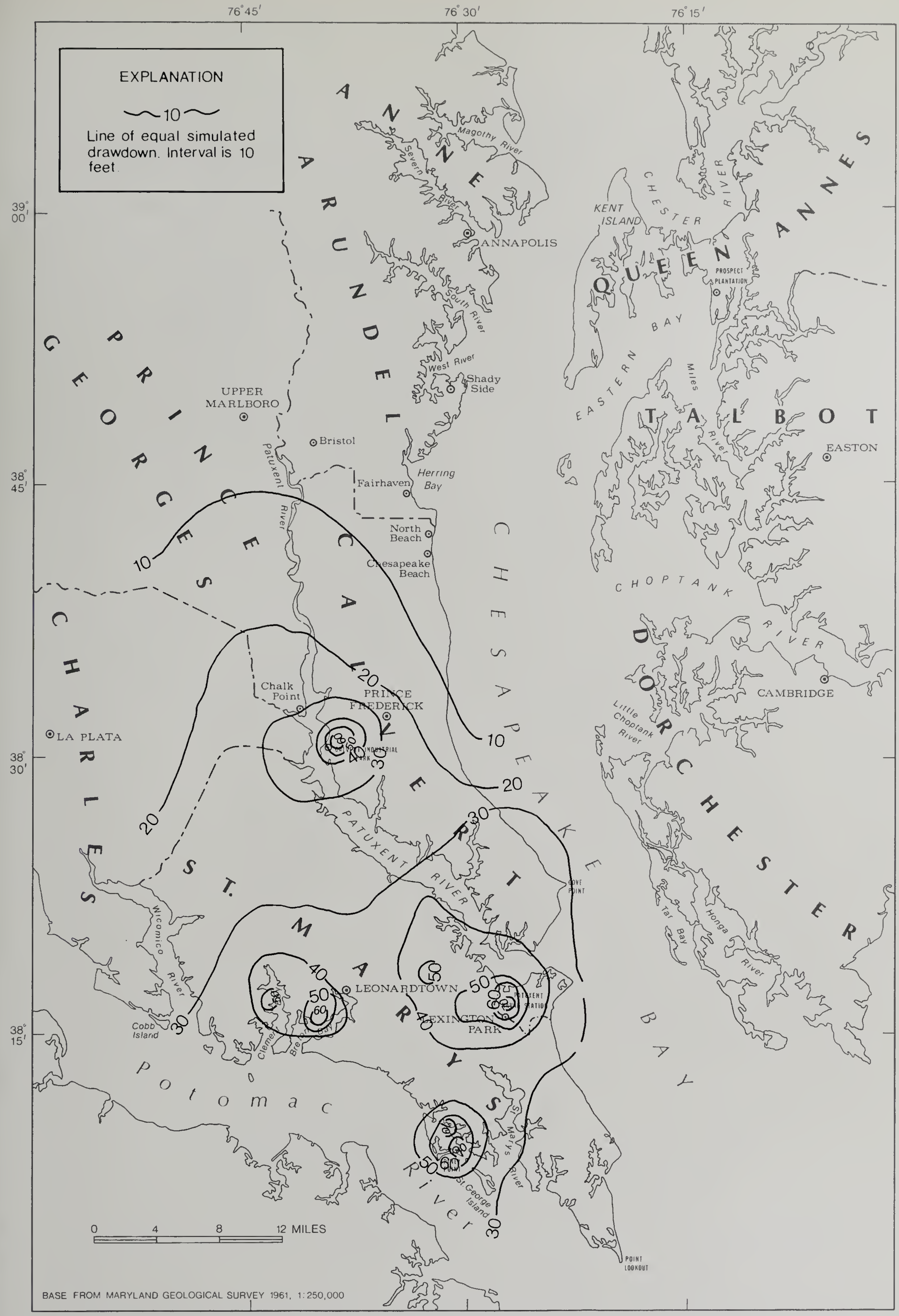


Figure 39.—Simulated drawdown from the 1980 potentiometric surface of the Aquia aquifer assuming all holders of 1980 Ground-Water Appropriation Permits pump their maximum allocations for 10 years.

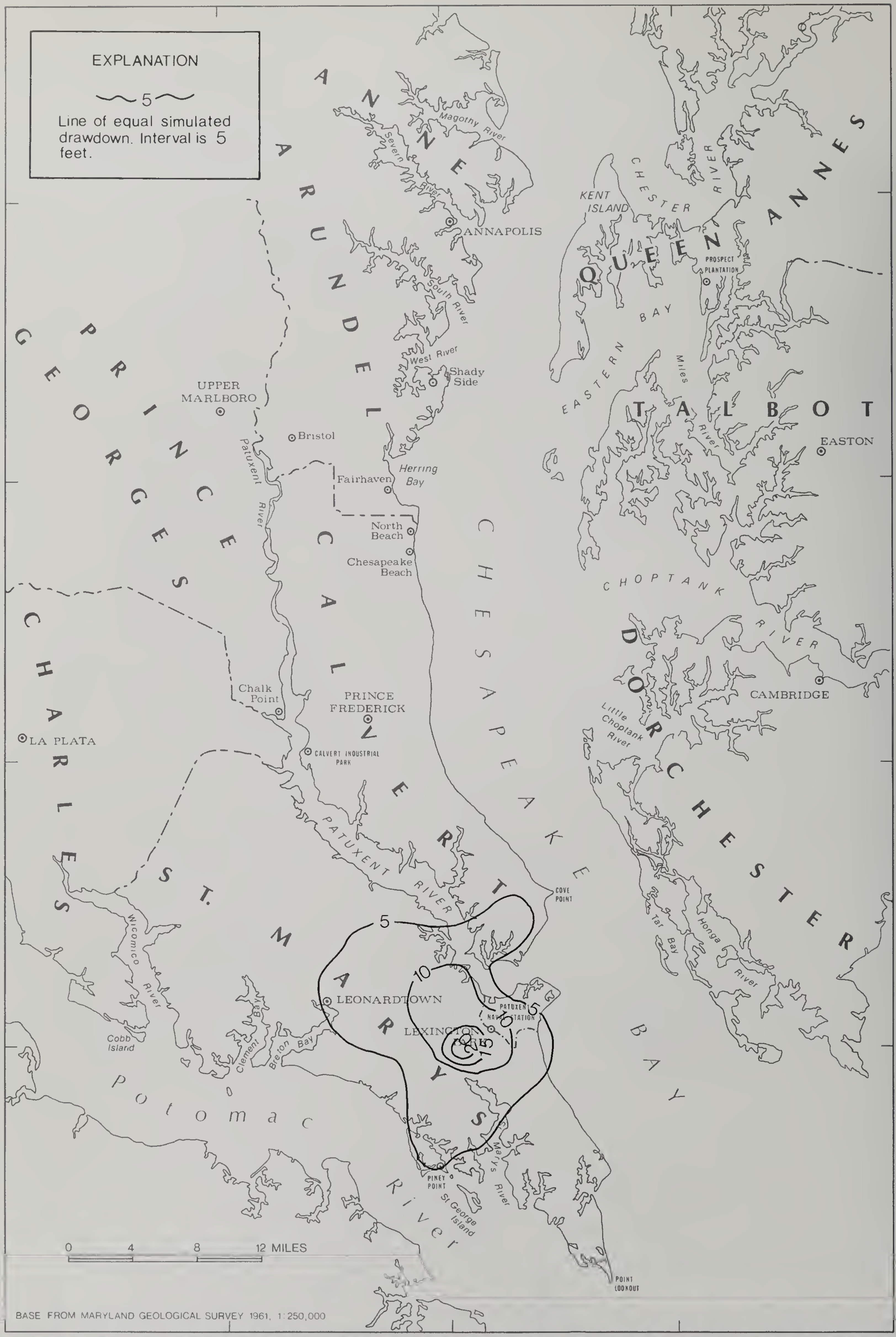


Figure 40.—Simulated drawdown from the 1980 potentiometric surface of the Piney Point-Nanjemoy aquifer assuming all holders of 1980 Ground-Water Appropriation Permits pump their maximum allocations fo 10 years.

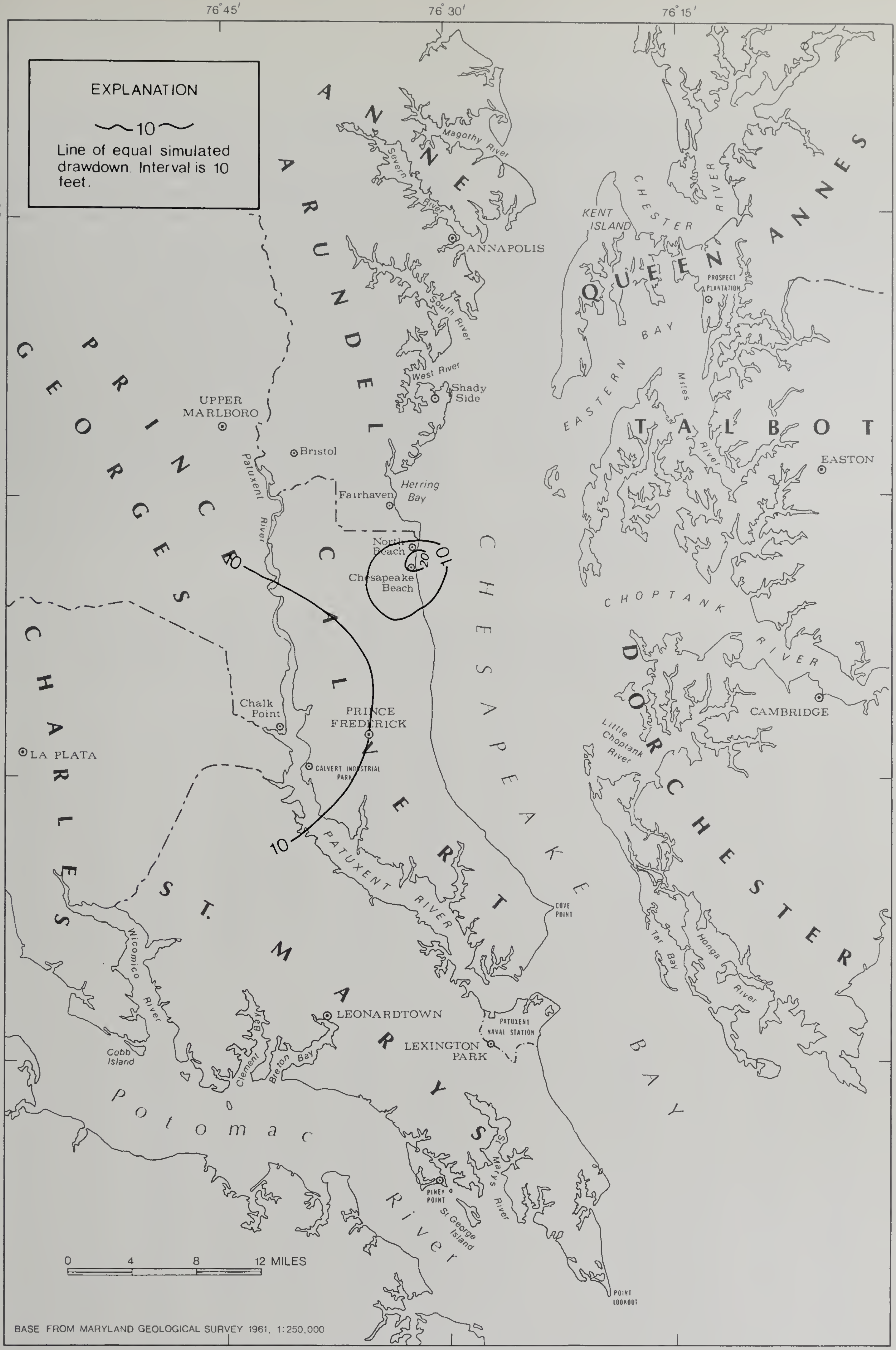


Figure 41.—Simulated drawdown from the 1980 potentiometric surface in the Aquia aquifer based on 0.5 Mgal/d pumpage for 5 years in the Chesapeake Beach area, Calvert County.

GROUND-WATER GEOCHEMISTRY

Introduction

The chemical quality of water produced by an aquifer system is an important consideration in determining its potential uses. In many communities ground water is utilized by a wide spectrum of citizens, some of whom may have widely different water-quality requirements. It is appropriate, therefore, to include a discussion on ground-water quality in a description of an aquifer system. It is also appropriate to discuss the chemical and physical processes which control the chemical character of the water. For the Aquia and Piney Point-Nanjemoy aquifers, this is of particular interest because the chemical character of their water changes markedly from place to place. Aquia water in Anne Arundel County, for example, has a chemical character which is significantly different from Aquia water in St. Mary's County. This change in chemical character can be directly related to chemical reactions which occur between ground-water and aquifer material.

The discussion of ground-water chemistry will be in two parts. The first part is a brief and general description of water quality in the Aquia and Piney Point-Nanjemoy aquifers. It is meant primarily to describe the water quality of the two aquifers and show how this quality changes from place to place. The second part is a more detailed discussion of

Table 9.—Representative analyses of Aquia water

WELL NUMBER	DATE OF SAMPLE	SILICA, DIS-SOLVED (MG/L AS SIO2)	IRON, DIS-SOLVED (UG/L AS FE)	IRON, TOTAL RECOV-ERABLE (UG/L AS FE)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MANGA-NESE, TOTAL RECOV-ERABLE (UG/L AS MN)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	ALKA-LINITY (MG/L AS CACO3)	SULFATE DIS-SOLVED (MG/L AS SO4)
						CALVERT COUNTY						
CA BB 9	52-04-30	15	--	200	--	0	30	14	3.2	9.2	132	14
CA BC 26	67-05-01	16	--	400	--	10	34	11	4.2	8.5	142	10
CA CB 11	58-02-27	20	--	80	--	20	32	13	--	--	137	12
CA CB 26	80-08-26	14	500	660	10	10	28	12	4.0	13	130	10
CA CC 17	52-01-23	15	--	300	--	--	42	13	4.3	10	142	9.2
CA CC 18	52-01-23	15	--	360	--	--	45	11	4.9	13	147	10
CA CC 19	52-01-23	15	--	520	--	--	35	12	4.3	9.6	147	9.5
	58-11-24	17	--	990	--	0	38	8.8	5.6	6.1	142	8.7
	60-06-21	16	--	4600	--	140	37	10	5.2	11	147	9.6
CA CC 40	54-10-13	13	--	310	--	20	43	12	5.4	8.9	146	11
CA DB 3	50-03-27	13	--	510	--	0	22	12	9.8	15	133	10
CA DB 5	47-01-13	9.8	--	--	--	--	22	12	9.8	16	133	12
CA DC 37	78-04-12	14	300	410	<10	<10	27	13	9.6	15	150	9.8
CA ED 1	52-04-30	15	--	30	--	0	9.8	2.8	30	13	109	4.5
CA GD 6	47-01-13	11	--	430	--	--	2.4	.7	52	6.4	122	8.4
CA GD 36	52-06-18	24	--	370	--	10	14	5.9	30	16	137	5.0
CA GD 36	52-06-24	12	--	670	--	<5	2.9	.4	50	5.3	107	5.5
	54-06-1[illegible]	21	--	830	--	<5	14	6.2	28	15	134	7.5
						ST MARYS COUNTY						
SM BB 4	50-03-24	11	--	450	--	0	18	11	9.6	12	100	13
SM BB 15	79-07-19	11	20	100	<10	<10	26	8.5	7.5	15	--	8.0
SM BC 16	67-05-16	13	--	420	--	0	21	11	11	16	133	11
SM BC 17	67-05-17	13	--	50	--	0	20	9.4	13	15	123	9.6
SM BD 1	47-01-17	13	--	650	--	--	15	8.7	18	15	115	10
SM CA 3	67-05-17	14	--	50	--	0	7.6	3.8	38	12	122	11
SM CA 7	80-08-05	12	10	110	0	10	2.8	.7	60	5.1	140	7.9
SM CB 1	47-01-17	14	--	50	--	--	11	4.4	34	12	121	9.9
SM DB 29	67-05-17	10	--	210	--	0	5.0	1.9	57	8.4	148	10
SM DC 12	50-03-24	50	--	30	--	<5	17	7.7	31	13	149	7.9
SM DC 17	52-04-02	12	--	420	--	0	4.2	.8	75	7.2	164	8.0
SM DF 1	51-10-24	12	--	0	--	--	2.4	1.0	76	9.0	173	5.5
	54-05-18	12	--	60	--	0	3.0	1.2	73	6.1	174	9.6
	56-03-13	13	--	270	--	0	2.5	.7	73	7.3	175	9.4
	57-04-12	12	--	30	--	20	3.2	.8	73	6.9	171	5.8
	58-06-02	12	--	20	--	0	1.7	.3	70	7.8	175	6.0
	59-08-13	12	--	10	--	0	3.7	1.9	71	6.0	171	7.6
	62-06-24	12	--	100	--	0	3.4	.6	76	7.9	173	6.4
SM DF 3	51-10-24	12	--	100	--	--	3.2	.7	72	9.0	164	6.5
	54-05-18	11	--	50	--	0	2.9	1.0	68	5.6	167	6.6
	56-03-13	13	--	20	--	0	2.5	.4	69	6.4	164	6.6
	57-04-09	13	--	190	--	20	2.7	.5	69	6.7	164	6.0
	58-06-02	11	--	0	--	0	2.0	1.6	69	6.1	169	7.0
	59-08-05	14	--	20	--	0	2.8	.9	69	9.9	163	4.3
	62-06-24	12	--	120	--	0	7.5	2.3	63	7.7	161	7.0
SM DG 1	51-11-21	12	--	0	--	--	2.8	1.6	76	7.0	173	6.0
	54-05-20	13	--	70	--	0	3.1	1.2	71	6.3	169	6.6
	56-03-15	12	--	70	--	70	3.4	1.0	68	6.7	167	5.8
	57-04-09	13	--	20	--	0	3.5	.7	70	6.7	170	5.6
	58-06-04	11	--	30	--	0	2.7	.3	70	6.4	178	6.0
	59-08-11	12	--	40	--	0	3.2	1.2	70	5.7	168	3.3

the chemical evolution of Aquia and Piney Point-Nanjemoy water. For this discussion, principles of equilibrium chemistry are utilized to identify the major chemical processes controlling the chemical character of the water.

Water Quality

Aquia Aquifer

Water produced from the Aquia aquifer generally has good chemical quality. Near the outcrop/subcrop area of the Aquia the water is a calcium and magnesium bicarbonate type water with relatively low (6.5-7.5) pH. Downgradient from the outcrop/subcrop area Aquia water changes to a sodium bicarbonate type water with relatively high (7.5-8.5) pH. Iron concentrations tend to be high (0.1-0.5 mg/L) near the outcrop area, but downgradient are very low (〈 0.1 mg/L). Water in the Aquia aquifer has generally low (8-12 mg/L) concentrations of sulfate, which do not change significantly along the flowpath. Aquia water normally contains about 2 to 3 mg/L of chloride, which is close to the concentration of chloride in precipitation in Southern Maryland (Junge and Werby, 1958). Aquia water is naturally fluoridated and typically contains 0.1 to 0.3 mg/L of fluoride. In addition to these dissolved chemical species, Aquia water commonly contains dissolved silica, manganese, potassium, and nitrate in minor amounts. Representative analyses of Aquia water are shown in Table 9.

Piney Point-Nanjemoy Aquifer

In many respects, ground water produced from the Piney Point-Nanjemoy aquifer is very similar in

CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	NITROGEN, NITRATE DISSOLVED (MG/L AS N)	NITROGEN, NO2+NO3 TOTAL (MG/L AS N)	PHOSPHORUS, TOTAL (MG/L AS P)	SOLID RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SUM OF CONSTITUENTS, DISSOLVED (MG/L)	HARDNESS (MG/L AS CACO3)	HARDNESS, NONCARBONATE (MG/L CACO3)	SPECIFIC CONDUCTANCE (UMHOS)	PH (UNITS)	TEMPERATURE (DEG C)	COLOR (PLATINUM-COBALT UNITS)	LITHIUM TOTAL RECOVERABLE (UG/L AS LI)	WELL NUMBER
CALVERT COUNTY														
1.2	.3	.10	--	--	162	166	132	0	276	7.7	--	1	--	BB 9
.7	.1	.00	--	--	173	170	130	0	285	7.2	18.3	5	--	BC 26
6.2	.3	.20	--	--	188	185	133	0	298	8.3	--	7	--	CB 11
.3	.2	--	.01	.010	150	160	120	0	293	7.4	18.0	0	--	CB 26
1.5	.3	.16	--	--	171	--	133	0	287	7.8	--	6	--	CC 17
3.1	.3	.05	--	--	181	--	133	0	295	8.0	--	3	--	CC 18
1.0	.3	.05	--	--	176	--	137	0	290	7.9	--	9	--	CC 19
2.2	.2	.00	--	--	175	172	131	0	303	7.7	--	5	<50	
2.0	.2	.00	--	--	180	180	135	0	301	7.7	--	2	--	
1.0	.1	.34	--	--	174	174	132	0	293	8.1	18.3	4	1000	CC 40
2.0	.2	.18	--	--	154	--	108	0	277	7.9	--	0	--	DB 3
1.1	.2	.16	--	--	153	163	104	0	279	8.0	--	3	--	DB 5
.7	.2	--	<.10	<.010	177	178	120	0	--	--	--	10	--	DC 37
2.1	.3	.05	--	--	137	143	36	0	222	7.9	17.7	1	--	ED 1
2.6	.2	.07	--	--	156	--	9	--	255	8.7	18.8	1	--	GD 6
2.5	.3	.14	--	--	180	181	59	0	279	7.9	--	7	--	GD 36
4.2	.3	.05	--	--	153	145	9	0	234	8.5	--	--	--	GD 36
4.0	.4	.09	--	--	184	177	60	0	276	7.8	10.0	6	1500	
4.2	.4	2.00	--	--	195	192	62	0	278	8.3	--	10	1000	
ST MARYS COUNTY														
4.4	.1	1.40	--	--	132	--	90	0	245	7.4	21.1	2	--	BB 4
2.1	.2	--	.15	<.010	154	78	100	--	--	--	--	5	--	BB 15
.6	.1	.05	--	--	165	164	98	0	270	8.0	17.7	3	--	BC 16
.6	.2	.00	--	--	164	155	89	0	240	7.9	17.2	2	--	BC 17
1.2	.1	.05	--	--	145	--	73	0	251	8.5	17.7	6	--	BD 1
.7	.1	.00	--	--	165	161	35	0	240	8.3	17.7	2	--	CA 3
1.0	.3	--	.01	.120	163	174	10	0	283	8.8	18.0	5	--	CA 7
1.1	.1	.00	--	--	155	159	46	0	258	8.4	16.1	3	--	CB 1
.7	.2	.02	--	--	190	182	21	0	292	8.2	16.1	3	--	DB 29
2.5	.4	.09	--	--	212	219	74	0	304	7.9	11.0	1	--	DC 12
9.2	.3	.15	--	--	213	216	14	0	340	8.2	--	3	--	DC 17
2.5	.5	.05	--	--	225	213	10	0	316	8.5	16.6	2	--	DF 1
2.7	.6	.02	--	--	217	--	13	0	336	8.8	18.8	3	1200	
2.5	.5	.02	--	--	216	--	9	0	341	8.8	--	4	1700	
2.8	.6	.11	--	--	219	--	11	0	342	8.8	--	1	500	
3.0	.5	.02	--	--	209	--	6	0	337	8.0	--	1	2500	
2.5	.6	.00	--	--	217	--	17	0	344	8.1	--	1	<50	
2.5	.2	.00	--	--	216	213	11	0	344	8.7	--	5	--	
2.8	.4	.05	--	--	204	--	11	0	301	8.6	16.6	3	--	DF 3
3.6	.5	.02	--	--	207	--	11	0	324	8.9	16.1	3	1200	
1.7	.5	.00	--	--	210	--	8	0	323	8.8	--	3	1600	
3.0	.5	.02	--	--	219	--	9	0	324	8.9	--	2	600	
3.0	1.4	.02	--	--	203	--	12	0	331	8.6	--	1	2100	
2.6	1.0	.05	--	--	216	--	11	0	331	8.6	--	3	--	
3.5	.7	.05	--	--	205	207	28	0	323	8.4	--	5	--	
4.2	.4	.07	--	--	208	214	14	0	325	8.5	18.8	1	--	OG 1
2.5	.5	.13	--	--	208	--	13	0	331	8.4	18.3	3	1500	
1.8	.4	.07	--	--	201	--	13	0	326	8.7	--	3	1500	
2.2	.5	.09	--	--	217	205	12	0	332	8.7	--	3	600	
3.0	.7	.02	--	--	210	209	8	0	334	7.9	--	1	2400	
2.2	.6	.00	--	--	217	--	13	0	334	8.3	--	2	--	

chemical quality to water produced from the Aquia aquifer. This is primarily because the lithologies of the Piney Point-Nanjemoy and Aquia aquifers are very similar. In upgradient areas, Piney Point-Nanjemoy water is a calcium magnesium bicarbonate type water with relatively low (6.0-7.0) pH. Downgradient, the water changes to a sodium bicarbonate type water with relatively high (7.0-8.2) pH. Concentrations of other dissolved ions such as iron (0-0.5 mg/L), sulfate (10 mg/L), chloride (2-3 mg/L), and fluoride (0.1-0.5 mg/L), also tend to be very similar to Aquia water. Two dissolved species which are notably different from Aquia water are potassium and silica. Piney Point-Nanjemoy water commonly has about 12-15 mg/L potassium, which is about double the average potassium concentrations in Aquia water. Similarly, silica concentrations in Piney Point-Nanjemoy water average between 50 and 60 mg/L, which is about 4 or 5 times the average composition of silica in Aquia water. Representative analyses of Piney Point-Nanjemoy water are shown in table 10.

