

UNIVERSITY OF DELAWARE  
DELAWARE GEOLOGICAL SURVEY  
REPORT OF INVESTIGATIONS No. 29

DIGITAL MODEL OF THE PINEY POINT AQUIFER  
IN KENT COUNTY, DELAWARE

BY  
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June, 1979

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Prepared under the Cooperative Program  
of the Delaware Geological Survey and  
the United States Geological Survey

June, 1979

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DIGITAL MODEL OF THE PINEY POINT AQUIFER  
IN KENT COUNTY, DELAWARE

ABSTRACT

A two-dimensional digital model was developed to simulate the effects of increased pumping on the Piney Point aquifer in Kent County, Delaware. The model represents 3,150 mi<sup>2</sup> (8,160 km<sup>2</sup>) of the Delmarva Peninsula, but is designed to make the most accurate predictions in an area of interest, 380 mi<sup>2</sup> (980 km<sup>2</sup>) of Kent County. The calibrated digital model was used to predict water-level declines as the aquifer responded to both changes in the distribution and increases in the quantity of pumping to the year 2000.

The model was calibrated using pumpage from 1970 to 1975. The calibration involved comparison of (1) nodal values of simulated and interpretive drawdowns, and (2) simulated and observed hydrographs. In the area of interest, the mean error and standard deviation between the simulated and interpretive drawdowns were 0.7 ft (0.2 m) and  $\pm 2.2$  ft ( $\pm 0.7$  m) respectively. Observed and simulated hydrographs agree.

The transmissivity of the aquifer was found to range from 7,350 ft<sup>2</sup>/d (683 m<sup>2</sup>/d) near Lebanon, Delaware to effectively zero at the boundaries of the aquifer. The vertical hydraulic conductivity of the confining bed ranges from  $3.0 \times 10^{-5}$  to  $5.0 \times 10^{-5}$  ft/d ( $9.1 \times 10^{-6}$  to  $1.5 \times 10^{-5}$  m/d).

Predictions show that: (1) under the 1975 stress of 2.68 Mgal/d (10,140 m<sup>3</sup>/d), water levels will stabilize at about 12 ft (4 m) below the 1975 water level at the center of the drawdown cone near Dover; (2) combined city and county withdrawal plans will cause static water levels to decline to within 20 to 30 ft (6 to 9 m) of the top of the aquifer by the year 2000; and, (3) by spreading development of the aquifer southwest of Dover, a withdrawal of 5.5 Mgal/d (20,820 m<sup>3</sup>/d) will result in stabilized water levels of 50 to 60 ft (15 to 18 m) below the 1975 level at the center of the Dover cone.



## INTRODUCTION

### Purpose and Scope

The Piney Point aquifer is one of the principal aquifers underlying the Delmarva Peninsula and is a major source of water for the cities of Dover, Delaware, and Cambridge, Maryland, as well as several additional communities and small industries. Withdrawal of water from the Piney Point aquifer has increased steadily since the first wells tapping the aquifer were drilled at Cambridge in 1888 (Mack and others, 1971) and at the mouth of the Mahon River near Dover in 1897 (Sundstrom and Pickett, 1968). The use of the Piney Point aquifer has created two regional cones of depression centered about the cities of Dover and Cambridge.

In 1974, pumpage from the Piney Point aquifer in the Dover area (see Figure 1) averaged 2.3 Mgal/d (8,710 m<sup>3</sup>/d) and 3.3 Mgal/d (12,490 m<sup>3</sup>/d) in the Cambridge area. In Kent County, Delaware, water levels in the Piney Point were declining 1 to 10 ft (0.3 - 3.0 m) per year as of 1975. Because of this decline and the potential for further development of the Piney Point aquifer, a digital model of the aquifer was developed. This model would provide planners with a way to predict and evaluate future water levels resulting from various proposed withdrawal schemes. The purpose of this report is to present: (1) the geologic and hydrologic data and concepts used in developing the digital model, (2) the methodology involved in calibrating the model, and, (3) predictions made by the calibrated model for several hypothetical withdrawal schemes.

### Acknowledgments

This study is part of a ground-water investigation of the principal aquifers of Kent County, Delaware made by the U. S. Geological Survey in cooperation with the Delaware Geological Survey, and with contributions from the officials of Kent County, the City of Dover, and the Department of Natural Resources and Environmental Control. Special thanks are given to Robert R. Jordan, State Geologist of Delaware, and to the staff of the Delaware Geological Survey who aided the study.

Jack R. Woods, Superintendent of Public Works for the City of Dover, furnished information on ground-water pumpage and water levels in the Dover area.

Digital simulations were made on a computer located at the University of Delaware. Costs of the computer runs were paid by the Delaware Department of Natural Resources and Environmental Control through the Cooperative Program.

Walter L. Fritz, Kent County Engineer, furnished hypothetical development plans for the Piney Point aquifer in Kent County.

### Location and Extent of Model Area

The location of the area of interest of the Kent County model is shown in Figure 1. The total area modeled is much larger than the immediate area of interest. Within the area of interest of about 380 mi<sup>2</sup> (Figure 1) the model is considered calibrated and results may be used for predictive purposes.

The model, representing an area of about 3,150 mi<sup>2</sup> (8160 km<sup>2</sup>), was designed because the location of geohydrologic boundaries and the large withdrawals of ground water in the Cambridge, Maryland area may effect results of the model in the Kent County study area. The total area modeled extends from southern New Jersey southwest to the eastern shore of Chesapeake Bay as shown in Figure 2. Predictions outside the Kent County area of interest, however, are not presented as they are likely to be in considerable error.

