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

REPORT OF INVESTIGATIONS NO. 31

SIMULATED CHANGES IN WATER LEVEL IN THE PINEY POINT AQUIFER IN MARYLAND

by
James F. Williams III

Prepared in cooperation with the
United States Department of the Interior
Geological Survey
and the Boards of County Commissioners of
Calvert, Caroline, and St. Mary's Counties

1979

CONVERSION OF MEASUREMENT UNITS

The following factors may be used to convert the Inch-pound units published in this report to International System (SI) metric units.

To convert from	Multiply by	To obtain
	Length	
inch (in.)	25.4	millimeter (mm)
foot (ft.)	0.3048	meter (m)
mile (mi.)	1.6093	kilometer (km)
	Area	
square mile (mi^2)	2.59	square kilometer (km^2)
acre	4047.	square meter (m^2)
	0.4047	hectare (ha)
	0.004047	square kilometer (km^2)
	Flow	
cubic foot per second (ft^3/s)	28.32	liter per second (L/s)
	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
million gallons per day (Mgal/d)	0.04381	cubic meters per second (m^3/s)
million gallons per year (Mgal/yr)	0.00012	cubic meters per second (m^3/s)
	Hydraulic units	
transmissivity- foot squared per day (ft^2/d)	0.0929	meter squared per day (m^2/d)
hydraulic conductivity foot per day (ft/d)	0.3048	meter per day (m/d)
foot per second (ft/s)	$3.5277 x 10^{-6}$	meter per day (m/d)

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SIMULATED CHANGES IN WATER LEVELS IN THE PINEY POINT AQUIFER IN MARYLAND

BY

JAMES F. WILLIAMS III*

ABSTRACT

A two-dimensional finite-difference computer model of the freshwater part (less than 250 milligrams per liter chloride) of the Piney Point aquifer in Maryland was developed to simulate and predict drawdown in the aquifer.

The Piney Point aquifer is of Eocene age and is composed of fine to very coarse sand varying from a few feet to more than 120 feet in thickness. It contains cemented, interbedded shell layers, and is highly glauconitic. The aquifer has no known outcrop area. Hydrogeologic information pertaining to the Piney Point is presented as a series of maps which show the potentiometric surface in the prepumping stage, the potentiometric surface in 1952 and 1976, the water-level change between 1952 and 1976, the available drawdown as of 1976, the transmissivity, the thickness, and the subsurface structure.

The Piney Point aquifer is a major source of water for several cities, communities, industries, housing subdivisions, and hundreds of individual homeowners in southern and eastern Maryland. The aquifer is also used as a water source in parts of Virginia, Delaware, and New Jersey. The total pumpage of the Piney Point in Maryland has increased from an estimated 0.5 million gallons per day in 1900, to an average of 4.33 million gallons per day between June 1975 and June 1976. A complex picture of water-level decline and rise has recently developed due to changes in the withdrawal rates from the major pumping centers.

The Piney Point was modeled as a confined aquifer recharged by leakage from an overlying aquifer which is separated from the Piney Point by semiconfining material. The calibration scheme consisted of simulating historical pumpage from an initially flat potentiometric surface. Pumpage was simulated over a period of 86 years (1890-1976) and was subdivided into seven separate pumping periods of various durations. Calibration was obtained by comparing computed versus measured water-level changes for the periods 1952-76, 1970-74, 1974-75, and 1975-76.

Values for aquifer characteristics used in the model to represent the Piney Point are: Transmissivity—100 to 6,200 square feet per day, and storage coefficient—3×10^{-4}. The values used to represent the semiconfining material were: Vertical hydraulic conductivity— 1×10^{-8} to 1×10^{-12} feet per second, specific storage— 6×10^{-6} per foot, and thickness— 50 to 305 feet.

*U.S. Geological Survey

INTRODUCTION

The Piney Point aquifer is one of the most important aquifers in southern and eastern Maryland. It is estimated that more than 3,000 wells presently tap the Piney Point aquifer in the southern half of St. Mary's and Calvert Counties. The Piney Point is the most important municipal, industrial, and domestic source of water in Dorchester County on the Eastern Shore of Maryland. The average daily pumpage in 1976 for the main municipality in Dorchester County, Cambridge, was 2.88 Mgal/d, of which the Piney Point supplied 67 percent. The Piney Point is also the main source of municipal water in Caroline County and the chief source of domestic water in the northwestern and southern sections of Talbot County. In certain parts of Delaware, southern New Jersey, and northeastern Virginia, the Piney Point aquifer is also a source of water.

Since the first major production well was drilled into the Piney Point aquifer at Cambridge in 1888, progressive declines of ground-water levels have accompanied increasing ground-water withdrawals. Significant water-level declines have occurred in the Cambridge area (over 100 ft. from 1888 to 1976). However, water levels in the Piney Point aquifer in the Cambridge area have risen since 1972 due to pumpage cutbacks. Southern Maryland experienced declines of more than 20 ft. between the years 1950-76. Recent heavy withdrawals (2.3 Mgal/d) from the aquifer in Delaware may affect water levels in Caroline County, Md.

Because the Piney Point aquifer is encountered at a reasonable depth (80-550 ft. below sea level), and, in most places contains water with suitable chemical properties, it will continue to be a favorite water source for individual domestic-well owners, cities, communities, and industries. State and local officials are concerned whether or not the Piney Point aquifer can continue to supply its share of the projected water needs of the area.

Water users and managers need to know how much additional drawdown future increases in pumpage will cause in an aquifer. At the present time, the use of the computer has made it possible to mathematically simulate an aquifer system and to estimate future changes in the water level of the aquifer based on various pumping arrangements.

The production capability of the Piney Point aquifer will affect the economic development of the study area. Large increases in population have been projected for several counties within this area. These counties will benefit by knowing in advance to what extent the Piney Point aquifer can be developed.

PURPOSE AND SCOPE

The purpose of this report is to show the drawdowns obtained from a two-dimensional model of the Piney Point aquifer in Maryland. The report presents the model of the entire freshwater (less than 250 mg/L chloride) part of the aquifer in Maryland.

An attempt was made to collect and tie together in one report all the relevant physical characteristics related to the Piney Point aquifer in Maryland that previously had been scattered among several different reports. New information collected during the course of this investigation is also presented.

The goal of the report is to use the model to test the effect various pumping rates and well location schemes will have on future water levels in the aquifer. Drawdown predictions based on the model may aid water-use administrators and planners in their decision-making process.

ACKNOWLEDGMENTS

Financial support for the project was provided by the Maryland Geological Survey and St. Mary's, Calvert, and Caroline Counties in a cooperative agreement with the U.S. Geological Survey.

The author expresses his appreciation to the many individual homeowners who consented to having water-level measurements made in their wells. Officials representing the water-supply systems of the city of Cambridge, the town of Denton, and the Patuxent Naval Air Base were also helpful in providing pumpage data, and in allowing active and abandoned wells to be used as observation wells.

Mr. Milton Stroud of the Patuxent Well and Pump Company was especially helpful with background information relating to the Piney Point-Nanjemoy aquifer in southern Maryland. Thanks are due to Mr. M. G. Marley of the St. Mary's County Metropolitan Commission, Mr. Jack Thye of the Calvert County Engineers Office, and to numerous other officials and private landowners who consented to having observation wells drilled on property under their control. Special appreciation is due to Dr. Patrick Leahy of the U.S. Geological Survey for providing helpful data and advice needed for modeling the aquifer in the Dover, Del., area. The author is grateful to Dr. Harry Hansen of the Maryland Geological survey for his ideas concerning future prediction simulations.

METHODS OF INVESTIGATION

The study technique used to investigate the hydraulic characteristics of the Piney Point aquifer was the two-dimensional finite-difference model. Data requirements for the model include the following: (1) Transmissivity of the aquifer, (2) storage coefficient of the aquifer, (3) pumpage history, (4) thickness of the confining material above the Piney Point aquifer, (5) vertical hydraulic conductivity of the confining material, (6) specific storage of the confining material, (7) initial starting head in the Piney Point aquifer and in the contributing (recharging) aquifer, (8) dimensions of the grid, and (9) boundaries of the model.

To collect data needed for model simulation, previously collected data were analyzed and a systematic field investigation was initiated to obtain new information in those areas where data were scarce. New field data contributed substantially to obtaining a better understanding of the physical and hydraulic characteristics of the Piney Point aquifer. New data were obtained by:

1. Establishing an observation-well network in the Piney Point aquifer—including the drilling of 17 new wells.
2. Installation of five continuous water-level recorders.
3. Laboratory analysis of the vertical hydraulic conductivity of cores from the upper confining material.
4. Electric and gamma-ray logging of 25 newly drilled wells.
5. Performing aquifer tests at nine sites to determine transmissivity and storage coefficient values.
6. Relating specific capacity (gallons per minute divided by drawdown (ft.)) to transmissivity by analyzing the pumping test reports of several hundred Piney Point aquifer wells.

LOCATION AND EXTENT OF THE STUDY AREA

The Piney Point aquifer occurs beneath parts of Calvert and St. Mary's Counties in southern Maryland and probably parts or all of the Maryland Eastern Shore counties, except Kent and Cecil. This report is primarily concerned with that part of the Piney Point aquifer in Maryland that yields water with less than 250 mg/L chloride. That part of the aquifer, the study area, is limited to Calvert, St. Mary's, Dorchester, Caroline, Talbot, and Queen Anne's Counties. Figure 1 shows the study area, boundaries of the model, Fall Line, and the 250 mg/L isochlor line. The total modeled area in Maryland is approximately 3,200 mi^2 of which 850 mi^2 is part of the Chesapeake Bay and Potomac River. A more detailed view of the model grid and modeled area is shown on plate 1.

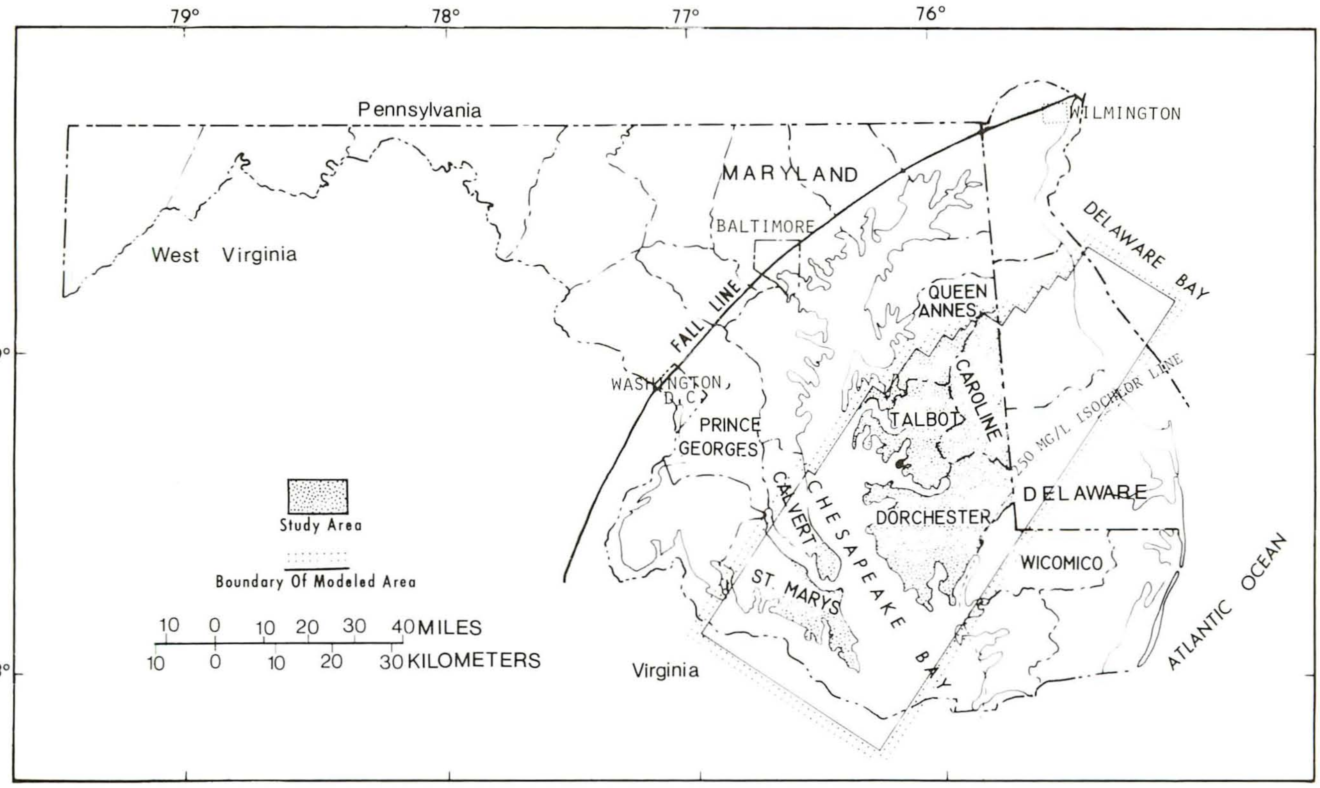


Figure 1.—Location of study area.

STRATIGRAPHY OF THE STUDY AREA

The Piney Point Formation is part of a sequence of geologic formations that occur in the Atlantic Coastal Plain Physiographic Province. This province is a broad plain underlain by a southeastwardly thickening wedge of layered beds of clay, silt, sand, gravel, and shell layers laid down on an older surface consisting largely of hard crystalline rocks referred to as the "basement."

The crystalline rocks occur at land surface west of a line roughly extending through Washington, D.C., Baltimore, Md., and Wilmington, Del. The line is commonly referred to as the "Fall Line" (fig. 1). East of this line, the crystalline rocks underlie the Coastal Plain sediments and occur progressively deeper eastward. For example, at Leonardtown (St. Mary's County), crystalline rocks are probably 2,500 ft. below sea level. On the Eastern Shore of Maryland at Easton (Talbot County), crystalline rock is probably 3,200 ft. below sea level, and at Cambridge (Dorchester County), 3,500 ft. below sea level.

This report focuses attention on one of the sand layers (Piney Point aquifer) found in the mass of unconsolidated Coastal Plain sediments. The term "Piney Point aquifer," as used in this report, refers to the aquifer part of the Piney Point Formation. Table 1 summarizes the age, lithology, thickness, and water-bearing characteristics of the various geologic units which are found beneath the study area. Figure 2 depicts two generalized geologic sections that show the trend of shallower formations (including the Piney Point) beneath the study area. Section A-A′ runs north-south through the Eastern Shore Counties of Talbot and Dorchester. This section is also typical of the subsurface section in Caroline County. Section B-B′ trends generally north-south through Calvert and St. Mary's County.

Table 1.—Generalized stratigraphy of southern and eastern Maryland.

System	Series (Group)	Stratigraphic units	Thickness in feet (meters)	Dominant lithologic character	Water-bearing properties
Quaternary and Tertiary (?)	Holocene, Pleistocene and Pliocene (?)	Lowland and upland deposits	0 - 190 (0 - 58)	Tan to orange stratified clay, silt, fine to coarse sand and gravel.	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 Piney Point Formation in southern Maryland. Not present in eastern Maryland.
		Salisbury Formation	0 - 145 (0 - 44)	Gray, red, orange, and brown unconsolidated deposits of gravelly sand, silts, and clays. Locally contains cemented hard ledges.	An important aquifer in eastern Maryland. Transmissivities range from 12,700 to 23,400 ft^2/d where tested. Not present in southern Maryland.
Tertiary	Miocene (Chesapeake Group)	St. Marys Formation	0 - 110 (0 - 34)	Greenish-blue to yellowish gray fossiliferous clay, sand, and sandy clay.	Functions generally as an aquiclude.
		Choptank Formation	0 - 130 (0 - 40)	Gray and brown very fine to medium sand and clay, containing shells.	Yields small to moderate amounts of water to wells in Caroline and eastern Dorchester Counties. In southern Maryland generally functions as an aquitard.
		Calvert Formation	20 - 300 (6 - 91)	Gray diatomaceous silts and clays containing lenses of gray sand and shell beds.	Largely an aquiclude, but contains two or three aquifers which locally yield large quantities of water at Easton, Federalsburg, Hurlock, and Vienna. The basal aquifer of this unit (Cheswold aquifer) is the upper recharging aquifer to the Piney Point Formation in most areas of eastern Maryland. Not a water source in southern Maryland.
	Eocene	Piney Point Formation	0 - 225 (0 - 69)	Olive-green to greenish-black to gray quartz sand, slightly to moderately glauconitic, fine to very coarse, with interbedded layers of shell, very fine sand, silt and clay.	Southern Maryland: Principal source of water in southern St. Marys and Calvert Counties. Yields reported up to 200 gal/min. Slowly but steadily declining water levels in most parts of St. Marys and Calvert Counties due to large numbers of domestic wells. Hydraulically connected to the Nanjemoy aquifer in some places. Eastern Maryland: The most important artesian aquifer in the area. Has yielded 1,200 gal/min to a municipal well at Cambridge. Large cone of depression throughout Dorchester and southern Talbot Counties. Small cones of depression around Denton and Greensboro.
		Nanjemoy Formation	0 - 290 (0 - 88)	Blackish-green to gray glauconitic sand, silt and clay.	A principal source of water in Calvert and St. Marys Counties. Yields reported in excess of 60 gal/min. Aquifer part of unit not restricted to one vertical position in unit. Hydraulically connected with overlying Piney Point Formation in some places. Not considered an aquifer in eastern Maryland. Varies from a leaky aquiclude in the west to a tight confining formation in the east.
	Paleocene	(Marlboro Clay) Aquia Formation	(0 - 30) 0 - 230+ (0 - 70+)	Green to greenish black glauconitic quartz sand, with lenses of clay and locally indurated shell beds. In Southern Maryland a pinkish to grayish clay (Marlboro Clay) generally overlies the Aquia.	Primary source of public water supply in St. Marys County. Main source of water in southwest Talbot and northwest Dorchester Counties. Not found as an aquifer south of a line connecting St. Marys City, Cambridge, Easton, and Denton.
		Brightseat Formation	20 - 40 (6 - 12)	Gray to dark-gray micaceous silty, sandy clays.	Functions generally as an aquitard.
Cretaceous	Upper Cretaceous	Monmouth, Matawan, and Magothy Formations, undifferentiated	350 - 1700 (110 - 520)	Glauconitic sands and clays containing abundant shells, small amounts of mica, lignite and carbonaceous matter.	The Magothy Formation yields moderate amounts of water at Easton and Cambridge, but is not present in southern Calvert or St. Marys Counties.
	Lower Cretaceous	Patapsco, Arundel, and Patuxent Formations, undifferentiated	300 - 2500 (91 - 760)	Chiefly variegated fine sands, silt and clay with interbedded coarse sand and gravel.	The Patapsco Formation in combination with the Raritan Formation yields moderate amounts of water to city wells in Cambridge. Not utilized in southern Maryland.
Paleozoic and Precambrian		Crystalline rocks (basement)	Unknown	Presumed to consist of schist, granite, and gneiss as found in outcrop areas.	Untested.

1/ Modified from Table 10 (Rasmussen and others, 1957), Table 2 (Mack and others, 1971), and Weigle and others (1970b).

The stratigraphic nomenclature used in this report is that of the Maryland Geological Survey and differs somewhat from that of the U.S. Geological Survey.