Table 10.—Representative analyses of Piney Point-Nanjemoy water

WELL NUMBER	DATE OF SAMPLE	SILICA, DIS-SOLVED (MG/L AS SIO2)	IRON, DIS-SOLVED (UG/L AS FE)	IRON, TOTAL RECOV-ERABLE (UG/L AS FE)	MANGA-NESE, DIS-SOLVED (UG/L AS MN)	MANGA-NESE, TOTAL RECOV-ERABLE (UG/L AS MN)	CALCIUM DIS-SOLVED (MG/L AS CA)	MAGNE-SIUM, DIS-SOLVED (MG/L AS MG)	SODIUM, DIS-SOLVED (MG/L AS NA)	POTAS-SIUM, DIS-SOLVED (MG/L AS K)	ALKA-LINITY (MG/L AS CACO3)	SULFATE DIS-SOLVED (MG/L AS SO4)
						CALVERT COUNTY						
CA BB 18	67-05-01	49	--	110	--	0	40	9.7	2.0	8.4	143	9.2
CA BB 28	80-06-27	45	380	1300	30	30	44	4.7	3.1	3.9	130	19
CA BC 27	67-05-01	48	--	230	--	0	54	14	3.2	9.5	179	30
CA CA 10	80-08-28	39	30	90	0	10	31	16	3.2	15	130	34
CA CB 9	51-03-06	36	--	200	--	0	28	13	5.2	17	128	22
CA DB 57	80-08-08	49	130	210	0	10	37	6.9	2.6	8.1	130	5.2
CA DC 12	67-05-05	45	--	230	--	0	35	11	3.1	11	141	12
CA DC 16	67-05-04	33	--	110	--	0	26	11	3.6	12	115	10
CA EB 9	67-05-05	54	--	180	--	20	32	11	2.8	9.0	125	8.4
CA EB 20	80-08-08	35	310	420	0	10	17	8.8	19	15	120	13
CA EC 1	47-01-13	40	--	--	--	--	28	11	3.9	12	118	14
CA FC 3	49-03-23	40	--	210	--	--	23	11	3.7	1.6	108	11
CA ED 14	67-05-0[illegible]	34	--	160	--	0	21	11	8.3	19	127	12
CA ED 19	67-05-03	31	--	140	--	0	21	11	5.2	17	121	11
CA FD 3	47-01-13	18	--	20	--	--	8.6	4.2	59	12	152	27
CA FD 38	67-05-09	43	--	70	--	0	15	9.1	46	13	179	12
CA FE 27	80-08-07	44	20	80	0	10	19	7.7	22	14	130	12
CA GD 4	47-01-13	19	--	3800	--	--	10	4.8	50	13	155	12
						ST MARYS COUNTY						
SM BB 22	80-07-01	29	340	1100	40	50	30	9.9	4.4	9.6	130	18
SM CD 1	49-03-09	43	--	230	--	--	23	11	5.5	3.0	116	8.7
SM CD 16	67-05-22	43	--	730	--	0	34	15	6.1	12	131	40
SM CD 20	67-05-16	44	--	570	--	0	27	8.8	3.4	7.9	111	10
SM CF 14	50-03-28	33	--	1300	--	30	27	15	9.0	17	149	14
SM CF 20	67-05-19	34	--	300	--	0	26	13	8.5	17	144	14
SM DD 62	80-07-01	28	100	270	0	10	10	3.5	9.8	7.7	73	24
SM DD 63	80-07-09	18	140	220	10	10	22	8.1	22	19	64	13
SM DF 32	67-05-19	59	--	230	--	0	31	13	2.2	6.0	135	7.6
SM DE 33	67-05-22	36	--	990	--	0	26	13	6.3	17	143	6.0
SM DF 6	51-11-27	61	--	110	--	--	30	14	4.6	10	143	7.5
	54-05-19	56	--	80	--	0	30	14	3.9	8.9	139	8.0
	56-03-13	63	--	130	--	0	30	14	3.6	3.6	139	8.0
	57-04-12	71	--	120	--	20	31	12	3.0	11	141	7.1
	58-06-09	61	--	300	--	0	30	12	6.0	12	141	6.8
SM DF 9	47-01-16	55	--	230	--	--	21	13	17	14	145	7.8
	51-11-06	54	--	100	--	--	21	12	18	12	146	7.2
	54-05-18	48	--	20	--	0	21	12	17	14	151	7.0
	56-03-14	55	--	30	--	0	21	11	17	14	148	6.6
	57-04-12	61	--	280	--	0	22	11	18	15	145	6.4
	58-06-03	52	--	30	--	0	23	11	15	13	145	5.8
	62-06-24	55	--	170	--	0	22	12	16	15	144	7.0
SM DF 14	51-11-27	56	--	80	--	--	22	12	17	12	143	6.8
	54-05-19	48	--	40	--	0	22	12	14	12	143	7.8
	56-03-20	56	--	90	--	10	22	11	13	12	137	7.6
	57-04-12	55	--	50	--	0	27	8.7	11	12	139	6.4
	58-06-09	50	--	100	--	0	22	9.6	20	13	140	7.2
	62-06-24	56	--	60	--	10	22	11	17	14	141	6.6
SM DF 38	51-11-27	60	--	120	--	--	27	14	7.7	12	147	6.8
	54-05-19	54	--	90	--	0	27	14	8.2	13	144	8.0
	56-03-14	62	--	160	--	0	27	13	7.4	12	146	8.2
	57-04-12	71	--	100	--	0	27	13	5.5	13	144	6.5
	58-06-09	55	--	80	--	0	28	12	8.0	14	144	6.0
	59-08-13	59	--	40	--	0	25	9.0	25	6.6	143	5.5
SM DF 39	51-11-27	54	--	100	--	--	21	12	17	14	144	8.8
	54-05-20	48	--	40	--	<5	21	12	18	12	140	9.0
	56-03-20	54	--	80	--	10	20	12	1.7	1.3	141	8.0
	57-04-12	53	--	90	--	<5	23	9.2	17	14	141	8.2
	58-06-09	49	--	80	--	<5	23	9.3	18	16	140	9.0
SM EE 35	67-05-23	48	--	330	--	0	16	7.6	32	15	149	8.0
SM FE 38	67-05-23	56	--	40	--	0	27	13	11	11	148	7.4
SM EE 39	67-05-25	49	--	60	--	0	18	9.3	24	15	148	9.6
SM FG 41	67-05-24	22	--	50	--	10	--	--	--	--	372	--
SM FG 46	67-05-25	27	--	120	--	10	4.4	2.2	120	7.6	280	3.0
SM FG 48	67-05-23	22	--	80	--	0	3.4	1.8	160	7.0	350	4.8
SM FG 50	67-05-22	36	--	130	--	0	6.1	3.3	74	10	198	4.0

Chemical Evolution of Ground Water

Background

In the past 30 years, the application of equilibrium chemistry to surface- and ground-water systems has provided insight into many types of geologic problems. Foster (1950), Garrels (1967), and Garrels and MacKenzie (1967) have applied the principles of equilibrium chemistry to the composition of ground water in different lithologic terrains. Jones (1966), and Eugster and Jones (1979) have shown how the composition of brine lakes evolve in a systematic fashion which depends on the chemistry of the enclosed basin. Similarly, Cleaves and others (1970) applied the principles of equilibrium chemistry to the weathering of metamorphic silicate rocks in Maryland and pointed out the geomorphic implications of such weathering. Clearly the techniques of ground-water geochemistry as they have developed are proving to be excellent tools in geologic investigations. In this report, these principles are utilized to provide a framework within which the chemical composition of ground water from the Aquia and Piney Point-Nanjemoy aquifers in Southern Maryland may be understood.

CHLORIDE, DISSOLVED (MG/L AS CL)	FLUORIDE, DISSOLVED (MG/L AS F)	NITROGEN, NITRATE DISSOLVED (MG/L AS N)	NITROGEN, NO2+NO3 TOTAL (MG/L AS N)	PHOSPHORUS, TOTAL (MG/L AS P)	SOLIDS, RESIDUE AT 180 DEG. C DISSOLVED (MG/L)	SOLIDS, SUM OF CONSTITUENTS, DISSOLVED (MG/L)	HARDNESS MG/L AS ACO3)	HARDNESS, NONCARBONATE (MG/L CACO3)	SPECIFIC CONDUCTANCE (UMHOS)	PH (UNITS)	TEMPERATURE (DEG C)	COLOR (PLATINUM-COBALT UNITS)	LITHIUM TOTAL RECOVERABLE (UG/L AS LI)	WELL NUMBER
					CALVERT COUNTY									
2.6	.1	.02	--	--	205	207	140	0	270	7.5	15.5	0	--	8B 18
2.5	.2	--	.00	.090	166	201	130	0	298	7.5	19.5	2	--	BB 28
2.7	.1	.05	--	--	268	269	192	14	372	7.4	17.2	3	--	BC 27
2.0	.2	--	.03	.010	210	219	140	13	350	7.8	17.5	0	--	CA 10
1.5	.1	.20	--	--	194	201	121	0	298	8.0	--	4	--	CB 9
1.8	.3	--	.09	.050	184	189	120	0	270	7.3	21.0	0	--	DB 57
2.0	.1	.00	--	--	201	204	133	0	290	8.3	16.1	1	--	DC 12
2.1	.3	.07	--	--	165	167	110	0	245	8.2	16.1	0	--	DC 16
2.5	.3	.05	--	--	189	195	125	0	256	8.3	16.1	0	--	EB 9
1.0	.4	--	.01	.020	164	182	79	0	273	7.5	18.0	0	--	EB 20
2.2	.2	.02	--	--	173	182	115	0	259	8.2	15.5	2	--	EC 1
2.5	.2	.36	--	--	168	160	103	0	246	7.7	13.3	10	--	EC 3
1.0	.3	.07	--	--	177	183	98	0	260	8.2	16.1	0	--	ED 14
1.5	.2	.00	--	--	164	170	98	0	250	8.1	16.6	3	--	ED 19
1.5	.4	.05	--	--	221	222	39	0	350	8.2	13.5	2	--	FD 3
1.2	.5	.05	--	--	240	247	75	0	342	8.2	16.6	0	--	FD 38
.8	.5	--	.02	.020	190	198	79	0	289	7.4	19.0	0	--	FE 27
3.1	.3	.02	--	--	204	205	45	0	327	8.0	15.0	5	--	GD 4
					ST MARYS COUNTY									
2.1	.3	--	.04	.060	160	182	120	0	296	7.8	19.0	0	--	88 22
3.0	.2	.07	--	--	176	169	103	0	255	7.9	15.0	5	--	CD 1
2.2	.3	.02	--	--	232	232	147	16	324	8.2	15.0	0	--	CD 16
1.4	.1	.00	--	--	174	169	104	0	228	8.5	16.1	1	--	CD 20
2.5	.3	.13	--	--	194	208	130	0	318	7.8	--	7	--	CE 14
1.8	.3	.11	--	--	210	201	119	0	298	8.2	16.6	1	--	CE 20
1.8	.3	--	.01	.030	164	129	39	0	318	7.9	19.0	0	--	DD 62
1.0	.3	--	.03	.020	91	142	88	24	320	7.5	17.0	0	--	DD 63
2.1	.2	.00	--	--	210	202	134	0	262	8.4	15.5	2	--	DE 32
3.1	.2	.02	--	--	190	194	119	0	270	8.4	15.5	2	--	DE 33
3.9	.3	.05	--	--	210	218	132	0	286	8.0	17.7	1	--	DF 6
3.0	.4	.02	--	--	211	--	133	0	285	7.9	16.6	3	1000	
3.0	.4	.02	--	--	218	--	133	0	285	8.1	--	4	900	
3.2	.4	.05	--	--	225	--	127	0	282	8.1	--	2	600	
2.2	.4	.00	--	--	216	--	124	0	289	7.8	--	5	--	
3.2	.5	.07	--	--	209	--	106	0	298	8.3	16.1	2	--	DF 9
3.5	.4	.11	--	--	206	214	102	0	295	7.9	15.0	2	--	
3.7	.5	.02	--	--	215	--	102	0	290	7.9	16.1	2	1300	
3.5	.4	.02	--	--	220	--	98	0	296	8.1	--	2	1500	
3.3	.5	.05	--	--	225	--	100	0	296	8.2	--	2	600	
3.5	.3	.02	--	--	212	--	103	0	298	7.4	--	1	1500	
3.0	.0	.00	--	--	209	216	102	0	295	7.8	--	5	--	
2.9	.3	.00	--	--	204	215	104	0	280	8.0	18.3	2	--	DF 14
3.8	.4	.05	--	--	215	--	104	0	279	8.1	17.7	5	1100	
1.6	.3	.02	--	--	206	--	100	0	283	7.9	--	5	300	
2.4	.5	.09	--	--	210	--	103	0	290	7.8	--	1	800	
3.0	.6	.05	--	--	211	--	94	0	291	7.7	--	5	--	
3.4	.0	.00	--	--	213	--	102	0	289	7.8	--	5	--	
2.8	.3	.02	--	--	210	219	124	0	284	8.0	--	0	--	DF 38
3.5	.3	.02	--	--	222	--	125	0	290	7.7	16.6	3	1100	
2.7	.4	.05	--	--	224	--	121	0	290	8.1	--	2	1400	
2.7	.4	.05	--	--	227	--	121	0	293	8.1	--	2	600	
2.5	.5	.05	--	--	215	--	119	0	296	7.8	--	5	--	
2.9	.5	.02	--	--	214	--	99	0	296	7.9	--	2	100	
2.9	.4	.02	--	--	210	217	102	0	284	8.0	--	1	--	DF 39
3.0	.6	<.01	--	--	212	208	100	0	290	7.8	16.0	4	1700	
1.6	.4	.02	--	--	210	184	99	0	289	8.1	--	3	300	
2.6	.6	.02	--	--	218	212	95	0	295	8.2	--	1	800	
3.0	.6	.05	--	--	216	212	96	0	294	7.8	--	5	--	
1.3	.4	.02	--	--	227	218	72	0	292	8.3	16.1	0	--	EE 35
1.8	.2	.07	--	--	220	217	121	0	282	8.3	16.1	0	--	EE 38
1.1	.3	.09	--	--	218	216	84	0	298	8.4	16.6	0	--	EE 39
4.2	--	--	--	--	--	--	14	--	687	8.6	16.6	--	--	FG 41
3.5	1.0	.02	--	--	342	337	20	0	488	7.6	16.1	3	--	FG 46
6.1	1.7	.09	--	--	420	417	16	0	620	8.5	17.7	2	--	FG 48
2.3	.3	.02	--	--	258	255	29	0	360	8.2	16.1	0	--	FG 50

Procedures

All chemical analyses of ground water used in subsequent calculations have been taken from the WATSTORE data base maintained by the U.S. Geological Survey. Only analyses that had less than a 5-percent charge-balance error were used. Activities and molalities of chemical species were obtained by the use of the computer program WATEQF (Plummer and others, 1976). Additionally, WATEQF was used to calculate the calcite saturation indices of Aquia water. Data on the distribution of calcite cementation in the Aquia Formation were obtained from drilling logs published by Bennion and Brookhart (1949), Cook and others (1952), Martin and Ferguson (1953), and Otton (1955).

The major ions in Aquia water are calcium, magnesium, sodium, and bicarbonate, which collectively account for about 95 percent of all dissolved constituents. The reaction models developed in this paper are designed to explain the distributions of these four ionic species.

The general procedures used to develop the chemical reaction models described in this report are:

1. Document the distribution of dissolved calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}), and bicarbonate (HCO_3^-) and demonstrate how these distributions relate to aquifer mineralogy and flow patterns.
2. Develop a set of reaction models to describe the observed changes in water chemistry along the flowpath.
3. Test the reaction models by comparing observed molar ratios of dissolved ions with molar ratios predicted by the reaction models.

The procedure for evaluating the origin of calcite cementation in the Aquia Formation will be to:

1. Perform mass balance calculations with the verified chemical reaction models.
2. Compare observed zones of calcite cementation to zones predicted by the mass balance calculations.
3. Show that the zones of calcite cementation and zones that lack cementation as predicted by mass balance calculations are consistent with the calcite saturation state of Aquia water.

Analyses of Aquia glauconite for cation exchange properties were performed at the U.S. Geological Survey Denver Central Laboratory using standard techniques. Glauconite was separated from other aquifer materials for these analyses using a magnetic separator.

Aquia Aquifer

Mineralogy

The mineralogy of the Aquia aquifer is dominated by quartz sand, glauconite, and shell debris which together make up about 98 percent of the aquifer material. Quartz is the most abundant mineral (50-65 percent). Glauconite is the second most abundant mineral (20-45 percent). Broken shell debris commonly makes up between 1 and 10 percent of the aquifer material. In addition to these major constituents, the Aquia contains traces of magnetite, garnet, kaolinite, ilmenite, hornblende, tourmaline, epidote, augite, andalusite, sillimenite, kyanite, staurolite, potassium feldspar, plagioclase, pyrite, and lignite.

All of the minerals in the Aquia react to some degree with ground water. The complexity generated by this mineralogy makes it impossible to construct a unique reaction model describing the water chemistry (Plummer and others, 1983). However, the effects of slow-reacting minerals, such as quartz, are small compared to the effects of fast-reacting minerals, such as carbonates (Garrels, 1975). This will be particularly true if the faster-reacting minerals are much more abundant than the slower-reacting minerals. The approach taken in this paper is to assume that fast-reacting minerals have a much greater impact on water chemistry than minerals that react relatively slowly. If this assumption results in an acceptable approximation, then the reaction models which are constructed will be non-unique but nevertheless useful.

Under ambient temperature, pressure, and pH conditions in the Aquia aquifer, the oxide and silicate trace minerals can be expected to react relatively slowly with water. For the purpose of this paper, they will be considered nonreactive. Similarly, quartz can be expected to react relatively slowly and will also be considered nonreactive.

Glauconite is an iron-bearing, hydrous aluminum silicate of the illite family and is an efficient cation exchange medium. Cation exchange reactions are relatively rapid (Foster, 1950), and will probably have a significant impact on the chemistry of Aquia water.

The shell material in the Aquia consists of calcium carbonate present both as calcite and aragonite. Additionally, shell material commonly contains up to 18 mole percent magnesium calcite (Wollast and others, 1971). Under most conditions encountered in fresh-water aquifers, chemical reactions involving carbonates are relatively rapid (Reardon, 1981). For this reason, the carbonate shell material present in the Aquia can be expected to have a major influence on the water chemistry.

Carbon dioxide (CO_2) contributes to the chemical evolution of Aquia water. Carbon dioxide is present in soil gas and can react with percolating water in the unsaturated zone (Pearson and Friedman, 1970). Carbon dioxide can also be generated in the aquifer by slow oxidation of lignite (Foster, 1950). In view of these sources, it is probably reasonable to assume that the Aquia aquifer is an open system with respect to carbon dioxide.

Ion Distributions

A convenient method of showing the distribution of dissolved ionic species in an aquifer is to graph ion concentrations as a function of distance along flowpaths. This method has the advantage of showing directly how water chemistry evolves as it moves down the hydrologic gradient. In the Aquia aquifer, the distance that water has moved along flowpaths can be estimated from the prepumping potentiometric surface (pl. 3). As a matter of convention the northern limit of the outcrop area can be chosen as zero distance.

The concentrations of $Ca^{2+}+Mg^{2+}$, Na^+, and HCO_3^- plotted as a function of distance along the flowpath are shown in figure 42. The curves drawn through the data points are to illustrate major trends and do not represent a rigorous statistical fit. The data of figure 42 suggest that the Aquia aquifer can be divided into three regions based on the changes in water chemistry:

Region I—This region is about 26 miles wide. It is parallel to and includes the outcrop/subcrop area of the aquifer. $Ca^{2+}+Mg^{2+}$ and HCO_3^- concentrations increase rapidly and level off. Concentrations of Na^+ remain relatively low.

Region II—This region is immediately downgradient of Region I and is about 22 miles wide. The water chemistry is characterized by relatively constant HCO_3^- concentrations, rising Na^+ concentrations, and declining $Ca^{2+}+Mg^{2+}$ concentrations.

Region III—This region is downgradient from Region II and continues to the downdip extent of the aquifer. The water chemistry is characterized by low $Ca^{2+}+Mg^{2+}$ concentrations and rapidly increasing Na^+ and HCO_3^- concentrations.

In addition to the changes in water chemistry shown in figure 42, the pH of Aquia water consistently increases downgradient. In Region I, pH ranges from about 6.0 to 7.5. In Region II, pH ranges from about 7.5 to 8.2, and in Region III, pH ranges from 8.0 to 8.9. Figure 43 shows Regions I, II, and III in plan view, and representative water analyses for each region.

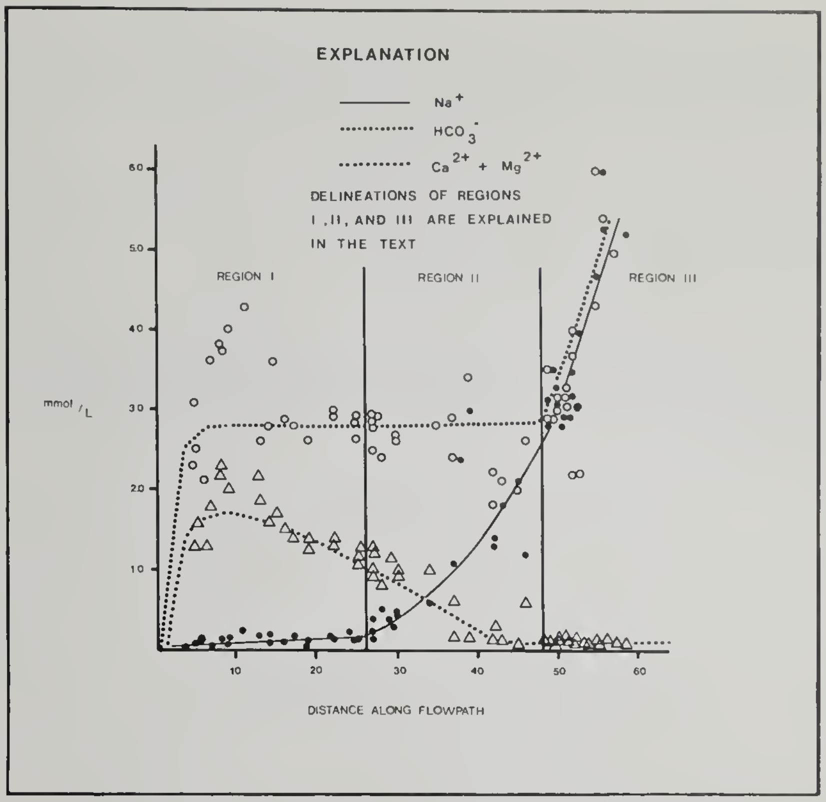


Figure 42.—Concentrations of dissolved sodium, calcium and magnesium, and bicarbonate versus distance along the flowpath for Aquia water.

The presence of different water-chemistry patterns in different parts of the Aquia aquifer implies that the chemical processes also differ. If this is the case, a single chemical model will not be sufficient to explain the changes in water chemistry. The approach taken will be to build separate (but related) chemical models for each region of the Aquia aquifer.

Development of Working Equations

The lithology of the Aquia aquifer suggests that shell material, carbon dioxide, and glauconite are the aquifer materials that most affect the chemistry of Aquia water. In order to quantify these effects, chemical equations that describe the reaction of each phase with water must be developed.

Shell material is commonly composed of at least three phases—calcite, aragonite, and magnesium calcite (Wollast and others, 1971). The reaction of calcite and aragonite with water can be represented by the equation

$$CaCO_{3(s)}+H_2O_{(L)} \rightleftharpoons Ca^{2+}_{(aq)}+HCO^-_{3(aq)}+OH^-_{(aq)} \qquad (3)$$

Calcite containing a significant percentage of magnesium can be treated similarly:

$$(Ca_{1-x}Mg_x)CO_{3(s)}+H_2O_{(L)} \rightleftharpoons$$

$$(1-x)Ca^{2+}_{(aq)}+HCO^-_{3(aq)}+OH^-_{(aq)} \qquad (4)$$

The reaction of CO_2 with water can be written

$$CO_{2(g)}+H_2O_{(L)} \rightleftharpoons H^+_{(aq)}+HCO^-_{3(aq)} \qquad (5)$$

The cation exchange reaction with glauconite acting as the exchange medium can be written

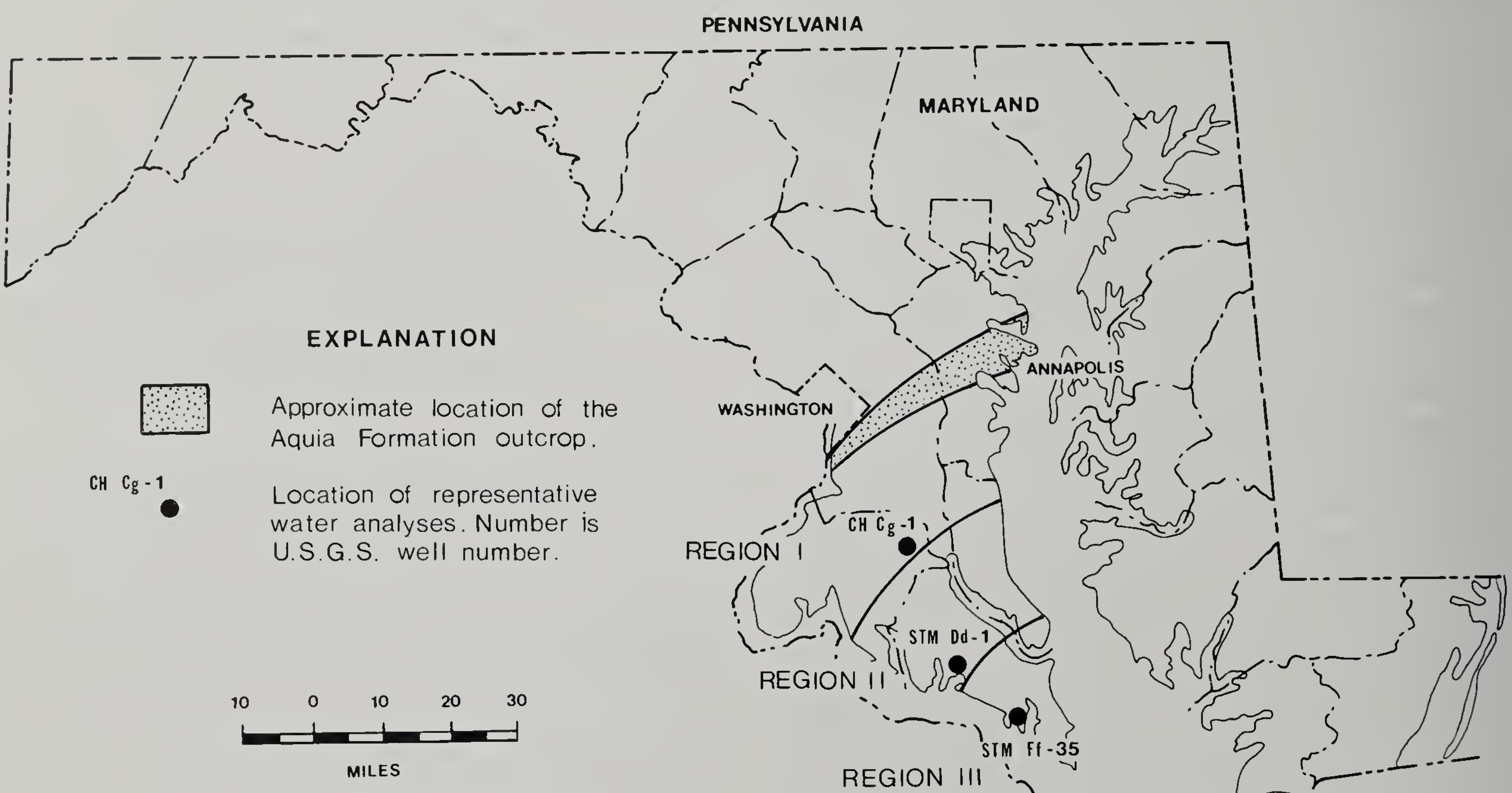
$$X^{2+}_{(aq)} + Na_2 \bullet Glau_{(ad)} \rightleftharpoons 2\,Na^{+}_{(aq)} + X \bullet Glau_{(ad)} \qquad (6)$$

where X can be Ca^{2+} or Mg^{2+}.

These equations are based upon idealized mineral compositions and, therefore, approximate the natural system.