### GEOLOGIC SETTING

The Delmarva Peninsula is a part of the Atlantic Coastal Plain that extends from Long Island, New York, southward to the Gulf of Mexico. The peninsula is underlain by unconsolidated marine and nonmarine deposits consisting of clay, silt, sand, and gravel. The sediments range in age from Early Cretaceous to Holocene and lie unconformably on a crystalline-rock basement. Cushing and others (1973) reported that the unconsolidated sediments range in thickness from a featheredge at the Fall Line to more than 8,000 ft (2400 m) along the Atlantic Coast in Maryland. The Coastal Plain sediments have been divided into stratigraphic units as shown in Table 1.

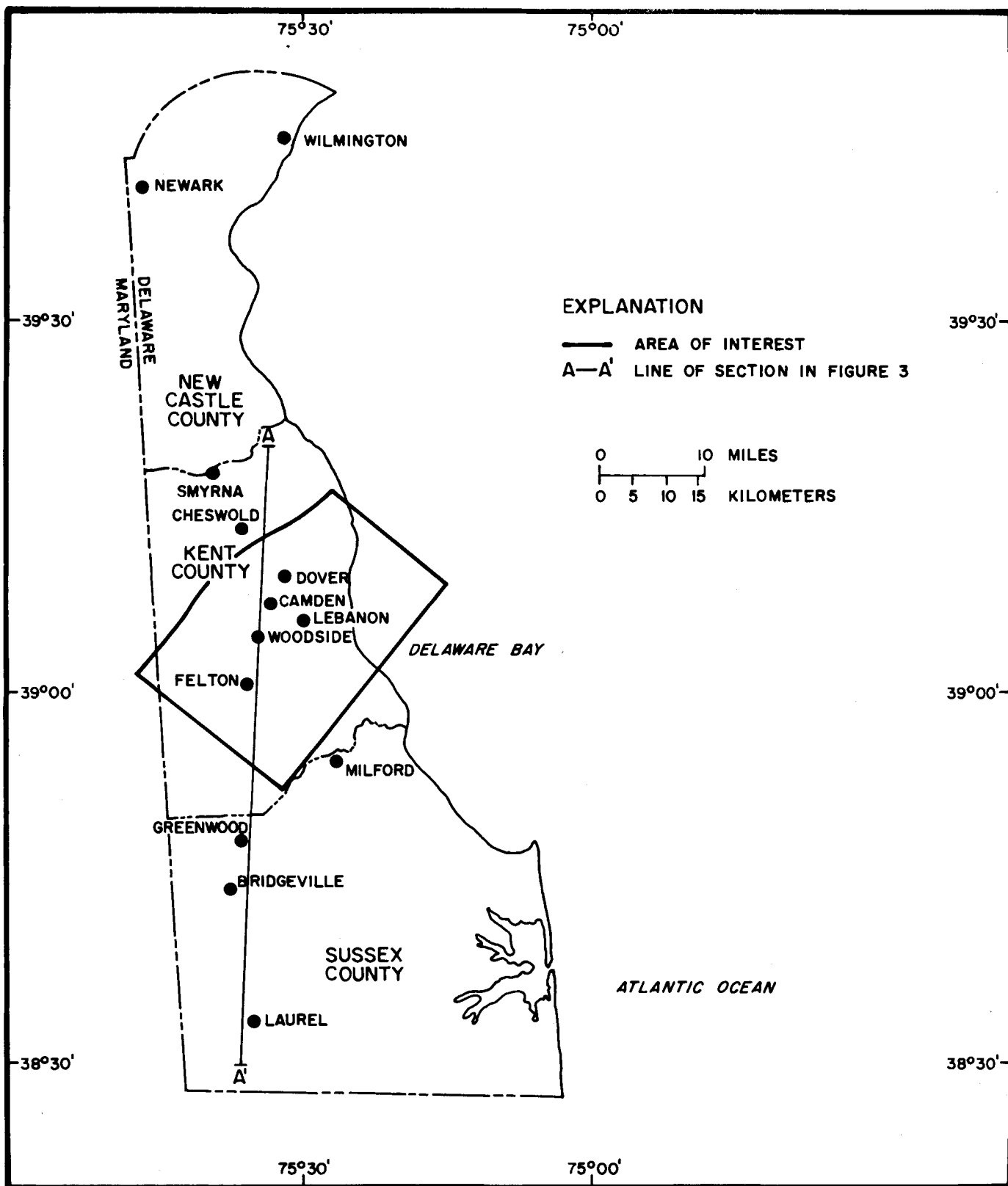



FIGURE 1  
LOCATION OF AREA OF INTEREST.

SYSTEM	SERIES	STRATIGRAPHIC UNITS		MAJOR AQUIFERS
		MARYLAND	DELAWARE	
QUATERNARY	HOLOCENE	-----	-----	Unconfined aquifer
	PLEISTOCENE	COLUMBIA GROUP undivided	COLUMBIA FM and COLUMBIA GROUP undivided	
	PLIOCENE(?)	BRANDYWINE FM	-----	
TERTIARY	MIOCENE	CHESAPEAKE GROUP	YORKTOWN FM ST. MARYS FM CHOPTANK FM CALVERT FM	CHESAPEAKE GROUP undivided
				
	OLIGOCENE			
	EOCENE	PINEY POINT FM NANJEMOY FM	PINEY POINT FM NANJEMOY FM	Piney Point aquifer
	PALEOCENE	AQUIA FM BRIGHTSEAT FM	RANCOCCAS GROUP VINCENTOWN FM HORNERSTOWN FM	Ranccocas aquifer
CRETACEOUS	UPPER CRETACEOUS	MONMOUTH FM	MOUNT LAUREL FM	Magothy aquifer
		MATAWAN FM	MARSHALLTOWN FM ENGLISH TOWN FM MERCHANTVILLE FM	
	MAGOTHY FM RARITAN FM	MAGOTHY FM		
	LOWER CRETACEOUS	POTOMAC GROUP PATAPSCO FM ARUNDEL FM PATUXENT FM	POTOMAC FM	Nonmarine Cretaceous aquifers


EXPLANATION: -----, no name assigned; , section not present.  
(From Cushing, Kantrowitz, and Taylor, 1973).