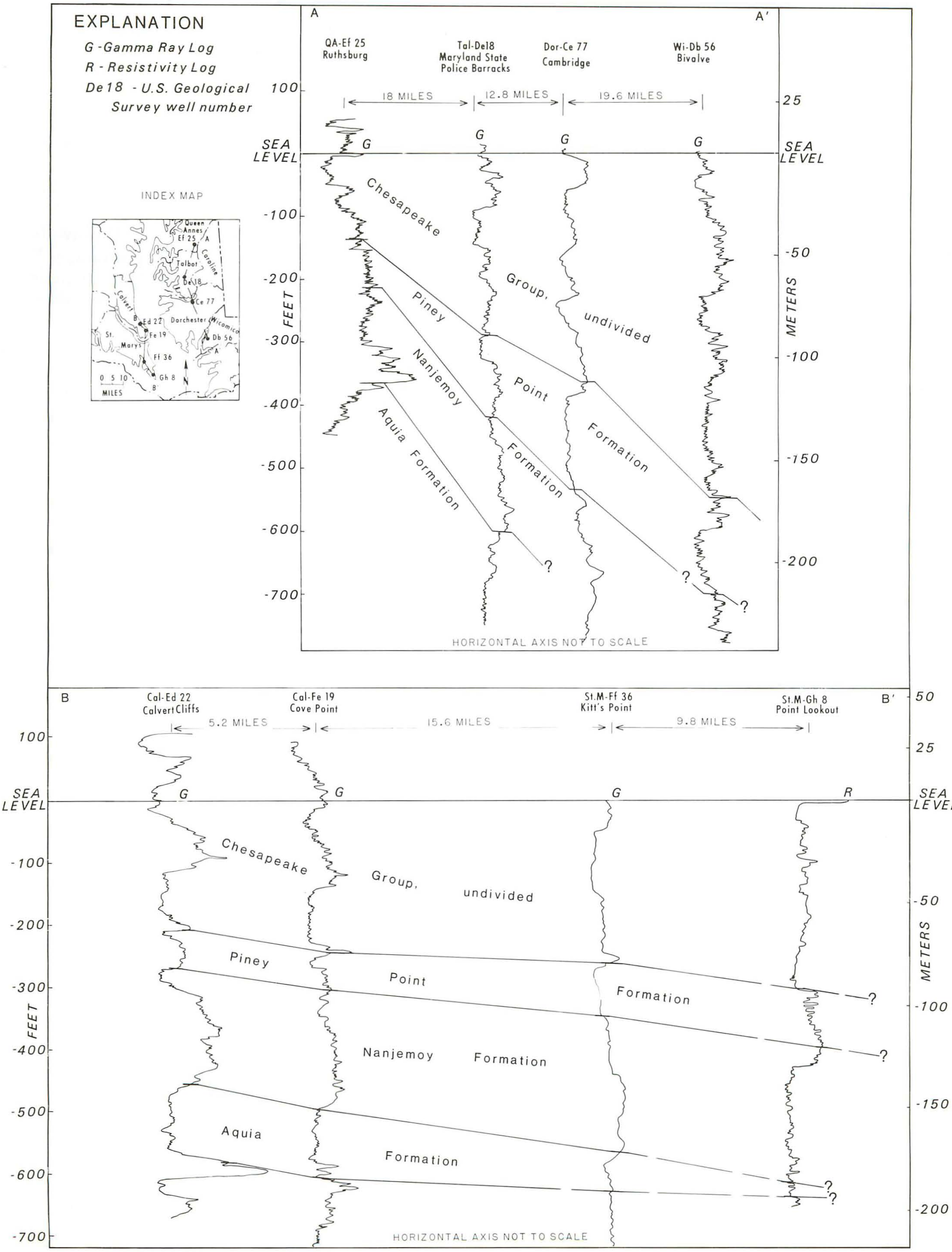


Figure 2.—Generalized geologic sections through southern and eastern Maryland.

MODELING THEORY AND DATA REQUIREMENTS

The purpose of the simulation model utilized in this study is to predict the hydraulic head in the Piney Point aquifer at any specified location and time.

The theory used in this study is based on the concept that ground-water movement can be expressed in two dimensions as a partial differential equation. The basic flow equation which is derived by combining Darcy's law and the equation for the conservation of mass, is given by:

$$(1) \quad \frac{\partial}{\partial x}\left(T_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_{yy}\frac{\partial h}{\partial x}\right) = S\frac{\partial h}{\partial t} + W(x,y,t)$$

in which

Txx, Tyy = principal components of the transmissivity tensor (L^2t^{-1});

h = height of the ground-water level above an arbitrary reference datum, usually sea level (L);

S = storage coefficient of the aquifer (dimensionless);

t = time (t); and

W = volumetric flux of recharge or withdrawal per unit surface area of the aquifer (Lt^{-1}).

Equation 1 can be broken down into finite-difference equations that can approximate the solution to the basic flow equation. The finite-difference equations can be rapidly solved by a digital computer (Trescott and others, 1976). The approximated equation 1 is shown as follows:

$$(2) \quad \frac{1}{\Delta x_j}\left\{\left[T_{xx(i,j+\frac{1}{2})}\frac{(h_{i,j+1,k}-h_{i,j,k})}{\Delta x_{j+\frac{1}{2}}}\right] - \left[T_{xx(i,j-\frac{1}{2})}\frac{(h_{i,j,k}-h_{i,j-1,k})}{\Delta x_{j-\frac{1}{2}}}\right]\right\}$$
$$+\frac{1}{\Delta y_i}\left\{\left[T_{yy(i+\frac{1}{2},j)}\frac{(h_{i+1,j,k}-h_{i,j,k})}{\Delta y_{i+\frac{1}{2}}}\right] - \left[T_{yy(i-\frac{1}{2},j)}\frac{(h_{i,j,k}-h_{i-1,j,k})}{\Delta y_{i-\frac{1}{2}}}\right]\right\}$$
$$= \frac{S_{i,j}}{\Delta t}(h_{i,j,k}-h_{i,j,k-1}) + W_{i,j,k}$$

where

i, j, k = indices in the x-, y-, and time dimensions; and

$\Delta x, \Delta y, \Delta t$ = increments in the x, y-, and time dimensions.

When the fluxes are comprised of: (1) withdrawals or recharge (for example, evapotranspiration, well pumpage, or well injection), and (2) leakage in or out of the aquifer through a confining bed, then $W(i,j,k,)$ in equation 2 is expressed as:

$$(3) \quad W_{i,j,k} = \frac{Q_{(i,j,k)}}{\Delta x_j \Delta y_i} - (h_{i,j,o} - h_{i,j,k})\frac{K_{v(i,j)}}{\left(\frac{\pi K_{v(i,j)}t}{3M^2_{i,j}S_{s(i,j)}}\right)^{\frac{1}{2}} M_{i,j}}$$
$$\cdot\left\{1 + 2\sum_{N=1}^{\infty}\exp\left[\frac{-N^2}{\left(\frac{K_{v(i,j)}t}{3M^2_{i,j}S_{s(i,j)}}\right)}\right]\right\} - \frac{K_{v(i,j)}}{M_{i,j}}(H_{i,j,o} - h_{i,j,o})$$

where

$H_{i,j,o}$ = hydraulic head in the aquifer above the confining bed (L);

$h_{i,j,o},$ = hydraulic head in the aquifer at the start of the pumping period (L);

$Kv_{(i,j)}$ = vertical hydraulic conductivity of the confining bed (L/t);

$M_{i,j}$ = thickness of the confining bed (L);

$Q_{(i,j,k)}$ = rate of withdrawal (positive sign) or recharge (negative sign) (L^3/t);

$Ss_{(i,j)}$= specific storage in the confining layer (L^{-1})

$K_{v(i,j)}t / M^2_{i,j}S_{s(i,j)}$ = dimensionless time; and

t= elapsed time of the pumping period (t).

The digital-model program used for this study is by Trescott and others (1976). It evolved from earlier work by Pinder (1969). The model is designed to simulate in two dimensions the response of an aquifer to an imposed stress.

As in most mathematical models, certain assumptions are presumed to govern the system. The main assumptions of the Trescott, Pinder, and Larson program as they relate to the Piney Point aquifer model study are:

1. Flow in the confined aquifer (Piney Point) is horizontal and in two dimensions, even though leakage may occur through the upper confining bed. This assumption is justified if the horizontal conductivity is appreciably greater than the vertical conductivity. In addition, the aquifer is assumed to be isotropic and homogeneous within the grid block.
2. Recharge to the Piney Point aquifer is derived only from the upper contributing aquifer, through leaking confining material. Hydraulic head in the contributing aquifer is assumed to be constant with time. Any recharge to the Piney Point aquifer from below is computed as if it was derived from the upper contributing aquifer.
3. Flow through the confining bed is vertical. This assumption is valid if the hydraulic conductivity of the confined aquifer is much greater than the hydraulic conductivity of the confining bed. Experimentally, it has been found that if the ratio of the aquifer's hydraulic conductivity to the confining bed's hydraulic conductivity is between 10:1 and 100:1, the error is 5 percent or less. When the ratio is greater than 100:1, the error is less than 1 percent. (R.L. Cooley, U.S. Geological Survey, Denver, Colo., written commun., 1976.) In this report, the ratio is estimated to be greater than 1,000:1.

The Piney Point aquifer was modeled using the Strongly Implicit Procedure (SIP) numerical technique to indirectly solve equation 1. The outline theory behind the computational algorithm of this method can be found in Remsen, Hornberger, and Molz (1971), and Trescott, Pinder, and Larson (1976).

In order for the model to be a reliable, predictive tool, it must be calibrated against past water-level conditions. The procedure used to calibrate the Piney Point aquifer model was to simulate historical pumpage and match measured against computed water-level changes.

GEOHYDROLOGY OF THE PINEY POINT AQUIFER

AREAL EXTENT AND DEPTH

The Piney Point Formation does not crop out, but is found only in the subsurface. The formation is truncated updip beneath an unconformity occurring at the base of the Calvert Formation. The truncation line is roughly 1 to 2 miles north of the -100-ft structure contour line in figure 3. In the downdip direction (SE), the Piney Point Formation gradually changes facies on electric logs from a sand to a sandy clay to finally a clay. The subsurface position of the clay line is not exactly known, but is thought to occur along an ill-defined line trending between Salisbury, Md., and Bridgeville, Del. (Location of cities can be found on plates 1-6). The Piney Point Formation probably terminates to the east beneath the Atlantic Ocean on the Continental Slope. The Piney Point also is known to extend laterally into Virginia and New Jersey.

The depth below land surface of the top of the aquifer can be determined by adding the land altitude to the structure contour lines of figure 3. The top of the Piney Point aquifer varies from less than 100 ft. below sea level at its western extent to more than 1,070 ft. below sea level at the Salisbury-Wicomico Airport. This report is concerned only with the part of the aquifer containing water with less than 250 mg/L chloride. The top of this part of the aquifer ranges from 80 to 550 ft. below sea level.

LITHOLOGY

The Piney Point aquifer is composed largely of quartz sand, glauconite, and shell fragments. The overall color of the material is olive green to greenish gray to greenish black. A hard layer (calcareously cemented shell fragments), commonly referred to by well drillers as a "rock" layer, is

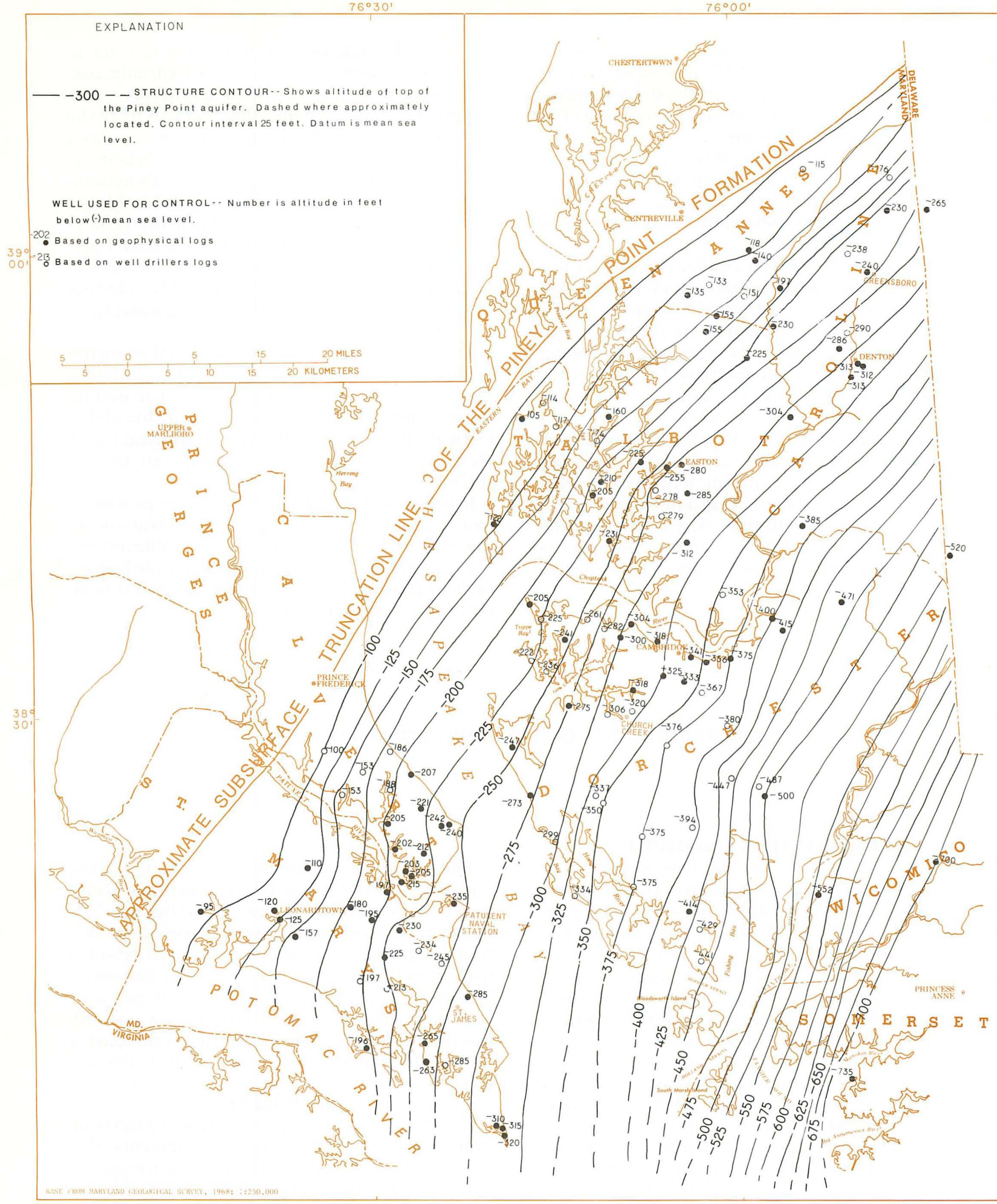


Figure 3.—Altitude of the top of the Piney Point aquifer.

normally found at the top of the formation. This layer is an excellent stratigraphic marker that stands out in geophysical and drillers' logs. Intercalated shell beds, usually less than a foot thick, occur throughout the Piney Point aquifer, but are more common in southern Maryland than in eastern Maryland. This sequence of sand and shell layers often prevents caving of boreholes and allows many wells in the Piney Point to be completed without a screen. Calcium carbonate cementation of the quartz sand and limonite encrustation of the glauconite is common and varies in severity from site to site. This phenomenon tends to reduce the effective porosity of the aquifer.

The Piney Point aquifer in Maryland appears to be coarsest in and around Cambridge. Samples from the Piney Point at Cambridge are medium- to very coarse-grained for the total thickness of the aquifer. Samples from wells a few miles away from Cambridge are fine- to medium-grained with occasional traces of coarse sand, and become even finer grained toward the lower part of the aquifer.

Results of mechanical analysis of a sample from the upper part of the Piney Point aquifer at Denton are presented in figure 4. This sample is classified as medium to coarse sand.

EFFECTIVE THICKNESS

The effective-thickness map shown on figure 5 (in pocket) represents an estimate of the thickness of the Piney Point Formation that is considered an aquifer. The aquifer part of the formation was determined from geophysical well logs and drill cuttings. The upper part of the formation in almost all instances is the most productive and most permeable. Geophysical logs and drill cuttings indicate that the formation becomes progressively more silty in its lower part. Those portions of the formation that were determined and believed to be very fine sand, sandy clay, silt and clay were subtracted from the total formation thickness to arrive at the effective thickness. Figure 5 represents an approximation, and because of the lack of data, cannot be verified everywhere within the study area.

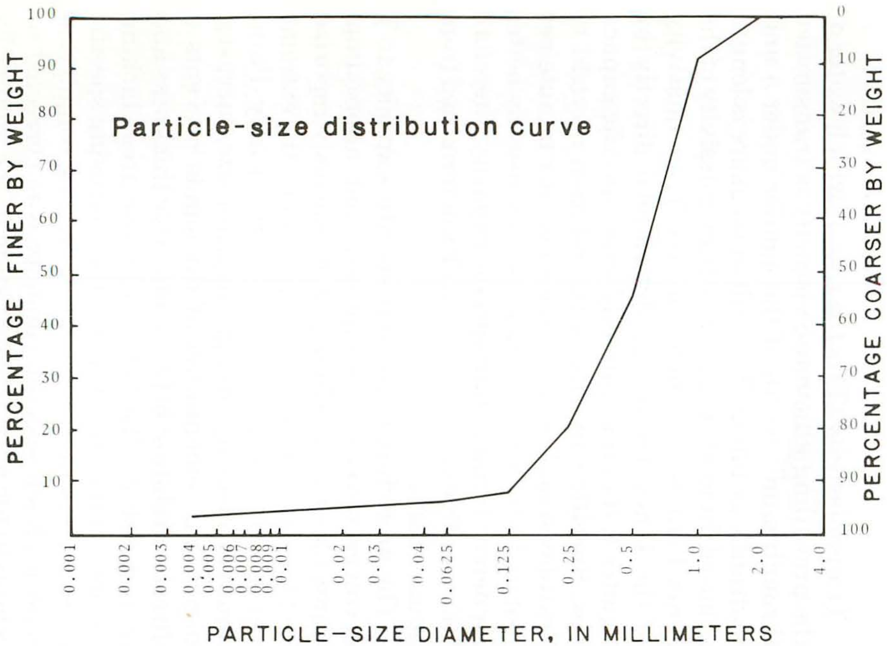
In parts of southern Maryland, the Piney Point aquifer is hydraulically connected and conformable with the underlying Nanjemoy aquifer. In such areas it is difficult to separate the two units and misclassification of these two aquifers undoubtedly has occurred. Hence, the effective thickness of the Piney Point probably includes, in some cases, the upper sandy portion of the Nanjemoy Formation as well as the Piney Point aquifer. This is true only for southern Maryland as the Nanjemoy Formation is mainly a silty clay unit in eastern Maryland and is not an aquifer

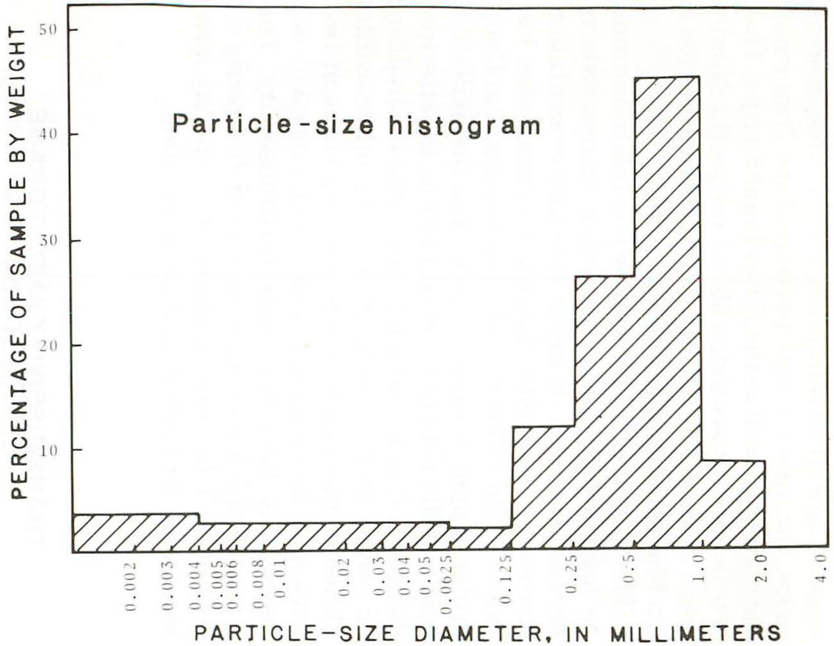
The effective thickness shown in figure 5 cannot be used directly in determining transmissivity because changes in grain size and cementation cause the permeability to vary from site to site. For example, the aquifer's effective thickness at Cambridge is approximately 100 ft. and the hydraulic conductivity is 40-60 ft./d. At Denton, the effective thickness is approximately 80 ft., but the hydraulic conductivity is only 20 ft./d. In other words, although the aquifer's effective thickness at two sites may be about the same, both sites will not necessarily have the same transmissivity. The effective thickness map was used indirectly to determine T by correcting specific capacity measurements for partial aquifer penetration.

TRANSMISSIVITY AND STORAGE CHARACTERISTICS

Transmissivity (T) is the rate at which water of the prevailing kinematic viscosity is transmitted through a unit width of the aquifer under a unit hydraulic gradient. The unit of measure is length squared divided by time. The transmissivity of the Piney Point is extremely variable. Transmissivity of the Piney Point was determined directly by aquifer tests and indirectly from specific capacities. Specific capacity is the relation of yield to drawdown and is given in gallons per minute per foot of drawdown. Aquifer tests are usually better for determining T than specific capacity; therefore more confidence was given to T's determined from aquifer tests.