Development of Reaction Models

In the simplified system that was considered in developing the working equations, the source of Ca^{2+} and Mg^{2+} ions is dissolution of calcite, aragonite, and magnesium calcite (eqs. 3 and 4). The only important source of Na^{+} is the glauconite exchange reaction (eq. 6). HCO_3^- ions are produced by dissolution of calcite, aragonite, and magnesium calcite (eqs. 3 and 4) and by reaction of CO_2 gas with water



REGION	I	II	III
Well number	CH-Cg 1	STM-Dd 1	STM-Ff 35
Constituent (mg./ l.)			
Hardness	130	14	15
Calcium	29	3.6	3.0
Magnesium	13	1.1	1.9
Sodium	5.3	49	140
Potassium	14	1.9	7.8
Bicarbonate	174	136	367
Chloride	1.4	2.5	2.4
Sulfate	12	8.9	13
Silica	10	10	11
Temperature	18.5	17.2	19.0
pH	7.7	8.5	8.4

Figure 43.—Regions I, II, and III of the Aquia aquifer and representative water analyses from each region.

(eq. 5). Various combinations of these working equations can be utilized to account for the water chemistry changes in Region I, II, and III.

In Region I, sources of Ca^{2+}, Mg^{2+}, and HCO_3^- ions are required. Because Na^+ remains essentially constant in this region, a Na^+ source is not required. Therefore, the chemistry of Region I can be simulated with the working equations:

$$CaCO_{3(s)}+H_2O_{(L)} \rightleftharpoons Ca^{2+}_{(aq)}+HCO^-_{3(aq)}+OH^-_{(aq)} \qquad (3)$$

$$(Ca_{1-x}Mg_x)CO_{3(s)}+H_2O_{(L)} \rightleftharpoons$$

$$(1-x)Ca^{2+}_{(aq)}+xMg^{2+}_{(ag)}+HCO^-_{3(aq)}+OH^-_{(aq)} \qquad (4)$$

$$CO_{2(g)}+H_2O_{(L)} \rightleftharpoons H^+_{(aq)}+HCO^-_{3(aq)} \qquad (5)$$

Adding these equations algebraically and balancing the coefficients yields:

$$(Ca_{1-x}Mg_x)CO_{3(s)}+CO_{2(g)}+H_2O_{(L)} \rightleftharpoons$$

$$(1-x)Ca^{2+}_{(aq)}+xMg^{2+}_{(aq)}+2HCO^-_{3(aq)} \qquad (7)$$

Given the simplifying assumptions made in developing the working equations, equation 7 is a stoichiometric model for the ground-water chemistry of Region I and will be referred to as Model I. The coefficients of Model I assume that the pH of the system is constant. However, because H^+ and OH^- concentrations are low ($\approx 10^{-8}$ M and $\approx 10^{-6}$ M, respectively) compared to the concentrations of the major ions ($\approx 10^{-3}$ M to 10^{-4}), the stoichiometry is valid for the range of pH found in Region I.

In Region II, HCO_3^- concentrations remain approximately constant. Concentrations of $Ca^{2+}+Mg^{2+}$ decrease and Na^+ concentrations increase. Because no source of HCO_3^- is required, equations 3, 4, and 5 are not required. In this region only equation 6, which is a sink for $Ca^{2+}+Mg^{2+}$ and a source of Na^+, applies.

$$X^{2+}_{(aq)}+Na_2 \bullet Glau_{(ad)} \rightleftharpoons X \bullet Glau_{(ad)}+2Na^+_{(aq)} \qquad (6)$$

where

$X=Ca^{2+}$ or Mg^{2+}.

This equation describes the major changes in water chemistry that occur in Region II and will hereafter be referred to as Model II.

In Region III, $Ca^{2+}+Mg^{2+}$ concentrations remain constant whereas Na^+ and HCO_3^- concentrations increase rapidly. Because a source of HCO_3^- is needed in this region, equations 3, 4, and 5 apply. Because a source of Na^+ and a sink for Ca^{2+} and Mg^{2+} ions is needed, equation 6 also applies. The working equations for this system will be

$$CaCO_{3(s)}+H_2O_{(L)} \rightleftharpoons Ca^{2+}_{(aq)}+HCO^-_{3(aq)}+OH^-_{(aq)} \qquad (3)$$

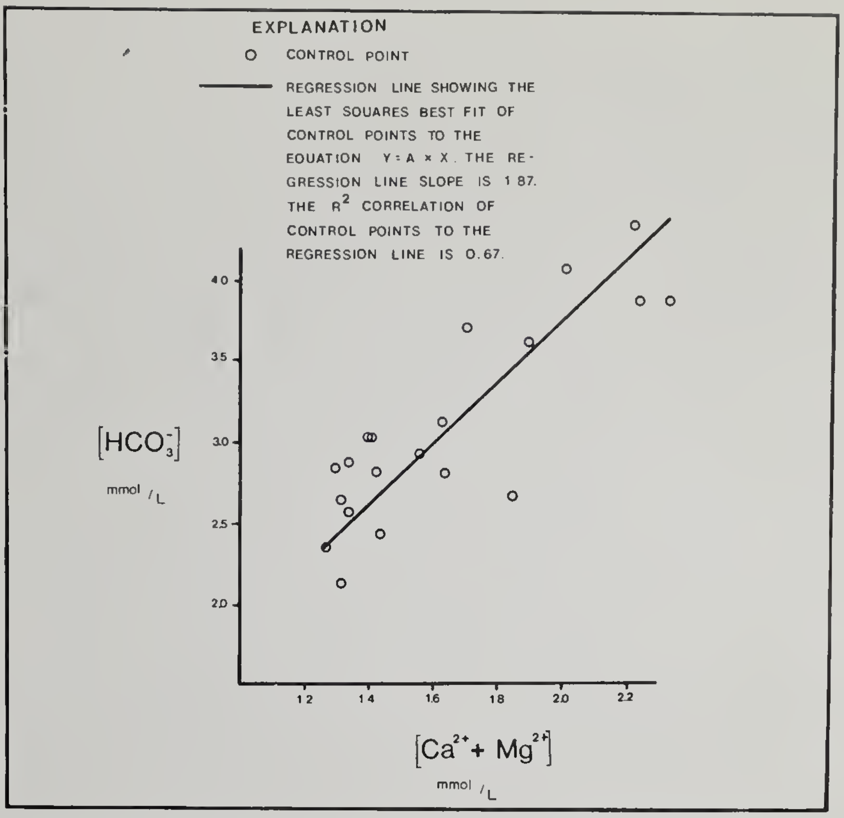


Figure 44.—Calcium and magnesium concentration versus bicarbonate concentration for water analyses in Region I of the Aquia aquifer.

$$(Ca_{1-x}Mg_x)CO_{3(s)}+H_2O_{(L)} \rightleftharpoons$$

$$(1-x)Ca^{2+}_{(aq)}+xMg^{2+}_{(aq)}+HCO_3^-+OH^-_{(aq)} \qquad (4)$$

$$CO_{2(g)}+H_2O_{(L)} \rightleftharpoons H^+_{(aq)}+HCO^-_{3(aq)} \qquad (5)$$

$$X^{2+}_{(aq)}+Na_2 \bullet Glau_{(ad)} \rightleftharpoons 2\,Na^+_{(aq)}+X \bullet Glau_{(ad)} \qquad (6)$$

where

$X=Ca^{2+}$ or Mg^{2+}.

Adding these equations algebraically and balancing the coefficient yields

$$(Ca_{1-x}Mg_x)CO_{3(s)}+CO_{2(g)}+H_2O_{(L)}+Na_2 \bullet Glau_{(ad)} \rightleftharpoons$$

$$2Na^+_{(aq)}+2HCO^-_{3(aq)}+Ca_{1-x}Mg_x \bullet Glau_{(ad)} \qquad (8)$$

This equation describes the water-chemistry changes in Region III and will hereafter be referred to as Model III. This equation is similar to one derived by Thorstenson and others (1979).

Model Predictions

Models I, II, and III must be tested to determine if they accurately predict water-chemistry changes in the regions for which they were designed. One method of testing these models is to graphically compare observed molar ratios of dissolved species with those predicted by the models. Good matches between predicted and observed curves will support the applicability of the models.

Model I states:

$$(Ca_{1-x}Mg_x)CO_{3(s)}+CO_{2(g)}+H_2O_{(L)} \rightleftharpoons$$

$$(1-x)Ca^{2+}_{(aq)}+xMg^{2+}_{(aq)}+2HCO^-_{3(aq)}.$$

Inspection of this equation shows that as carbonate shell material dissolves, the molar proportion of $Ca^{2+}+Mg^{2+}$ to HCO_3^- should be linear with a slope of +2.0. Because it is difficult to quantify the relative proportions of Ca^{2+} and Mg^{2+} in shell material, they have been considered together. Figure 44 shows $Ca^{2+}+Mg^{2+}$ plotted as a function of HCO_3^- for analyses of water in Region I. The linear least squares best fit for this plot has a slope of 1.87, which is close to the predicted slope of 2.0. The r-square correlation for this plot is 0.67, indicating a good fit between the model and the data. The statistical significance of this correlation relative to sample size can be tested using the Fisher Z transformation (Miller and Freund, 1977, p. 325). Use of this test statistic shows that the correlation of $Ca^{2+}+Mg^{2+}$ to HCO_3^- is significant at the 95-percent confidence level.

Model II states:

$$X^{2+}_{(aq)}+Na_2 \bullet Glau_{(ad)} \rightleftharpoons 2Na^+_{(aq)}+x \bullet Glau_{(ad)}$$

$$X=Ca^{2+} \text{ or } Mg^{2+}.$$

This equation predicts that Na^+ ions will enter solution at twice the rate that $Ca^{2+}+Mg^{2+}$ ions are removed from solution. Therefore, the molar relationship between $Ca^{2+}+Mg^{2+}$ and Na^+ in Region II should be a straight line with slope −2.0. Figure 45 shows $Ca^{2+}+Mg^{2+}$ plotted as a function of Na^+ for water analyses taken in Region II. The linear least squares best fit for this plot has a slope of −1.75, which is close to the predicted slope of −2.0. Also, the r-square correlation for this plot is 0.86 indicating a good fit between the model and the data. This correlation is significant at the 95-percent confidence level.

Model III states:

$$(Ca_{1-x}\, Mg_x)CO_{3(s)}+CO_{2(g)}+H_2O_{(L)}+Na_2 \bullet Glau_{(ad)}$$

$$\rightleftharpoons 2Na^{2+}_{(aq)}+2HCO^-_{3(aq)}+Ca_{1-x},\, Mg_x) \bullet Glau_{(ad)}.$$

This equation predicts that the molar proportions of Na^+ and HCO_3^- will be related linearly with a slope of +1.0. Figure 46 shows the plot of Na^+ as a function of HCO_3^- for all available water analyses in Region III. The least squares best fit for this data is a line with slope 0.99, which is very close to the predicted slope of 1.0. The linear r-square for this plot is 0.98, which shows excellent correlation between the model and the data. This correlation is significant at the 95-percent confidence level.

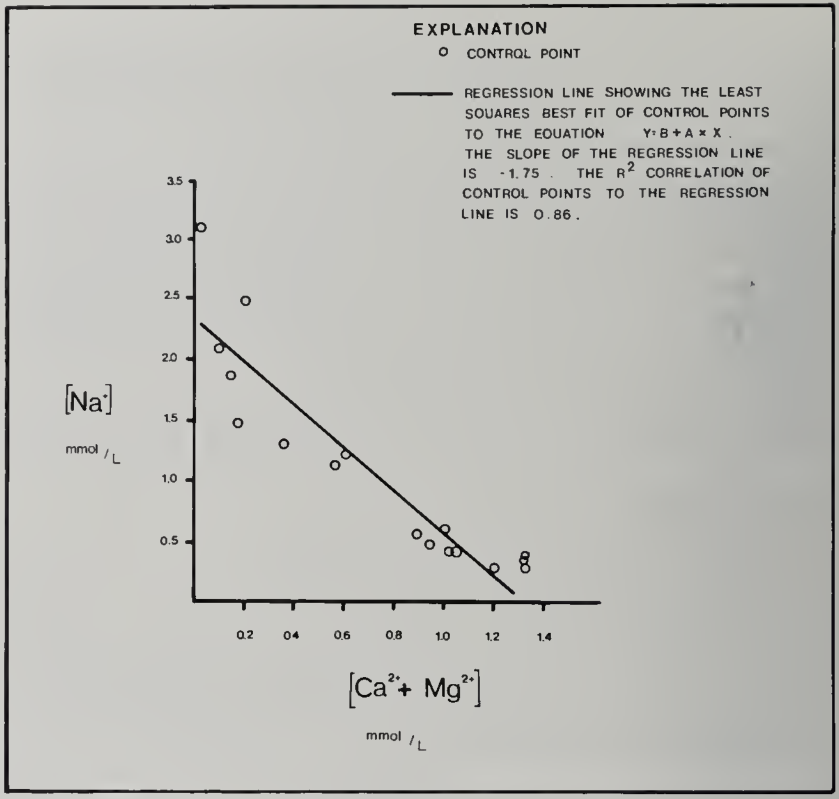


Figure 45.—Calcium and magnesium concentration versus sodium concentration for water analyses in Region II of the Aquia aquifer.

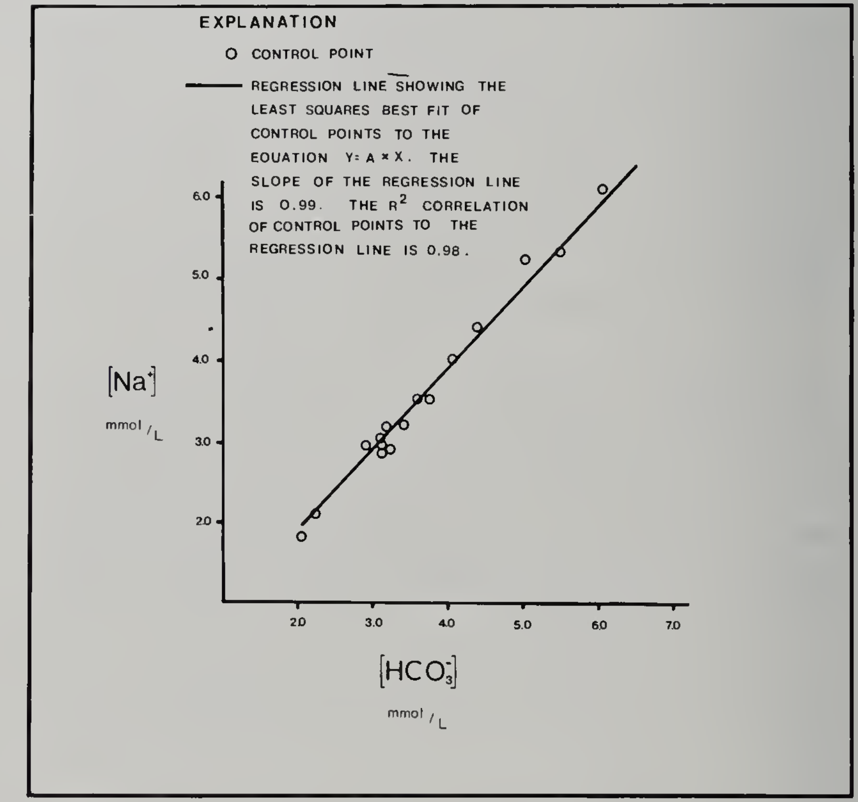


Figure 46.—Sodium concentration versus bicarbonate concentration for water analyses in Region III of the Aquia aquifer.

The generally close matches between predicted water chemistry and measured water chemistry supports the validity of Models I, II, and III. These models were constructed by assuming relatively simple aquifer mineralogy and by assuming idealized mineral compositions, and therefore these are not unique models. However, for the system specified, they work well.

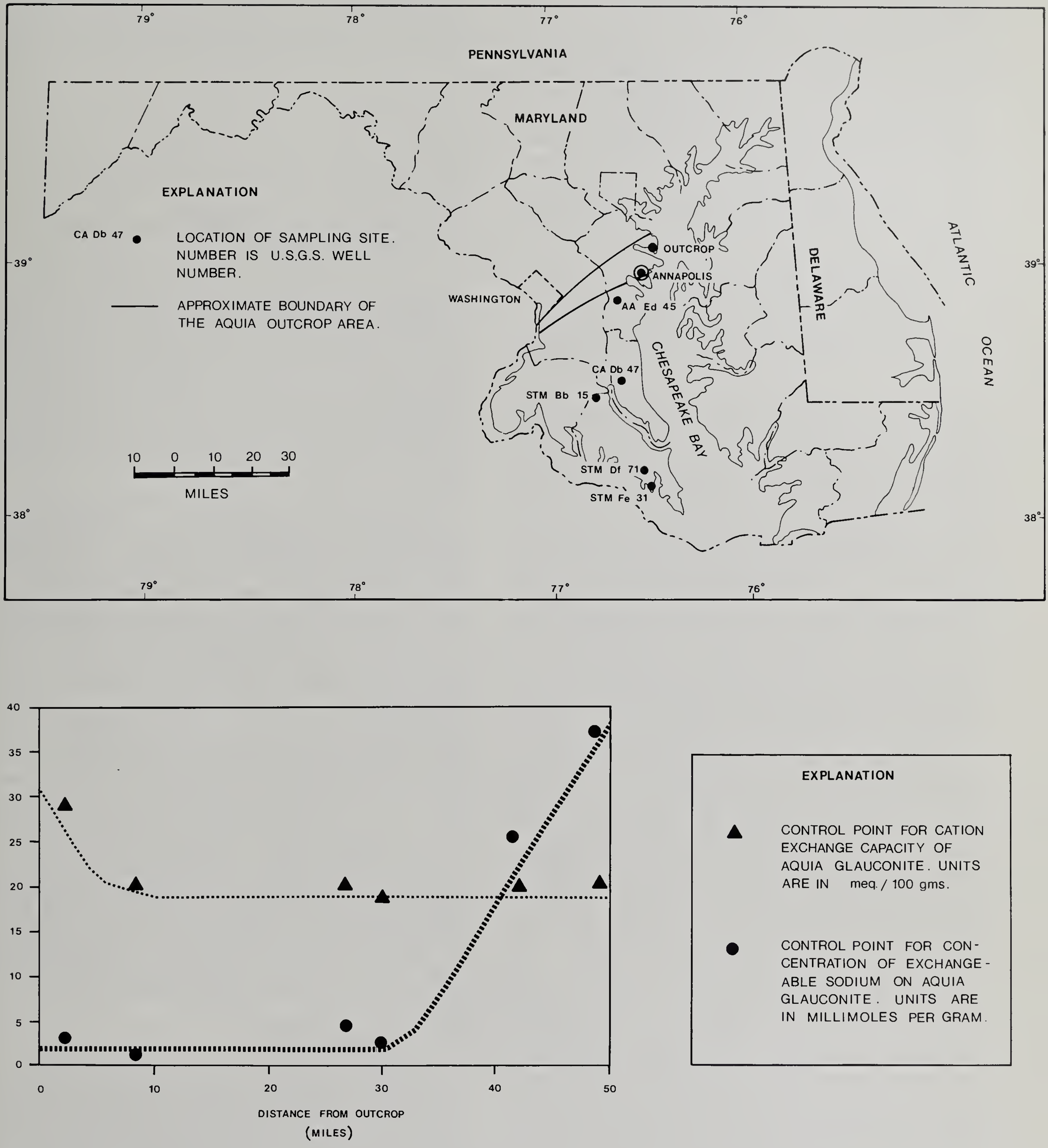


Figure 47.—Cation exchange capacity and concentration of exchangeable sodium of glauconite samples from the Aquia aquifer plotted versus distance along the flowpath.

Discussion

It has been shown that concentration changes of Ca^{2+}, Mg^{2+}, Na^{+}, and HCO_3^- in Aquia water can be described by three models. Model I applies to the region including and closest to the outcrop area. Model II applies to the region immediately downgradient from this. Model III applies to the most southeastern area of the Aquia aquifer. These regions are shown in figure 43. Although these models can predict water-chemistry changes along the flowpath, they do not explain why certain reactions occur in some regions of the aquifer, but not in other regions. Two questions in particular should be addressed:

1. Why is cation exchange an important reaction in Regions II and III, but not in Region I?
2. Why is shell material dissolution an important reaction in Regions I and III, but not in Region II?

The first question was addressed by determining the cation exchange properties of some Aquia glauconite samples. Six samples of Aquia aquifer material were obtained. Five of these samples were from drill cuttings and one was from an Aquia outcrop. The glauconite was separated from the samples and analyzed for cation exchange capacity and concentrations of exchangeable cations. The cation exchange capacity and concentration of exchangeable sodium plotted as a function of distance along the flowpath are shown in figure 47. Also shown are the locations of the six sample sites. The cation exchange capacity of these samples is relatively constant. The concentrations of exchangeable sodium, however, are low near the outcrop area but increase substantially at about 30 miles downgradient. A comparison of figure 47 with figure 42 shows that the increase of exchangeable sodium on the glauconite coincides with the increase of dissolved Na^{+} in Aquia water. It can be concluded, therefore, that cation exchange is not an important reaction in Region I because the glauconite has low concentrations of exchangeable sodium. Cation exchange occurs in Regions II and III because the glauconite has higher concentrations of exchangeable sodium.

The lower exchangeable sodium content of upgradient glauconite, as opposed to that of downgradient glauconite, has probably developed over the history of the aquifer. In upgradient areas, Ca^{2+} and Mg^{2+} produced by shell material dissolution would quickly react with glauconite and thus deplete exchangeable sodium. Water from upgradient areas (now low in Ca^{2+} and Mg^{2+}) would subsequently move downgradient. Glauconite in downgradient areas would be in contact with water containing little Ca^{2+} and Mg^{2+} and exchangeable sodium would not be depleted as quickly.

The second question can be addressed by evaluating the equilibrium of calcite in the Aquia aquifer. The equilibrium of a mineral-water reaction is usually defined in terms of the Saturation Index (SI). SI is defined as

$$SI=\log \frac{IAP}{K}$$

IAP=ion activity product of the mineral-water reaction.

K=the equilibrium constant for the mineral-water reaction.

If the SI for calcite is zero or close to zero for a particular water analysis, then that water is in equilibrium with calcite. If SI is negative, the water is subsaturated. Langmuir (1971) suggests that indexes within ± 0.1 of zero should be considered saturated. Therefore, if SI is zero ± 0.1 or positive, dissolution of calcite should not occur. If SI is more negative than -0.1, dissolution of calcite should occur.

The calcite SI's as calculated by WATEQF for available analyses of Aquia water in Southern Maryland are shown in figure 48. In Region I, the Aquia aquifer is recharged by meteroic water that is relatively unmineralized and is subsaturated with respect to calcite. When this water enters the aquifer it will rapidly dissolve calcite until equilibrium is reached (Reardon, 1981). Figure 48 shows that water analyses in Region I are either close to saturation or supersaturated (average $SI=\pm 0.07$) indicating that calcite dissolution has occurred and equilibrium is being approached. In Region II where water has moved downgradient from Region I, the analyses show that the water remains close (average $SI=-0.07$) to calcite saturation. Therefore, significant calcite dissolution in Region II is not to be expected. In Region III, practically all analyses are subsaturated (average $SI=-0.31$) and calcite dissolution should occur. This subsaturation in Region III is probably due to the loss of Ca^{2+} ions to the cation exchange reaction. This lowers the IAP for the calcite equilibrium and results in subsaturation.

Calcite Cementation

The Aquia aquifer in places is characterized by considerable thickness of sandstone ledges that are cemented by calcite. These ledges, or "hardbeds" as they are often called, are distinctive because their relative hardness makes them difficult to drill. Individual hardbeds range in thickness from a few

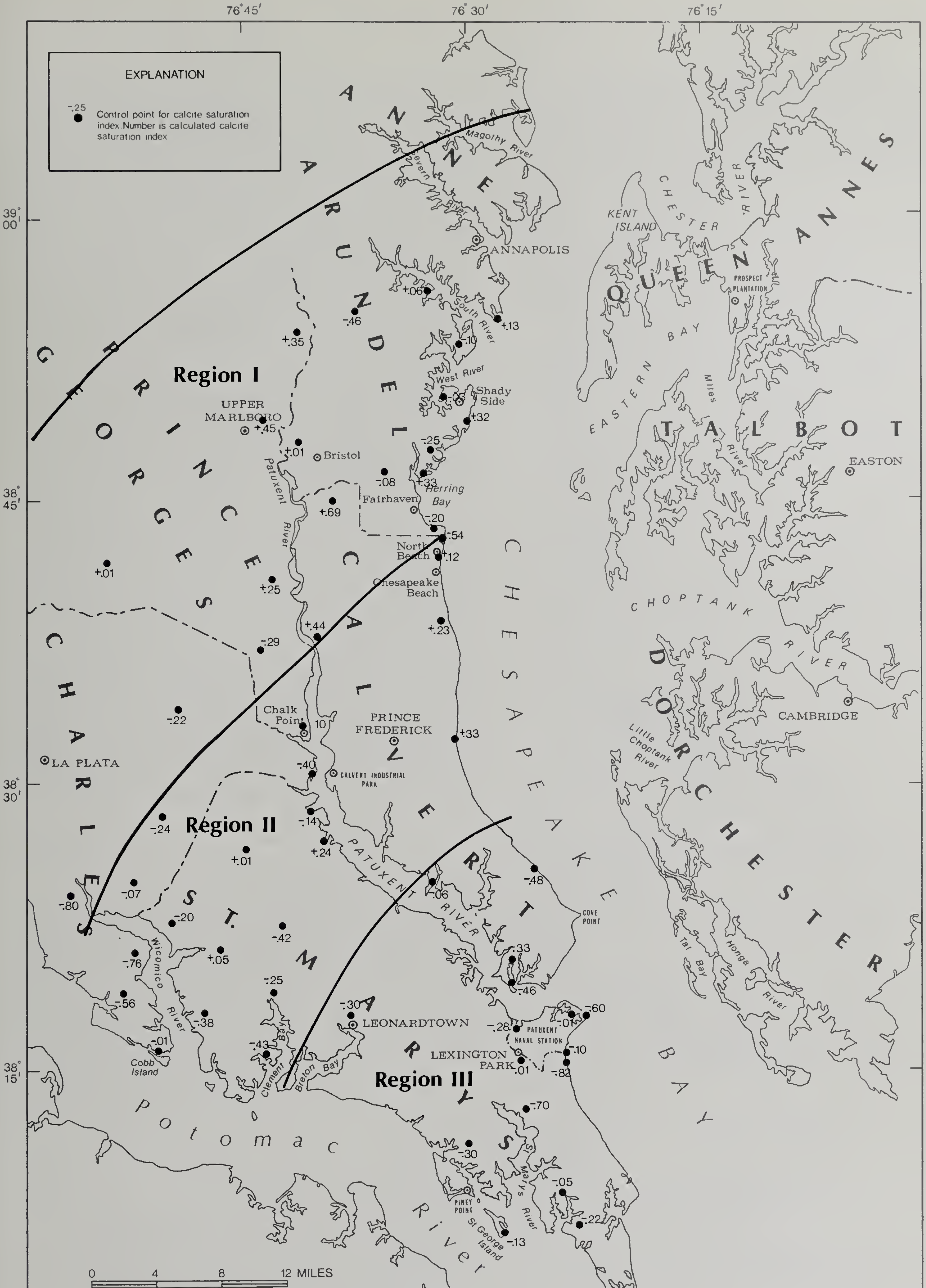


Figure 48.—Calcite saturation indexes calculated from chemical analyses of Aquia water.