TABLE 1. Stratigraphic Units and Major Aquifers underlying the Coastal Plain of Delaware and Maryland.

## HYDROGEOLOGY OF THE PINEY POINT AQUIFER

### Lithology

The Piney Point Formation consists of marine sediments of Eocene age. Otten (1955) named the formation on the basis of data from a well at Piney Point in Southern Maryland. Rasmussen and Slaughter (1957) extended the use of the term Piney Point Formation to the upper Eocene sediments of the Eastern Shore, Maryland. Brown, Miller, and Swain (1972) examined the Piney Point type section and found it to be of Claiborne (middle Eocene) age. In Delaware, Rasmussen, Groot, and Depman (1958) on the basis of paleontology, lithology, and well logs were able to recognize the Piney Point Formation in a test well at the Dover Air Force Base. The formation at this location was considered to be Jacksonian (late Eocene) in age. However, Jordan (1962) points out that additional paleontological work suggested that much of the unit is middle Eocene in age. Talley (1975) also assigned an Eocene age to the Piney Point Formation in the Greenwood test well (Nc13-3).

The Piney Point Formation was described as a green, fine to medium glauconitic sand by Jordan (1962). The occurrence of glauconite is important, because it is useful in determining the contact between the Piney Point Formation and overlying nonglauconitic sediments of the Chesapeake Group. The southeast dipping Piney Point Formation is largely restricted to an elongate, lenticular body of sediments trending roughly northeast-southwest. The maximum known thickness of the formation is 251 ft (76.5 m) at Greenwood, Delaware. The thickness decreases to zero, updip, a few miles north of Dover, and to the northeast and southwest along strike in southern New Jersey and southern Maryland. In central and southern Kent County, Talley (1975) determined the strike of the Piney Point Formation to be between N.30°E. and N.47°E. and the dips as 15 to 31 ft/mi (2.8 to 5.9 m/km) to the southeast.

In this report, the term aquifer is used as defined by Lohman and others (1972) as a formation, group of formations, or part of a formation that contains sufficient saturated, permeable material to yield significant quantities of water to wells. The Piney Point aquifer occurs as the upper part of the Piney Point Formation in much of southern New Jersey. On the Delmarva Peninsula however, the Piney Point aquifer consists of almost the entire thickness of the Piney Point Formation except near the updip and downdip limits of the aquifer. The upper part of the aquifer appears to be the

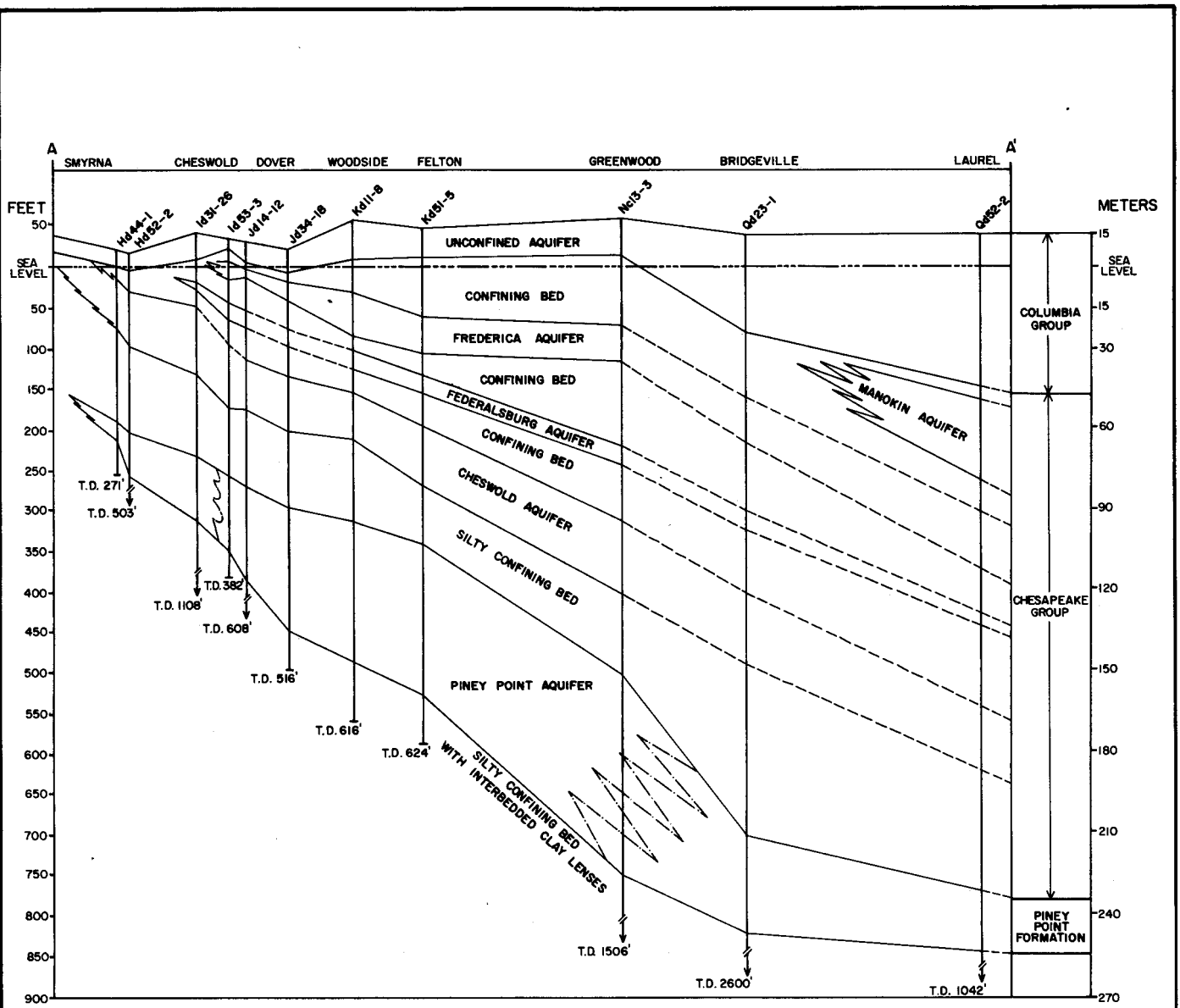
most productive as evidenced by geophysical logs, which show the aquifer becoming progressively more silty with depth (Cushing and others, 1973). Updip the aquifer becomes thinner and more silty; it pinches out north of Dover. Downdip the Piney Point aquifer thins and becomes progressively more silty and clayey. Because of this gradual facies change, the Piney Point Formation can not be considered a productive aquifer much farther south than Greenwood or Milford, Delaware.