The procedure to convert specific capacity to T involves several assumptions and approximations, plus the possibility of erroneously reported yield and drawdowns. Unfortunately, the extreme variation in permeability of the Piney Point aquifer caused by changes in grain size, encrustations, and cementation of the sands prevents a direct correlation between effective thickness and transmissivity. Therefore, in those areas lacking an aquifer test, the T was estimated using specific capacity calculated from well-drillers' completion reports. Each specific capacity was corrected (if required) for partial penetration of the aquifer by





Particle-size analysis (expressed in percent)

CLAY SIZES	SILT SIZES	SAND SIZES mm					GRAVEL SIZES
<0.004mm	0.004-0.0625mm	Very Fine 0.0625-0.125	Fine 0.125-0.25	Medium 0.25-0.5	Coarse 0.5-1	Very Coarse 1-2	>2mm
3.8	2.9	2.1	11.9	26.0	45.1	8.3	0

Statistical characteristics of grain-size analysis

MEDIAN SIZE mm	SORTING COEFFICIENT	SKEWNESS	KURTOSIS	UNIFORMITY COEFFICIENT
0.53	1.7	0.78	0.29	4.6

Heavy mineral analysis: number is frequency per 100 grains

GLAUCONITE 70; CARBONATE 18; PYRITE 6;

MAGNETITE 3; PYROXENE 1; STAUROLITE 2

Figure4.—Grain-size analysis of the uppermost material of the Piney Point aquifer at well Co-Dd 46, Denton, Md.

using a method discussed in "Groundwater Resources Evaluation" (Walton, 1970, p. 319). Aquifer thickness was determined from figure 5. Transmissivity was then estimated from the corrected specific capacity by utilizing a procedure developed by Hurr (Kruseman and DeRidder, 1970, p. 171-173). Not all of the T values calculated from specific capacity were utilized. Extreme values not fitting in with the majority were eliminated.

Plate 5 shows the estimated transmissivity of the Piney Point aquifer in Maryland and Delaware.

The areas of highest transmissivity are in and around Cambridge, Md., and Dover, Del. These areas also happen to be the main pumping centers of the Piney Point aquifer on the Delmarva Peninsula. Because it appears somewhat odd to have two of the largest cities on the Delmarva Peninsula positioned where the Piney Point aquifer attains its highest transmissivity, the situation deserves an explanation. Since the Delaware portion of plate 5 was adapted from Leahy (1978), only the Maryland portion of the map will be discussed. However, the T situation around Dover, Del., appears to be similar to the conditions at Cambridge, Md. Aquifer tests available in and near Cambridge indicate T's from 4,000 to 6,000 $ft.^2/d$. An analysis of aquifer tests and specific capacities surrounding Cambridge definitely shows a lower T radiating in all directions away from Cambridge. West of Cambridge, the Piney Point effectively ceases to be utilized as an aquifer beyond the village of Cornersville. North, east, and south of Cambridge, the T decreases so rapidly that T values less than 1,000 $ft.^2/d$ are found within 7 miles of the city. The effective thickness of the Piney Point (fig. 5) is generally greatest around the Cambridge area, which is an indirect indicator to substantiate plate 5. In general, the effective thickness map does agree with the T map. Anomalous T's shown in northwestern Talbot County are believed due to less cementation and larger grain sizes of the aquifer in those areas.

Plate 5 is believed to be a reasonable representation of the T of the Piney Point aquifer. The T cannot be verified everywhere within the study area because of the lack of data. New data may warrant transmissivity adjustments.

Only a few storage coefficient values have been determined for the Piney Point aquifer. The range of values, which was determined from aquifer test data, is from 0.00009 to 0.0004.

PUMPAGE

It is not known when the first well to the Piney Point aquifer was drilled in Maryland. The first major production well was drilled for municipal use at Cambridge in 1888. Several canneries in Cambridge also drilled wells into the aquifer during the early 1900's. The towns of Secretary, Denton, and Greensboro, in eastern Maryland have used the Piney Point aquifer as a source of municipal water for more than 40 years. In southern Maryland, the Piney Point aquifer has been used as a domestic water source since before 1890. During World War II, several naval installations in St. Mary's and Calvert Counties used wells which withdrew moderate quantities from the Piney Point aquifer. These withdrawals continued until the early 1950's when complaints concerning water-level declines caused withdrawals to be reduced. The city of Leonardtown utilized the Piney Point aquifer at one time as a municipal water source, but has since abandoned the Piney Point for the deeper and more productive Aquia aquifer.

Accurate historical pumping rates are difficult to document because records were rarely maintained. Even though present-day holders of groundwater appropriation permits whose wells pump 10,000 gal/d or more are required to submit semiannual pumpage reports to the Maryland Water Resources Administration, not all permit holders faithfully follow the required procedure. Consequently, many of the pumping rates used for the model calibration are best-guess estimates.

Piney Point pumpage in Maryland and Delaware between 1952 and 1976 is shown in figure 6. A more detailed breakdown of this pumpage is presented in table 2 which shows the average pumping rate at selected time periods for the major users of the Piney Point aquifer in Maryland and Delaware.

A large number of domestic wells have been completed in the Piney Point aquifer. Otton (1955, p. 88) estimated that between 500 and 1,000 wells were tapping the Piney Point aquifer in Calvert and St. Mary's Counties in 1951. Since that time, approximately 2,000 additional wells in the Piney Point have been drilled in those counties. Because the Piney Point aquifer and the Nanjemoy aquifer are contiguous in places in southern Maryland, some of these wells may tap the Piney Point--Nanjemoy aquifer. In eastern Maryland, at least

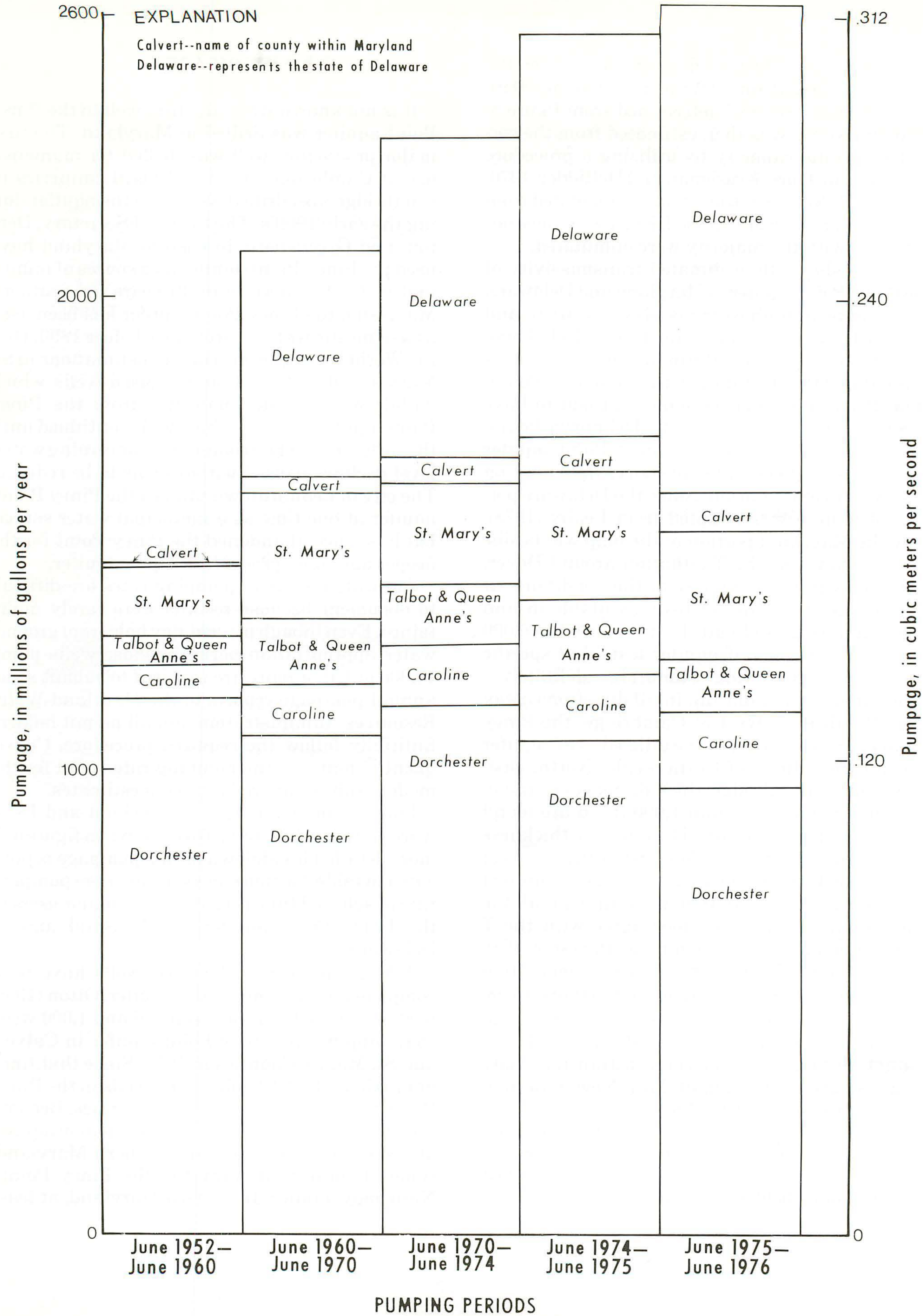


Figure 6.—Pumpage from the Piney Point aquifer in Maryland and Delaware, 1952- 76.

1,000 wells in the Piney Point have been drilled since 1951. Pumpage from the domestic wells contributes substantially to the total withdrawal from the aquifer. Estimated domestic and small commercial-industrial pumping rates have been totaled and are listed in table 2.

Domestic pumpage being withdrawn from the Piney Point aquifer was determined by the following procedure: Each domestic well in the Piney Point aquifer was assumed to serve a family of four. Before 1960, each domestic well was assumed to yield 250 gal/d to the household. After 1960, 300 gal/d were used. Next, the average number of domestic wells located within each node of the model during each pumping period was approximated. By multiplying the appropriate daily usage by the number of wells in that node, the required domestic pumpage was calculated for each of the pumping periods. The domestic pumpage was added to the pumpage of the major users if a major user also was located in the same node.

RELATION OF WATER LEVELS TO PUMPING

Prepumping Water Levels

Few historical static water-level measurements from wells tapping the Piney Point aquifer are in existence. Furthermore, the accuracy of many of the available measurements is questionable. The earliest published records of water levels in the Piney Point in Maryland are presented by Darton (1896), who reported that many of the wells drilled where the land elevation was near sea level flowed. Listed below are excerpts from Darton's tabulation of Maryland Coastal Plain wells.

Locality	Depth (ft)	Height to which water rises, in feet above (+) or below (-) land surface	Gallons per minute
Cambridge (6 wells)	370	+15	Flow 160 to 250 each
LeCompte's Store, 6 mi. west of Cambridge	358	+16½	Pumped 4
Denton	359	- 4	Pumped 30
Leonardtown	300	+20	Flow 2
Piney Point	270	+12	Pumped 5
St. Inigoes (10 wells)	300	+12	Pumped 2
Solomons Island	252	+ 4	Pumped 150

A study by Clark, Mathews, and Berry (1918) was the first comprehensive publication exclusively devoted to Maryland hydrology. Listed below are the more significant Piney Point wells contained in that publication.

Location	Altitude of land surface (feet)	Depth (feet)	Head above (+) or below (-) land surface	Drilled	Remarks
Cambridge	25	405	-22	1909	
Cambridge	—	390	-15	1914	
Cambridge 2 mi west.	10	360	+ 3	—	
Church Creek	5	395	+ 1	—	
Easton 3 mi. west.	12	297	- 6	—	
Easton	20	366	+10	1886	Flowed 3 gal/min in 1886
Trappe	50	375	-14	1909	
Greensboro	20	285	+ 5	—	Originally flowed
Broomes Island	3	225	+ 6	1912	Flowing
Solomons	5	265	+ 8	1903	Do.
Leonardtown	10	263	+14	1907	Do.
Piney Point	5	272	+ 7	—	Do.
St. George Island	5	265	+ 7	1904	Do.
St. Inigoes	20	298	+18	1889	

Unlike Clark and others, Darton's table does not contain land altitudes for the respective well sites. Land altitudes are critical in order to relate ground-water levels to a sea-level datum. If approximate altitudes are assumed for the Cambridge and southern Maryland wells referred to in Darton's report, then a comparison can be made between Darton's and Clark's water levels in the Piney Point. When comparing the two tables in this manner, it is apparent that water levels in the Piney Point aquifer in the Cambridge area had declined approximately 30 ft between the early 1890's and 1909. These declines were related to pumping, because by 1909 the city of Cambridge and nearby cannery operations were withdrawing several hundred thousand gallons a day from the Piney Point aquifer.

In southern Maryland, wells tapping the Piney Point by 1907 were utilized primarily for domestic and small business purposes. No large-capacity wells were reported in the aquifer. However, cumulative domestic pumpage and free-flowing wells doubtless amounted to a significant quantity of water and, consequently, a reduction in the head of the Piney Point aquifer as great as 15 ft took place in southern Maryland between the early 1890's and 1907.

Figure 7 is an approximation of the prepumping Piney Point potentiometric surface. This map is based on historical data (Darton, 1896, and Clark and others, 1918) and reflects the author's conceptual model of the natural flow pattern in the aquifer.

Table 2.—Major users of the Piney Point aquifer and their pumping rates.

[E is scientific notation (for example, 3.92E-2 = 3.92×10^{-2})]

County	Owner or name	USGS No.	Grid No.	Average pumping rate ft^3/s (Mgal/yr)				
				June-June 1952-1960	June-June 1960-1970	June-June 1970-1974	June-June 1974-1975	June-June 1975-1976
			MARYLAND					
Calvert	White Sands Corp. 1/	CAL-Ed 17 Ed 32	5-15	3.15E-3 (0.74)	1.82E-2 (4.29)	1.86E-2 (4.39)	1.90E-2 (4.48)	2.10E-2 (4.95)
	Long Beach Water Co. 1/	CAL-Ed 19 Ed 20 Ed 33	5-17	3.60E-3 (0.85)	3.27E-2 (7.71)	3.81E-2 (8.99)	3.81E-2 (8.99)	3.81E-2 (8.99)
	Chesapeake Biological Lab.	CAL-Gd 46	8-11	-	7.42E-3 (1.75)	7.42E-3 (1.75)	7.42E-3 (1.75)	7.42E-3 (1.75)
	Shepherd's Marina	CAL-Gd 54	8-11	-	-	1.27E-2 (2.99)	1.60E-2 (3.77)	1.60E-2 (3.77)
	Chesapeake Ranch Estates	CAL-Fd 38	8-13	-	8.4E-3 (1.98)	9.3E-3 (2.19)	1.80E-2 (4.25)	1.80E-2 (4.25)
	Domestic and small industrial	-	Various locations	3.92E-2 (9.25)	8.11E-2 (19.13)	1.43E-1 (33.73)	2.12E-1 (50.05)	2.60E-1 (61.34)
		Total County Pumpage		4.595E-2 (10.84)	1.478E-1 (34.87)	2.291E-1 (54.05)	3.105E-1 (73.25)	3.605E-1 (85.04)
St. Mary's	Town Creek Water System	St-M-Df 49 Df 54 Df 67 Df 68 Df 69	7-9	3.45E-2 (8.14)	1.16E-1 (27.36)	1.83E-1 (43.17)	1.86E-1 (43.8)	1.53E-1 (36.09)
	Esperanza Middle School Greenview Knolls Fred Painter	St-M-Df 50 St-M-Df 53 St-M-Df 60 St-M-Df 56	8-8	2.54E-2 (5.99)	4.67E-2 (11.01)	4.67E-2 (11.01)	4.01E-2 (9.46)	4.05E-2 (9.55)
	James Hill	St-M-Ef 65 Ef 66	9-6	4.00E-2 (9.40)	4.00E-2 (9.40)	3.5E-2 (8.26)	3.00E-2 (7.08)	3.10E-2 (7.31)
	Patuxent Naval Air Base	St-M-Df 6 Df 9 Df 14 Df 38	9-9	2.30E-1 (54.3)	1.47E-1 (34.7)	1.13E-1 (26.7)	1.07E-1 (25.2)	1.15E-1 (27.13)
		Df 39	10-9	2.10E-3 (0.5)	1.90E-3 (0.45)	1.80E-3 (0.42)	1.80E-3 (0.42)	1.80E-3 (0.42)
		Armory	10-11	2.10E-3 (0.50)	1.90E-3 (0.45)	1.80E-3 (0.42)	1.80E-3 (0.42)	1.80E-3 (0.42)
		St-M-Dg 2 2/	11-10	-	-	-	3.57E-2 (8.42)	2.82E-2 (6.65)
		St-M-Df 4	11-11	2.10E-3 (0.5)	1.90E-3 (0.45)	1.80E-3 (0.42)	1.80E-3 (0.42)	1.80E-3 (0.42)
	Steuart Petroleum Co.	St-M-Fe 23 Fe 24	10-4	3.59E-2 (8.47)	3.61E-2 (8.51)	3.86E-2 (9.10)	4.63E-2 (10.92)	5.23E-2 (12.34)
	Domestic and small industrial users.	-	Various locations	2.39E-1 (56.3)	3.08E-1 (72.7)	4.91E-1 (115.8)	6.93E-1 (163.4)	7.194E-1 (169.7)
		Total County Pumpage		6.111E-1 (144.15)	6.995E-1 (165.00)	9.127E-1 (215.30)	1.143 (269.74)	1.145 (270.05)

Table 2., Con't.

[E is equal to 10 (for example, 3.92E-2 = 3.92×10^{-2})]

County	Owner or name	USGS No.	Grid No.	Average pumping rate ft^3/s (Mgal/yr) June-June 1952-1960	June-June 1960-1970	June-June 1970-1974	June-June 1974-1975	June-June 1975-1976
MARYLAND--Continued								
Caroline	Town of Greensboro	CO-Cd 48	11-45	4.24E-2 (10.00)	4.24E-2 (10.00)	8.78E-2 (20.72)	9.56E-2 (22.55)	1.46E-1 (34.43)
	Greensboro School	CO-Cd 49 Cd 50	11-45	-	-	2.20E-3 (0.52)	4.40E-3 (1.04)	4.40E-3 (1.04)
	Electro-Therm, Inc.	CO-Dc 130	12-42	-	-	1.00E-2 (2.36)	2.30E-2 (5.43)	2.30E-2 (5.43)
	Denton High School	CO-Dc 133	12-43	-	1.54E-2 (3.63)	1.54E-2 (3.63)	1.54E-2 (3.63)	1.54E-2 (3.63)
	Martinak State Park	CO-Dc 132	13-40	-	-	2.10E-3 (0.50)	2.20E-3 (0.54)	2.20E-3 (0.54)
	Town of Denton	CO-Dd 2 Dd 46	13-41	1.3E-1 (30.67)	2.0E-1 (47.18)	0.380 (89.64)	0.399 (94.13)	0.43 (101.44)
		CO-Dd 1	13-42	1.3E-1 (30.67)	2.0E-1 (47.18)	5.08E-2 (11.98)	5.08E-2 (11.98)	6.70E-2 (15.80)
		Total County Pumpage		3.024E-1 (71.34)	4.578E-1 (108.00)	5.483E-1 (129.35)	5.904E-1 (139.28)	6.88E-1 (162.30)
Queen Anne's	Friel Cannery	QA-Ee 12 Ee 18 Ee 19 Ee 20 Ee 21	5-39	6.36E-2 (15.00)	1.01E-1 (23.82)	1.47E-1 (34.68)	1.85E-1 (43.64)	1.79E-1 (42.22)
Talbot	Tilghman Packing Co.	TAL-Db 43	4-28	1.70E-2 (4.01)	1.70E-2 (4.01)	1.70E-2 (4.01)	1.70E-2 (4.01)	1.70E-2 (4.01)
	Martingham Inn	TAL-Cc 34	4-33	-	-	5.00E-3 (1.18)	1.58E-2 (3.72)	1.58E-2 (3.72)
	Town of Trappe	TAL-Ee 1 Ee 35	11-32	4.48E-2 (10.57)	5.00E-2 (11.79)	6.90E-2 (16.28)	8.90E-2 (21.00)	8.90E-2 (21.00)
	Trappe Frozen Foods	TAL-Ee 7	12-32	9.10E-2 (21.46)	1.40E-1 (33.02)	1.89E-1 (44.60)	2.10E-1 (49.54)	4.20E-3 (0.99)
	Domestic and small industrial	-	Various locations	4.66E-2 (10.99)	8.68E-2 (20.48)	1.14E-1 (26.89)	1.58E-1 (37.27)	1.74E-1 (41.04)
		Total County Pumpage		1.994E-1 (47.04)	2.938E-1 (69.30)	3.94E-1 (92.94)	4.90E-1 (115.54)	3.00E-1 (70.77)

Changes Between The Prepumping And 1952 Potentiometric Surfaces

By the early 1950's, water levels in parts of the Piney Point aquifer had undergone drastic declines. On the Eastern Shore, a significant cone of depression was centered around Cambridge. This cone had spread as far as Honga, approximately 20 mi southwest of Cambridge. In southern Maryland, water levels had not declined as much as they had in Cambridge; however, a small cone of depression was evident in and around the Patuxent Naval Air Base at Lexington Park. In other parts of southern Maryland, pumpage from domestic wells resulted in a significant drawdown. Water levels in the Piney Point aquifer declined in all but the extreme northern part of the southern Maryland study area.