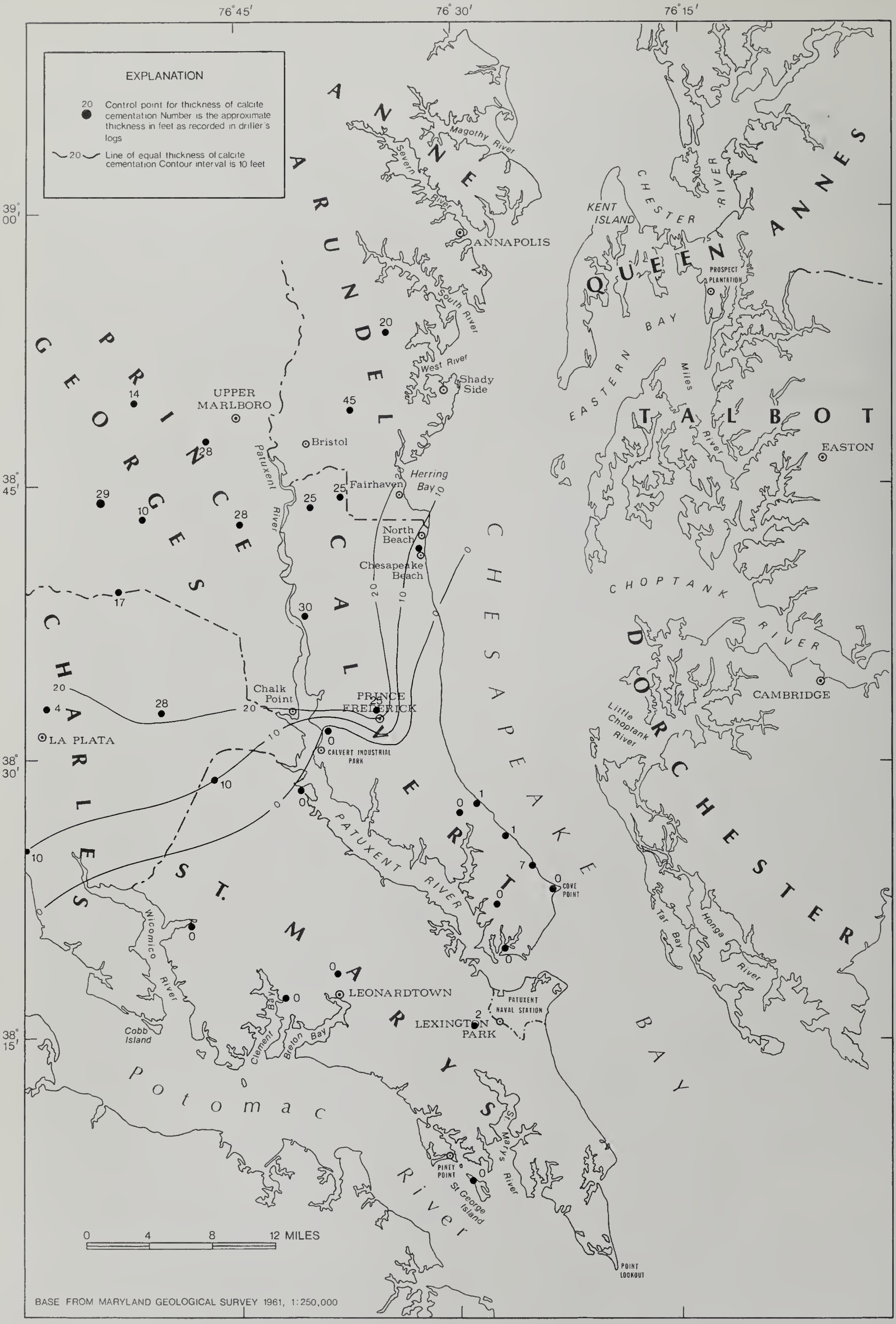


Figure 49.—Approximate thickness of calcite cementation in the Aquia aquifer.

inches to several feet and are often associated with lenses of abundant shell material. There may be anywhere from one to several dozen separate hardbeds in a given vertical section of the Aquia. The spatial distribution of this calcite cementation follows a pattern. Localities in and near the outcrop area are characterized by abundant calcite cementation, whereas areas further downgradient exhibit little cementation. This pattern is illustrated in figure 49, which shows thicknesses of cementation as recorded in published drilling logs. In Prince Georges and Anne Arundel Counties, which are near the outcrop area, total thicknesses of 30 feet or greater are common. Further downgradient in St. Mary's County, well logs record little or no cementation. This observed difference is not related to a change in available shell material. Shell material is as abundant in areas lacking cementation as it is in areas with abundant cementation.

The calcite cementation may be a primary sedimentary feature of the Aquia as has been proposed by Hansen (1974) and Wright and Huffman (1979). It is also possible that the cementation is secondary in origin and has resulted from the reaction of ground water with aquifer material. If the calcite cementation is secondary, the chemical reaction models developed in this paper should be consistent with the observed spatial distribution of the cementation. The procedure now will be to determine if the chemical reaction models are consistent with the distribution of calcite cementation.

Mass Balance

In order to test if the reaction models are consistent with the distribution of calcite cementation, the mass balance technique (Plummer and Back, 1980) was used. This technique has the advantage of quantitatively considering solid phase products of reactions and can take into account the production or nonproduction of secondary calcite.

For a specified system, mass balance can be described by N equations of the form

$$\sum_{j=1}^{\phi} \alpha_j \ \beta_{c,j} = \Delta Mc \quad {}_{c=1,N} \qquad (9)$$

where

ϕ = total number of minerals and gases considered;

N = minimum number of constituents needed to define the composition of the chosen minerals and gases;

α_j = stoichiometric coefficient of the mineral or gas in moles per Kg;

$\beta_{c,j}$ = stoichiometric coefficent of the c^{th} constituent in the j^{th} mineral or gas;

ΔMc = the change in moles per Kg H_2O of the C^{th} constituent in the aqueous phase along the reaction path.

When ΔMc is known from chemical analyses and $N=\phi$, a mass balance of the chosen minerals and gases can be obtained by simultaneous solution of the N equations. This algebraic problem can be conveniently solved by computers. One such computer program, BALANCE (Plummer, written commun., 1980), was used to perform the calculations in this paper.

Mass balance calculations were performed for the water chemistries of Regions I, II, and III using the reactions of Models I, II, and III. In Region I, the number of minerals and gases (ϕ) considered by Model I was equal to the number of active dissolved constituents (N) so that a mass balance could be found directly. For Regions II and III, however, it was necessary to transform the equations of Models II and III so that the requirement $\phi = N$ was satisfied. The cation exchange reaction

$$X^{2+}_{(aq)} + Na_2 \bullet Glau_{(ad)} \rightleftharpoons 2Na^{+}_{(aq)} + X \bullet Glau_{(ad)} \qquad (6)$$

$X^{2+} = Ca^{2+}$ or Mg^{2+}

was written as two reactions

$$(Ca^{2+}_{(aq)} + Na_2 \bullet Glau_{(ad)} \rightleftharpoons 2Na^{+}_{(aq)} + Ca \bullet Glau_{(ad)} \qquad (10)$$

$$Mg^{2+}_{(aq)} + Na_2 \bullet Glau_{(ad)} \rightleftharpoons 2Na^{+}_{(aq)} + Mg \bullet Glau_{(ad)} \qquad (11)$$

Also, the calcite and Mg-calcite dissolution-precipitation reactions

$$CaCO_{3(s)} + H_2O_{(L)} \rightleftharpoons Ca^{2+}_{(aq)} + HCO^{-}_{3(aq)} + OH^{-}_{(aq)} \qquad (3)$$

and

$$(Ca_{1-x}Mg_x)CO_{3(s)} + H_2O_{(L)} \rightleftharpoons$$

$$(1-x)Ca^{2+}_{(aq)} + xMg^{2+}_{(aq)} + HCO^{-}_{3(aq)} + OH^{-}_{(aq)} \qquad (4)$$

were combined with the carbon dioxide dissolution reaction

$$CO_{2(g)} + H_2O_{(L)} \rightleftharpoons H^{+}_{(aq)} + HCO^{-}_{3(aq)} \qquad (5)$$

to yield

$$(Ca_{1-x}Mg_x)CO_{3(s)} + CO_{2(g)} + H_2O_{(L)} \rightleftharpoons$$

$$(1-x)Ca^{2+}_{(aq)} + xMg^{2+}_{(aq)} + 2HCO^{-}_{3(aq)} \qquad (7)$$

and

$$CaCO_{3(s)} + CO_{2(g)} + H_2O_{(L)} \rightleftharpoons Ca^{2+}_{(aq)} + 2HCO^{-}_{3(aq)} \qquad (12)$$

This approach eliminated the direct consideration of CO_2 gas as a phase in BALANCE.

Table 11.—Results of mass balance calculations

Chemical processes	Reactions	Water composition (mole/liter)x10^{-4}				Change in water composition (moles/liter)x10^{-4}				Solid-phase products
		Ca^{2+}	Mg^{2+}	Na^{+}	HCO_3^-	Ca^{2+}	Mg^{2+}	Na^{+}	HCO_3^-	(moles/liter)x10^{-4}
	Meteoric Water	0	0	2.30	0	-	-	-	-	-
	MODEL I REACTIONS									
Dissolve Mg-calcite	$(Ca_{.9}Mg_{.1})CO_{3(s)} + H_2O_{(L)} \rightleftharpoons .9Ca^{2+}_{(aq)} + .1Mg^{2+}_{(aq)} + HCO_3^- + OH^-_{(aq)}$	46.8	5.20	2.30	52.0	+46.8	+5.20	0	+52.0	-
Precipitate calcite	$CaCO_{3(s)} + H_2O_{(L)} \rightleftharpoons Ca^{2+}_{(aq)} + HCO^-_{3(aq)} + OH^-_{(aq)}$	7.00	5.20	2.30	12.2	-39.8	0	0	-39.8	39.8 $CaCO_3$
Dissolve CO_2 gas	$CO_{2(g)} + H_2O_{(L)} \rightleftharpoons H^+_{(aq)} + HCO^-_{3(aq)}$	7.00	5.20	2.30	28.0	0	0	0	+15.8	-
	Region I Water (CH-Cg-2)	7.00	5.20	2.30	28.0	-	-	-	-	39.8 $CaCO_3$
	MODEL II REACTIONS									
Exchange Ca^{2+} for Na^+	$Ca^{2+}_{(aq)} + Na_2 \cdot Glau_{(ad)} \rightleftharpoons 2Na^+ + Ca \cdot Glau_{(ad)}$	1.60	5.20	13.1	28.0	-5.40	0	+10.8	0	-
Exchange Mg^{2+} for Na^+	$Mg_{(aq)} + Na_2 \cdot Glau_{(ad)} \rightleftharpoons 2Na^+ + Mg \cdot Glau_{(ad)}$	1.60	1.00	21.5	28.0	0	-4.20	+ 8.4	0	-
Dissolve Mg-calcite	$(Ca_{.9}Mg_{.1})CO_{3(s)} + H_2O_{(L)} + CO_{2(g)} \rightleftharpoons .9Ca^{2+}_{(aq)} + .1Mg^{2+}_{(aq)} + 2HCO^-_{3(aq)}$	2.12	1.06	21.5	29.16	+ .52	+ .06	0	+1.16	-
Precipitate calcite	$CaCO_{3(s)} + H_2O_{(L)} + CO_{2(g)} \rightleftharpoons Ca^{2+}_{(aq)} + 2HCO^-_{3(aq)}$	1.38	1.06	21.5	27.72	- .72	0	0	-1.44	0.72 $CaCO_3$
	Region II Water (SM-Dd-1)	1.38	1.06	21.5	27.72	-	-	-	-	0.72 $CaCO_3$
	MODEL III REACTIONS									
Dissolve Mg-calcite	$(Ca_{.9}Mg_{.1})CO_{3(s)} + H_2O_{(L)} + CO_{2(g)} \rightleftharpoons .9Ca^{2+}_{(aq)} + .1Mg^{2+}_{(aq)} + 2HCO^-_{3(aq)}$	15.78	2.60	21.5	59.72	+14.4	+1.6	0	+32.0	-
Dissolve calcite	$CaCO_{3(s)} + H_2O_{(L)} + CO_{2(g)} \rightleftharpoons Ca^{2+}_{(aq)} + 2HCO^-_{3(aq)}$	17.96	2.66	21.5	64.08	+ 2.18	0	0	+ 4.36	-
Exchange Ca^{2+} for Na^+	$Ca^{2+}_{(aq)} + Na_2 \cdot Glau_{(ad)} \rightleftharpoons 2Na^+_{(aq)} + Ca \cdot Glau_{(ad)}$	0.56	2.66	56.8	64.08	-17.4	0	+34.8	0	-
Exchange Mg^{2+} for Na^+	$Mg_{(aq)} + Na_2 \cdot Glau_{(ad)} \rightleftharpoons 2Na_{(aq)} + Mg \cdot Glau_{(ad)}$	0.56	0.62	60.38	64.08	0	-2.04	+ 4.08	0	-
	Region III Water (STM-Ff-35)	0.56	0.62	60.38	64.08	-	-	-	-	0

Wollast and others (1971) show that natural carbonate material commonly contains between 1 and 18 percent magnesium carbonate. On this basis it was judged that 10 mole percent magnesium carbonate would be a reasonable estimate of shell material composition in the Aquia. Under this assumption, equation 10 becomes

$$(\mathrm{Ca}_{.9}\mathrm{Mg}_{.1})\mathrm{CO}_{3(s)}+\mathrm{CO}_{2(g)}+\mathrm{H}_2\mathrm{O}_{(L)}\rightleftharpoons$$

$$.9\mathrm{Ca}^{2+}_{(aq)}+.1\mathrm{Mg}_{(aq)}+2\mathrm{HCO}_{3(aq)}. \qquad (13)$$

In Region II, it was necessary to specify equations 7 and 13 in addition to equations 10 and 11 so that $\phi = N$. Equation 13 was used to represent the dissolution reaction of magnesium calcite in Region III.

The results of the mass balance calculations are shown in table 11. These calculations use the water analyses of wells CH-Cg1, SM-Dd1, and SM-Ff35 (fig. 43) as the water compositions of Regions I, II, and III, respectively. The transformed equations of Models I, II, and III are shown in table 11 together with the chemical processes that the equations represent. Table 11 is designed to show the compositional changes of water as it moves along the flowpath. The average composition of rainfall in southern Maryland (Junge and Werby, 1958) is acted on by the Model I reactions to produce the water composition of Region I. Region I water is then acted on by the Model II reactions to produce the composition of Region II water. Finally, Region II water is acted on by the reactions of Model III to produce the composition of Region III water.

The calculations summarized in table 11 show that dissolution of magnesium calcite and simultaneous precipitation of calcite is required to obtain mass balance in Region I. In Region II, the calculations indicate that cation exchange reactions are the most important chemical processes. Magnesium calcite dissolution and calcite precipitation account for only a small portion of the mass balance. This is consistent with the earlier conclusion that Region II water chemistry is dominated by cation exchange reactions. In Region III, cation exchange, dissolution of magnesium calcite, *and* dissolution of calcite is required for mass balance.

A comparison of figures 43 and 49 shows that in Region I, where mass balance requires precipitation of calcite, the greatest thicknesses of calcite cementation are observed. Region II, which does not require significant precipitation of calcite for mass balance, shows much less cementation. Region III, where dissolution of magnesium calcite and calcite is needed for mass balance, calcite cementation is generally absent. This mass balance is also consistent with the equilibrium chemistry of the system. In Region I, where calcite cementation precipitation is needed for mass balance, the water is generally either near saturation or supersaturated with respect to calcite (fig. 48). Similarly in Region III, where calcite dissolution is required, the water is subsaturated with respect to calcite.

While the preceding analysis presents an internally consistent picture, it should be reemphasized that the chemical models used are not unique. Therefore, the mass balance obtained also is not unique. Specifically, the exact composition of magnesium calcite in the Aquia is not known and, therefore, this phase cannot be evaluated exactly. However, additional mass balance calculations that specified 5 and 15 mole percent magnesium calcite resulted in exactly the same patterns of dissolution-precipitation shown in table 11. Only the relative amounts of magnesium calcite dissolving and calcite precipitating were affected. Also, because aragonite has the same stoichiometry as calcite, its relative importance in the dissolution and precipitation of calcite cannot be evaluated with the mass balance technique. Because aragonite is less stable than calcite, it is likely that dissolution of aragonite *and* dissolution of magnesium-rich calcite contribute to the upgradient supersaturation of water with respect to calcite. These uncertainties, however, do not alter the basic picture presented in this paper. The chemical reaction models that were designed to predict changes in water chemistry along the flowpath are also consistent with the observed distribution of calcite cementation. This strongly suggests that the observed calcite cementation in the Aquia is a post depositional feature that has resulted from the reaction of ground water with aquifer material.

Piney Point-Nanjemoy Aquifer

Background

The chemical quality of Piney Point-Nanjemoy water is very similar to the chemical quality of Aquia water. Both are calcium magnesium bicarbonate type water near their outcrop areas, and both change to a sodium bicarbonate type water downgradient. This is not surprising because the mineralogy and ground-water flow patterns of the two aquifers are very similar. Given this, it seems reasonable that the techniques which were used to investigate Aquia water chemistry should be applicable to Piney Point-Nanjemoy water chemistry. For the purposes of this report, the procedures used to evaluate the chemical evolution of Piney Point-Nanjemoy water will be the same as those used for the Aquia aquifer.

Mineralogy

The Piney Point-Nanjemoy aquifer consists of olive-green to greenish-gray glauconitic quartz sand. Sands near the top of the unit have less glauconite (approximately 5 to 10-percent glauconite) than sands near the bottom of the unit (40 to 60-percent glauconite). Shell material is common in the unit and makes up 1 to 5 percent of the aquifer material. Staurolite, sillimanite, garnet, tourmaline, and zircon are the most commonly identified heavy minerals present in the Piney Point-Nanjemoy (Glaser, 1971).

For the purposes of this report, quartz is considered to be a non-reactive phase. It is also assumed that the minor minerals have negligible impact on water chemistry. Given these assumptions, shell material, glauconite, and carbon dioxide gas are the phases which will have the most effect on water chemistry.

Ion Distributions

Figure 50 shows the molar concentrations of calcium and magnesium, sodium, and bicarbonate plotted as functions of distance along the flowpath. The curves drawn through the data are to illustrate major trends and do not represent statistical significance. Figure 50 is strikingly similar to figure 42 which shows calcium and magnesium, sodium, and bicarbonate concentrations versus distance for Aquia water. This similarity implies that the chemical processes which control the composition of water from the two aquifers are similar. Inspection of figure 50 suggests that the Piney Point-Nanjemoy aquifer can be divided into three regions based on observed water-chemistry changes:

Region I—This region is about 35 mi wide and is parallel to and includes the outcrop area. Calcium and magnesium and bicarbonate concentrations are high and constant throughout the region, and sodium concentrations are low and constant.

Region II—This region is immediately downgradient from Region I, and is about 8 mi wide. It is characterized by decreasing calcium and magnesium, increasing sodium, and constant bicarbonate concentrations.

Region III—This region is downgradient from Region II and is about 10 mi wide. It is characterized by rapidly increasing sodium and bicarbonate concentrations, and constant low concentrations of calcium and magnesium.

Figure 51 shows Regions I, II, and III of the Piney Point-Nanjemoy aquifer in plan view. Also shown are representative analyses of water from each region. The different trends in each region imply that the chemical processes occurring in each region are also different. The approach taken now will be to build separate chemical models for each region of the Piney Point-Nanjemoy aquifer.

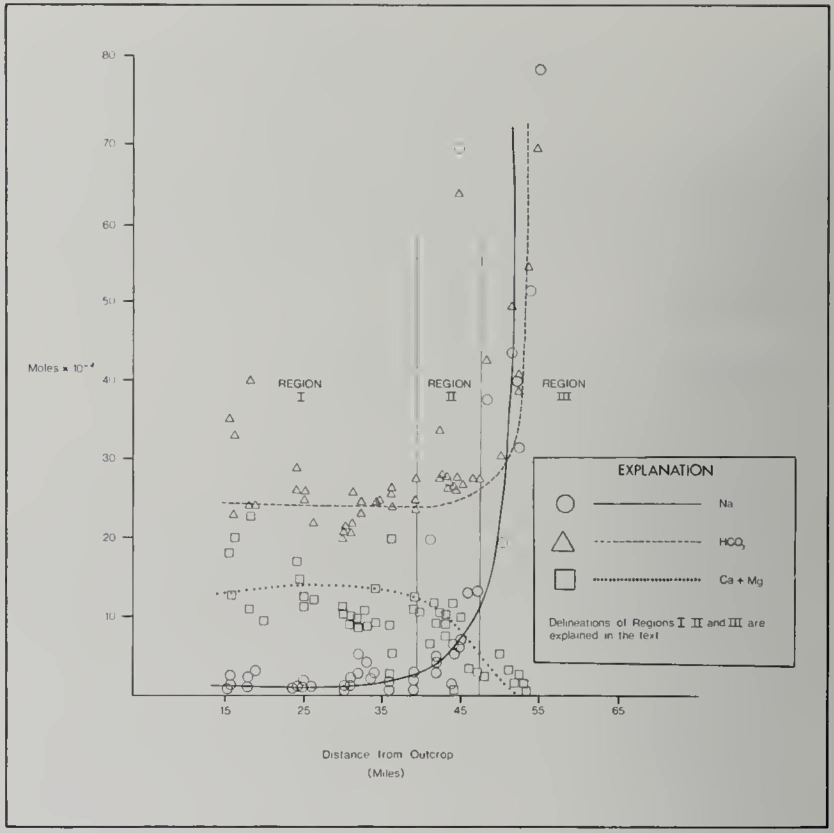


Figure 50.—Concentrations of dissolved sodium, calcium and magnesium, and bicarbonate versus distance along the flowpath for Piney Point-Nanjemoy water.

Working Equations and Reaction Models

The bulk mineralogy of the Piney Point-Nanjemoy aquifer is very similar to that of the Aquia aquifer. Because of this similarity, the development of working equations which describe the dominant chemical reactions is identical to the development used for the Aquia aquifer. Furthermore, the patterns of major ion concentration changes in the Piney Point-Nanjemoy and Aquia aquifers are very similar. Because of this, the reaction models which describe the chemistry of the Piney Point-Nanjemoy will be identical to those which describe the chemistry of the Aquia. The only difference is that Regions I, II, and III of the aquifers are not the same. The detailed procedures for development of working equations and reaction models have been given previously in the section on the chemical evolution of Aquia water and will not be repeated here. Following those procedures, Model I (eq. 7) will be a chemical model for Region I of the Piney Point-Nanjemoy aquifer. Model II (eq. 6) will be a chemical model for Region II, and Model III (eq. 8) will be a chemical model for Region III of the Piney Point-Nanjemoy aquifer.

Model Predictions

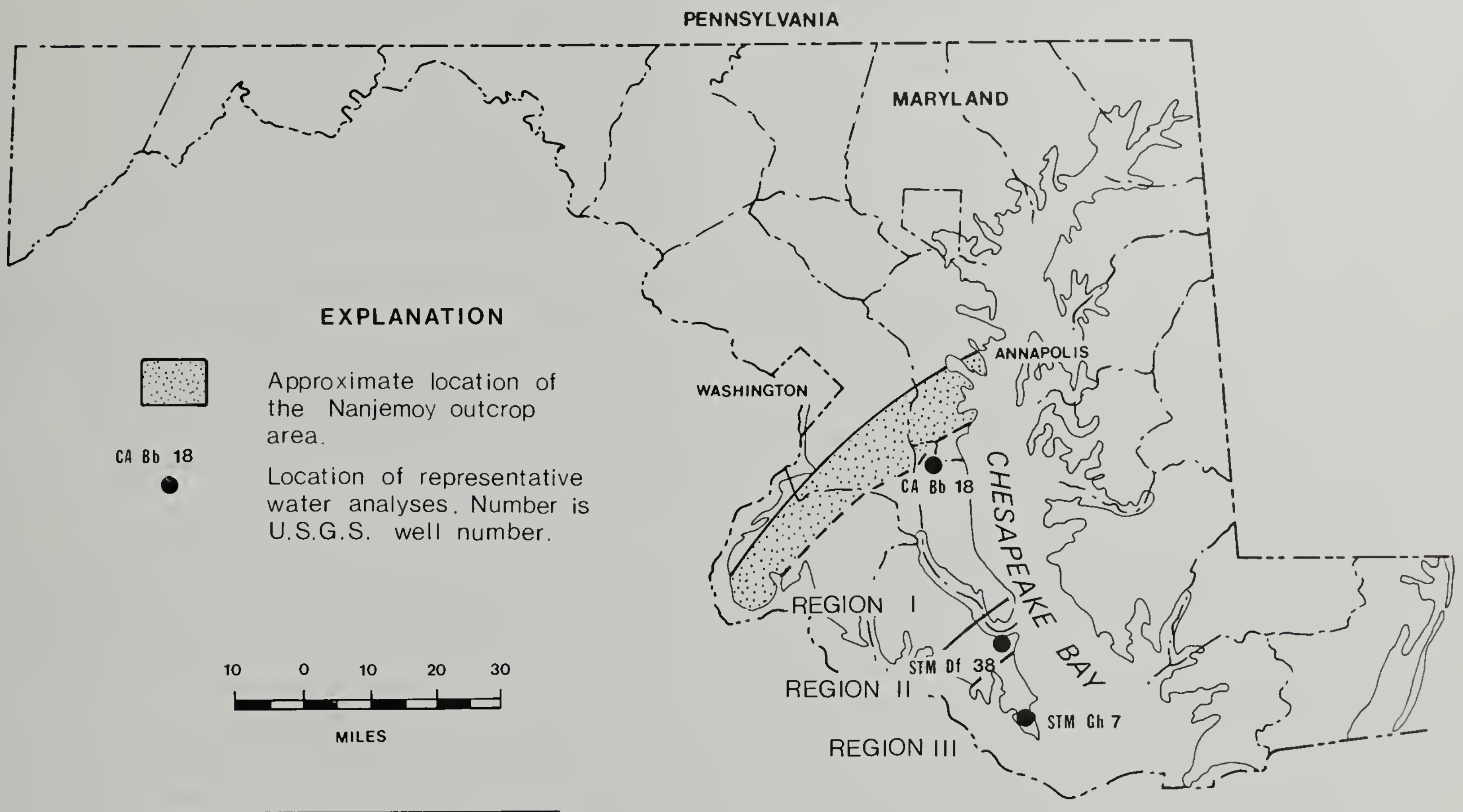
The chemical models can be tested by comparing observed molar relationships of major ions determined by linear regression to molar relationships predicted by the models. Good matches between predicted and measured curves will support the accuracy of the models.