Figure 3 shows a generalized geologic cross section to the base of Piney Point Formation. Aquifers overlying the Piney Point aquifer are also shown.

### Source and Movement of Ground Water

The Piney Point aquifer neither crops out nor subcrops an overlying aquifer and therefore, is recharged by vertical leakage through adjacent confining units. Based on the mechanical analyses of cores taken at the Dover Air Force Base observation well, Je32-4 (Figure 4), Jordan (1962) described the confining unit underlying the Piney Point aquifer in the Dover area as consisting mostly of silt with some clay layers. The writer (Leahy, 1976) found the overlying confining unit to be chiefly silt. Because of the apparent low vertical conductivity of the confining bed underlying the Piney Point aquifer, it is assumed that a very large percentage of the recharge to the aquifer occurs as vertical leakage through the more permeable overlying confining units and aquifers rather than through the less permeable underlying confining unit. Under natural or prepumping conditions, water in the Piney Point aquifer was recharged from overlying aquifers in updip areas, moved laterally through the aquifer, and discharged to overlying aquifers in downdip areas.

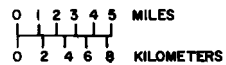
The original hydrologic equilibrium within the Piney Point aquifer has been disturbed by the withdrawal of large amounts of water, causing two regional coalescing cones of depression centered around Cambridge, Maryland, and Dover, Delaware. Pumping now accounts for a large part of the Piney Point aquifer discharge. Water levels in the Piney Point aquifer in the Dover area have not stabilized in response to this pumping stress. However, additional recharge has been induced from both the overlying confining bed and Cheswold aquifer by the increased head difference between the Piney Point and Cheswold aquifers. Eventually, if pumpage remains constant, water levels in both aquifers will



**EXPLANATION**

- APPROXIMATE UPDIP LIMIT OF THE PINEY POINT AQUIFER
- APPROXIMATE DOWNDIP LIMIT OF THE PINEY POINT AQUIFER

**HORIZONTAL SCALE**



VERTICAL EXAGGERATION x 264  
 LOCATION OF SECTION IN FIGURE 1

FIGURE 3

**GENERALIZED GEOLOGIC CROSS-SECTION FROM SMYRNA, DEL. TO LAUREL, DEL. SHOWING RELATION OF PINEY POINT TO OVERLYING AQUIFERS.**