Otton (1955) published the first potentiometric map of the Piney Point-Nanjemoy aquifer in southern Maryland. Rasmussen and Slaughter (1957), in their study of the hydrogeology of Caroline, Dorchester, and Talbot Counties, published the first potentiometric map of the Piney Point aquifer in eastern Maryland. Between the study by Clark (1918) and that of Otton and Rasmussen and

Table 2., Con't.

[E is scientific notation (for example, 3.92 = 3.92×10^{-2})]

County	Owner or name	USGS No.	Grid No.	Average pumping rate ft³/s (Mgal/yr) June-June 1952-1960	June-June 1960-1970	June-June 1970-1974	June-June 1974-1975	June-June 1975-1976
				MARYLAND--Continued				
Dorchester	Cambridge Country Club	DOR-Cd 48	11-27	-	-	-	1.42E-2 (3.35)	1.46E-2 (3.44)
	City of Cambridge	DOR-Cd 43	13-27	-	7.50E-1 (176.92)	1.18 (278.35)	1.37 (323.17)	1.41 (332.60)
		Ce 2 Ce 4 Ce 5 Ce 6	14-27	2.65 (625.11)	1.24 (292.50)	8.10E-1 (191.07)	6.30E-1 (148.61)	-
		Ce 10	14-28	2.60E-1 (61.33)	1.00E-1 (23.59)	3.70E-2 (8.73)	2.60E-2 (6.13)	-
		Ce 12 Ce 13	15-27	5.40E-1 (127.38)	1.15 (271.27)	8.50E-1 (200.51)	8.97E-1 (211.59)	9.07E-1 (213.95)
		Ce 78	15-26	-	3.81E-1 (89.87)	1.18 (278.35)	9.40E-1 (221.74)	1.17 (275.99)
	Andrews and Son Cannery	DOR-Cd 50	14-25	-	-	6.70E-3 (1.58)	3.40E-2 (8.02)	2.60E-2 (6.13)
	Hanover Brands, Inc.	DOR-Ce 61	16-27	5.70E-1 (134.46)	4.14E-1 (97.66)	3.63E-1 (85.63)	2.45E-1 (57.79)	1.52E-1 (35.86)
	Bumble Bee Cannery	DOR-Ce 62 72	16-27	6.80E-1 (160.40)	2.78E-1 (65.57)	1.71E-1 (40.34)	9.7E-2 (22.88)	1.14E-1 (26.89)
	Blackwater Farms, Inc.	DOR-Dd 11	17-21	-	-	-	1.90E-3 (0.45)	2.00E-3 (0.47)
	Bonnie Brook Subdivision	DOR-Ce 74 75	17-28	-	2.10E-2 (4.954)	2.58E-2 (6.086)	2.88E-2 (6.793)	2.92E-2 (6.888)
	Town of Secretary	DOR-Bf 1	18-32	6.00E-2 (14.15)	6.00E-2 (14.15)	4.00E-2 (9.44)	4.24E-2 (10.00)	4.24E-2 (10.00)
	Domestic and small industrial	-	Various locations	9.37E-2 (22.10)	1.27E-1 (30.05)	1.40E-1 (33.02)	1.51E-1 (35.62)	1.57E-1 (37.03)
		Total County Pumpage		4.854 (1145.00)	4.521 (1066.46)	4.803 (1133.09)	4.477 (1056.05)	4.024 (949.26)
		TOTAL FOR MARYLAND		6.076 (1433.36)	6.223 (1468.06)	7.034 (1659.38)	7.195 (1697.55)	6.696 (1579.74)
				DELAWARE				
Kent	Various owners	Various numbers	Various locations	-	2.03 (478.89)	2.877 (678.70)	3.663 (864.12)	4.239 (1000.00)
		TOTAL FOR MARYLAND AND DELAWARE		6.076 (1433.36)	8.253 (1946.93)	9.911 (2338.06)	10.858 (2561.46)	10.935 (2579.62)

1/ Combination Piney Point-Nanjemoy aquifer.
2/ Well screened in the Aquia Formation until April 1973. After that date, well redesigned as multi-aquifer well with screens in the Piney Point, Nanjemoy and Aquia aquifers. Half of annual pumpage assumed to be from Piney Point aquifer.
NOTE: Pumpage values shown are rounded to two decimal places. Many values given for pumping periods 1960-70 and earlier were approximated.

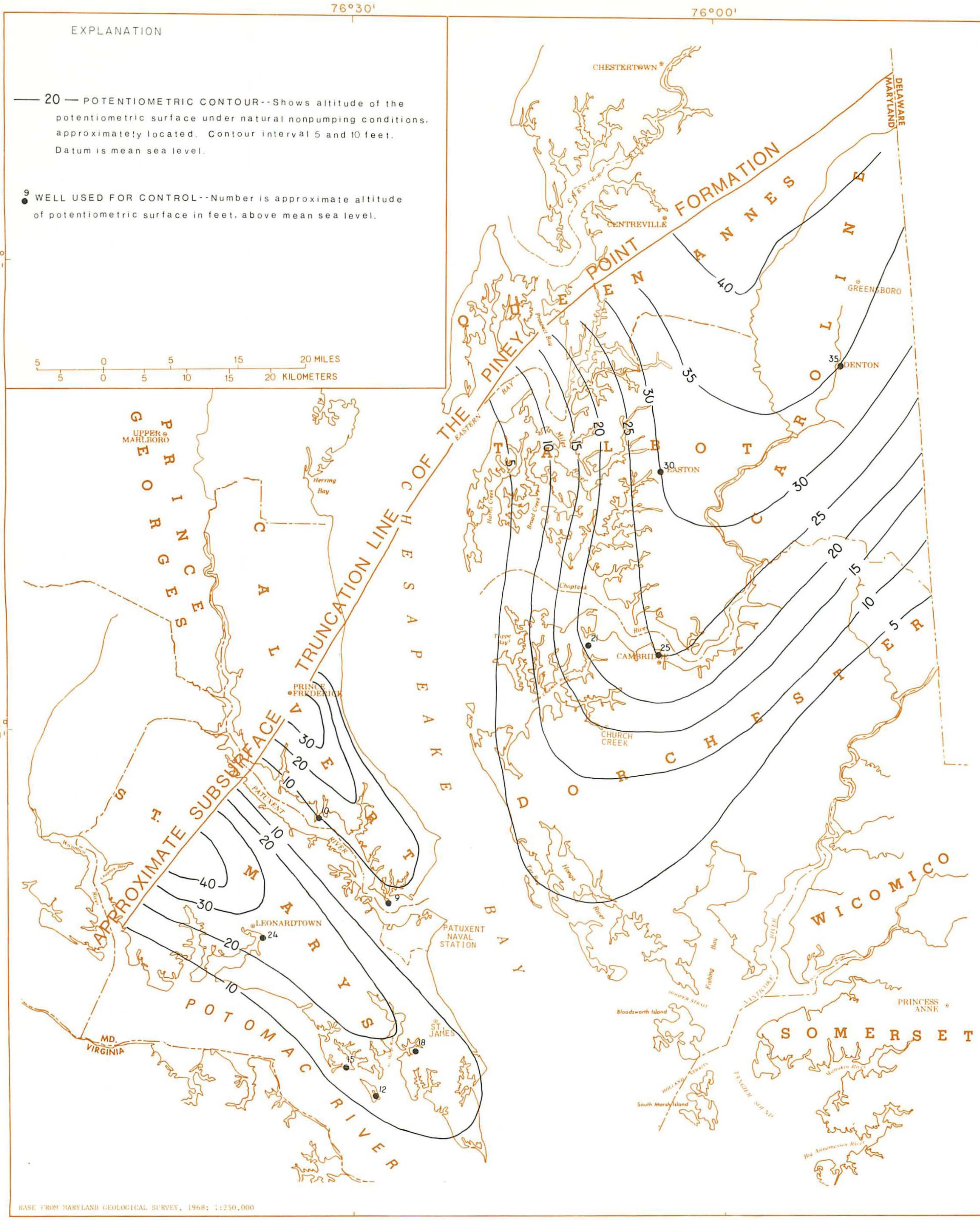


Figure 7.—Estimated prepumping potentiometric surface of the Piney Point aquifer.

Slaughter, very few reliable water-level measurements of the Piney Point aquifer were recorded.

Plate 2 shows the potentiometric surface of the Piney Point aquifer in 1952 for Maryland and Delaware. This plate was prepared by combining selected water-level measurements of the Piney Point from Otton (1955), Rasmussen and Slaughter (1957), and historical water-level data from Delaware (P.P. Leahy, U.S. Geological Survey, Dover, Del., oral commun., 1977). The data in plate 2 represent the basis for a large part of the calibration of the model.

Water-Level Changes Between 1952 And 1976

During May 27-28, 1976, water-level measurements were made in 104 Piney Point wells. A map of the potentiometric surface of the aquifer was prepared (pl. 3); this map is the first synoptic water-level contour map ever made of the entire Piney Point aquifer in Maryland and Delaware. Lack of observation wells and hence, lack of control in southern Dorchester County necessitated the use of a few reported water levels obtained from well drillers' reports.

The 1976 map was compared with the 1952 map and a water-level change map between 1952 and 1976 was prepared (pl. 4). The most noticeable changes between the 1952 and 1976 potentiometric surfaces are: (1) The rise in water levels in Cambridge and the Patuxent Naval Air Station, (2) the large water-level declines in Delaware resulting in an extensive cone of depression centered around Dover, and (3) the small cone of depression established around Denton.

Various approximations were inherent in preparing the water-level change map. The measurements for the 1952 map were collected during a period of more than a year compared to only a 2-day period for the 1976 map. In most cases, different control points were utilized in preparing the two maps, and the 1952 water-level surface in Delaware was only approximately known because of the relatively few wells in the Piney Point aquifer. However, even with the above discrepancies, plate 4 is probably reasonably accurate. The 1952-76 water-level change map is one of the key controlling factors in the calibration of the Piney Point model.

Observation-Well Trends 1950-76

To determine the trend and rate of change of the potentiometric surface of an aquifer, it is necessary to periodically measure the water levels of wells that are screened only in that aquifer. Up until 1975, only a few wells in the Piney Point aquifer had been measured by the U.S. Geological Survey on a periodic basis. During 1975 and 1976, 17 additional wells in the Piney Point were drilled and added to this network (table 2a). Figure 8 shows selected hydrographs of the pre-1975 observation-well network. Of these hydrographs, well Cal-Gd-5, located at Solomons in Calvert County, has the longest measurement period (1950 to 1977). Water levels in this well were generally constant until the fall of 1963. From that date until 1976, water levels declined 10 ft. because of a large increase in pumping for residential and business use. The two wells in the Piney Point in St. Mary's County, Ef-57 and Fg-45, both depict a slightly downward water-level trend.

The other pre-1975 observation wells in the Piney Point shown in figure 8 are located in Dorchester County. Two of these are located within the city limits of Cambridge and their water levels are constantly affected by nearby pumping wells. Despite the erratic nature of the record caused by pumping wells being turned off and on, the long-term water-level trend in these wells can be recognized. Both of the Cambridge observation wells, Cd-42 and Ce-21, show slightly rising water levels from 1958 until mid-1963, declining water levels from 1963 to 1971, and rising water levels from late 1971 until the present. Well Cd-1, located 4 mi southwest of Cambridge, is outside the range of the day-to-day influence of major pumping centers, although it does respond very rapidly to changes in the overall pumping pattern at Cambridge. The water level in this well is representative of the static water level of the Piney Point aquifer and confirms the trend observed for wells Cd-42 and Ce-21.

The expanded observation-well network (23 wells in 1977) provides a more adequate picture of the water-level trends in the Piney Point aquifer and will provide a more reliable base for future modeling studies.

Table 2a.—Records of Piney Point observation wells drilled during the project.

Geophysical logs: G, gamma ray; M, multi-point electric; S, single-point electric.

U.S.G.S. well No.	State permit No.	Location (Grid No.)	Latitude / Longitude	Altitude of land surface (ft)	Date drilled	Drilled depth (ft below land surface)	Construction data: Diameter (in)	Construction data: Screen position (ft below land surface)	Core sample (ft below land surface)	Geophysical logs	Driller	Static water level (ft below land surface) / Date of measurement
CA-Fd-50	CA-73-1448	Appeal (8-13)	38°21'19" 76°25'59"	94	9-20-76	401	6-2	340-350	257-260	G	Patuxent Pump & Well Inc.	109.6 9-22-76
CA-Fd-51	CA-73-1449	Calvert Cliffs Park (6-15)	38°24'08" 76°26'04"	120	9-29-76	390	6-2	342-352	---	S	Patuxent Pump & Well Inc.	122.69 2- 8-77
CA-Fd-52	CA-73-1450	Sollers (6-13)	38°23'16" 76°28'48"	101	9-27-76	318	6-2	308-318	130	G, S	Patuxent Pump & Well Inc.	91.70 11-16-76
CA-Fe-22	CA-73-1386	Cove Point (8-15)	38°23'24" 76°24'47"	102	6-10-76	350	6-2	340-350	---	G, M, S	Patuxent Pump & Well Inc.	111.87 6-29-76
CO-Bd-53	CO-73-0541	Goldsboro (10-47)	39°02'27" 75°47'02"	60	2-12-76	312	6-2	300-312	---	G, M	Delmarva Drilling Co. Inc.	28.76 3- 4-76
CO-Dd-47	CO-73-0486	Denton (14-41)	38°52'17" 75°49'06"	46	11- 3-75	380	4-2	370-380	---	G, M	Ideal Well Drillers	65.65 4-23-76
CO-Fc-29	CO-73-0546	Preston (17-34)	38°42'16" 75°54'12"	28	2-25-76	520	6-2	480-520	398.0-398.5	G, M	Delmarva Drilling Co. Inc.	49.58 3- 4-76
DO-Bg-59	DO-73-0612	Hurlock (21-34)	38°37'08" 75°50'38"	25	9-22-76	559	6-2	527-537	---	G, S	Shannahan Artesian Well Co. Inc.	34.85 10- 4-76
DO-Db-17	DO-73-0557	Taylor Island (9-19)	38°28'00" 76°18'07"	4	6-30-76	320	---	270-280	---	G, S	Ideal Well Drillers	6.96 5-18-77
SM-Dd-46	SM-73-1992	Redgate (5-4)	38°16'16" 76°36'47"	115	7-19-76	341	6-2	286-296	237.0-237.1	G, S	Patuxent Pump & Well Inc.	110.46 10- 6-76
SM-Df-66	SM-73-1990	California (8-10)	38°18'41" 76°28'44"	15	7-15-76	341	6-2	248-258	---	G, S	Patuxent Pump & Well Inc.	37.40 7-21-76
SM-Eg-27	SM-73-1993	St. James (14-7)	38°12'13" 76°22'28"	10	7-23-76	341	6-2	310-320	---	---	Patuxent Pump & Well Inc.	21.1 8-10-76
SM-Fe-30	SM-73-1917	Piney Point (11-3)	38°08'34" 76°30'34"	9	6- 3-76	297	6-2	260-270	197	G, M	Patuxent Pump & Well Inc.	15.35 8-25-76
TA-Bf-80	TA-73-0756	Cordova (8-37)	38°52'27" 75°59'47"	47	10- 6-76	459	6-2	351-371	---	G	Shannahan Artesian Well Co. Inc.	12.48 10- 7-76
TA-Cc-35	TA-73-0767	Tunis Mills (5-34)	38°49'23" 76°10'06"	5	7- 8-76	220	6-2	170-180	157-159	G, S	Ideal Well Drillers	2.75 8- 3-76
TA-Cc-36	TA-73-0750	Newcomb (6-33)	38°45'14" 76°10'37"	7	9-20-76	259	6-2	231-241	---	G, S	Shannahan Artesian Well Co. Inc.	11.30 10- 7-76
TA-Cf-22	TA-73-0798	Mathews (12-37)	38°49'31" 75°55'20"	34	10- 5-76	399	6-2	361-371	---	G, S	Shannahan Artesian Well Co. Inc.	32.20 10- 7-76

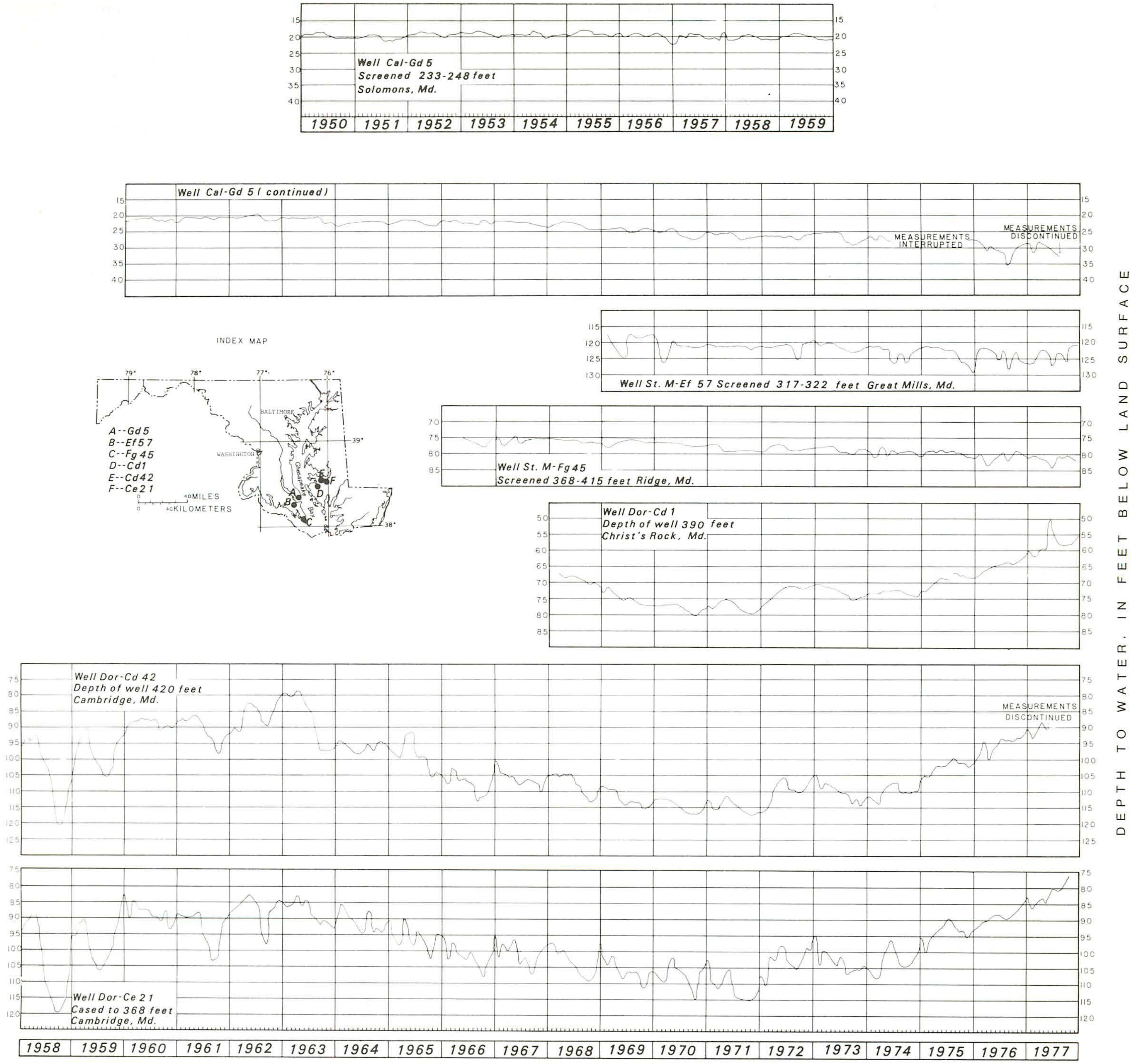


Figure 8.—Selected hydrographs of observation wells in the Piney Point aquifer.

RECHARGE AND DIRECTION OF FLOW

Because the Piney Point aquifer does not outcrop at the land surface, it cannot receive its recharge directly from precipitation. Instead, it obtains water from other aquifers. This occurs when the head differential between the Piney Point and aquifers above or below are great enough to induce water to leak through semiconfining material separating the aquifers. For example, in the Cambridge area, the next major aquifer (Cheswold) above the Piney Point has a water-level 60 to 80 ft. higher than that of the Piney Point.

In the horizontal direction, ground water generally moves at right angles to potentiometric contours and from contours with high values to those with lower values. Figure 7 shows the estimated potentiometric surface of the Piney Point aquifer before pumping. Ground-water movement in the aquifer on the Eastern Shore was toward the Chesapeake Bay in the western part of that area and toward the Nanticoke River in the eastern part.

When an aquifer is heavily pumped, the withdrawal of water alters the natural flow pattern. For example, plate 3 shows that heavy withdrawals at Cambridge, Md., have caused ground-water movement in the aquifer in that area to reverse its natural flow pattern and develop a new flow system with movement toward Cambridge.