Model I states

$$(Ca_{1-x}Mg_x)\,CO_{3(s)}+CO_{2(g)}+H_2O_{(L)} \rightleftharpoons$$

$$(1-x)Ca^{2+}_{(aq)}+xMg_{(aq)}+2HCO_{3(aq)}. \qquad (7)$$

Inspection of this equation shows that in Region I the molar relationship of calcium and magnesium to bicarbonate should be a straight line with slope +2.0. Figure 52 shows calcium and magnesium plotted versus bicarbonate for available water analyses in Region I. The least square best fit for this



REGION	I	II	III
Well number	CA-Bb 18	STM-Df 38	STM-Gh 7
Constituent (mg./l.)			
Hardness	140	99	15
Calcium	40	25	3.0
Magnesium	9.7	9.0	1.7
Sodium	2.0	25	185
Potassium	8.4	6.6	8.3
Bicarbonate	174	191	460
Chloride	2.6	2.9	2.6
Sulfate	9.2	5.5	4.2
Silica	49	59	36
Temperature	15.5	16	16.1
pH	7.5	8.0	8.7

Figure 51.—Regions I, II, III of the Piney Point-Nanjemoy aquifer and representative water analyses from each region.

plot has a slope of 1.95, which is very close to the predicted slope. The r-square correlation for this plot is 0.75 indicating a good fit between the model and the data. This correlation is significant at the 99-percent confidence level.

Model II states

$$X^{2+}_{(aq)} + Na \bullet Glau_{(ad)} \rightleftharpoons 2Na_{(aq)} + X \bullet Glau_{(ad)} \qquad (6)$$

where

$X = Ca^{2+}$ or Mg^{2+}.

This equation predicts that the molar relationship between calcium and magnesium and sodium should be a straight line with slope −2.0. Figure 53 shows calcium and magnesium plotted versus sodium for water analyses taken in Region II. The least squares best fit for this plot has a slope of −1.20 and the r-square correlation of the plot is 0.68. This correlation is significant at the 99-percent confidence level.

It is significant that the slope of the regression line (−1.20) differs substantially from the slope predicted by Model II (−2.0). This implies that the assumptions used to build Model II were not sufficiently accurate to describe the chemistry of Region II within an acceptable error margin. Model II assumes that cation exchange is the dominant chemical process in Region II. The negative slope of the calcium and magnesium versus sodium plot suggests that cation exchange is indeed occurring. However, because the slope of the regression is not closer to −2.0, it can be concluded that chemical processes other than cation exchange are modifying the composition of Region II water. It is possible that these additional chemical processes include dissolution-precipitation reactions of carbonate shell material.

Model III states

$$(Ca_{1-x}Mg_x)\,CO_{3(s)} + H_2O_{(L)} + Na_2\,Glau \rightleftharpoons$$

$$2Na^{+}_{(aq)} + 2HCO_{3(aq)} + (Ca_{1-x}, Mg_x) \bullet Glau_{(ad)}. \qquad (8)$$

This equation predicts that sodium and bicarbonate will increase with a 1:1 molar ratio. Figure 54 shows the plot of sodium versus bicarbonate for available water analyses in Region III. The least squares best fit for this data is a line with slope 0.99, which is very close to the predicted slope of 1.0. The linear r-square for this plot is 0.69 indicating a good fit between the model and the data. This correlation is significant at the 99-percent confidence level.

Discussion

It has been shown that concentrations of dissolved calcium, magnesium, sodium, and bicarbonate in the Piney Point-Nanjemoy aquifer change systematically along the flowpath. Based on these changes in chemistry, the aquifer was divided into three regions. Because water chemistry of these regions is similar to that of the Aquia aquifer, the chemical models derived for the Aquia aquifer were

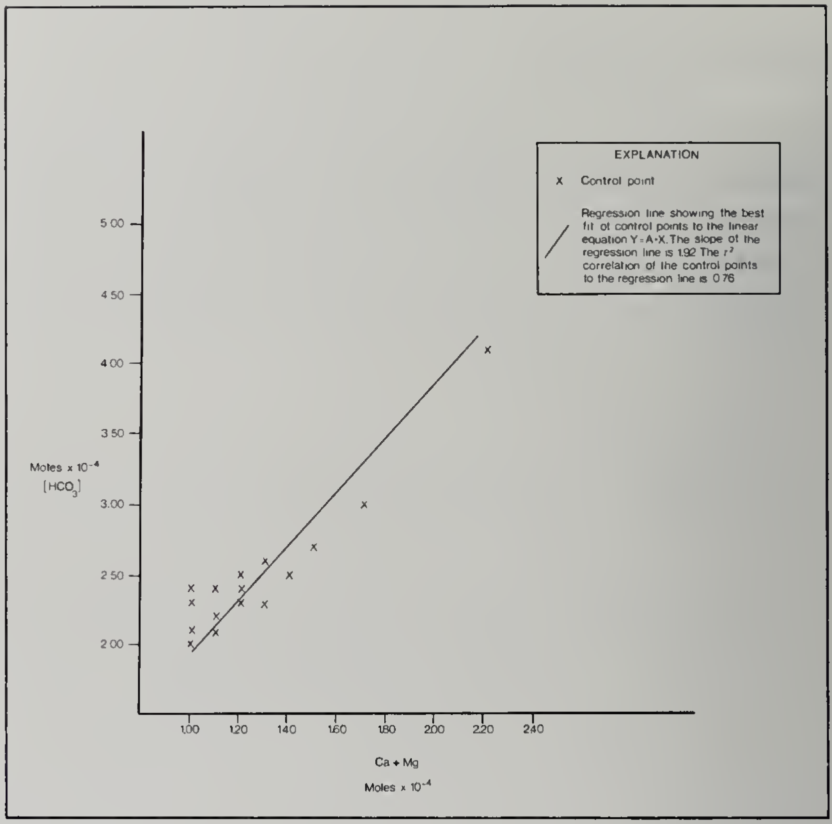


Figure 52.—Calcium and magnesium concentration versus bicarbonate concentration for water analyses in Region I of the Piney Point-Nanjemoy aquifer.

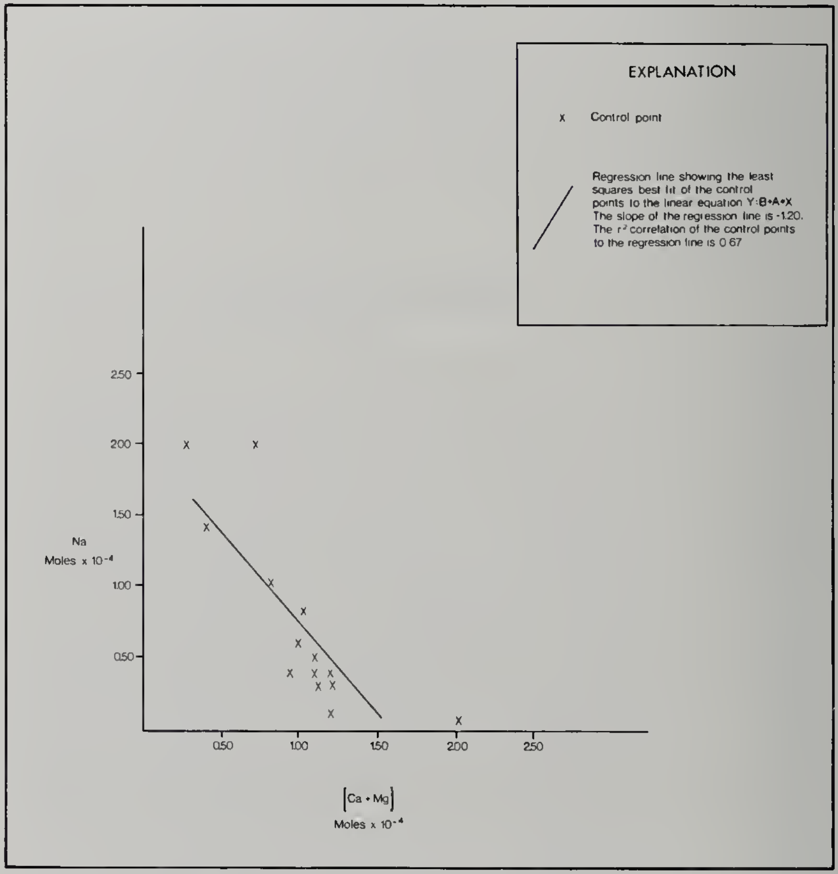


Figure 53.—Sodium concentration versus calcium and magnesium concentration for water analyses in Region II of the Piney Point-Nanjemoy aquifer.

applied to the chemistry of the Piney Point-Nanjemoy aquifer. Good matches between predicted and measured water chemistry were found in Regions I and III of the Piney Point-Nanjemoy aquifer. A poor match was found for Region II. This analysis suggests that the chemical processes which control the water chemistry of the Piney Point-Nanjemoy aquifer are similar, but not identical to the processes which control the water chemistry of the Aquia aquifer.

Calcite Cementation

There is a significant difference in the patterns of calcite cementation between the Piney Point-Nanjemoy aquifer and the Aquia aquifer. In the Aquia aquifer, calcite cementation is present near the outcrop area, but generally absent in downgradient areas. In contrast, calcite cementation is present in both upgradient and downgradient areas of the Piney Point-Nanjemoy aquifer. This pattern of calcite cementation is consistent with the equilibrium chemistry of the Piney Point-Nanjemoy aquifer. Figure 55 shows calculated saturation indexes of Piney Point-Nanjemoy water analyses (table 10). Figure 55 shows that the water is supersaturated with respect to calcite along the entire length of the aquifer.

It is likely that the supersaturation of Piney Point-Nanjemoy water has resulted from dissolution of magnesium calcite and aragonite. Both of these phases are less stable than stoichiometric calcite in aqueous systems. It is possible that the dissolution of magnesium calcite and aragonite and simultaneous precipitation of calcite is a continuing process in the Piney Point-Nanjemoy aquifer. Wollast (1971) has proposed such a mechanism on theoretical grounds. Wollast (1971) writes:

> "If we accept that aragonite is more soluble than calcite, then we must expect to see a gradual dissolution of the aragonite and a preference for the nucleation of calcite . . ."

A process such as that proposed by Wollast (1971) could possibly explain the lack of correlation between the water chemistry of Region II and model II. It should also be noted that this process is not inconsistent with the good match of water chemistry in Region III with model III. Model III requires the dissolution of calcium carbonate. This calcium carbonate can be calcite or aragonite. The same argument applies to Region I.

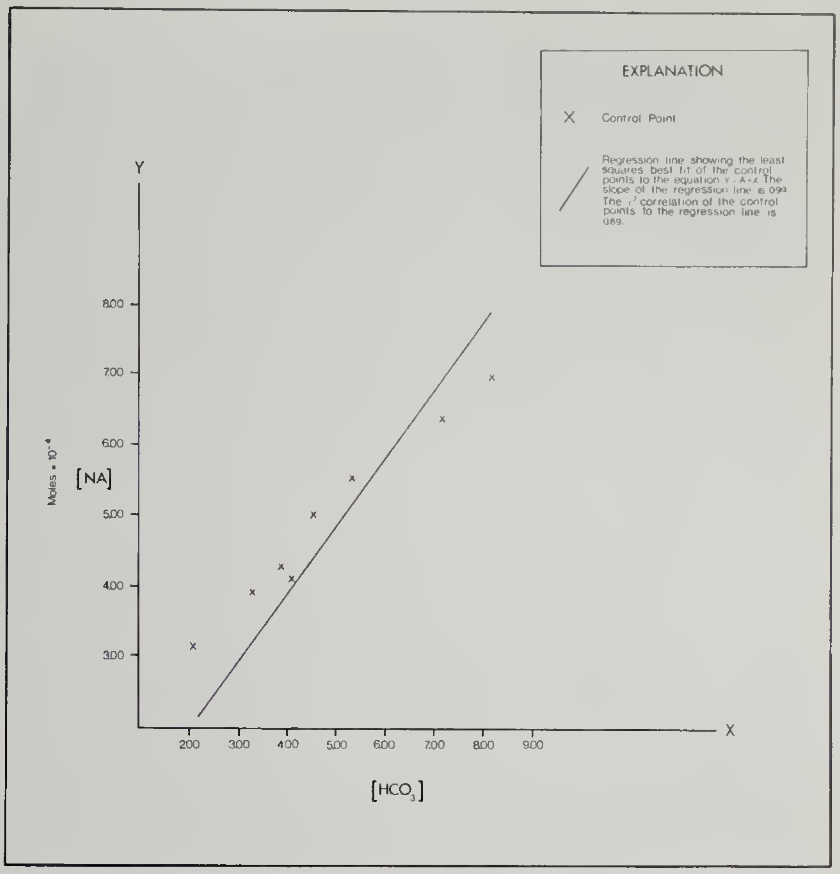


Figure 54.—Sodium concentration versus bicarbonate concentration for water analyses in Region III of the Piney Point-Nanjemoy aquifer.

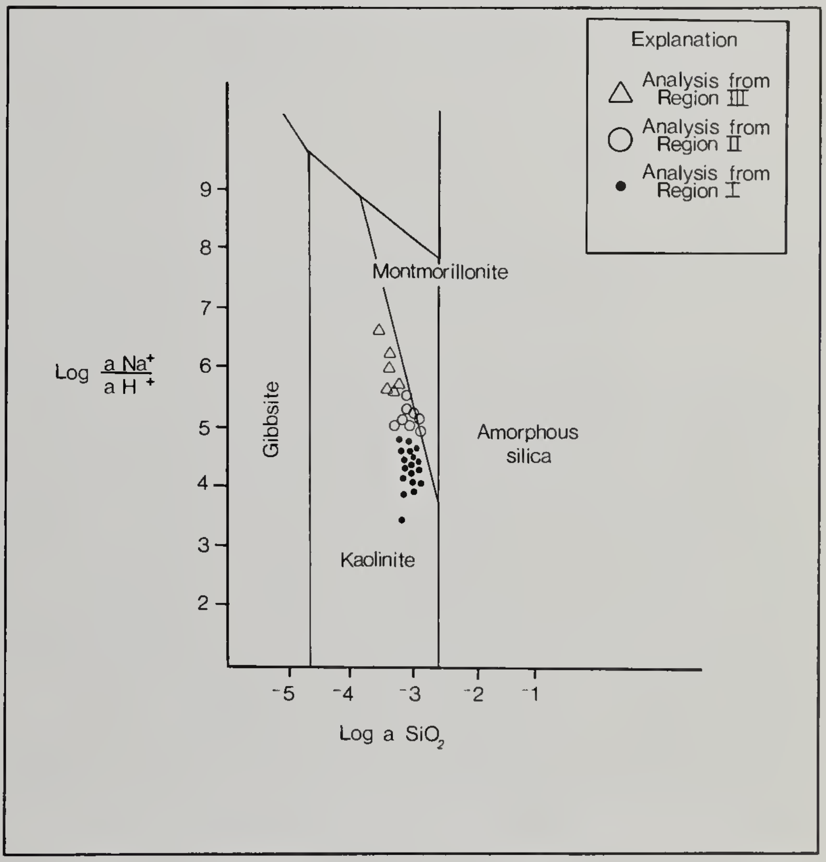


Figure 56.—Composition of Piney Point-Nanjemoy water plotted as a function of $Na+$, $H+$, and SiO_2 in the system $Na_2O - A1_2O_3 - SiO_2 - H_2O$.

Dissolved Silica

An interesting feature of Piney Point-Nanjemoy water is the relatively high concentration of dissolved silica. Piney Point-Nanjemoy water typically contains 45 to 65 mg/L silica. In contrast, Aquia water commonly contains only 10 to 15 mg/L silica.

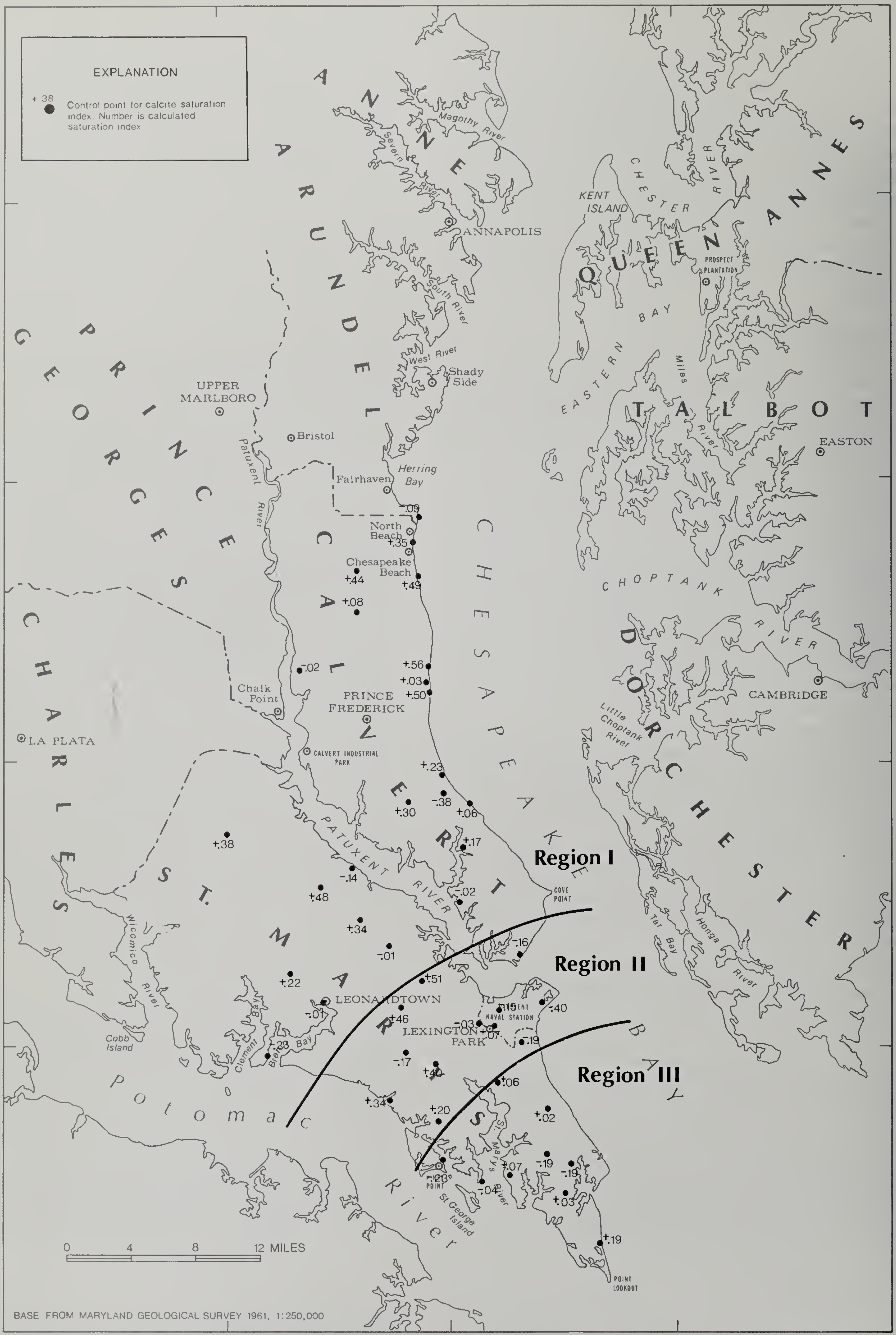


Figure 55.—Calcite saturation indices calculated from the chemical analyses of the Piney Point-Nanjemoy water.

This high silica content in Piney Point water has been documented by Mack and others (1971). These authors note that the Piney Point-Nanjemoy is overlain by the highly diatomaceous Calvert Formation. They hypothesize that dissolution of the siliceous diatoms and vertical leakage of Calvert water into the Piney Point-Nanjemoy causes the high silica content. One problem with this hypothesis is that water in equilibrium with amorphous silica should have silica concentrations much higher than those observed in the Piney Point aquifer (Garrels, 1975). Assuming that the source of the silica is dissolution of diatoms in the Calvert Formation, an additional mechanism must be limiting silica concentrations to the observed 45-65 mg/L. It is possible that simple dilution is the limiting mechanism. It is also possible that reaction of dissolved silica with the silicate minerals in the aquifer may be the limiting factor.

It is not possible to test the dilution mechanism hypothesis easily. It is possible, however, to test the silicate reaction hypothesis. Garrels (1975) has calculated a phase diagram on which water can be plotted as a function of dissolved sodium, hydrogen-ion, and silica in the system $Na_2O-A1_2O_3-SiO_2-H_2O$. With this diagram, Garrels (1975) has demonstrated that most dilute ground and surface water falls in the kaolinite field of stability. Garrels (1975) also shows that water tends to evolve along the kaolinite-montmorillonite stability boundary. This effectively limits dissolved silica concentrations to less than 70 mg/L. If a similar mechanism is operating on silica concentrations of Piney Point-Nanjemoy water, a similar pattern should develop. Figure 56 shows available analyses of Piney Point-Nanjemoy water plotted as a function of dissolved sodium, hydrogen-ion, and silica in the system $Na_2O-A1_2O_3-SiO_2-H_2O$. The stability diagram used is after Garrels (1975). This figure shows clearly that the composition of water is indeed evolving along the kaolinite-montmorillonite boundary. Water from Region I of the Piney Point-Nanjemoy aquifer plots on the lower part of this diagram. Water from Region III plots on the upper part, and water from Region II is intermediate. This trend is consistent with the observation that sodium concentrations increase along the flowpath and hydrogen-ion concentrations decrease. The significant feature of this diagram is that it shows the silica concentrations adjust to the changing log a Na^+/a H^+ ratio so that the water compositions remain in the kaolinite stability field. This strongly suggests that the stability relationship of kaolinite and montmorillonite is the controlling mechanism which limits the concentration of dissolved silica in Piney Point-Nanjemoy water.

SUMMARY AND CONCLUSIONS

The Aquia Formation is a fine- to medium-grained glauconitic quartz sand that has abundant shell material. The Aquia Formation serves as a fresh-water aquifer in most of Southern Maryland. The Aquia outcrops in a band paralleling the Fall Line. Recharge to the Aquia aquifer occurs as leakage from the Pleistocene water-table aquifer and leakage from adjacent confining beds. The transmissivity of the Aquia aquifer in Southern Maryland is highest in Anne Arundel County. The transmissivity decreases to the south and is not usable as an aquifer in southern St. Marys County.

The upper sands of the Nanjemoy Formation and the sands of the Piney Point Formation in Southern Maryland are hydraulically connected and function as one hydraulic unit. The Piney Point-Nanjemoy aquifer is a fine- to coarse-grained glauconitic quartz sand. The sands of the Piney Point-Nanjemoy aquifer are thickest in St. Marys County and thin the northeastern direction. The sands are truncated in the subsurface of northern Calvert and southern Prince Georges Counties as a result of the Oligocene withdrawal of the sea. The Piney Point-Nanjemoy aquifer is recharged from the Pleistocene water-table aquifer by leakage through the Chesapeake Group confining bed. The highest transmissivity of the Piney Point-Nanjemoy aquifer occurs in St. Marys County.

The subsurface continuity of the Aquia and Piney Point-Nanjemoy aquifers and their confining beds has been modified by Pleistocene erosion. The Aquia aquifer is completely truncated in the Chesapeake Bay near Kent Island. Similarly, the Chesapeake Group sediments are completely truncated near Benedict, Md. These Pleistocene erosional channels are a major control on the head distribution of the Aquia and Piney Point-Nanjemoy aquifers. The truncation of aquifers and confining beds by Pleistocene channels increases the possibility of brackish-water intrusion in some places. The Aquia aquifer near Kent Island and Anne Arundel County in particular may be susceptible to future brackish water-intrusion if heads fall below sea level.

A digital finite-difference quasi three-dimensional ground-water flow model was constructed of the Aquia and Piney Point-Nanjemoy aquifer system in Southern Maryland. The model was calibrated by matching computed potentiometric surfaces against measured potentiometric surfaces for three stages of aquifer development. Calibration was achieved by varying vertical hydraulic conductivities of confining beds within the range of values indicated by laboratory tests of confining-bed material. When computed heads at each stage of the aquifer system's development matched measured heads at the specified times, the model was considered calibrated.

After calibration, the model was used to predict future water levels based upon possible scenarios of future pumpage. These simulations included:

(1) A series of simulations using estimates of future pumpage for the periods 1980-1985, 1980-1990, and 1980-2000. This series of simulations predicts that by the year 2000 the potentiometric surface of the Aquia aquifer near Lexington Park will be more than 100 ft below sea level. It is possible that these lowered water levels will make water production from some domestic wells impractical near Lexington Park by the year 2000. These lowered water levels may also significantly increase the cost of pumping from existing municipal wells. Because of these possibilities, the development of deeper Cretaceous aquifers for water production might be considered at Lexington Park.

(2) A series of simulations in the Lexington Park-PNATS area to predict water levels in the period 1980-2000, assuming the Aquia aquifer is pumped 1.5 Mgal/d, 2.0 Mgal/d, 2.5 Mgal/d, and 3.0 Mgal/d. This series of simulations provides water planners with drawdown estimates for different pumping rates. The simulations were designed to help planners estimate the maximum pumpage rate that can be sustained by the Aquia aquifer. If, for example, water planners decide that an additional average drawdown of more than 60 ft would be undesirable, the yield of the Aquia aquifer in this area would be limited to between 2.0 and 2.5 Mgal/d.

(3) A series of simulations showing the effects of 1 Mgal/d pumpage from the Aquia aquifer in northern St. Marys County. One simulation assumed 1 Mgal/d pumpage from a single METCOM well field. Another simulation assumed that the 1 Mgal/d pumpage was spread among four METCOM well fields. This simulation was made to illustrate to water planners the effects of spreading pumpage over a broad area as opposed to concentrating it in one area. This simulation shows that spreading pumpage results in drawdowns over a larger area, but that the drawdowns are less. Spreading pumpage among several well fields would therefore minimize impacts on already existing domestic and small industrial wells.

(4) A series of simulations in the Lexington Park-PNATS area to show the drawdown effects on the Piney Point-Nanjemoy aquifer due to pumpage from the Aquia. These simulations indicate that 90 ft of drawdown in the Aquia aquifer over 10 years results in 4 ft of drawdown in the Piney Point-Nanjemoy aquifer. This result shows that Aquia pumpage will have drawdown effects on the Piney Point-Nanjemoy, but these effects are not large.

(5) A series of simulations to show the effects of placing a 0.5 Mgal/d well field in southern Anne Arundel County near the towns of Shady Side, Bristol, and Fairhaven. This simulation indicates that pumpage of 0.5 Mgal/d near any one of these towns will have a moderate impact on water levels.

(6) A simulation of 0.5 Mgal/d from the Aquia for the Chalk Point Power Plant. This simulation shows that about 45 ft of drawdown develops after 10 years of pumping. This relatively large impact is partly due to the low transmissivity of the Aquia at Chalk Point, and partly due to domestic and small industrial pumpage in the same area.

(7) A hypothetical simulation that assumed all GAP holders in the Aquia and Piney Point-Nanjemoy aquifers pumped their maximum water allocations for a period of 10 years. Large drawdowns occur in the Aquia aquifer near Lexington Park, Leonardtown, Piney Point, the Calvert Industrial Park, and Cove Point. The drawdown effects of this simulation were not as large on the Piney Point-Nanjemoy aquifer because most GAP ground-water users in Southern Maryland pump from the Aquia aquifer. Large drawdowns are also predicted to occur in the Aquia aquifer near the planned community of Prospect Plantation in Queen Anne's County. The cone of depression in this area is predicted to spread to the subsurface truncation of the Aquia aquifer under the Chesapeake Bay. This could possibly result in brackish water being drawn into the Aquia at this location. This simulation suggests that near Lexington Park, Leonardtown, and Piney Point in St. Mary's County appropriation requests for additional Aquia ground water should be carefully reviewed. The Piney Point-Nanjemoy aquifer does not appear to be nearing the limits of production capability.