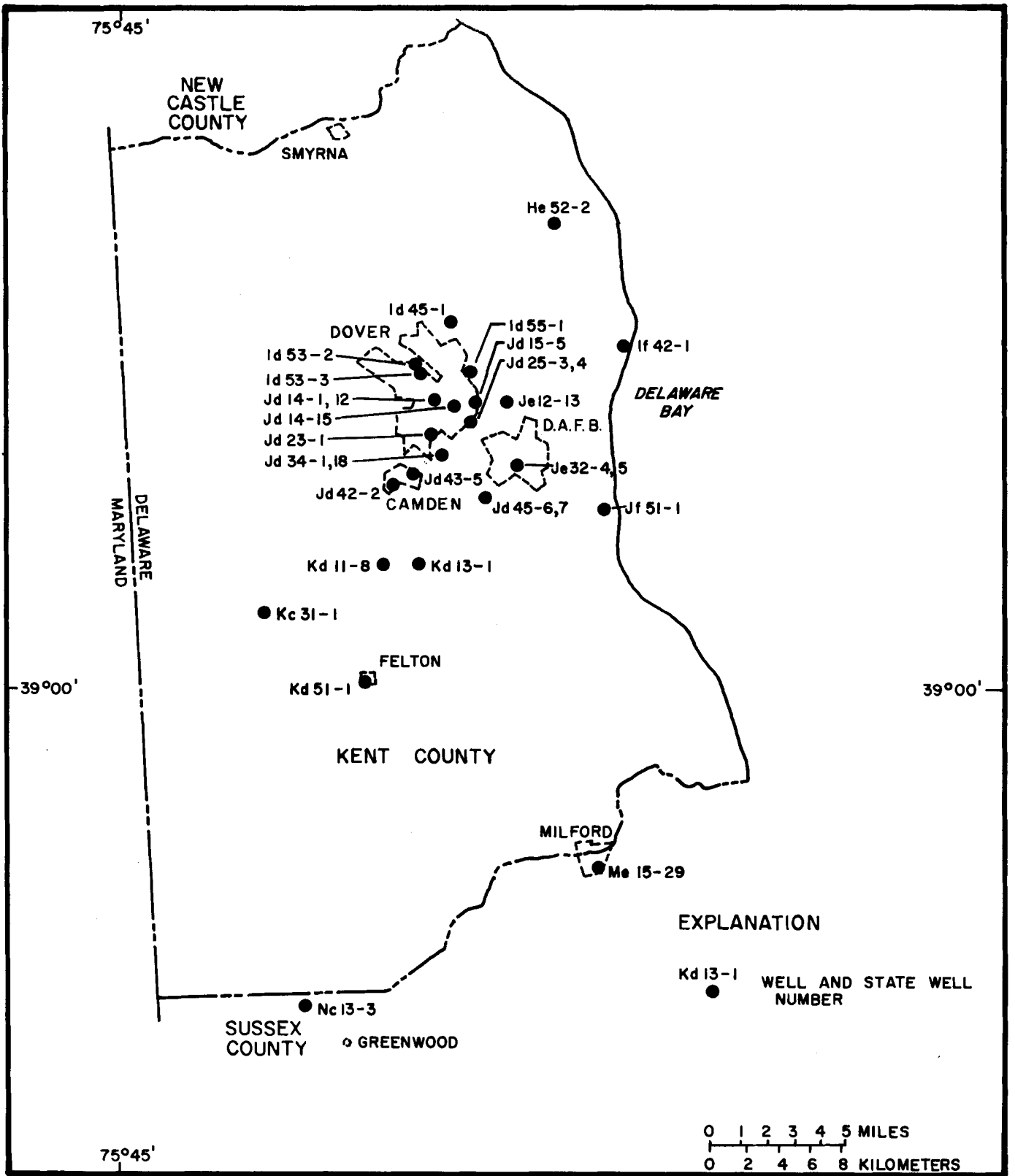


FIGURE 4  
 LOCATION OF WELLS REFERRED TO IN THE TEXT.



stabilize, reaching a new equilibrium or steady state. However, if future ground-water withdrawals increase or decrease in any aquifer in the system, additional time will be required to reach a new steady-state condition.

### Pumpage

The largest users of water from the Piney Point aquifer are the cities of Dover, Delaware, and Cambridge, Maryland. Prior to 1957, there was little development of the Piney Point aquifer in Delaware. However, with the drilling of a production well (Kd11-8) at a vegetable cannery in Woodside in 1959, withdrawals increased significantly. Pumpage from the aquifer in Delaware further increased with the drilling of the following large capacity production wells: (Kd51-1) at a poultry processing plant in Felton (1960), (Je32-5) at Dover Air Force Base near Dover (1963), and finally (Id52-3, Id53-3, Jd14-15, Jd23-1, Jd25-3, Jd34-1, and Jel2-13) at the City of Dover (1962 to 1972). The location of these wells and others referred to in the text are shown in Figure 4.

Total average withdrawals from the Piney Point aquifer for the entire Delmarva Peninsula in 1970 were 7.3 Mgal/d (27,630 m<sup>3</sup>/d). Withdrawals in the Kent County area were 2.1 Mgal/d (8,020 m<sup>3</sup>/d) in 1970. Total pumpage from the aquifer in 1974 was 6.6 Mgal/d (24,980 m<sup>3</sup>/d) of which an average of 2.5 Mgal/d (9,390 m<sup>3</sup>/d) was withdrawn from wells in Kent County, Delaware (including the Dover area). Total pumpage from the Piney Point aquifer was decreased approximately 10.6 per cent in the 5-year period from January 1970 to December 1974. Decreases in Piney Point withdrawals of 30 per cent by the City of Cambridge, Maryland caused the overall decline in total pumpage on the Delmarva Peninsula, although the Kent County area pumpage increased by 17 per cent. Table 2 gives the average daily pumpage from the Piney Point aquifer.

Average yearly pumpage in Delaware from the Piney Point aquifer is shown in Figure 5. Early data (1957-1967) for this plot are based on estimated pumpages reported by Sundstrom and Pickett (1968). Late data (1968-1977) came from a canvass of major users of the Piney Point aquifer.

TABLE 2. Average Daily Pumpage for Piney Point Aquifer by Individual Wells in Delaware and by Community in Maryland for 1970 and 1974.

WELL NUMBER	NAME AND LOCATION OF WELL	AVERAGE DAILY PUMPAGE (Mgal/d)	
		1970	1974
Id53-3	McKee Run Generating Plant, Dover	0.374	0.367
Jd14-15	Treatment Plant, Dover	0.071	0.225
Jd23-1	Crossgates, Dover	0.126	0.269
Jd25-3	Danner Farm, Dover	0.265	0.363
Jd34-1	Rodney Village, Dover	0.094	0.245
Jd42-2	Wyoming Ice Company, Wyoming	<sup>1</sup> 0.060	<sup>1</sup> 0.060
Jd43-5	Camden-Wyoming Water Authority, Camden-Wyoming	<sup>1</sup> 0.200	<sup>1</sup> 0.200
Jd45-6	Dover Air Force Base Housing, Lebanon	0.000	<sup>2</sup> 0.043
Je12-13	Horsepond Road, Dover	0.000	<sup>3</sup> 0.624
Je32-5	Dover Air Force Base near Dover	0.656	0.526
Kd11-8	Woodside	<sup>1</sup> 0.107	<sup>1</sup> 0.052
Kd13-1	Kent County Vocational Technical High School, Woodside	<sup>1</sup> 0.011	<sup>1</sup> 0.011
Kd51-1	Felton	0.160	<sup>1</sup> 0.160
	Cambridge, Maryland <sup>4</sup>	4.38	3.30

TABLE 2 (continued).