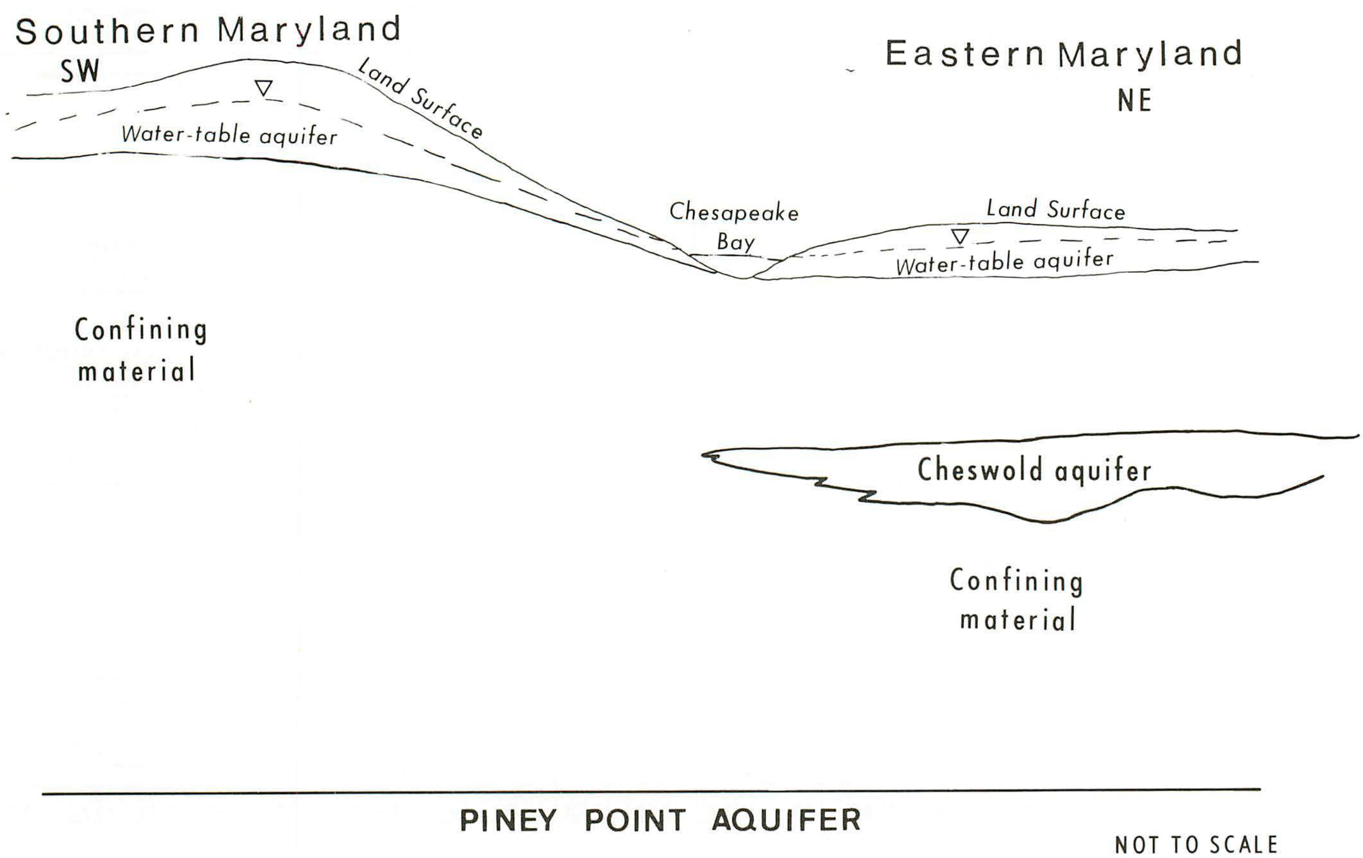


Figure 9.—Relationship of the confining material and contributing aquifer.

GEOHYDROLOGY OF THE UPPER CONFINING MATERIAL AND CONTRIBUTING AQUIFER

THICKNESS OF THE UPPER CONFINING MATERIAL

The upper confining material of the Piney Point aquifer refers to the layers of clay, silt, clayey sand, and thin sand stringers overlying the Piney Point aquifer and below the base of the next major aquifer above the Piney Point. Depending upon the location within the study area, the next major aquifer above the Piney Point aquifer may either be the Cheswold aquifer in eastern Maryland, as defined by Cushing and others (1973), or the lowland and upland deposits in southern Maryland, as defined by Otton (1955). The lowland and upland deposits function as a water-table aquifer and will be referred to as the "water-table" aquifer. Figure 9 is a schematic diagram showing the relationship of the Piney Point aquifer, the upper confining material, and the contributing aquifers.

The thickness map of the upper confining material (fig. 10) was constructed from geophysical logs of boreholes that penetrated at least to the top of the Piney Point aquifer. The difference between the base of the next major aquifers above the Piney Point and the top of the Piney Point aquifer is the thickness of the upper confining material.

VERTICAL HYDRAULIC CONDUCTIVITY OF THE CONFINING MATERIAL

During the test-drilling phase of this study, several undisturbed cores of the upper confining material were recovered for laboratory testing of vertical hydraulic conductivity (Kv). The results of these tests, shown in table 3, represent vertical hydraulic-conductivity values at a specific position within the confining material and may or may not represent the average vertical hydraulic conductivity of the entire confining material. Leahy (1976) reported vertical hydraulic-conductivity values of 4.63×10^{-10} to 1.04×10^{-9} ft/s, determined during a 25-day pumping test in Dover, Del. Nemickas and Carswell (1976) reported vertical hydraulic-conductivity of four cores from Cumberland County, N.J., to range from 2.31×10^{-10} to 6.02×10^{-10} ft/s. Although it may be somewhat speculative to make generalizations concerning the vertical hydraulic conductivity of the upper confining material because of the sparsity of available data, the vertical hydraulic - conductivity values available seem to indicate a trend toward lower values in an easterly direction.

WATER-LEVEL TRENDS IN THE CONTRIBUTING AQUIFER

The principal source of water for recharging the Piney Point aquifer is leakage from the next major aquifer above the Piney Point, the Cheswold aquifer in eastern Maryland and the water-table aquifer (lowland and upland deposits) in southern Maryland.

Table 3.—Vertical hydraulic conductivity values (Kv) of the upper confining material determined by laboratory methods.

County	Nearest town	USGS well No.	Sample depth meters (ft)	Hydraulic conductivity, K, from consolidation cm/sec (ft/sec)	Consolidation load, Kg/cm^2 (lb/in^2)	Permeant
Caroline	Preston	CO-Fc-29	121.31-121.46 (398-398.5)	7.1×10^{-8} (2.33×10^{-9})	7.03 (100)	Simulated formation water.
			121.46-121.55 (398.5-398.8)	2.57×10^{-6} (8.45×10^{-8})	70.3 (1000)	Do.
Talbot	Tunis Mills	TA-Cc-35	48.00-48.16 (157.5-158)	8.4×10^{-6} (2.76×10^{-7})	6.33 (90)	Distilled water.
			48.16-48.46 (158-159)	5.6×10^{-6} (1.8×10^{-7})	6.33 (90)	Do.
Calvert	Sollers	CA-Fd-52	39.62-39.78 (130-130.5)	3.39×10^{-7} (1.11×10^{-8})	6.33 (90)	Distilled water.
St. Marys	Redgate	SM-Dd-46	72.24-72.27 (237-237.1)	9.0×10^{-6} (2.95×10^{-7})	6.33 (90)	Distilled water.
	St. James	SM-Eg-28	66.14-66.29 (217-217.5)	1.20×10^{-7} (3.94×10^{-9})	70.3 (1000)	Simulated formation water.

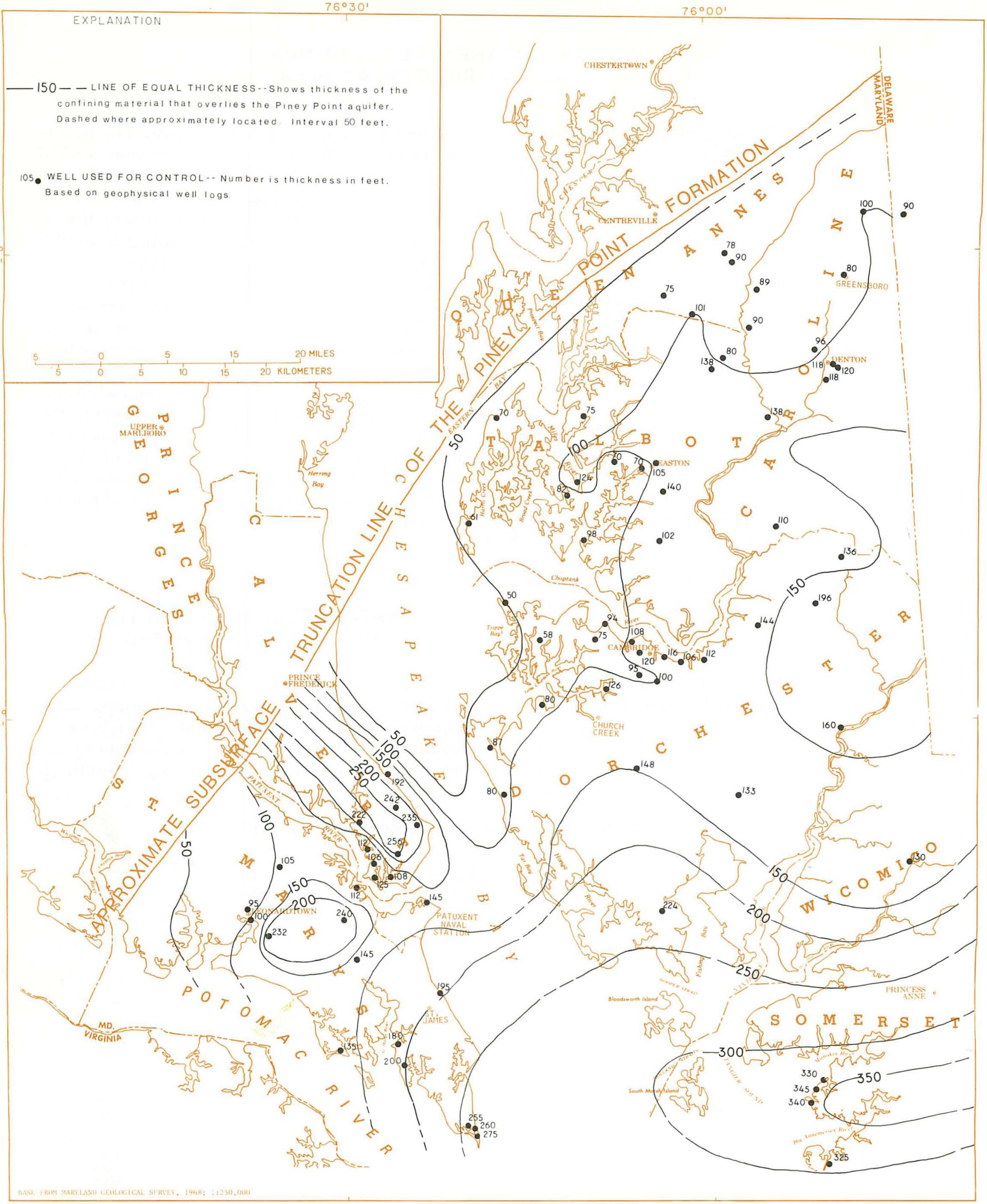


Figure 10.—Thickness of the confining material overlying the Piney Point aquifer.

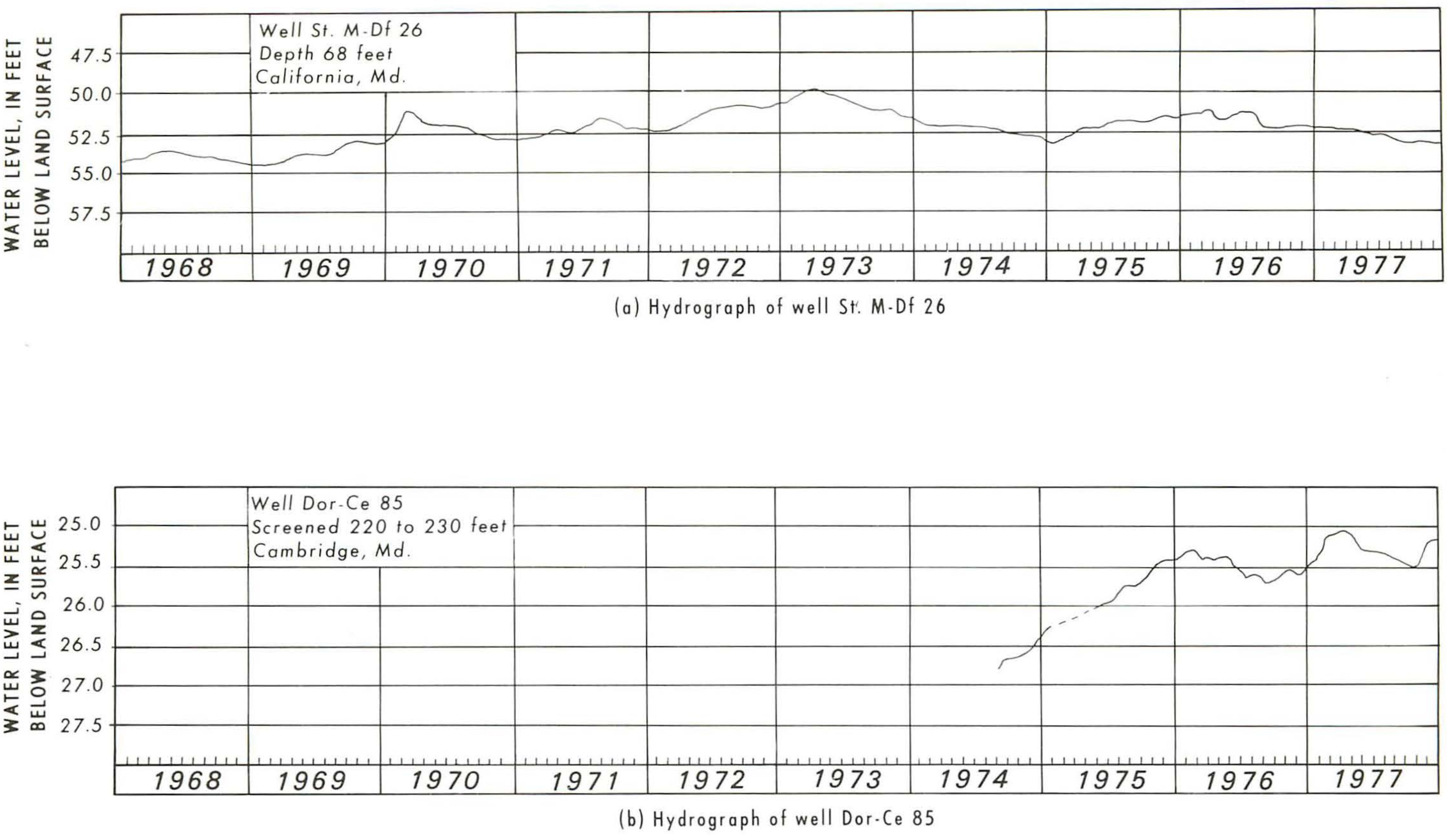


Figure 11.—Selected hydrographs of wells in the upper contributing aquifers.

The water-table aquifer in southern Maryland is presently utilized only by domestic well owners. As these shallow wells increase in age and require repair work, they are in many cases, abandoned. The replacement well is more often than not drilled into the Piney Point and (or) Nanjemoy aquifer.

Figure 11(a) shows a hydrograph of well St.M-Df 26 from 1968 to 1977. The hydrograph reflects the present trend of the water-level surface within the water-table aquifer. An earlier hydrograph of this same well, from 1948 to 1968, is shown in Weigle and Webb (1970*a*, pl. 4). This water level shows little fluctation (+2.5 ft), and the trend appears to be relatively flat. The water levels do not appear to be influenced by water-level declines in the Piney Point, indicating that recharge from precipitation greatly exceeds the amount of downward leakage.

The Cheswold aquifer in eastern Maryland is more heavily pumped than the water-table aquifer of southern Maryland. Cushing and others (1973, p. 43) estimate that 7.5 Mgal/d are pumped from the Cheswold aquifer on the Delmarva Peninsula, 90 percent of which is withdrawn in or near Dover, Del. The heavy pumpage in Dover has resulted in 50 to 100 ft of water-level declines in the Cheswold aquifer in that area.

In Maryland, the Cheswold aquifer is mainly used for domestic and small commercial - industrial purposes near Cambridge, along a strip from Easton to Queen Anne to Denton, and in southwestern and northern Caroline County. The present water-level trend in the Cheswold aquifer at Cambridge shows a slight rise [fig. 11(b)]. In the early 1900's, water levels in the Cheswold aquifer in Cambridge were approximately at sea level. The altitude of land surface at well Dor-Ce 85 is about 15 ft above sea level. Therefore, water levels in the Cheswold aquifer have declined about 10 ft at that site. Because the Cheswold aquifer has never been heavily pumped in the Cambridge area, part of this decline in the water level in well Dor-Ce 85 is believed to be due to a lowering of head in the Piney Point aquifer, which is inducing leakage of water from the Cheswold into the Piney Point. Water-level declines in the Cheswold aquifer in Cambridge probably halted during the early 1960's when withdrawals from the Piney Point aquifer began to level off. The slight rise in water levels (approximately 1.5 ft between 1974 and 1977) in the Cheswold aquifer is probably due to the cutback in pumpage of the Piney Point.

DESCRIPTION OF THE PINEY POINT AQUIFER MODEL

Grid Design

The modeled area was divided into a rectangular grid having 25 rows and 59 columns for a total of 1,475 blocks (pl. 1). A variable grid was used with density of blocks being greater where greater accuracy was desired. A multiplication factor of 1.5 was used to vary the block size. The smallest block size is 1 mi^2 and the largest is 17.1 mi^2. By convention, the point at the center of each block is called the node. The row-column system I,J was used to label each node. For example, the index for the node (3,4) refers to the center of the block which corresponds to row 3, column 4 of the grid. Each input value (transmissivity, vertical conductivity, etc.) 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.

Model and Boundaries

One of the first steps toward the construction of the aquifer model was the selection of boundaries. The model boundaries do not coincide with the boundaries of the study area (fig. 1). The Piney Point aquifer extends from Virginia to New Jersey, and from the subsurface truncation line (approximately 1 to 2 miles north of the -100-ft. contour line) in Maryland to beneath the Atlantic Ocean. The northwestern boundary of the model approximates the subsurface truncation boundary of the Piney Point aquifer and is assumed to be a no-flow boundary. The northeastern, southeastern and southwestern boundaries of the model are also assumed to be no-flow boundaries and were placed far enough away from the study area to have minimal effect on water levels within the study area. The southwestern and southeastern boundaries are placed in areas of low transmissivity (pl. 5) so that the assumption of no flow is reasonable. The northeastern boundary is far removed from the principal areas of concern in this study and its effects are masked by the pumping center at Dover, Del.

Lower and upper boundaries are also needed for the model. The lower boundary separating the base of the Piney Point aquifer from the underlying confining material is modeled as a no-flow boundary. Some vertical leakage might exist between the Piney Point aquifer and the aquifer underlying the Piney Point. However, extremely tight clay layers (for example, Marlboro Clay, member of the Nanjemoy Formation, and others) are believed to limit to a small amount any leakage through the lower boundary. In fact, in the Cambridge area approximately 600 ft of clay and silty clay separate the Piney Point from the next lower aquifer. For modeling purposes, any leakage through the lower boundary is lumped with leakage through the upper boundary. The upper boundary is defined in the model as a vertical leakage boundary that transmits recharge into the Piney Point through overlying confining materials. The rate of vertical leakage depends on the gradient across the confining bed and the vertical conductivity of the confining bed.

Transmissivity And Storage Coefficient

Average transmissivity values for each block of the grid were estimated from plate 5 and entered into the model as a matrix. The value of $3.0x10^{-4}$ represents an average of the storage coefficient values available and was used for the entire aquifer.

Starting Head In The Piney Point Aquifer

Actual steady-state (prepumping) head values were not accurately known, so they could not be used as a starting surface for the Piney Point aquifer during model simulations. Therefore, the principle of superposition was utilized; pumpage was treated as a change imposed on an initial condition of no flow within the aquiifer; drawdown was considered to take place from an initially flat potentiometric surface.

Vertical Hydraulic Conductivity Of The Upper Confining Material

Values for this parameter were determined by the trial and error method during calibration of the model. For example, if the model simulation showed that less leakage was required to match the model's simulated water-level changes with the actual measured changes, then the vertical hydraulic conductivity value was lowered for that area. The range of values is from 1.0×10^{-8} ft/s to 1.0×10^{-12} ft/s. The values used are generally lower than those determined from core analysis (table 3), but agreement was usually within an order of magnitude in most instances.