(8) A simulation of 0.5 Mgal/d from the Aquia aquifer near Chesapeake Beach. This simulation results in about 20 ft of drawdown occurring over 5 years.

Water produced from the Aquia aquifer generally has good chemical quality. Near the outcrop/subcrop area of the Aquia the water is a calcium and magnesium bicarbonate type water with relatively low (6.5-7.5) pH. Downgradient from the outcrop/subcrop area, Aquia water changes to a sodium bicarbonate type water with relatively high (7.5-8.5) pH. It has been shown that the Aquia aquifer can be divided into three regions based on water chemistry. Chemical models which predict water composition in each region of the aquifer have been developed. These models were tested by comparing predicted changes of water chemistry to measured changes of water chemistry for three regions of the Aquia aquifer. The matches obtained by these comparisons were good in all three cases and this supports the applicability of the models. Mass balance calculations with these models suggest that the observed calcite cementation of the Aquia aquifer is post-depositional and has resulted from reaction of ground water with aquifer material.

Water produced from the Piney Point-Nanjemoy aquifer also has generally good chemical quality. In upgradient areas, the water is a calcium and magnesium bicarbonate type water with relatively low (6.0-7.0) pH. Downgradient, Piney Point-Nanjemoy water is a sodium bicarbonate type water with relatively high (7.0-8.2) pH. The Piney Point-Nanjemoy aquifer can be divided into three regions based on water chemistry in a similar manner as the Aquia aquifer. The chemistry of these regions can be described by the same chemical models which were developed for the regions of the Aquia aquifer.

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[1] The name of this agency was changed to the Maryland Geological Survey in June 1964.

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Plate 1.—Cross section A-A′ showing major hydrologic units in Southern Maryland

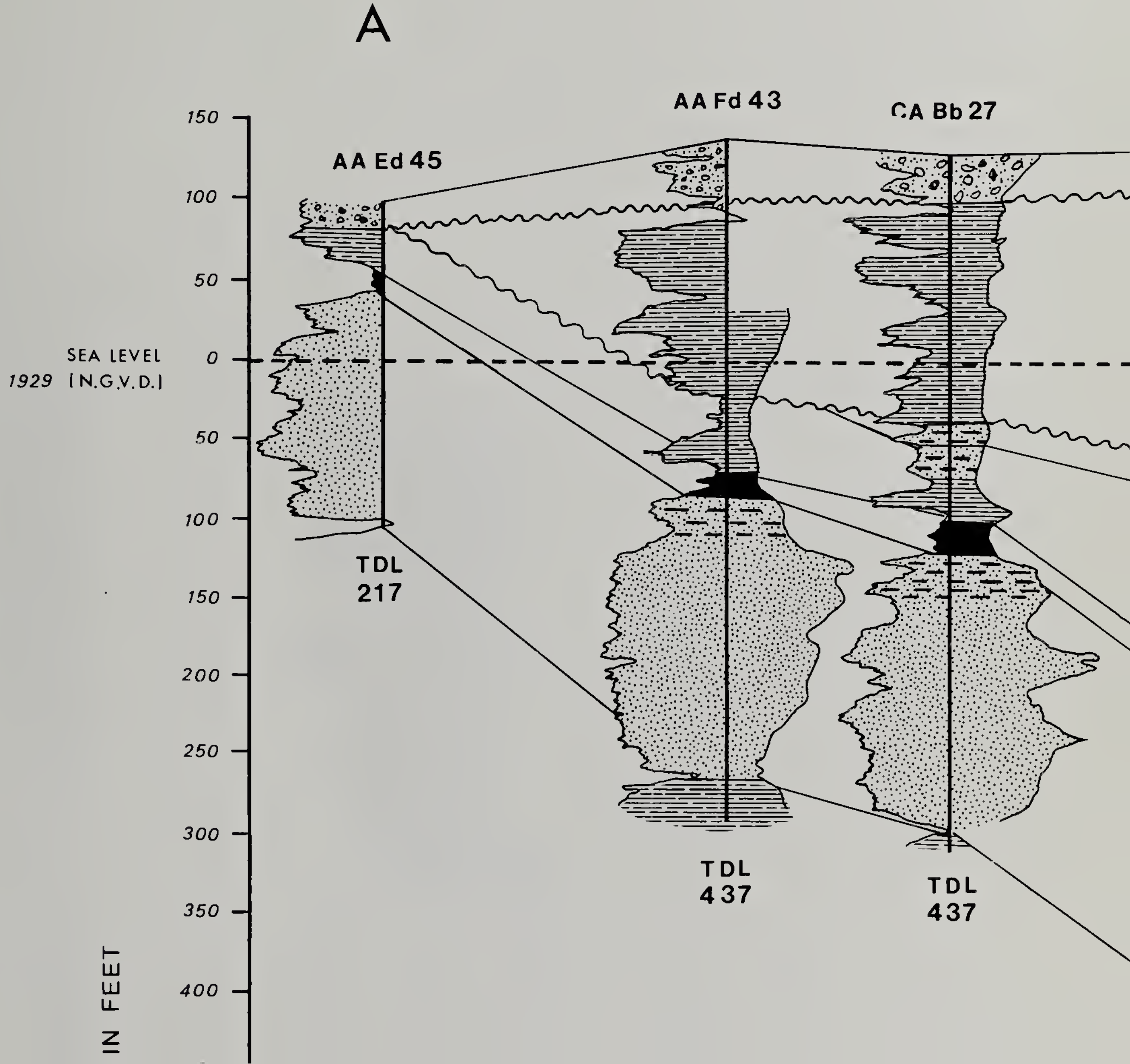


Plate 1.—Cross section A-A′ showing major hydrologic units in Southern Maryland

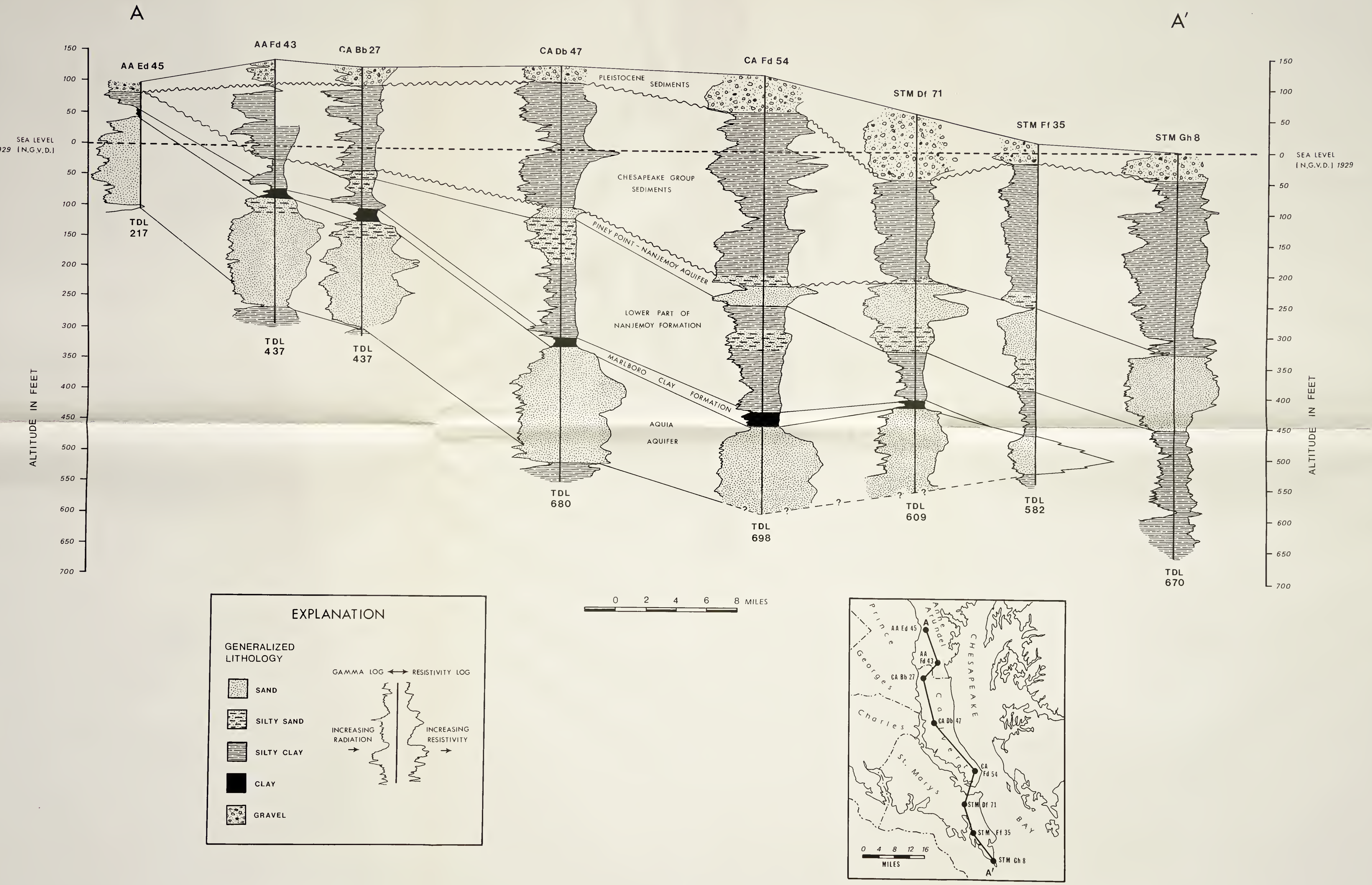


Plate 2.—Cross section B-B′ showing major hydrologic units in Southern Maryland

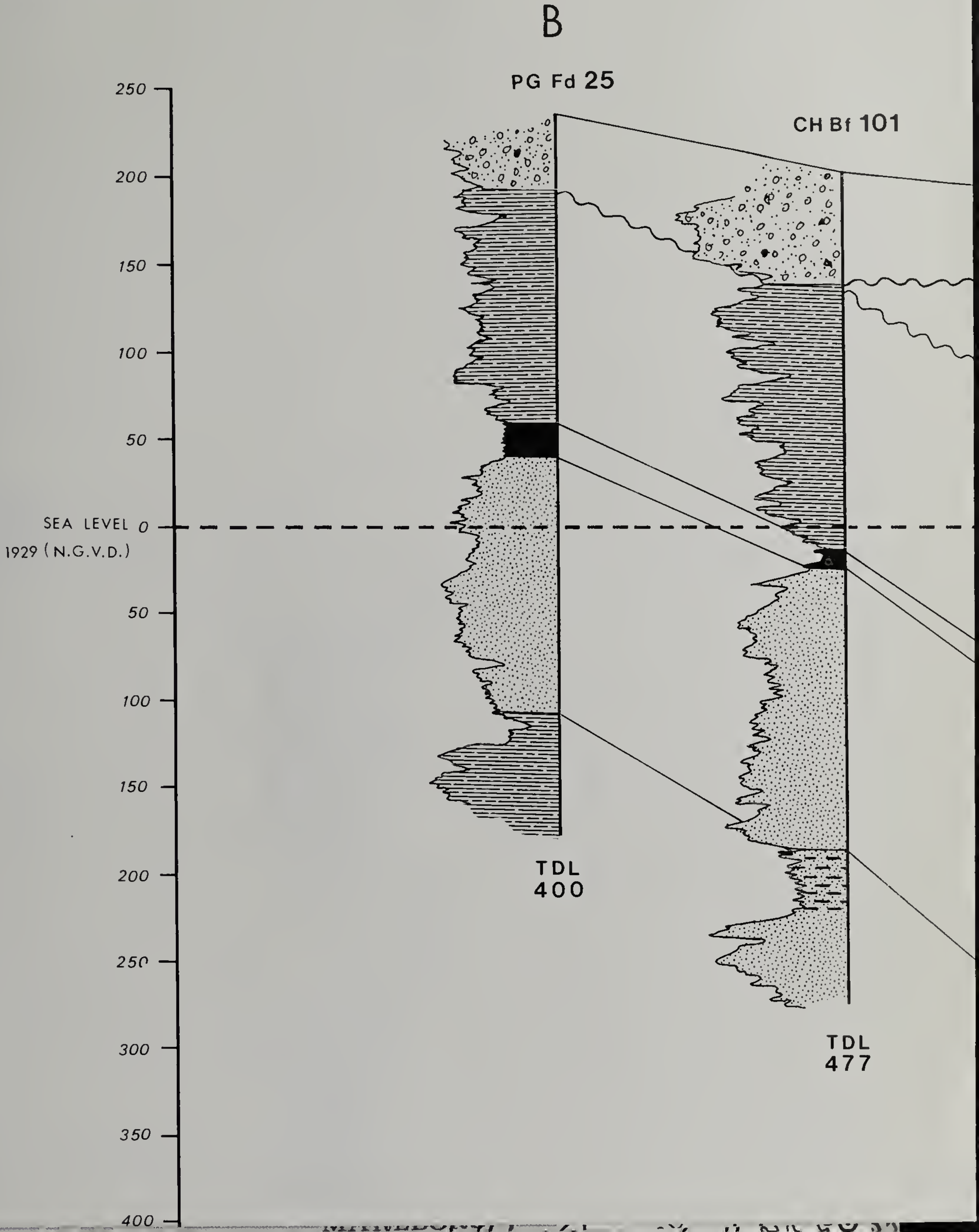


Plate 2.—Cross section B-B′ showing major hydrologic units in Southern Maryland

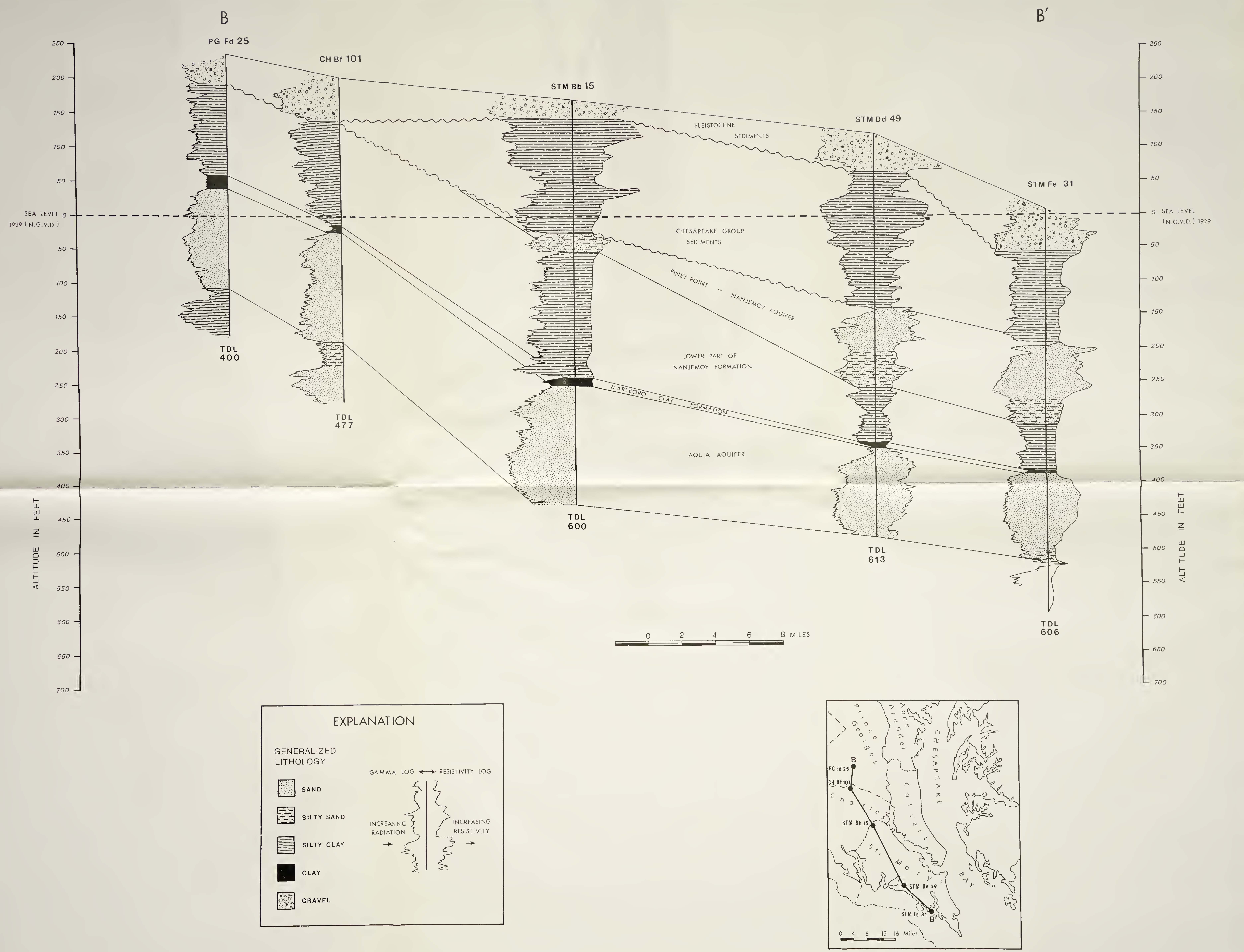


Plate 3.—Map showing the approximate pre-pumping potentiometric surface of the Aquia aquifer

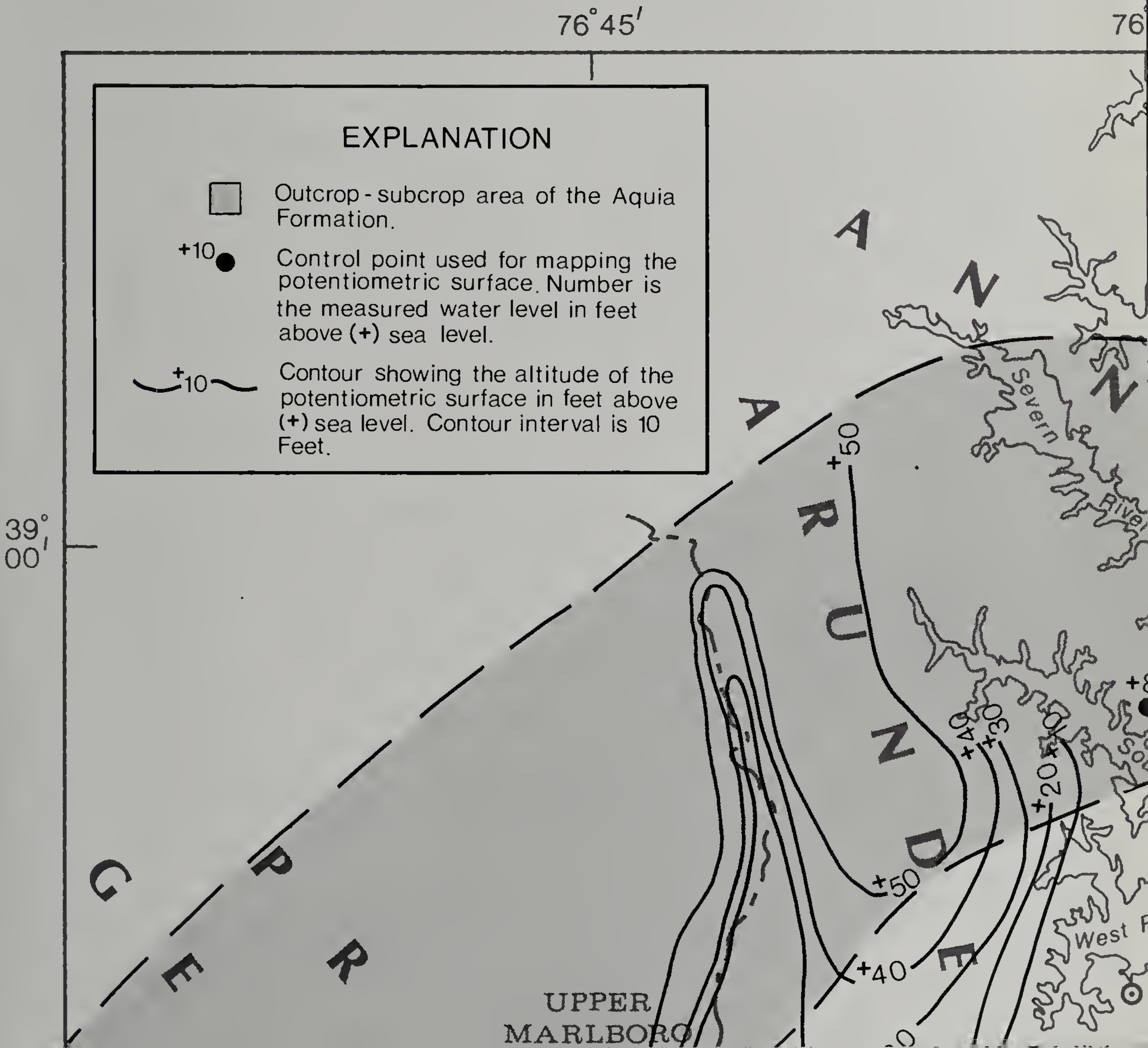


Plate 3.—Map showing the approximate pre-pumping potentiometric surface of the Aquia aquifer