WELL NUMBER	NAME AND LOCATION OF WELL	AVERAGE DAILY PUMPAGE (Mgal/d)	
		1970	1974
	Greensboro, Maryland <sup>4</sup>	<sup>1</sup> 0.250	<sup>1</sup> 0.250
	Denton, Maryland <sup>4</sup>	<sup>1</sup> 0.440	<sup>1</sup> 0.440
	<u>Wye Mills, Maryland<sup>4</sup></u>	<u><sup>5</sup>0.112</u>	<u><sup>5</sup>0.112</u>
	Total pumpage	7.3	<sup>6</sup> 6.6

<sup>1</sup>Estimated by P. P. Leahy.

<sup>2</sup>Withdrawals began late 1975. This well was not used in the calibration period but was included in the verification and predictive runs. Withdrawal estimated by P. P. Leahy.

<sup>3</sup>Withdrawals began in 1976. This well was not used in the calibration period but was included in the verification and predictive runs.

<sup>4</sup>Location shown on Figure 2.

<sup>5</sup>Estimated by J. F. Williams.

<sup>6</sup>Total does not include pumpage from Dover Air Force Base housing (Jd45-6) or Horsepond Road (Jel2-13) wells.

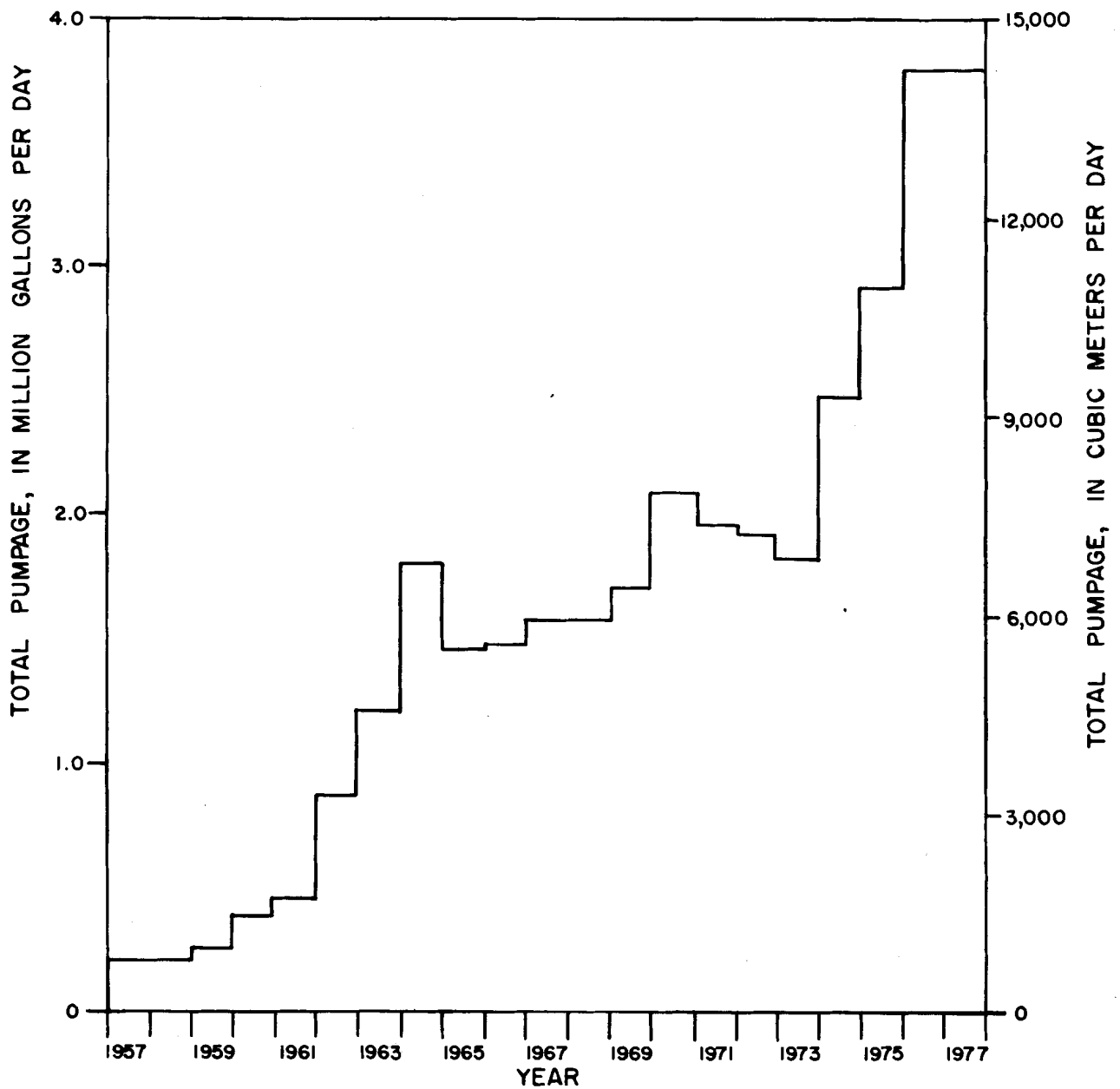


FIGURE 5  
 PUMPAGE IN KENT COUNTY, DELAWARE, FROM THE PINEY  
 POINT AQUIFER, 1957-1977.

## Hydraulic Properties of the Piney Point Aquifer in Kent County

### Transmissivity, Hydraulic Conductivity and Specific Capacity

The transmissivity of the Piney Point aquifer has been computed from aquifer tests at eleven locations throughout Kent County; most of the tests have been in the Dover area. The transmissivities reported (Table 3) range from a high of 7,350 ft<sup>2</sup>/d (683 m<sup>2</sup>/d) for well Jd45-7 (Figure 4) near Lebanon to a low of 26 ft<sup>2</sup>/d (2.4 m<sup>2</sup>/d) for well Mel5-29 (Figure 4) near Milford.