Specific Storage Of The Confining Material

Leahy (1978, in preparation) used a value of 6.0×10^{-6} ft^{-1} for specific storage of the confining material in Delaware. This value was based on a 25-day hydraulic test of the overlying confining material near Dover (Leahy, 1976). In the absence of other data, 6.0×10^{-6} ft^{-1} was also used in this study.

Thickness Of The Upper Confining Material

Average thickness of the confining material for each block of the grid was estimated from figure 10. This parameter was one of the better known quantities and therefore was not varied in the calibration procedure.

Starting Head In The Contributing Aquifer

An initial starting surface equal to that of the starting surface for the Piney Point aquifer was entered for the head of the contributing aquifer. This satisfies the initial boundary conditions of no flow into or out of the aquifer that are required for use of the superposition technique. The model does not have the capability of varying the head in the contributing aquifer during simulation.

CALIBRATING THE MODEL

In order for a model to be used for predictive purposes, its ability to predict past events should be confirmed. The model usually must be adjusted (calibrated) before confirmation is achieved.

The process of calibrating the Piney Point aquifer model consisted of varying certain parameters (vertical hydraulic conductivity of the confining material, and to a limited degree, domestic pumpage) while at the same time holding other parameters constant (storage coefficient, transmissivity, thickness of the confining bed, specific storage, and documented pumpage of major users) and then comparing the model's predicted results with field measurements of water-level changes. Parameters are varied until a reasonable match is obtained.

Several different confirmation methods were evaluated in the attempt to calibrate the Piney Point aquifer model. They included: (1) Entering the prepumping Piney Point and prepumping contributing aquifer potentiometric maps as starting-head surfaces, (2) entering the 1952 Piney Point potentiometric surface and a 1952 potentiometric surface for the contributing aquifer as starting-head surfaces, and (3) entering the same starting-head surface for both the Piney Point and the contributing aquifer.

The many unknowns associated with the prepumping surface and the instability of initial conditions of the 1952 potentiometric surface prevented the model from obtaining a good calibration by methods 1 and 2. Therefore, method 3 was selected as the more accurate means of calibrating.

In order to simulate the calibration period, pumpage from the aquifer was divided into seven pumping periods. The year 1890 was chosen as the initial starting time because little pumpage had taken place in the Piney Point aquifer before then, and it was, therefore, reasonable to assume that the Piney Point was in a steady-state condition. The pumping periods and associated rates of pumping are listed below.

Pumping period	Duration	Total pumping rate for Maryland and Delaware (ft^3/s)
1	1890-30	1.30
2	1930-52	4.88
3	1952-60	6.08
4	1960-70	8.25
5	1970-74	9.91
6	1974-75	10.86
7	1975-76	10.94

The average withdrawal per pumping period has been further subdivided and assigned to the appropriate node in the model.

Table 4.—Comparison of observed and computed water-level changes at four observation wells.

County	U.S.G.S. Well No.	Well node location		Water-level decline (-) or rise (+), in feet							
				1952 - 76		June 1970 - June 1974		June 1974 - June 1975		June 1975 - June 1976	
		Row	Column	Measured	Computed	Measured	Computed	Measured	Computed	Measured	Computed
St. Marys	St.M-Ef 57 1/	9	6	- 9	- 9.4	-1.1	-0.6	-0.5	-0.3	-1.0	-0.8
	St.M-Fg 45 2/	18	4	-15	-13.3	-2.0	-2.5	-0.4	-1.2	-1.2	-1.2
Calvert	Cal-Gd 5 2/	8	11	-10.5	-10.5	-3.0	-2.1	-1.2 4/	-1.7	-1.5 4/	-2.1
Dorchester	Dor-Cd 1 3/	13	23	-11	-13.2	-	-	+3.8	+2.7	+4.2	+6.8

1/ Water levels affected daily from nearby pumping well.
2/ Water levels affected periodically from nearby pumping well.
3/ Water levels affected by pumping pattern in Cambridge.
4/ Estimation.

The calibration of the model was checked by comparing the computed water-level changes with measured water-level changes for the time interval 1952-76 (pl. 6). Intermediate periods (June 1970-June 1974, June 1974-June 1975, and June 1975-June 1976) were also computed and compared against measured water-level changes. Table 4 gives the results of the calibration run at the four observation wells. The locations of these wells are shown on plate 1. In general, agreement between the computed water-level changes and the measured water-level changes was good. Further refinement was believed to be unwarranted because of the uncertainties of the measured field data, particularly the 1952 potentiometric surface. No endeavor was made to verify the model before 1952 because the 1952 potentiometric surface was not in a steady-state condition. However, pumping periods prior to 1952 were incorporated into the model to arrive at the 1952 transient conditions.

Unfortunately, only a few observation wells with long-term water-level measurements existed in the Piney Point aquifer before the 1976-77 observation-well network was drilled. This lack of an adequately spaced observation-well network prevented intermediate calibration testing at most sites within the study area. Calibration of the model may be improved in the future by simulating and comparing the computed water-level values with measurements from the new observation-well network.

FUTURE WATER LEVELS

After the model was calibrated, it was used to predict future water-level changes. One of the main objectives of this study was to determine whether or not the Piney Point aquifer can continue to meet its share of the required ground-water needs of the study area. Several different schemes were simulated in order to test the effects new pumping rates would have on the future water levels of the Piney Point aquifer. The simulations consist of the following:

1. A steady-state simulation using the June 1975 to June 1976 average pumping rate.
2. A series of simulations using the best estimates of future pumpage for the following periods:
   a. June 1976 and January 1980,
   b. June 1976 and January 1985, and
   c. June 1976 and January 1990.
3. A series of predictive simulations showing the effect that additional pumpage from two proposed nuclear powerplants might have on the future water levels of the Piney Point aquifer.
4. A predictive simulation showing the amount of water-level change that could occur between June 1976 and January 1990, as a result of the withdrawal of the average yearly ground-water amount appropriated to the major appropriators and the best estimates of nonappropriated future pumpage.
5. A simulation showing what percentage of the predicted total drawdown can be directly related to domestic pumping.

All simulations essentially utilized the same withdrawal nodes as those used for the model calibration. The main withdrawal nodes are shown on plate 1. The predictive simulations were treated as continuation runs. By this process, past and future pumpages have an influence on future water levels.

The additional drawdown available in the Piney Point aquifer as of May 27-28, 1976, is shown in figure 12. If these drawdowns are exceeded, dewatering of the aquifer will take place. Dewatering may cause irreparable harm to the aquifer and its future productive capability may be threatened. If figure 12 is compared to each of the following simulation runs, excessive drawdown areas, if any, can be singled out.

Steady-State Simulation Using The June 1975-June 1976 Average Pumping Rate

Figure 13 shows a steady-state simulation using the average pumping rate (APR) of 10.94 ft^3/s between June 1975 and June 1976. This figure depicts the maximum water-level change (for all practical purposes) that can occur in the Piney Point aquifer after June 1976, if the 1975-76 APR is held constant indefinitely and if the system reaches equilibrium. The predicted steady-state potentiometric surface can be obtained by algebraically adding the water-level changes shown on figure 13 to the potentiometric surface at the start of the simulation (pl. 3). The area around Cambridge represents the most striking feature of the map as it reflects rising water levels due to the cutback in municipal and industrial pumpage that has been taking place in that area for the past several years. To place an approximate time on when these maximum water-level changes will occur, a series of transient predictions were run based on the 1975-76 APR, and the results were compared to the steady-state simulation. (A transient simulation is time dependent.) It was determined from the transient simulations that steady-state conditions would take place in the Piney Point aquifer about the year 2000, if the 1975-76 APR is held constant.

Projected Water-Level Changes Based On Best Estimates Of Future Withdrawals

A series of transient predictions was simulated using best estimates of future withdrawals. For Maryland, these pumpage estimates were based on information supplied by the Planning Departments of Calvert, Caroline, St. Mary's, Talbot, and Dorchester Counties. Simulated withdrawals represent the most likely future pumpages from the Piney Point aquifer in Maryland. Best estimates of future withdrawals in Delaware were obtained from P.P. Leahy of the U.S. Geological Survey, Dover, Del. Future increases for domestic and small industrial-commercial users were difficult to predict. However, estimates were made based on projected population growth (table 5) and the proportion of the increased population that would utilize the Piney Point aquifer. (Part of the future population will use other aquifers). Figure 14 shows the estimated future Piney Point pumpage in Maryland and Delaware.

Table 5.—Predicted population trends between 1970 and 1990 for those counties within the study area.

(Data based on the respective county's planning department projections.)

County	1970[1]	1975	1980	1990
St. Mary's[2]	39,103	42,139	45,784	52,815
Calvert[2]	6,400	7,800	9,300	12,800
Dorchester	29,405	29,900	31,150	32,000
Caroline	19,781	21,641	23,500	27,300
Talbot	23,682	24,866	26,050	27,353

[1] 1970 Census.
[2] Represents only that portion of the total County population that lives or will live within the boundaries of the Piney Point aquifer.

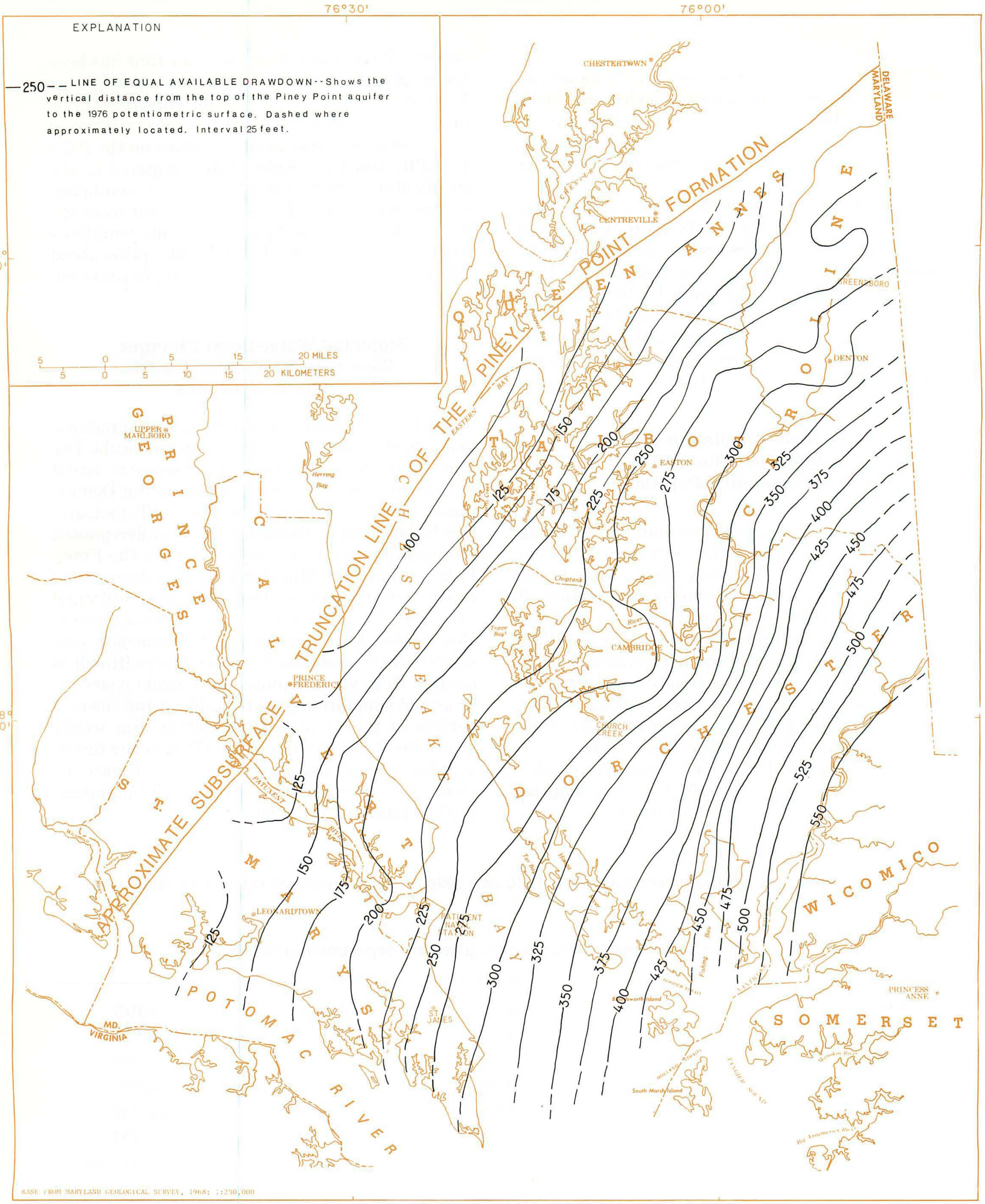


Figure 12.—Additional drawdown available in the Piney Point aquifer as of May 27-28, 1976.

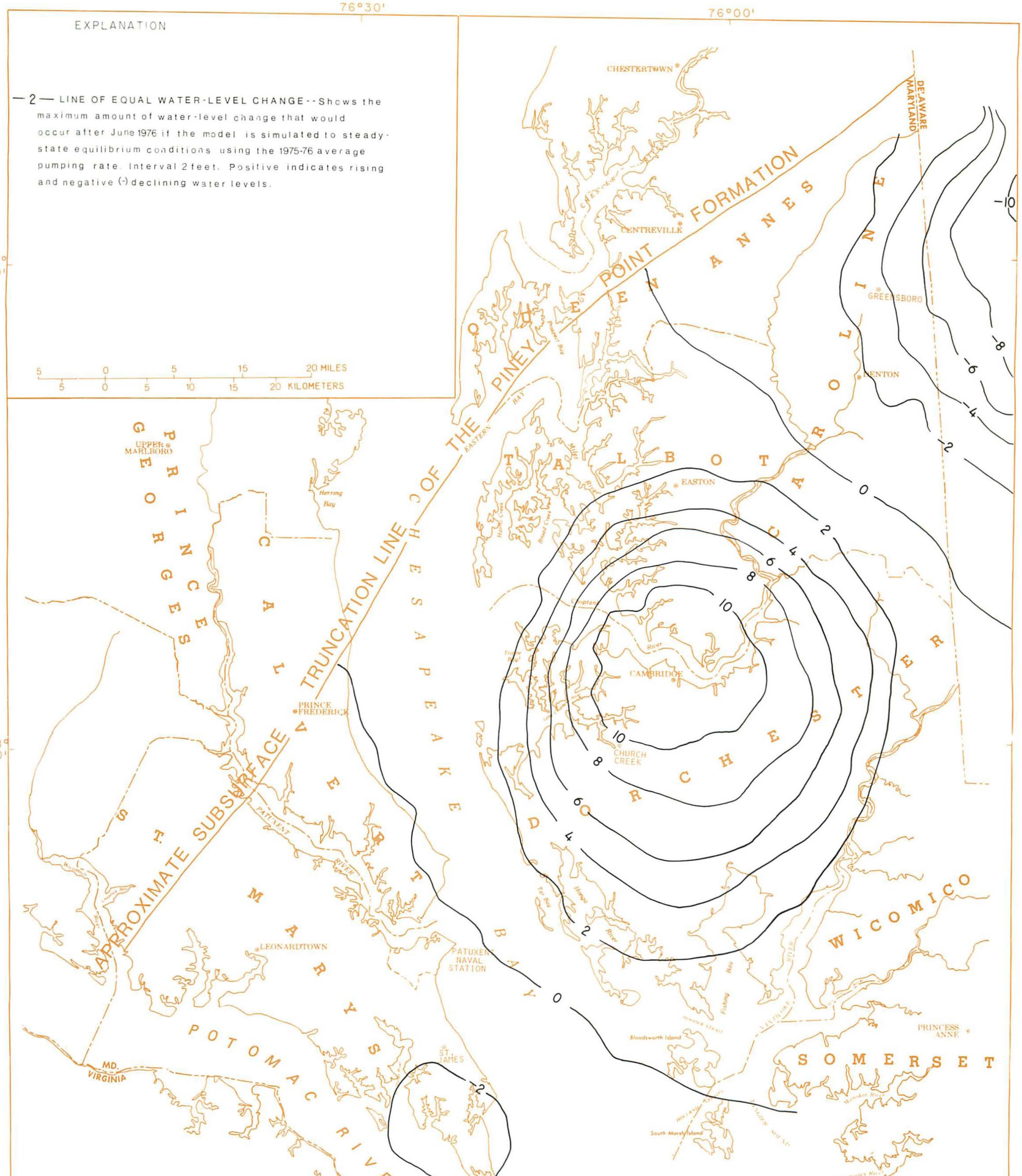


Figure 13.—Computed steady-state water-level changes in the Piney Point aquifer after June 1976 using the 1975-1976 average pumping rate.

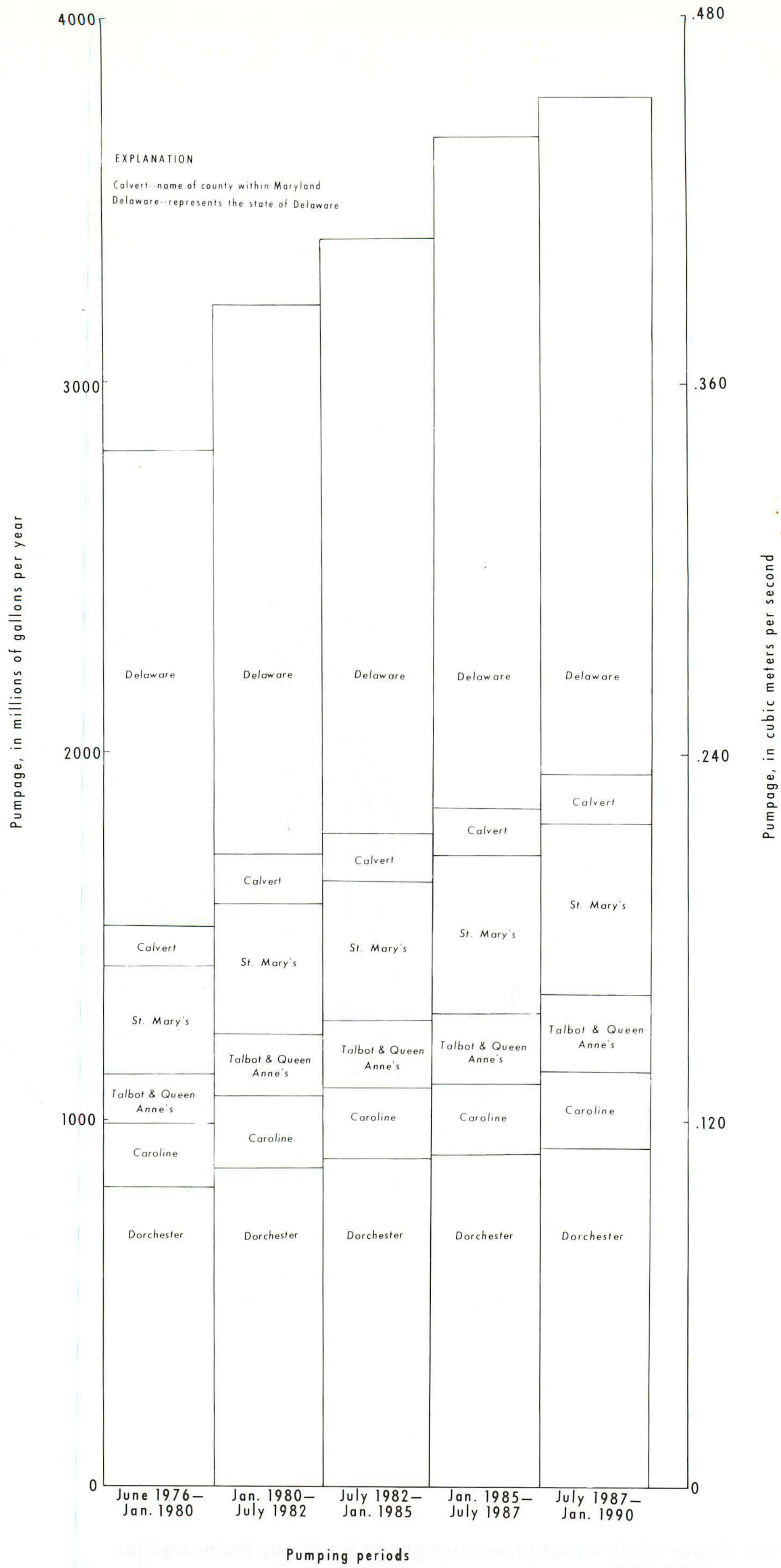


Figure 14.—Estimated future withdrawals from the Piney Point aquifer in Maryland and Delaware.

Figure 15 shows the additional drawdown predicted to occur between June 1976 and January 1980 as a result of estimated future pumping (fig. 14). Water levels around Cambridge will rise because future Piney Point pumpage in this area is estimated to be less than previous rates. Water levels in southern Maryland will decline at a rate of one-half foot per year. The projected withdrawal rates in Delaware will affect water levels in northern Caroline County. The effects of the Delaware pumping seem to extend to a point about halfway between Greensboro and Denton. (See plates for location of these cities.)