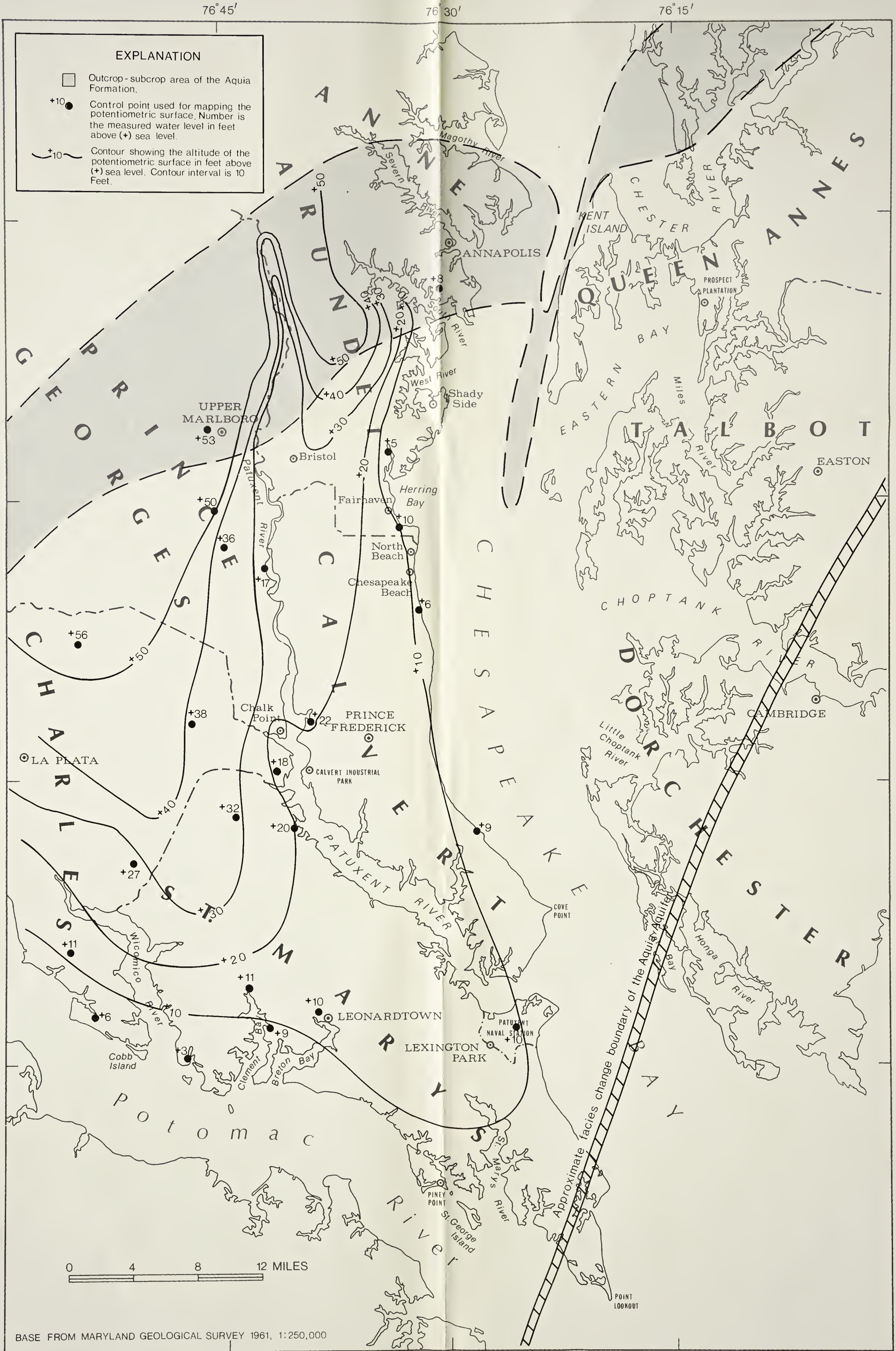


Plate 4.—Map showing the potentiometric surface of the Aquia aquifer, 1952

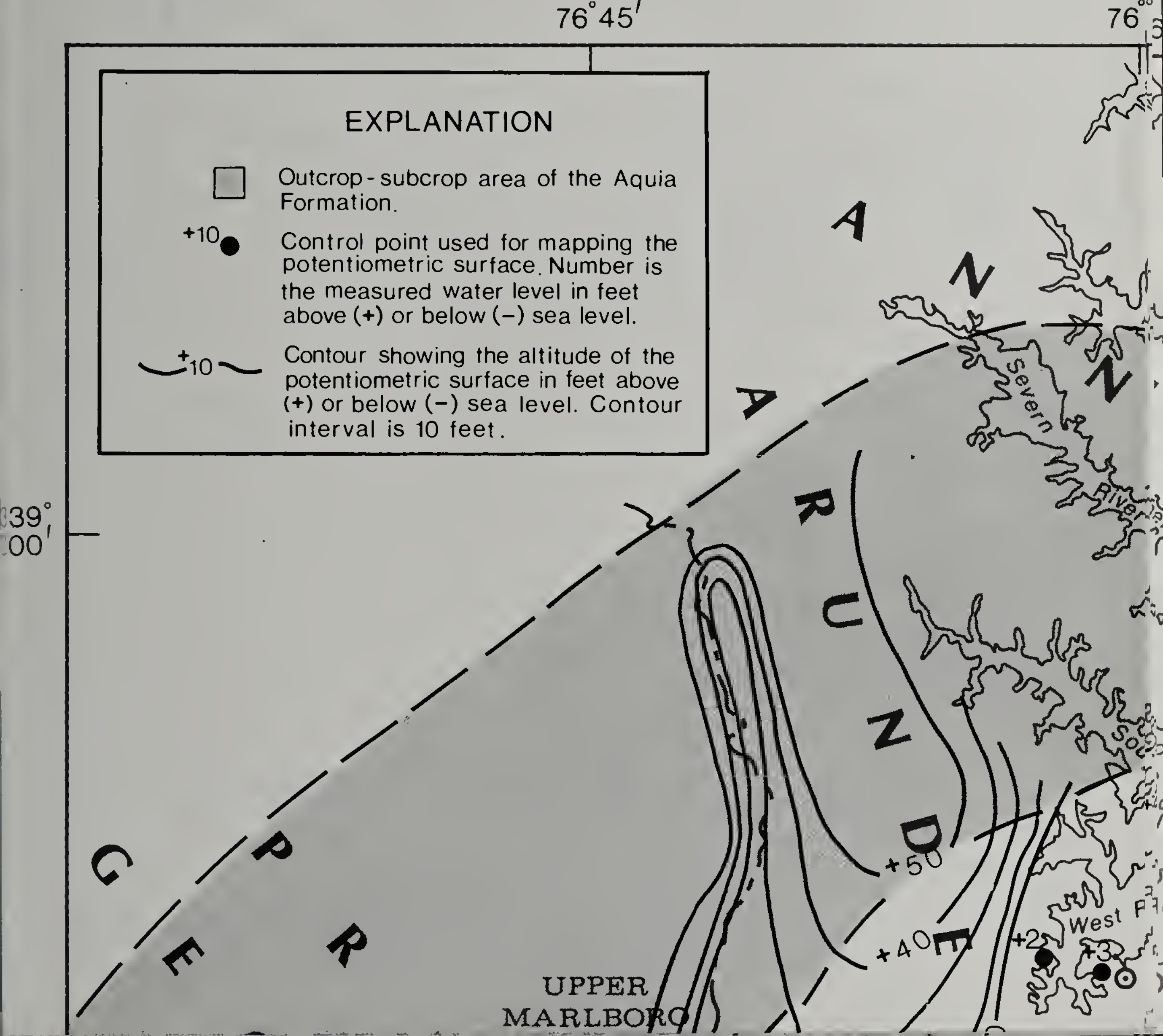


Plate 4.—Map showing the potentiometric surface of the Aquia aquifer, 1952

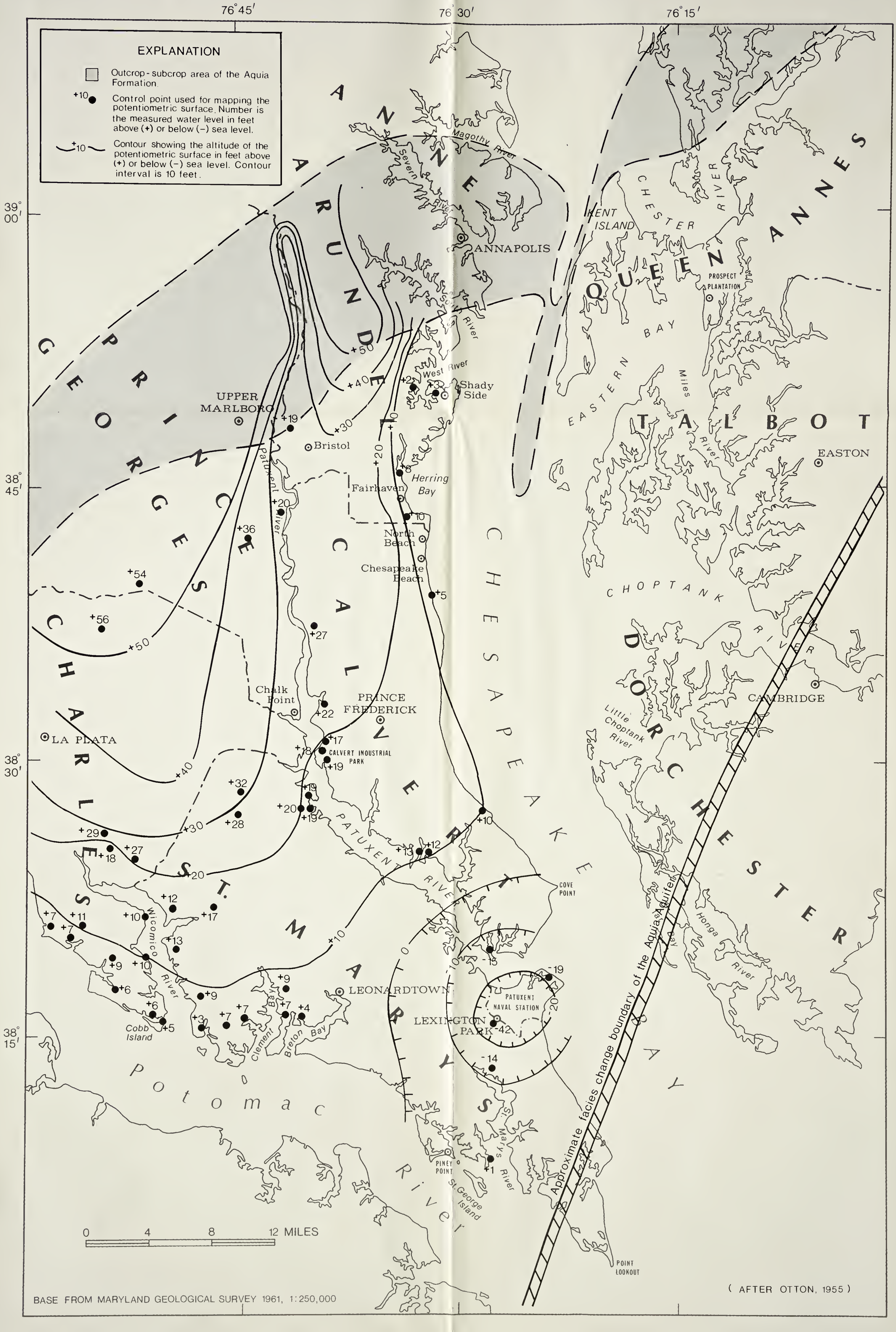


Plate 5.—Map showing the potentiometric surface of the Aquia aquifer, May 19-23, 1980

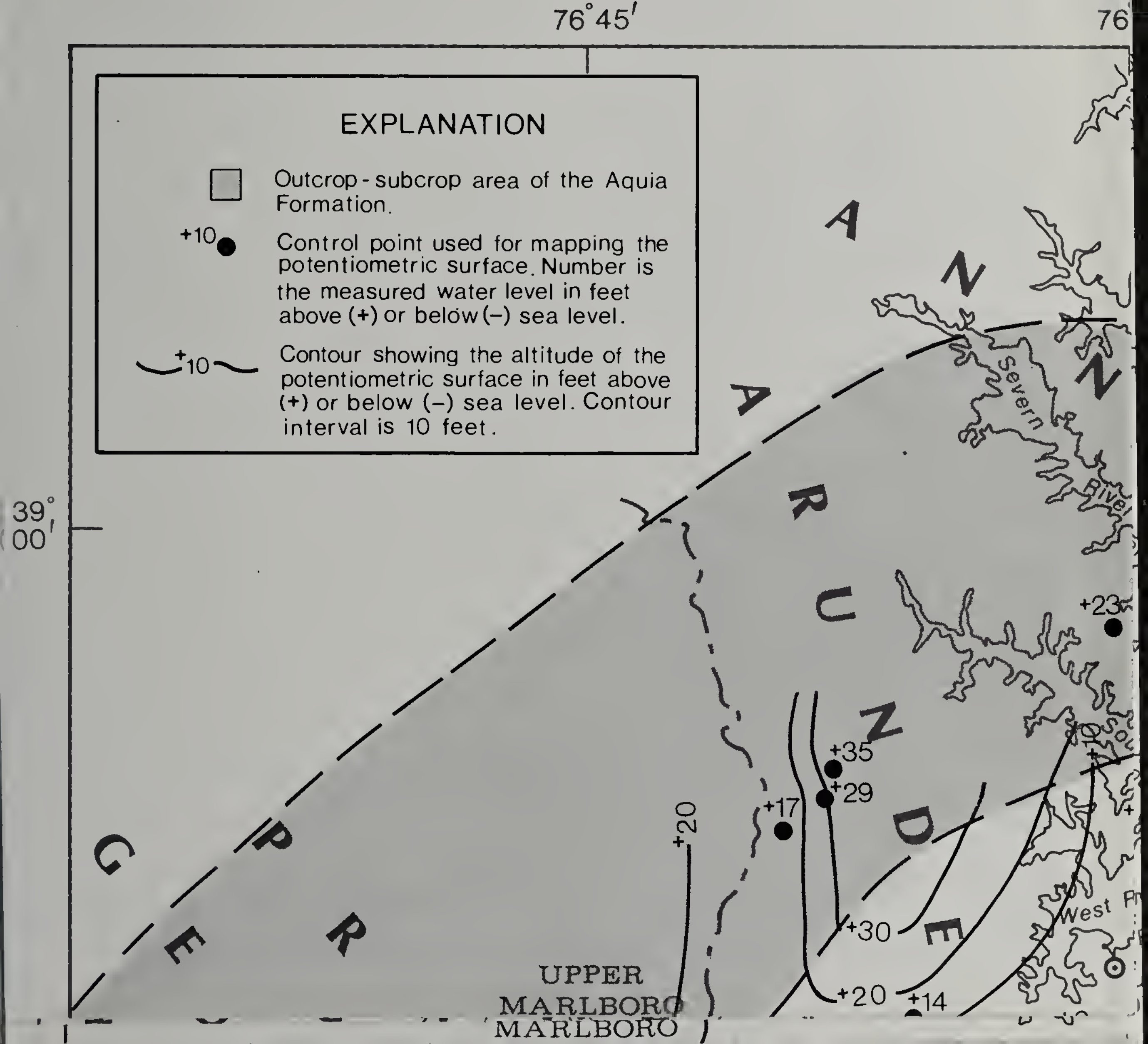
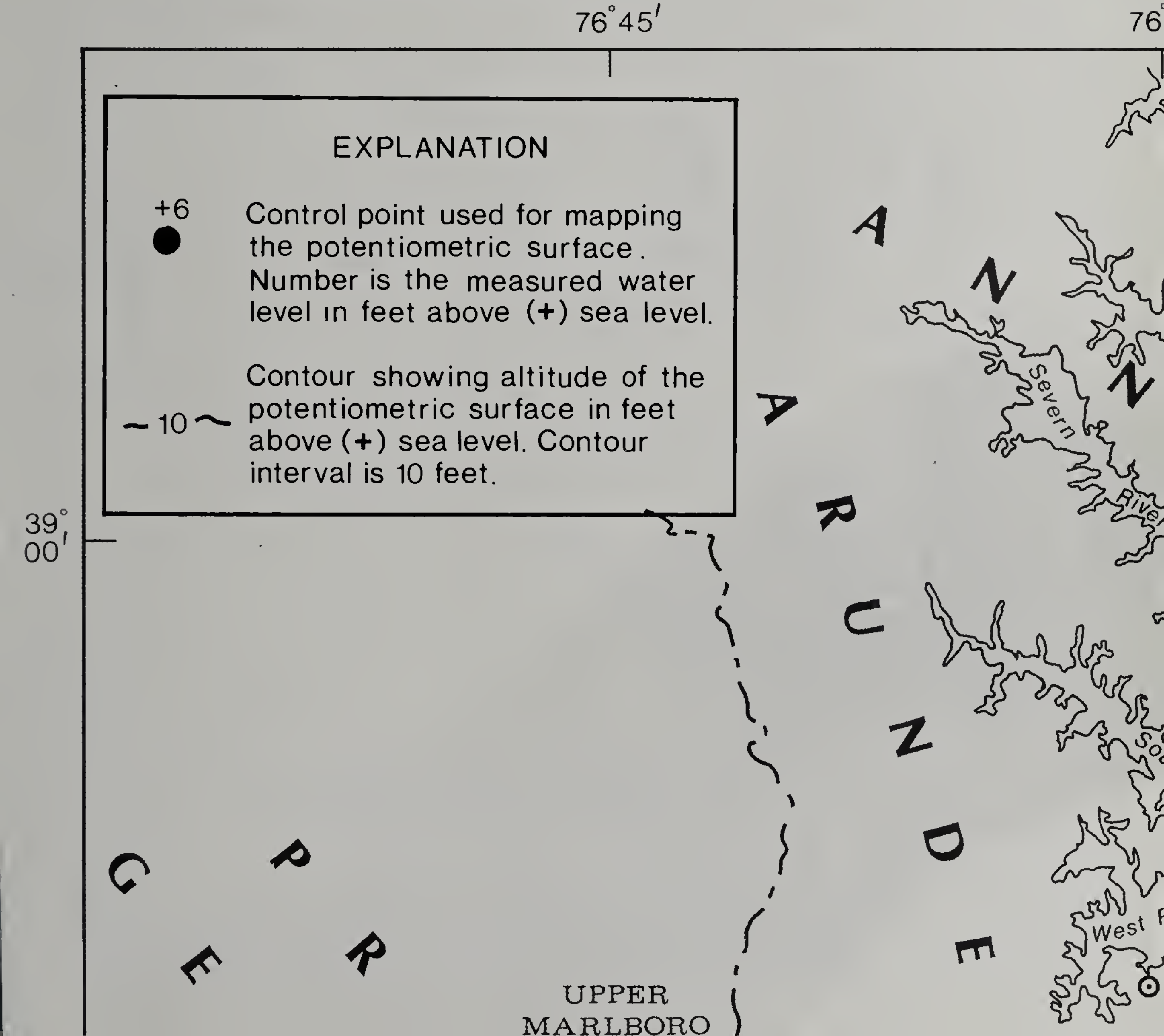


Plate 5.—Map showing the potentiometric surface of the Aquia aquifer, May 19-23, 1980

Plate 6.—Map showing the approximate pre-pumping potentiometric surface of the Piney Point-Nanjemoy aquifer



EXPLANATION

● +6 Control point used for mapping the potentiometric surface. Number is the measured water level in feet above (+) sea level.

~10~ Contour showing altitude of the potentiometric surface in feet above (+) sea level. Contour interval is 10 feet.

Plate 6.—Map showing the approximate pre-pumping potentiometric surface of the Piney Point-Nanjemoy aquifer

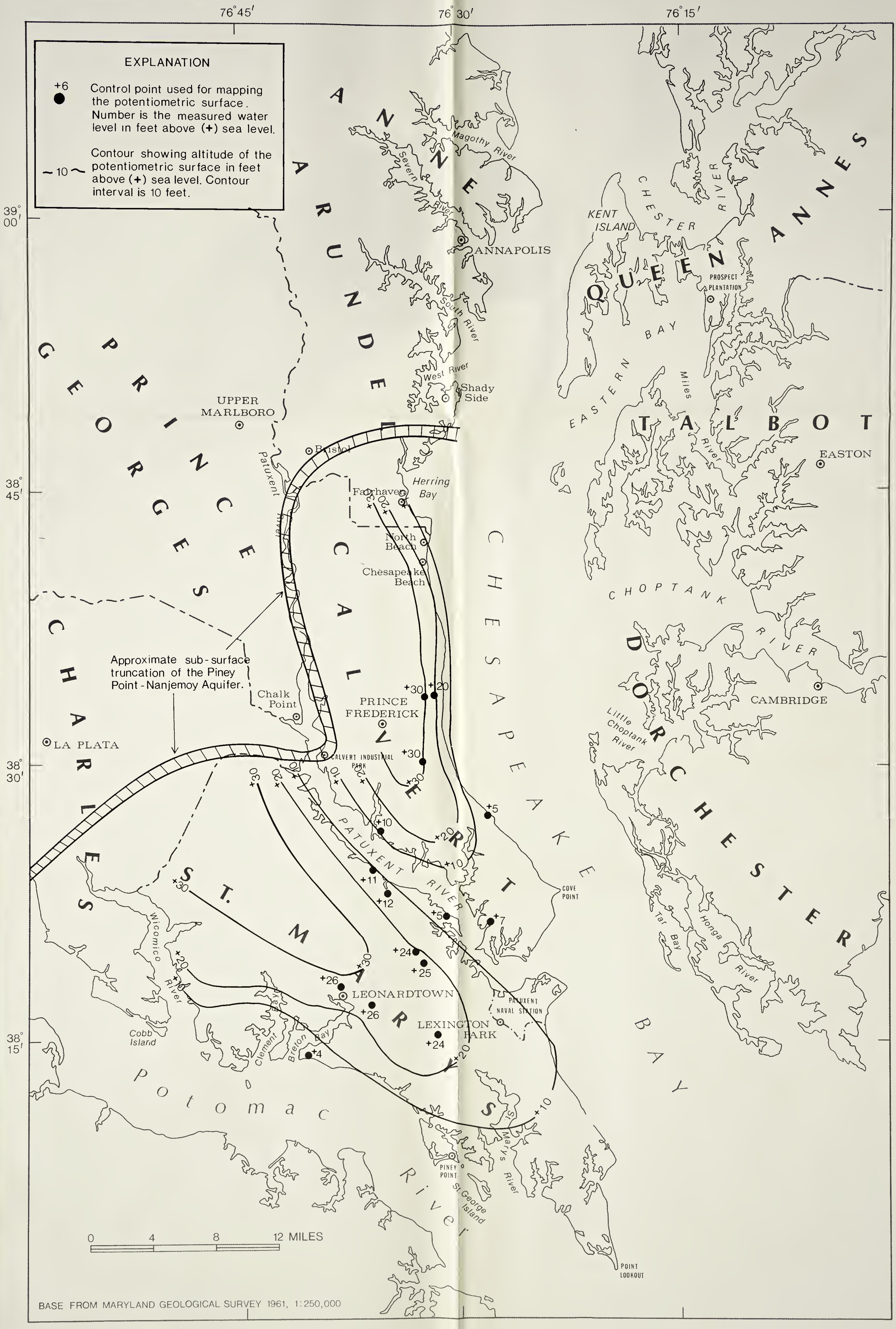


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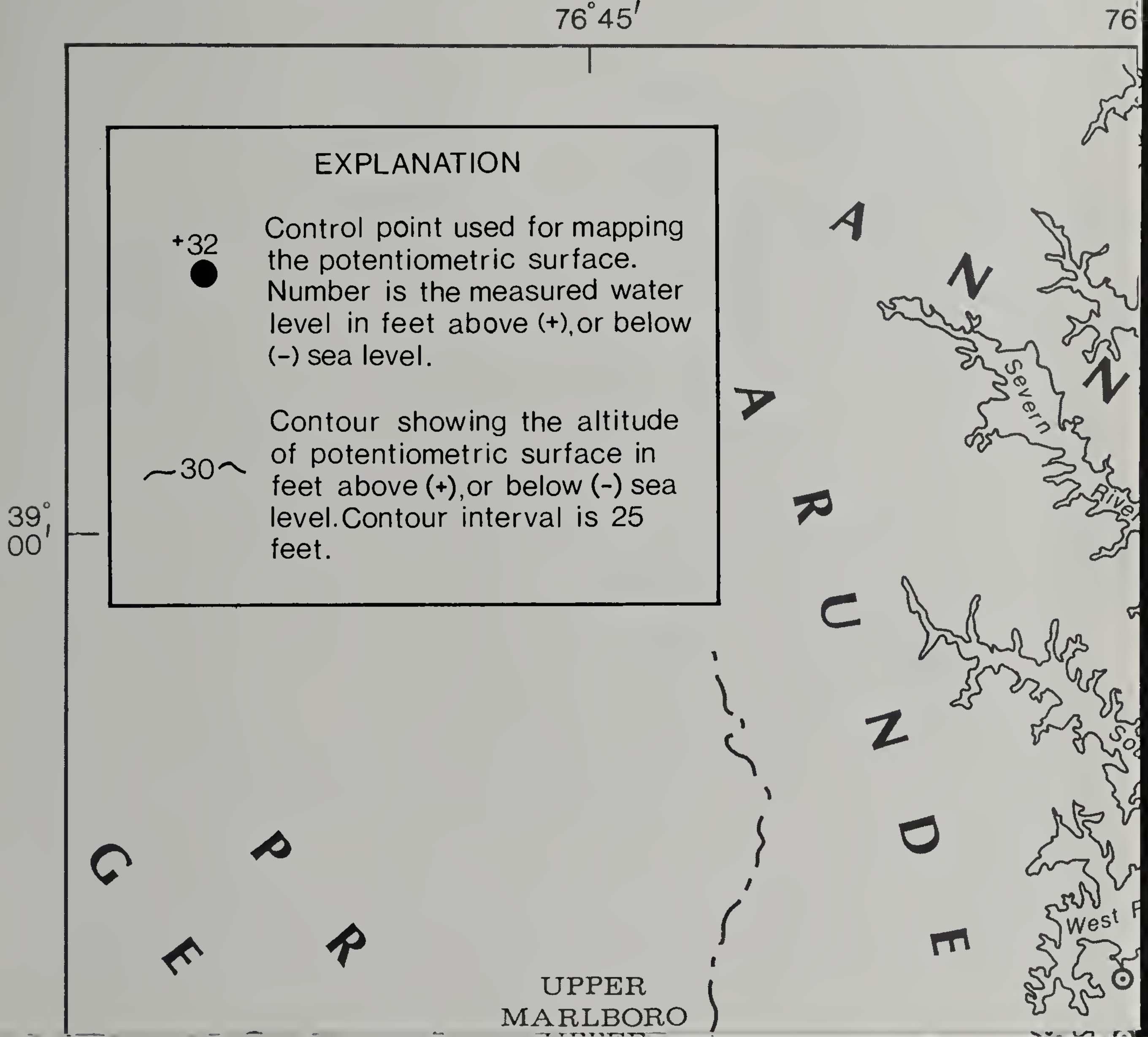
Plate 7.—Map showing the potentiometric surface of the Piney Point-Nanjemoy aquifer, 1952


EXPLANATION

+32 ● Control point used for mapping the potentiometric surface. Number is the measured water level in feet above (+), or below (-) sea level.

—30— Contour showing the altitude of potentiometric surface in feet above (+), or below (-) sea level. Contour interval is 25 feet.

Plate 7.—Map showing the potentiometric surface of the Piney Point-Nanjemoy aquifer, 1952

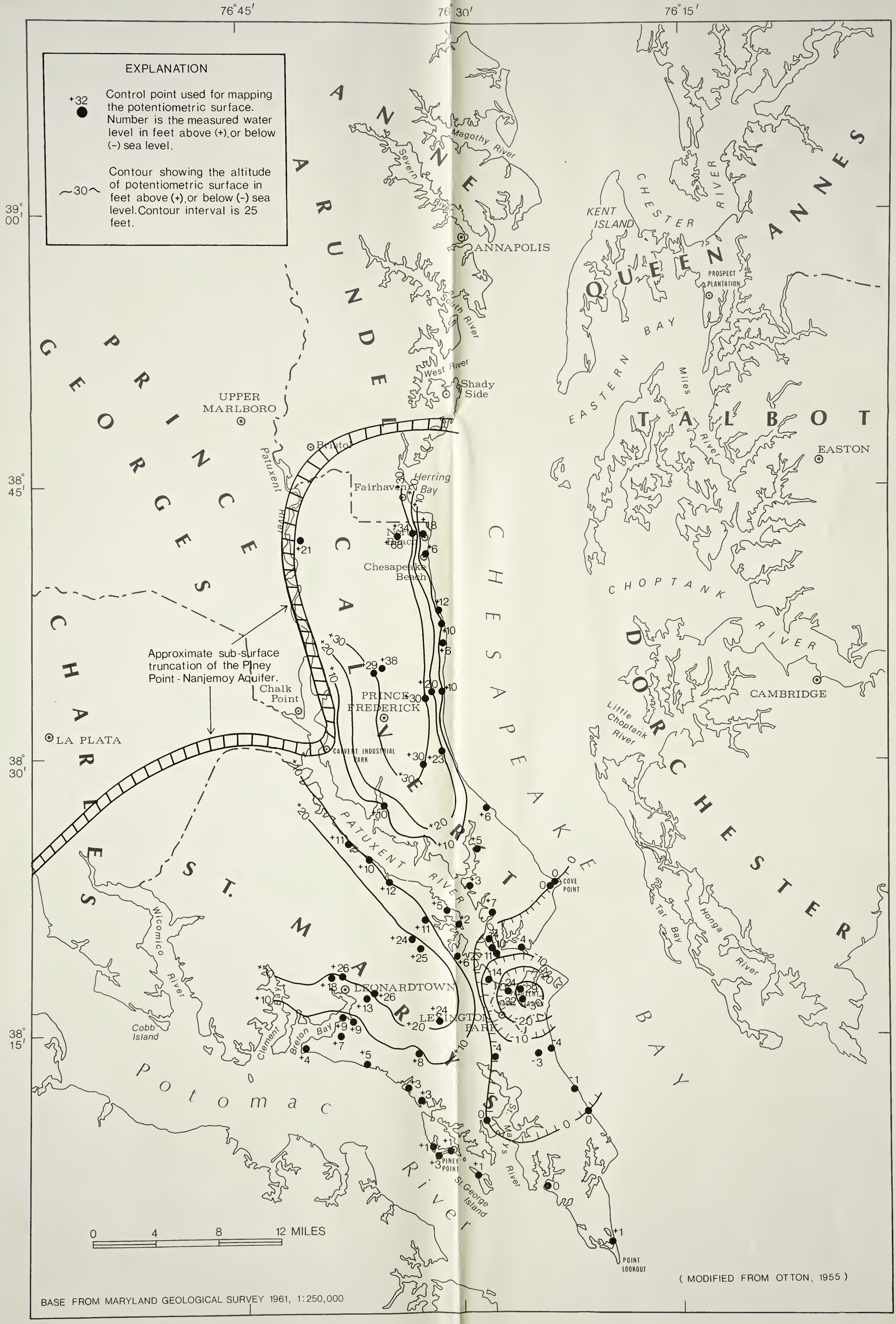
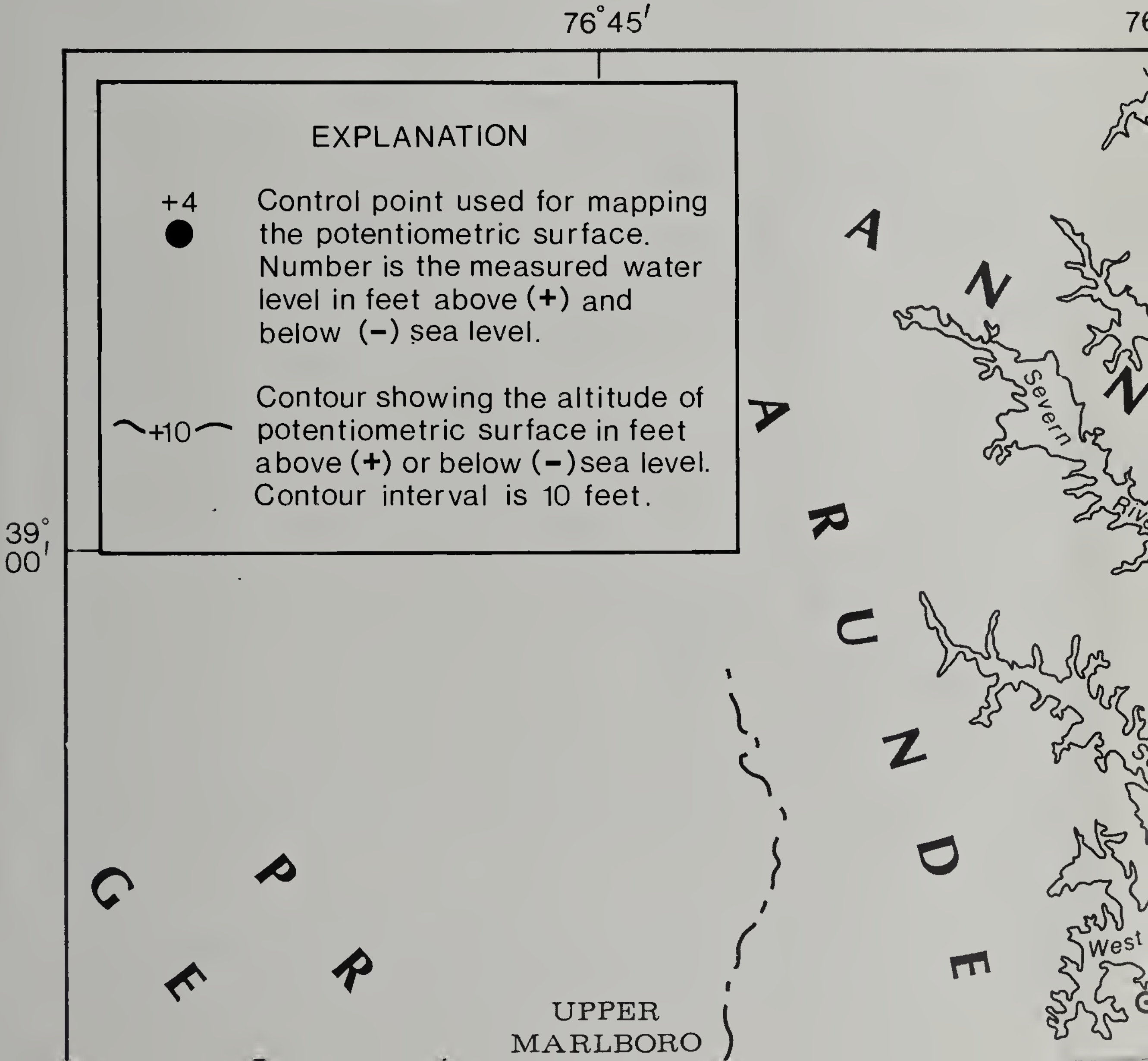


Plate 8.—Map showing the potentiometric surface of the Piney Point-Nanjemoy aquifer, May 19-23, 1980



EXPLANATION

● +4 Control point used for mapping the potentiometric surface. Number is the measured water level in feet above (+) and below (−) sea level.