Although the Piney Point aquifer is recharged by leakage, the duration of most of the aquifer tests precluded observing the effects of leakage in the drawdown data. Thus, the standard nonleaky methods of analysis were considered adequate for many of the tests.

The hydraulic conductivity of the aquifer was calculated from the transmissivity and thickness data. The conductivity values generally range from 20 to 30 ft/d (6.1 to 9.1 m/d) except in the low transmissivity areas. Conductivity values found in this study generally match those for a fine- to medium-grained sand as presented by Lohman (1972).

The specific capacity of a well is defined by Lohman and others (1972) as the rate of discharge of water from the well divided by the drawdown of water level within the well. Specific capacity varies with the duration of pumping, and is affected by construction and development of the well. However, if well losses caused by construction and development are not significant, then specific capacity is roughly proportional to the transmissivity of the aquifer.

The specific capacity of well Kc31-1 (Figure 4), southwest of Dover, was used to estimate transmissivity. The specific capacity of the well was 4.0 (gal/min)/ft [0.8(L/s)/m] after 12 hours of pumping, and, using the method described by Brown (1963), the transmissivity of the aquifer was estimated to be 2,300 ft<sup>2</sup>/d (210 m<sup>2</sup>/d). Sundstrom and Pickett (1968) report that the specific capacities of 12 wells tapping the Piney Point aquifer range from 0.3 to 14.6 (gal/min)/ft [0.06 to 3.02(L/s)/m]. As expected, the lower values of specific capacity are for wells in low transmissivity areas located near the updip and downdip limits of the aquifer. The specific capacities reported by Sundstrom and Pickett (1968)

TABLE 3. Transmissivities and Coefficients of Storage for the Piney Point Aquifer as Determined by Aquifer Tests in Kent and Sussex Counties, Delaware and Caroline County, Maryland.

WELL NUMBER	DATE OF TEST	NAME AND LOCATION OF WELL	ANALYSIS BY	METHOD OF ANALYSIS	TRANSMISSIVITY ft <sup>2</sup> /d	COEFFICIENT OF STORAGE	DURATION OF TEST
Id53-2	4-4-62	McKee Run Generating Plant No. 6, Dover	R. W. Sundstrom	Theis recovery	800		21 hours
Id53-3	4-4-62	McKee Run Generating Plant No. 7, Dover	R. W. Sundstrom	Theis recovery	1140		21 hours
Jd14-12	10-19-61	Division Street, Dover	R. W. Sundstrom	Theis recovery	3200		5 hours
Jd23-1	8-2-65	Crossgates, Dover	R. W. Sundstrom	Theis recovery	2800		1 day
Jd25-4	5-16-75	Danner Farm, Dover	P. P. Leahy	Hantush modified leaky artesian	4100	2.8 x 10 <sup>-4</sup>	23 days
Jd34-1	1-2-69	Rodney Village, Dover	R. H. Johnston	Theis non-leaky artesian	3300		1 day
Jd45-7	5-1-74	Dover Air Force Base Housing, Lebanon	R. H. Johnston and P. P. Leahy	Theis non-leaky artesian	7350	3 x 10 <sup>-4</sup>	1 day
Je12-13	7-22-75	Horsepond Road, Dover	R. H. Johnston and P. P. Leahy	Theis recovery	4000		2 hours
Je32-4	7-24-63	Dover Air Force Base near Dover	R. D. Varrin and R. W. Sundstrom	Theis non-leaky artesian	4300 to 5350	3 x 10 <sup>-4</sup>	several hours
Kd11-8	3-11-59	Woodside	R. W. Sundstrom	Theis recovery	4400		several hours

TABLE 3 (continued)

WELL NUMBER	DATE OF TEST	NAME AND LOCATION OF WELL	ANALYSIS BY	METHOD OF ANALYSIS	TRANSMISSIVITY ft / d	COEFFICIENT OF STORAGE	DURATION OF TEST
Kd51-1	7-6-60	Felton	R. W. Sundstrom	Theis recovery	5100		several hours
Me15-29	2-19-68	Test Well, Millford	R. W. Sundstrom	Theis recovery	26		4 hours
Nc13-3	10-14-70	U.S.G.S./D.G.S. near Greenwood	I. H. Kantrowitz and R. H. Johnston	Theis recovery	200		12 hours
Care Cd50	8-6-75	Greensboro Elementary School, Greensboro, Maryland	P. P. Leahy and J. F. Williams	Theis non-leaky artesian	720	$1.9 \times 10^{-4}$	17 hours
Care Dd TW-1	5-20-68	Denton, Maryland	P. P. Leahy	Theis non-leaky	1500	$3.6 \times 10^{-4}$	3 hours

were not used to estimate transmissivity because at most of the wells, pumping test data was also available for computing transmissivity.

### Storage Coefficient

Few determinations of storage coefficient have been made for the Piney Point aquifer in the Delmarva Peninsula. Sundstrom and Pickett (1968) report only two values. One was computed from aquifer test data at Dover Air Force Base ( $3.0 \times 10^{-4}$ ), and the other from aquifer test data from an observation well at Cambridge, Maryland, ( $3.6 \times 10^{-4}$ ).

Four additional values of storage coefficient, ranging from  $3 \times 10^{-4}$  to  $1.9 \times 10^{-4}$ , have been determined since 1968 from pumping test analyses made by the author for wells in Kent County, Delaware and Caroline County, Maryland.