Figure 16 shows the predicted additional water-level change between June 1976 and January 1985 based on the best estimates of future pumping (fig. 14). The situation around Cambridge will be similar to the results of the 1980 simulation. Southern Maryland will experience additional drawdown because of increased withdrawals. The increase in Delaware pumping will have a moderate effect on Piney Point wells in northern Caroline County, where maximum drawdowns between 1976 and 1985 are predicted to be as much as 20 ft.

Figure 17 shows the results of a similar simulation for June 1976 through January 1990. By 1990, water levels will be as much as 15 ft higher in the Cambridge area than they were in 1976 if the estimated pattern of water use is followed. This simulation shows water levels to be a few feet lower in 1990 in the Cambridge area than they were in 1985. This is due to a projected withdrawal increase for Cambridge between 1985 and 1990. Water levels in southern Maryland will continue their slow decline and in some areas will be 14 ft. lower than they were in 1976. The average rate of decline in St. Mary's and Calvert Counties is predicted to be about 1 foot per year. Northern Caroline County will experience additional water-level declines of between 8 and 15 ft more than the 1985 levels, due mainly to increased pumping in Delaware. The available drawdown (fig. 12) in the northern portion of Caroline County is approximately 275 ft—far more than the 35 ft of drawdown predicted for the area between 1976 and 1990.

Projected Water-Level Changes Based On Hypothetical Withdrawal Situations

This next group of simulations reflects hypothetical examples of what might happen to the water levels in the Piney Point aquifer if certain new pumping rates and additional well fields are established. It should be kept in mind that these circumstances will most likely not happen as shown in this report.

NUCLEAR POWERPLANT CASES

The possible construction of two nuclear powerplants within the study area was recently investigated by the State of Maryland (Maryland Power Plant Siting Program 1974; 1977). The proposed locations of the powerplants are shown on plate 1. The following three cases show the change that is predicted to occur in the water levels of the Piney Point if the aquifer is required to supply the total ground-water demand of the powerplants (approximately 1 Mgal/d per plant). In each of the cases simulated, steady-state conditions will not have been reached at the end of the simulation period (1990).

Case I (Dorchester County Site): Figure 18 shows the water-level change predicted between June 1976 and January 1990 if a proposed nuclear powerplant withdraws 1 Mgal/d, beginning in 1985, from the Piney Point aquifer at Church Creek in Dorchester County. The withdrawal rate at the powerplant is in addition to other estimated future withdrawals occurring throughout the study area. By 1990, the additional withdrawal will have substantially affected water levels as can be seen by comparing figures 17 and 18. The additional withdrawal caused by the powerplant pumpage would not immediately place the aquifer in danger of being dewatered because the available drawdown in the vicinity of the site is 250 ft. However, the additional drawdowns in Dorchester County may cause problems for domestic well owners. Pumpage at the proposed Dorchester County powerplant site will only slightly affect water levels in southern Maryland and will have essentially no effect on water levels in Caroline County.

Case II (St. Mary's County Site): Figure 19 reflects a similar set of circumstances as in Case 1,

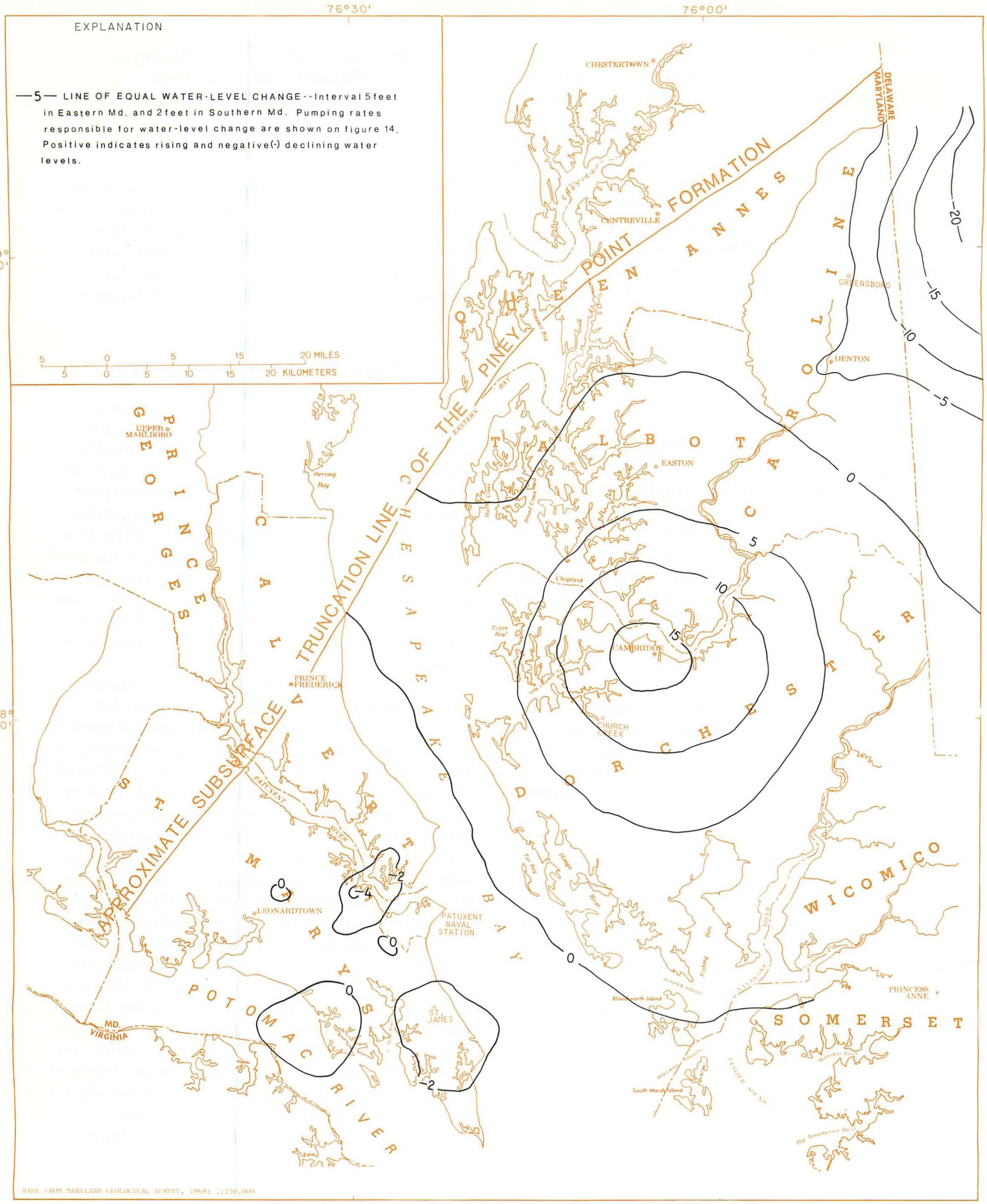


Figure 15.—Simulated water-level changes in the Piney Point aquifer between June 1976 and January 1980 using estimated future withdrawals.

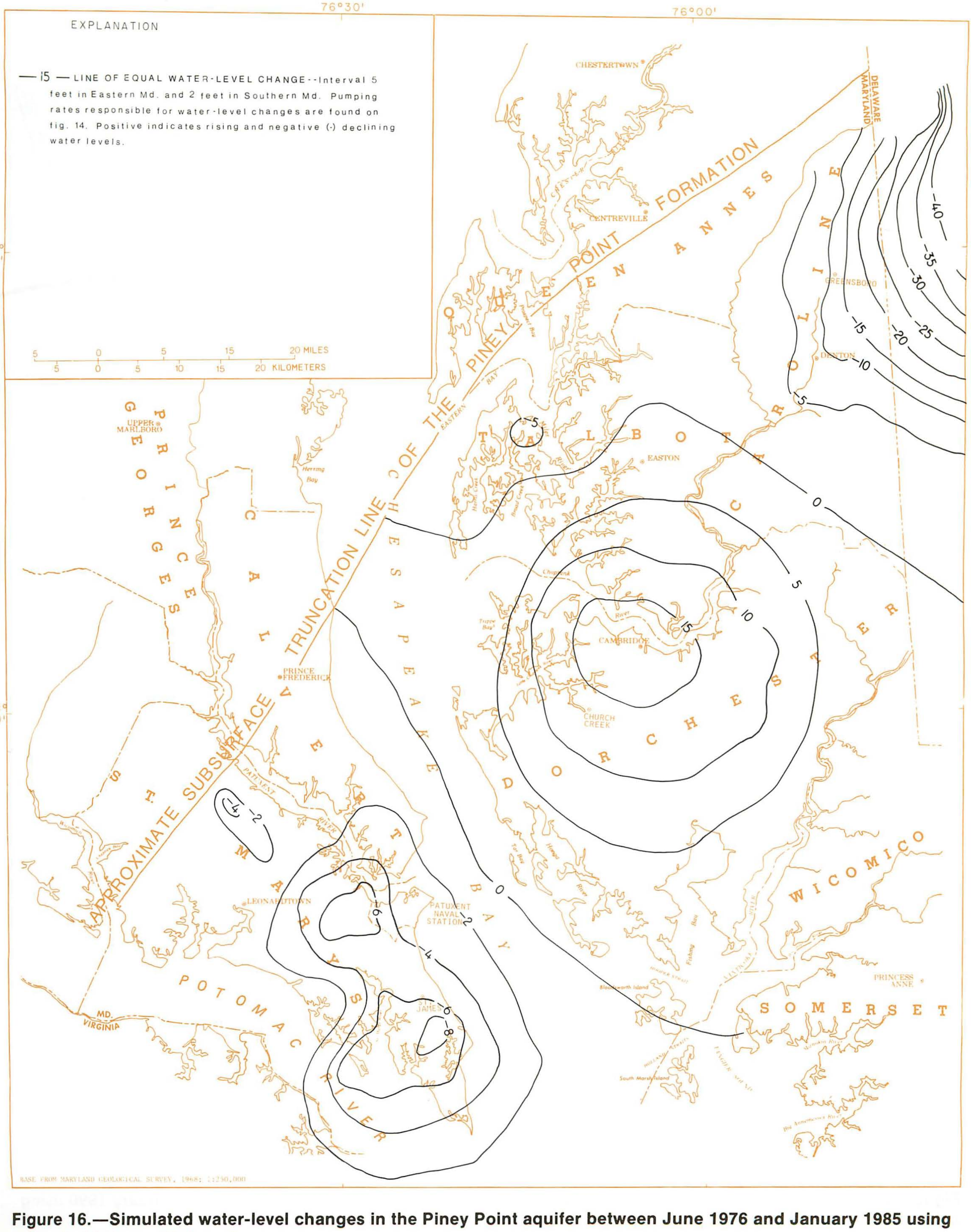


Figure 16.—Simulated water-level changes in the Piney Point aquifer between June 1976 and January 1985 using estimated future withdrawals.

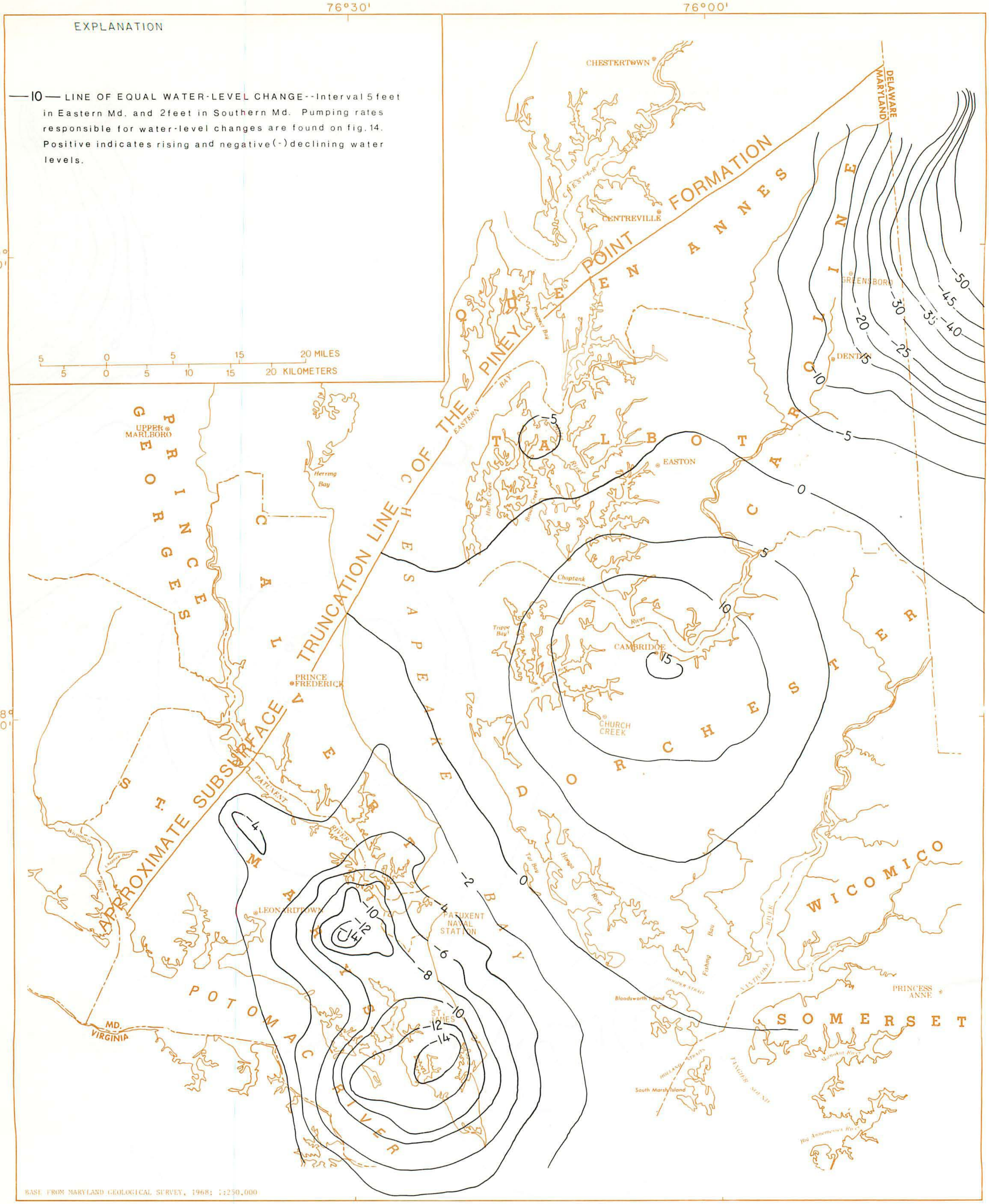


Figure 17.—Simulated water-level changes in the Piney Point aquifer between June 1976 and January 1990 using estimated future withdrawals.

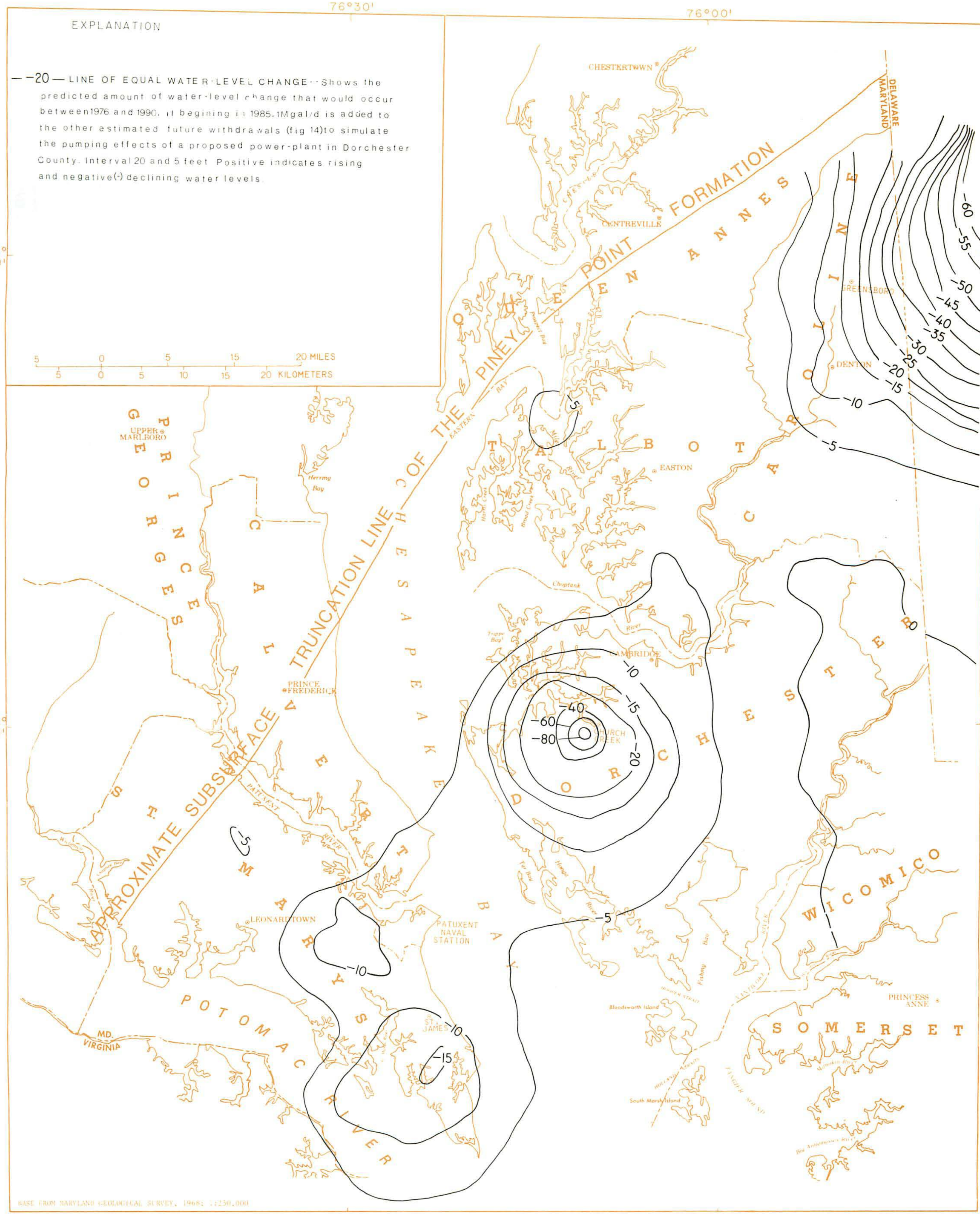


Figure 18.—Predicted water-level change in the Piney Point aquifer between June 1976 and January 1990, if pumpage were equal to estimated future pumpage plus proposed powerplant water requirements for Dorchester County.

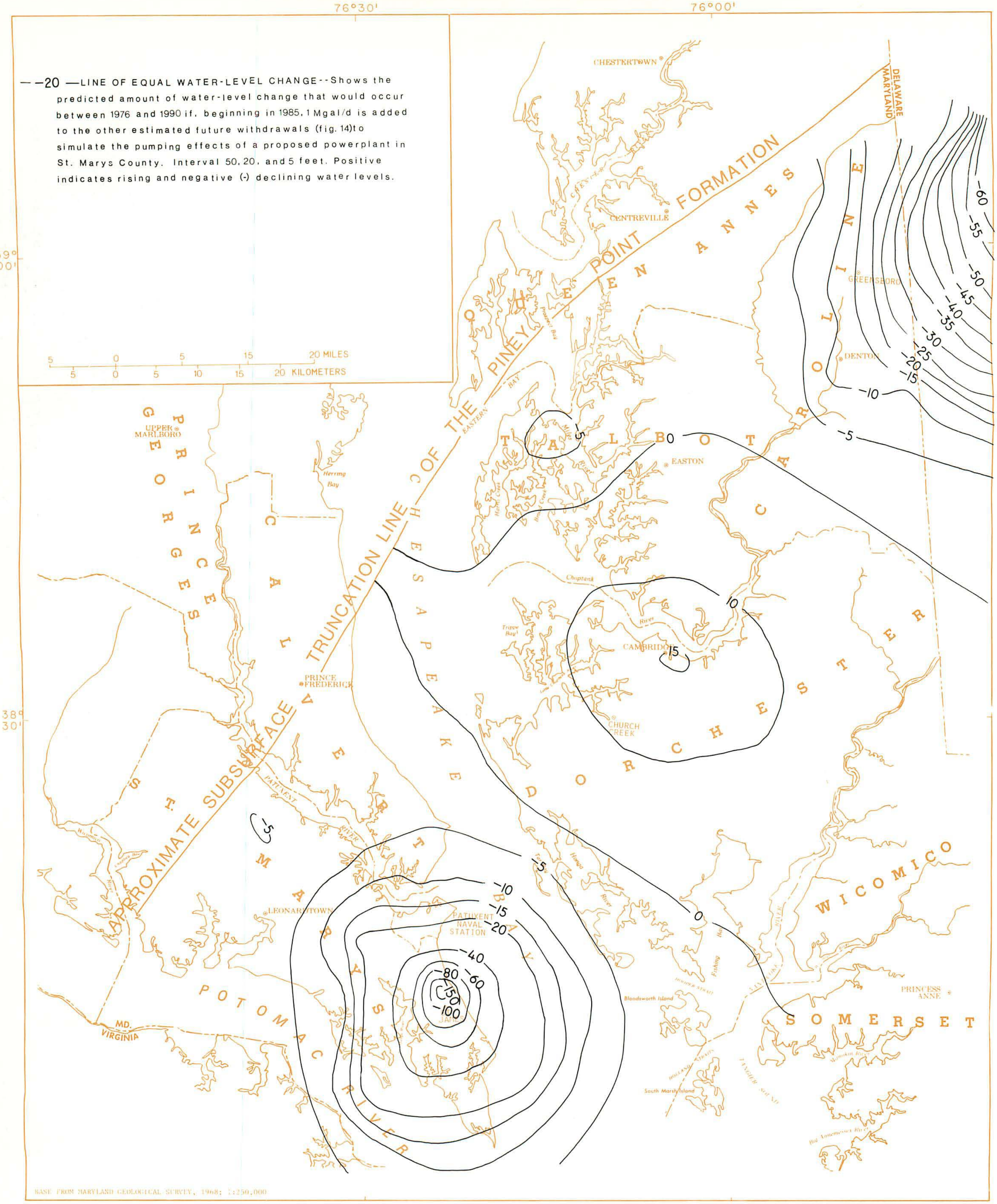


Figure 19.—Predicted water-level change in the Piney Point aquifer between June 1976 and January 1990, if pumpage were equal to the estimated future pumpage, plus proposed powerplant water requirements for St. Mary's County.