+10 Contour showing the altitude of potentiometric surface in feet above (+) or below (−) sea level. Contour interval is 10 feet.

Plate 8.—Map showing the potentiometric surface of the Piney Point-Nanjemoy aquifer, May 19-23, 1980

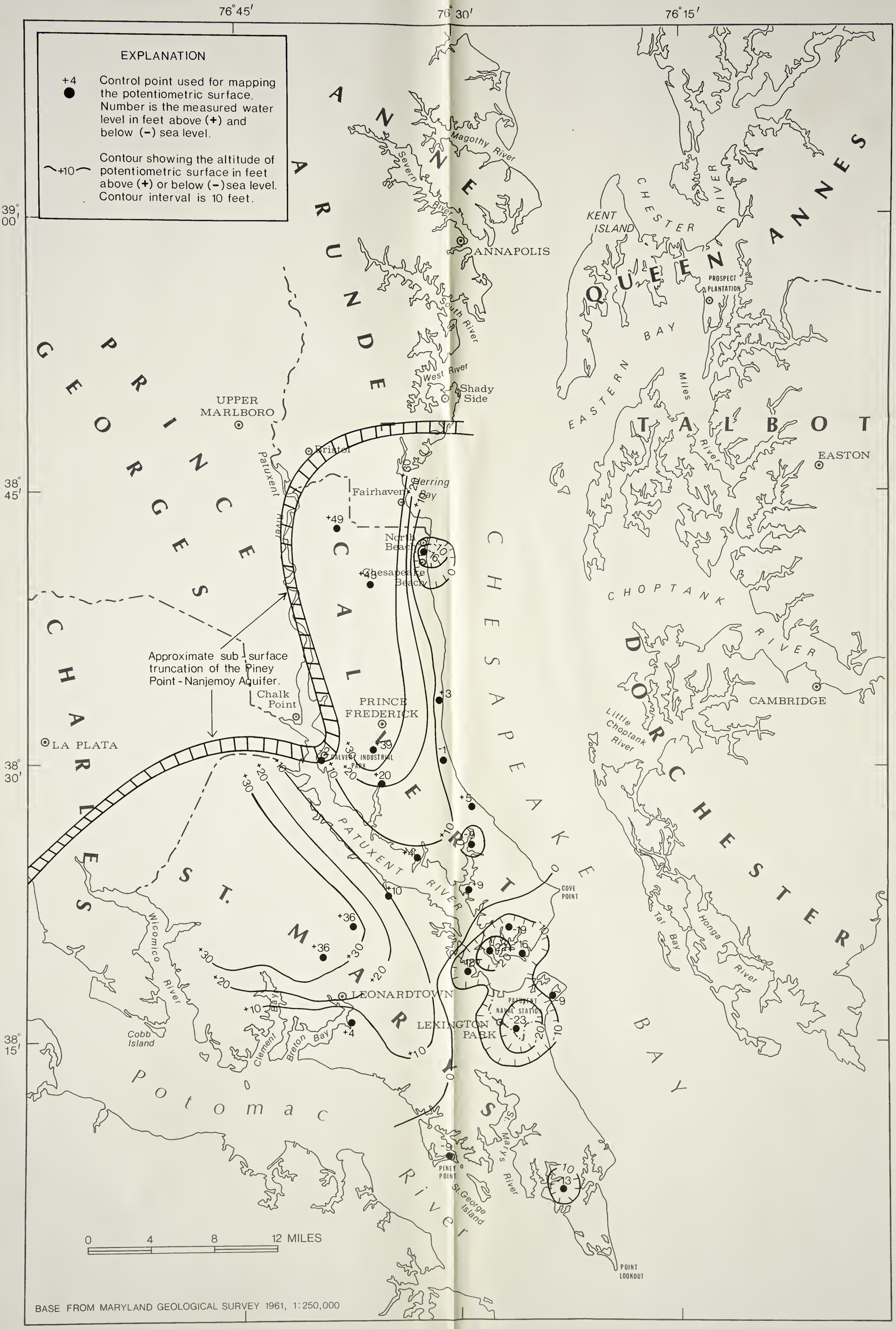


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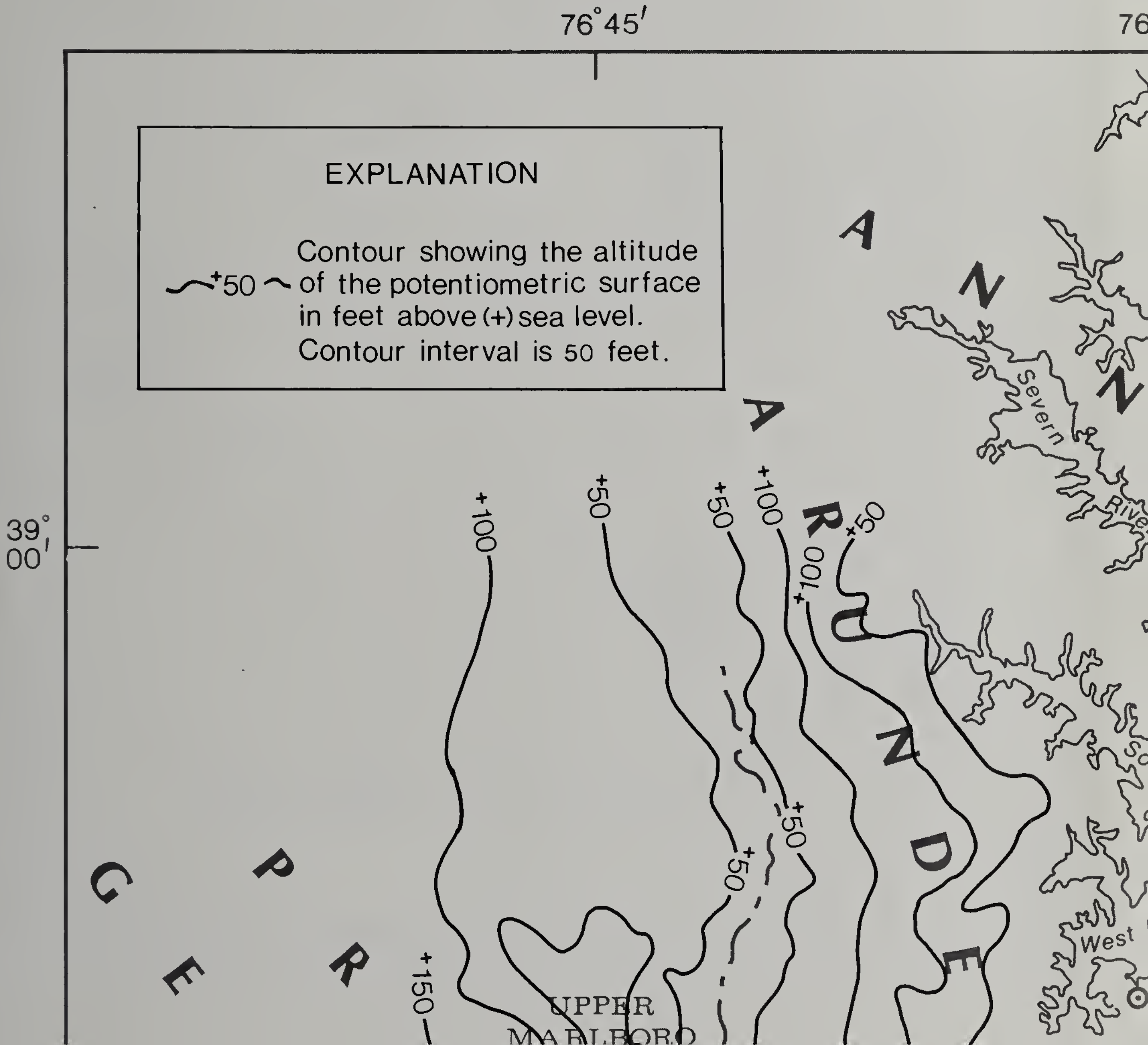
Plate 9.—Map showing the potentiometric surface of the water-table aquifer of Southern Maryland



EXPLANATION

Contour showing the altitude of the potentiometric surface in feet above (+) sea level. Contour interval is 50 feet.

Plate 9.—Map showing the potentiometric surface of the water-table aquifer of Southern Maryland

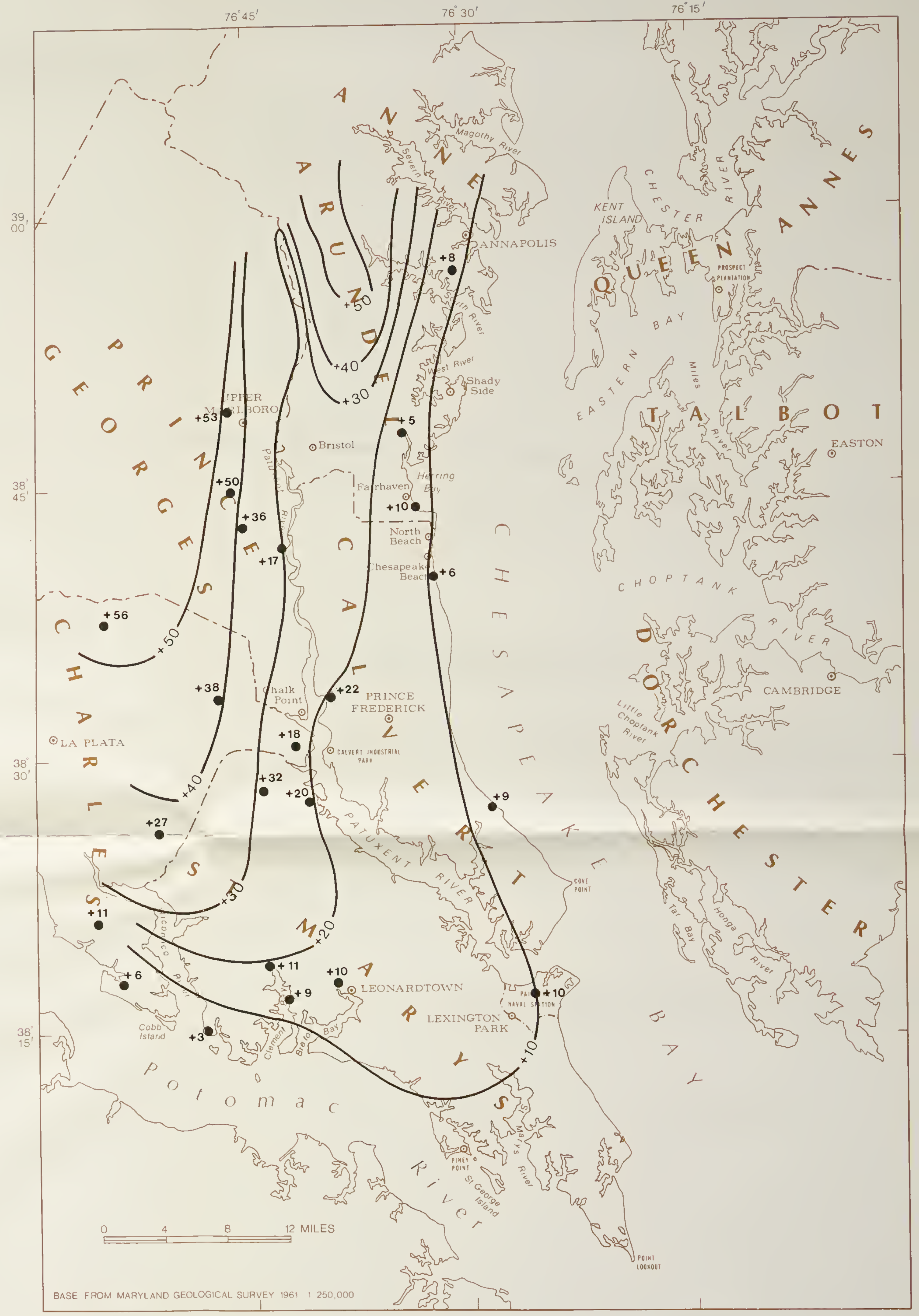
BASE FROM MARYLAND GEOLOGICAL SURVEY 1961, 1:250,000

Plate 10.—Map showing simulated prepumping, 1952, and 1980 potentiometric surfaces of the Aquia aquifer superimposed on measured water levels

Plate 10.—Map showing simulated prepumping, 1952, and 1980 potentiometric surfaces of the Aquia aquifer superimposed on measured water levels

Simulated 1980 potentiometric surface and water levels measured May 19–23, 1980.

Simulated potentiometric surface of 1952 and water levels measured in 1952 by Otton (1955).



Simulated pre-pumping potentiometric surface and water levels measured early in aquifer development as reported by Darton (1896), Clark and others (1918), and Otton (1955).

EXPLANATION

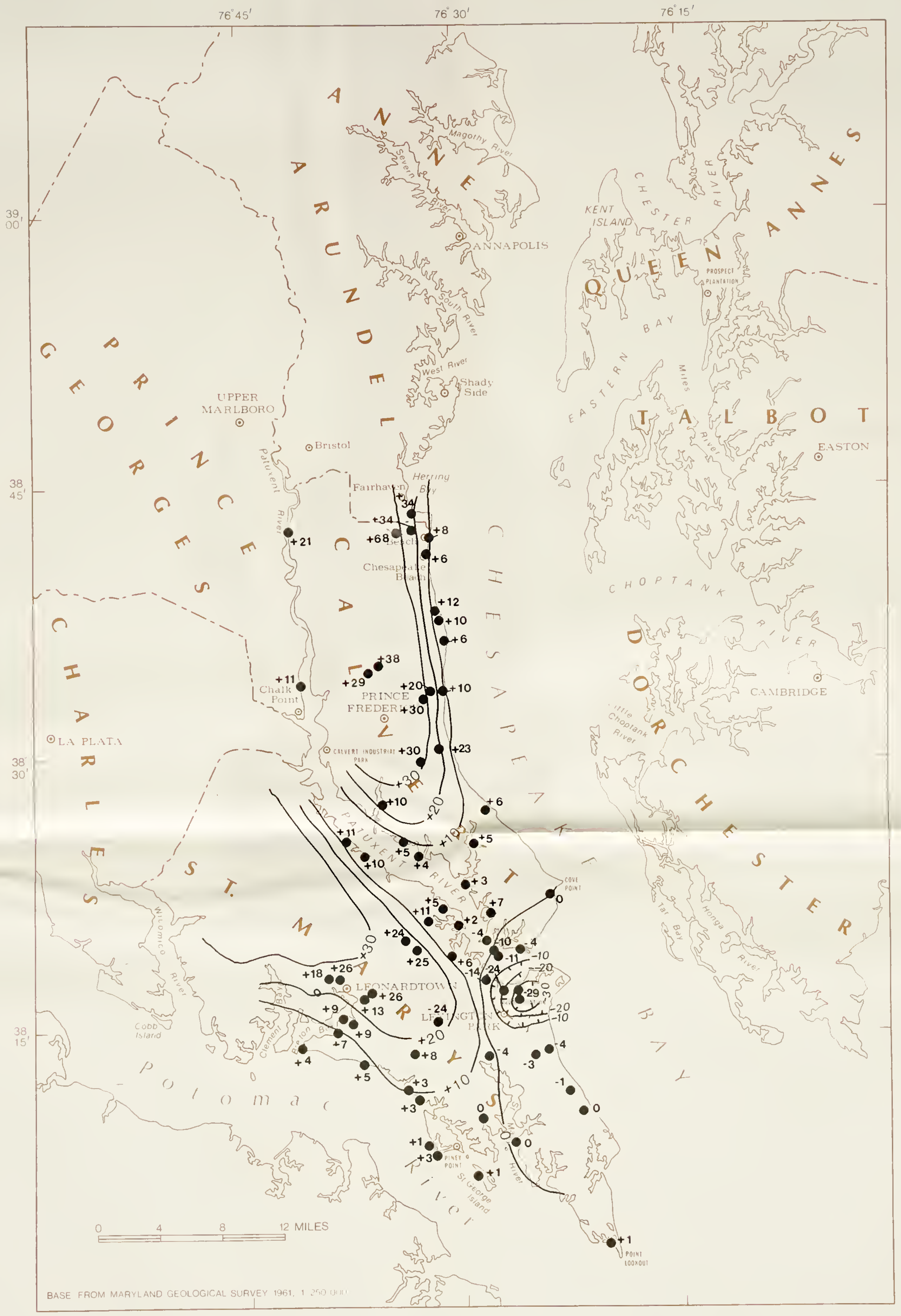
—+10— Simulated potentiometric contour in feet above (+) or below (−) sea level. Contour interval is 10 feet.

+8 ● Location of well used for water level control. Number is measured water level in feet above (+) or below (−) sea level.

Plate 11.—Map showing simulated prepumping, 1952, and 1980 potentiometric surfaces of the Piney Point-Nanjemoy aquifer superimposed on measured water levels

Plate 11.—Map showing simulated prepumping, 1952, and 1980 potentiometric surfaces of the Piney Point-Nanjemoy aquifer superimposed on measured water levels

Simulated pre-pumping potentiometric surface and water levels measured early in aquifer development as reported by Darton (1896), Clark and others (1918) and Otton (1955).



Simulated potentiometric surface of 1952 and water levels measured approximately 1952 by Otton (1955).

Simulated 1980 potentiometric surface and water levels measured May 19-23, 1980.

EXPLANATION

—+10— Simulated potentiometric contour in feet above (+) or below (−) sea level. Contour interval is 10 feet.

+8 ● Location of well used for water level control. Number is measured water level in feet above (+) or below (−) sea level.

Plate 12.—Locations of selected observation wells in the Aquia aquifer

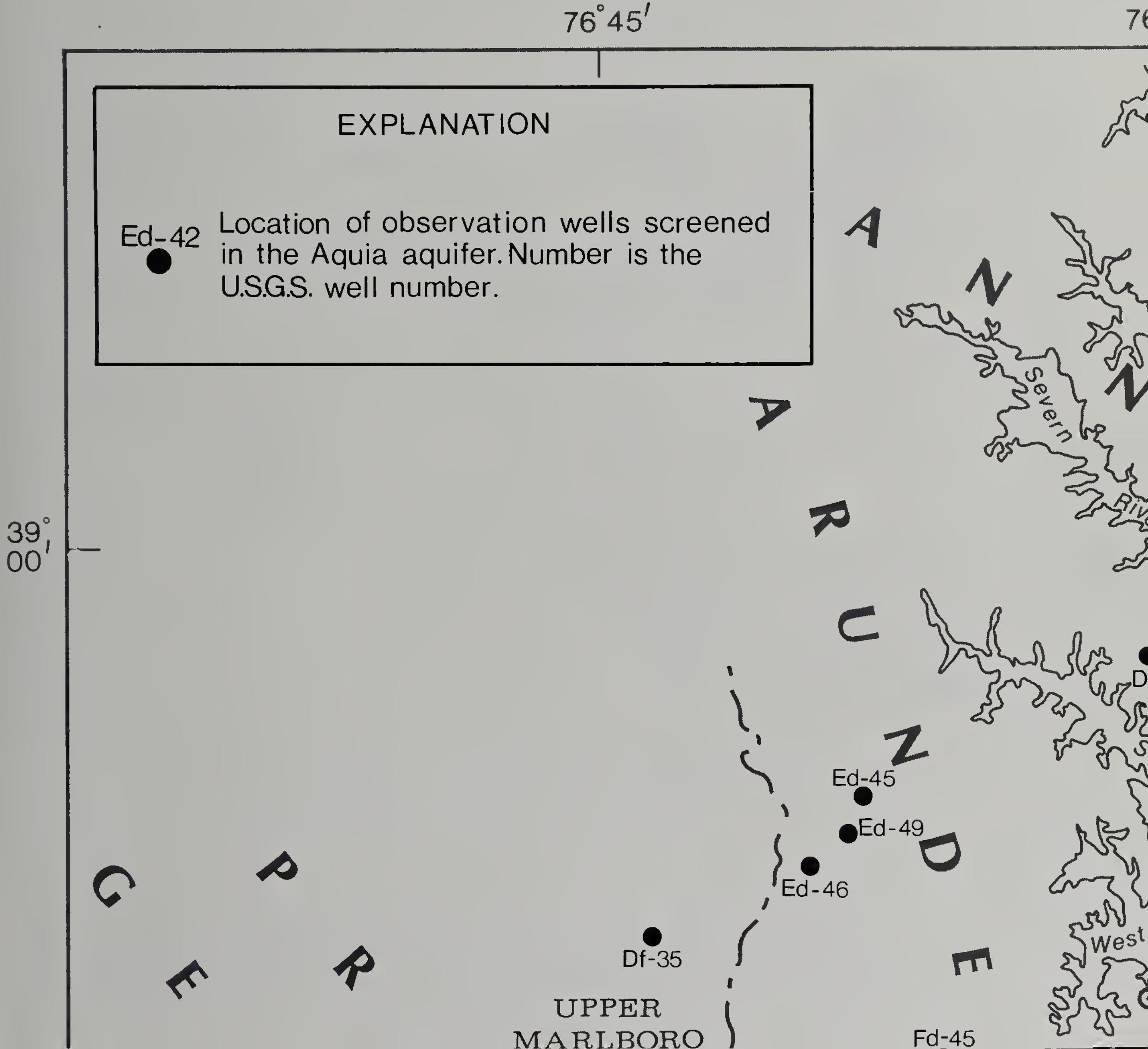


Plate 12.—Locations of selected observation wells in the Aquia aquifer

BASE FROM MARYLAND GEOLOGICAL SURVEY 1961, 1:250,000

Plate 13.—Locations of selected observation wells in the Piney Point-Nanjemoy aquifer

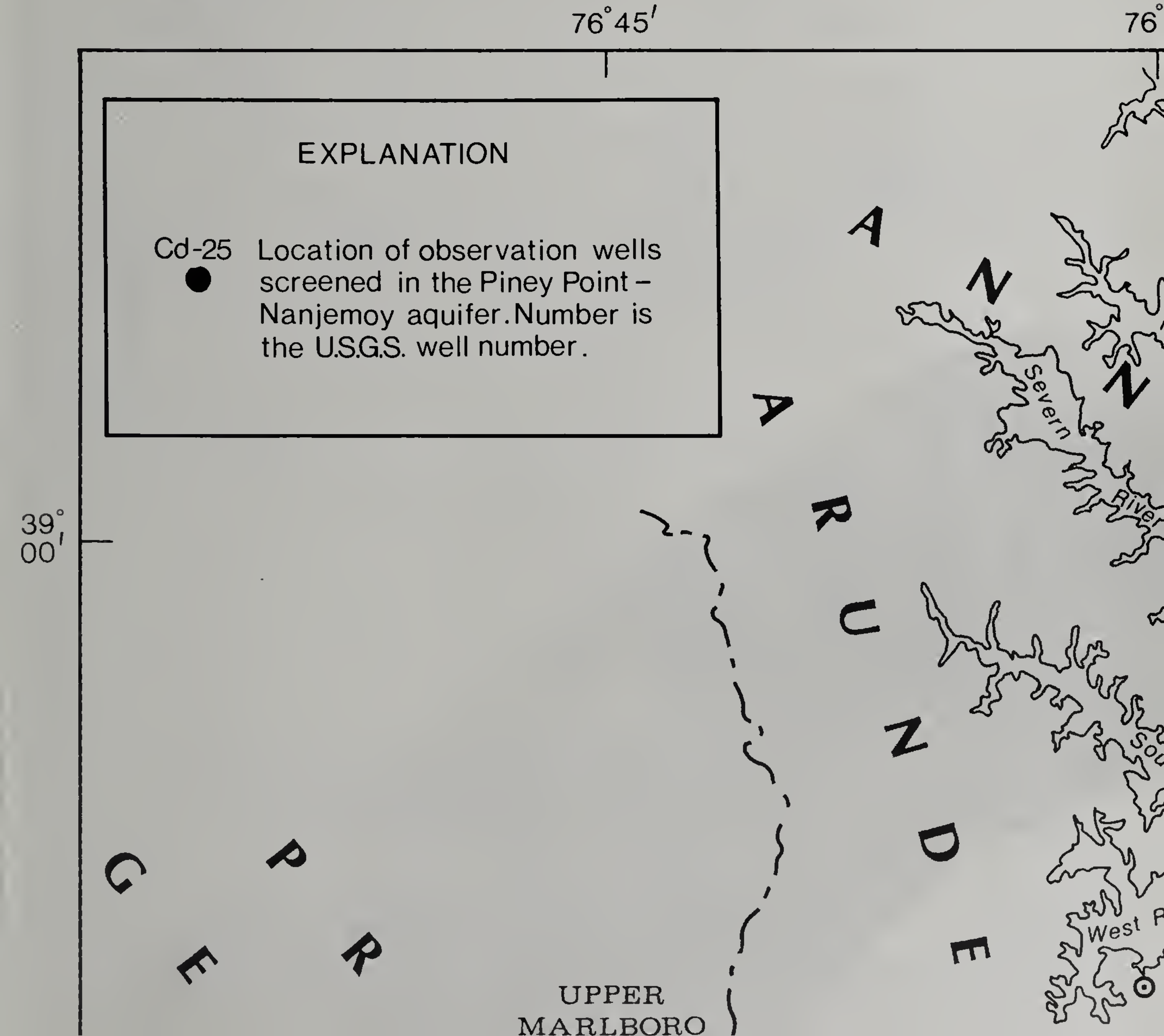


Plate 13.—Locations of selected observation wells in the Piney Point-Nanjemoy aquifer