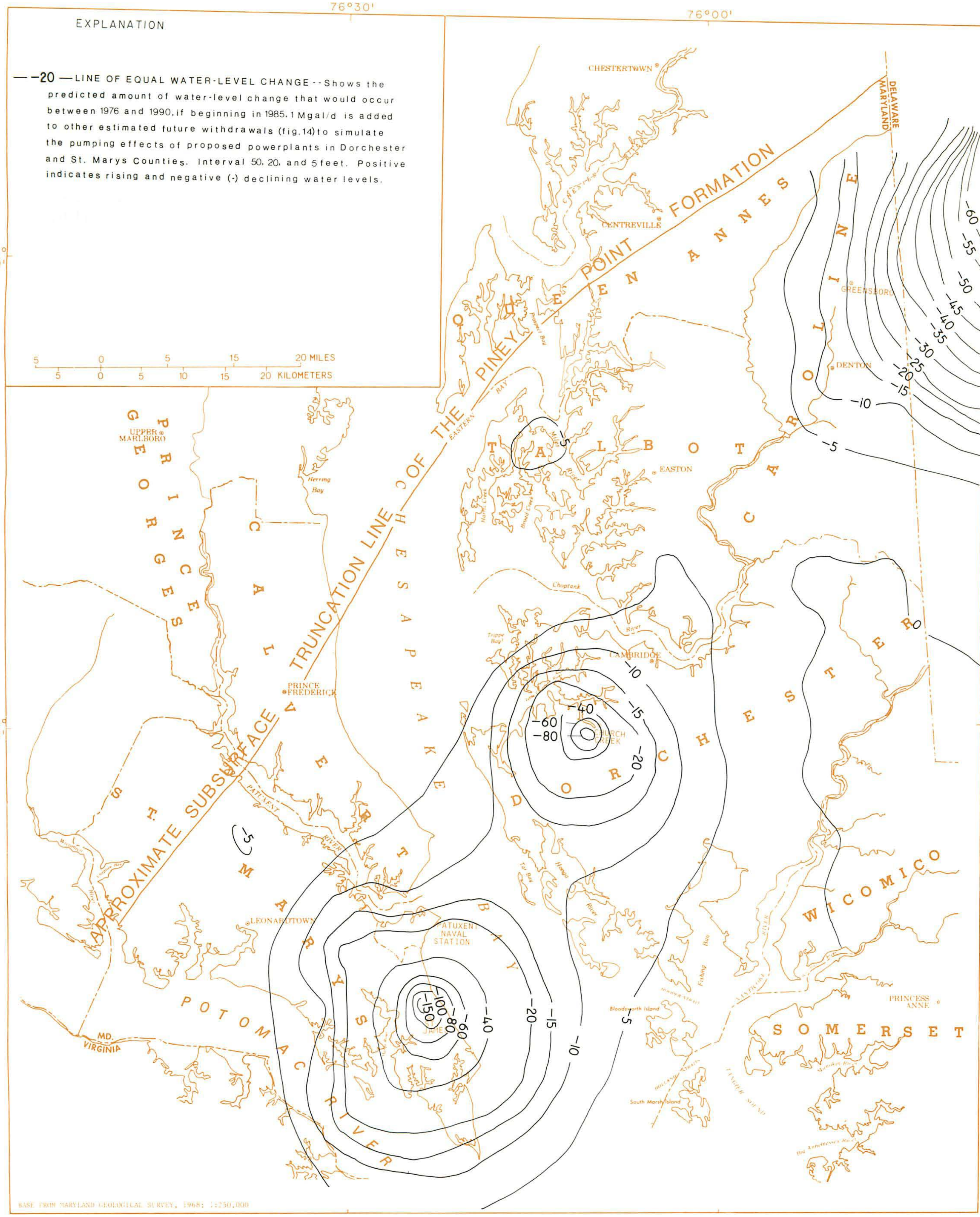


Figure 20.—Predicted water-level change in the Piney Point aquifer between June 1976 and January 1990, if pumpage were equal to estimated future pumpage, plus proposed powerplant water requirements for Dorchester and St. Mary's Counties.

except in this instance the powerplant is located near St. James (Elms site) in St. Mary's County. In this case by 1990 water levels at St. James will be as much as 180 ft. lower than their 1976 levels. Even though the available drawdown in the vicinity of the powerplant is 250 ft., the water-level decline caused by the powerplant pumpage would result in serious problems for individual domestic well owners living in the area.

Case III (Case I and II combined): Figure 20 shows the results of simultaneous pumping, beginning in 1985, at both powerplants. The drawdowns caused by the powerplants are not cumulative except in southern Dorchester County and beneath parts of Chesapeake Bay.

APPROPRIATION CASE

Maryland law requires that users of ground water obtain an appropriation permit from the Maryland Water Resources Administration. The only exceptions are single household units and farm use. As a hypothetical example to determine whether the Piney Point aquifer has been over-appropriated in certain areas, the amount appropriated by the largest users plus the best estimate of future nonappropriated pumpage was simulated. Table 6 lists the major appropriators of ground water that have a right to withdraw water from the Piney Point aquifer as of 1976. Some of the firms listed are no longer in business and do not presently (1977) pump any ground water. However, they still have an appropriation permit and presumably have the right to withdraw water if the business is reestablished.

Figure 21 shows the results of the appropriation simulation and depicts the water-level changes predicted to occur between June 1976 and January 1990. If over-appropriation is considered to be that rate of pumping which causes the water level to decline below the top of the aquifer, then the Piney Point appears not to be over-appropriated, as of 1976.

DOMESTIC VERSUS TOTAL PUMPAGE CASE

Some digital ground-water models only simulate the pumping of the large water users in the belief that pumping by small users does not cause significant water-level declines. In areas such as southern Maryland where numerous wells yielding small quantities make up a high percentage of the total water withdrawn, errors could occur in the model calibration by ignoring this pumpage. The following example illustrates the point that domestic pumpage can contribute significantly to water-level declines.

The estimated average future Piney Point pumpage between June 1976 and January 1980 (fig. 16) was simulated for a period of 10 years from an initially flat surface. Under the same circumstances, only the domestic portion of the estimated pumpage was simulated. Table 7 shows a comparison of the results of these two simulations for the southern Maryland portion of the study area. Domestic pumpage causes between 23 and 91 percent of the total drawdown.

Table 6.—Ground-water appropriation of the major Maryland users of water from the Piney Point aquifer.

[E is scientific notation (for example, 3.92E-2 = $3.92x10^{-2}$)]

County	Owner or Name	Appropriation No.	Average yearly ground-water appropriation ft^3/s (Mgal/yr)
Dorchester	City of Cambridge	DO71GAP005	8.5 (2,005.1)
	Bumble Bee Cannery	DO62GAP003	4.64E-1 (109.5)
	Hanover Brands, Inc.	DO62GAP002	4.64E-1 (109.5)
	Town of Secretary	DO76GAP012	1.16E-1 (27.4)
	Town of East New Market	DO74GAP003	4.64E-2 (11.0)
	Bonnie Brook Subdivision	DO63GAP005	6.78E-3 (1.6)
	Cambridge Country Club	DO54GAP002	4.64E-2 (11.0)
	Andrews and Son Cannery	DO53GAP002	4.96E-2 (11.7)
Talbot	Trappe Frozen Foods	TA46GAP001	7.43E-1 (175.2)
	Tilghman Packing Co.	TA46GAP003	4.66E-2 (11.0)
	Martingham Inn, Inc.	TA71GAP002	1.16E-1 (27.4)
	Bethany House, Inc.	TA71GAP006	7.63E-3 (1.8)
Caroline	Town of Denton	CO71GAP002	6.19E-1 (146.0)
	Saulsbury Brothers, Inc.	CO46GAP002	1.24 (292.0)
	Town of Greensboro	CO70GAP009	4.64E-1 (109.5)
	Electro-Therm, Inc.	CO70GAP002	1.86E-2 (4.4)
	Martinak State Park	CO70GAP011	3.81E-3 (0.9)
	Tuckahoe Shopping Center	CO69GAP004	7.63E-3 (1.8)
Queen Anne's	Friel Cannery	QA56GAP001	1.53E-1 (36.1)

Table 6., Con't.

E is scientific notation (for example, 3.92E-2 = $3.92x10^2$)

County	Owner or Name	Appropriation No.	Average yearly ground-water appropriation ft^3/s (Mgal/yr)
St. Mary's	Patuxent Naval Air Base	SM74GAP018	1.55 (365.0)
	James Hills	SM52GAP002	1.55E-1 (36.5)
	Fred Painter	SM56GAP007	2.97E-2 (7.0)
	Steuart Petroleum Co.	SM50GAP002	3.39E-2 (8.0)
	Town Creek Water Co.	SM52GAP004	1.55E-1 (36.5)
	Greenview Knolls Water Co.	SM67GAP001	3.86E-2 (9.1)
Calvert	Long Beach Water System	CA62GAP001	1.24E-1 (29.2)
	White Sands Corp.	CA56GAP002	1.70E-2 (4.0)
	Shepherd's Marina	CA71GAP004	7.63E-3 (1.8)
	Chesapeake Biological Laboratory	CA62GAP003	4.66E-3 (1.1)
	Chesapeake Ranch Water Company	CA60GAP002	1.93E-1 (45.6)
TOTAL			15.838 (3736.01)

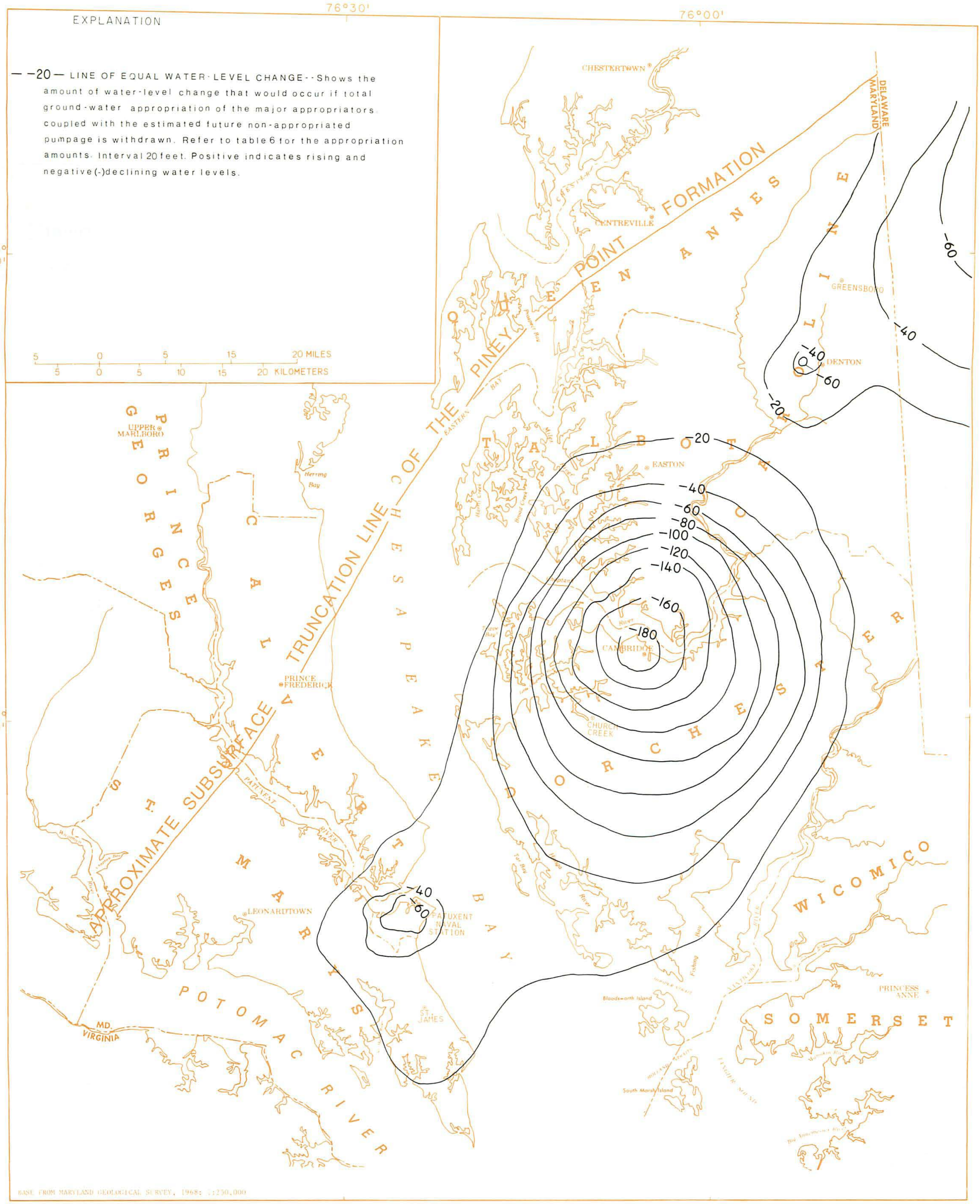


Figure 21.—Predicted water-level change in the Piney Point aquifer between June 1976 and January 1990, if pumpage were equal to the maximum allowable appropriation of the major appropriators plus estimated future withdrawals of nonappropriated users in Maryland and Delaware.

Table 7.—Hypothetical case showing the isolation of drawdown produced by domestic and small commercial—industrial users in southern Maryland.

County	Node	Drawdown (ft) over a 10-year pumping period		Percent
		Total (A)	That portion due to domestic and small commercial-industrial users (B)	$\left(\frac{B}{A}\right)$
St. Mary's	5-5	6.5	5.3	81
	5-10	6.0	4.3	72
	7-5	10.2	6.4	63
	7-9	29.5	6.7	23
	7-10	20.5	6.5	32
	9-5	11.8	7.6	64
	9-10	19.6	7.2	37
	11-5	11.9	8.6	72
	11-10	12.5	5.8	46
	13-5	14.2	11.8	83
	13-10	9.0	5.7	63
	15-5	14.2	12.3	87
	15-10	7.6	5.4	71
	17-5	16.1	14.7	91
	17-10	6.5	4.9	75
	19-5	9.6	8.7	91
	19-10	4.7	3.8	81
Calvert	4-15	2.5	1.6	64
	5-15	5.5	2.5	45
	5-17	5.9	1.7	29
	8-11	19.8	6.7	34
	8-13	11.9	6.5	55

SUMMARY AND CONCLUSIONS

1) A two-dimensional finite-difference digital computer model of the Piney Point aquifer in Maryland was developed to simulate future drawdown in the aquifer. This model is a first generation and must not be considered as "the final Piney Point model." The model is substantiated only in places. However, it is useful for many types of planning purposes. Additional revision and testing of the model should be accomplished as more data become available.

2) The Piney Point aquifer consists of fine to very coarse quartz sand with abundant glauconite and shell fragments. The aquifer has no known outcrop area. Effective thickness of the aquifer varies from a few feet to more than 120 feet. The Piney Point is overlain and recharged through leaky confining material composed of clays, clayey silts, silts, and very fine sands ranging in thickness from less than 50 ft to aproximately 200 ft. Transmissivity of the aquifer is highly variable and ranges from less than 100 ft^2/d to approximately 6,000 ft^2/d.

3) Calibration of the model was achieved by comparing computed and measured water-level

changes between 1952 and 1976 within the entire study area and comparing computed and measured water-level changes at four observation wells for three time periods between 1970 and 1976. The model's first pumping period began in the year 1890 when virtually steady-state conditions existed. Pumpage used in the simulation increased from 1.30 ft^3/s for the 1890-1930 time period to 10.94 ft^3/s for the 1975-76 time period.

4) Predictive simulations indicate that:

(a) If the Piney Point aquifer were stressed by the best estimates of future withdrawals, excessive drawdowns would not occur in Maryland during any of the periods simulated (1976-80, 1976-85, and 1976-90). For the 1976-90 simulation, the model predicted an average drawdown rate of 1 ft per year for the Piney Point aquifer in southern Maryland, a 15-ft rise in water levels in Cambridge due to reduction of withdrawal, and a decline of 15-35 ft in northern Caroline County.

(b) Additional withdrawals from the Piney Point aquifer that may be required to furnish water for proposed nuclear powerplants in Dorchester and St. Mary's Counties will greatly affect water levels in the aquifer. This added withdrawal would produce water-level declines of more than 90 ft. near the proposed powerplant site in Dorchester County and 180 ft near the site in St. Mary's County.

(c) The Piney Point aquifer appears not to be over-appropriated at the present time (1976), that is, if all appropriators pumped their full appropriations.

5) Lack of historical water-level and pumpage data weakened the calibration process. To obtain a good confirmation of the model throughout the study area, it would be necessary to have historical water-level data from a network of strategically placed observation wells. Because pumpage data were rarely recorded before 1972, many of the older pumpage rates used in the model were best guess estimates.

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Figure 5.--Effective thickness of the Piney Point aquifer.

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Plate 1.-- Study area showing grid and selected wells.

SIMULATED CHANGES IN WATER LEVEL IN THE PINEY POINT AQUIFER IN MARYLAND
BY
JAMES F. WILLIAMS III, 1979

Plate 2.--Potentiometric surface of the Piney Point aquifer, approximately 1952.

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MARYLAND GEOLOGICAL SURVEY

REPORT OF INVESTIGATIONS NO. 31
PLATE 3 OF 6

Plate 3.--Potentiometric surface of the Piney Point aquifer, May 27-28, 1976.

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Plate 4.--Approximate water-level change in the Piney Point aquifer between 1952 and 1976.

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Plate 5.-- Approximate transmissivity of the Piney Point aquifer.

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Plate 6.--Observed versus simulated water-level changes in the Piney Point aquifer (1952-76).

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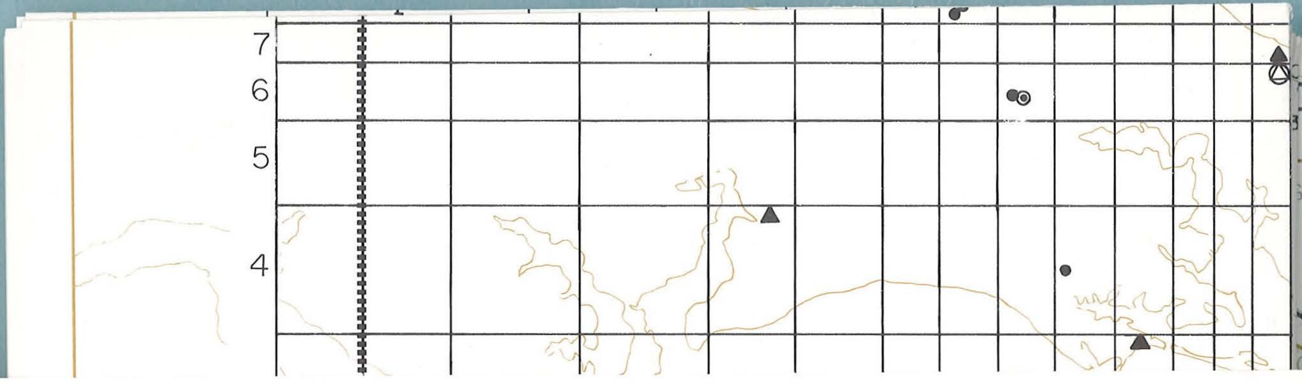
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Simulated Changes In Water Level In
The Piney Point Aquifer In Maryland

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