### Water Levels in the Piney Point Aquifer

The potentiometric surface of the Piney Point aquifer in January 1970 is shown in Figure 6. The surface is based on the measured water levels shown in Table 4 supplemented by reported water-levels measured from early 1969 to late 1970 in areas little affected by City of Dover pumping. The potentiometric surface for January 1975, as shown in Figure 7, is based on water-level measurements made on December 21, 1974 (Table 4). Table 4 shows the head declines observed during the 5-year period. The greatest declines during the period occurred in the Dover-Camden area. A decline of 32.0 ft (9.8 m) was observed in well Jd43-5 at Camden. For the same period, observation well Id55-1 at White Oak Road, City of Dover, showed a head decline of 26.2 ft (8.0 m). Near the downdip limit of the aquifer, the water-level declined 4.4 ft (1.4 m) in observation well Ncl3-3 at Greenwood. The areal distribution of drawdown for the 5-year period from January 1970 to January 1975 is shown in Figure 8.

Three long-term observation wells screened in the Piney Point aquifer are maintained in Delaware. Two of the observation wells, Je32-4 at Dover Air Force Base and Id55-1 at White Oak Road, are located in or near Dover (Figure 4). Continuous water-level recorders have been in use on these wells since 1957 and late 1969 respectively. Water-levels in these two wells, as shown in Figures 9 and 10, are affected by seasonal fluctuations in City pumpage. The other long-term observation well, Ncl3-3 at Greenwood, is located



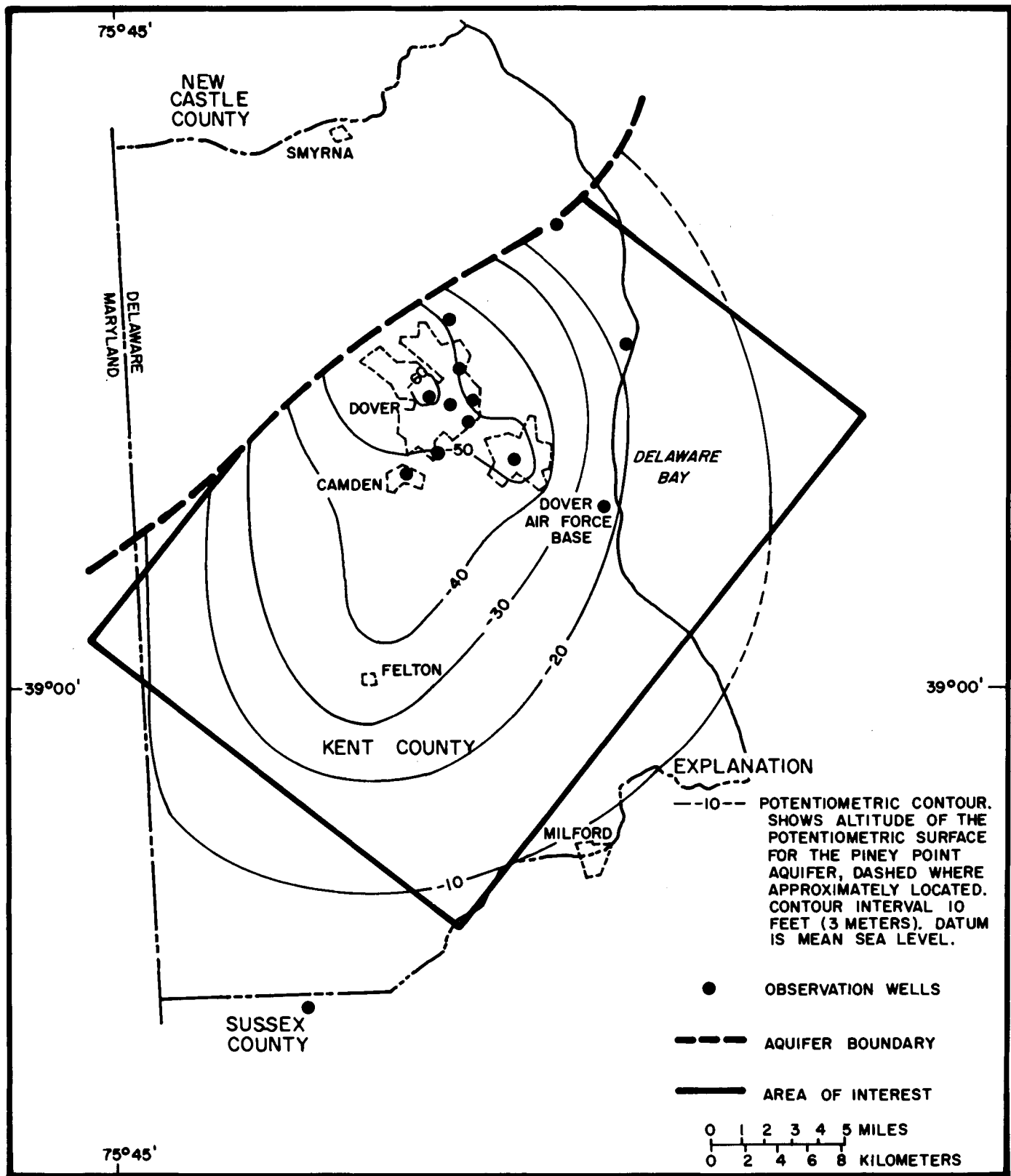


FIGURE 6  
 POTENTIOMETRIC SURFACE OF THE PINEY POINT AQUIFER  
 FOR JANUARY, 1970.

TABLE 4. Water Levels in the Piney Point Aquifer, 1969-70 and December 1974.

WELL NUMBER	NAME AND LOCATION	MEASURED WATER LEVEL (FEET BELOW MEAN SEA LEVEL)	MEASURED DATE	MEASURED WATER LEVEL FOR DECEMBER 21, 1974 (FEET BELOW MEAN SEA LEVEL)	HEAD DECLINE (DRAWDOWN) FOR 5-YEAR PERIOD
He52-2	Bombay Hook Wildlife Refuge Observation Well, Bombay Hook	118.2	5/69	27.6	9.4
Id45-1	Persimmon Tree Lane Observation Well, Dover	52.3	1/70	73.6	21.3
Id53-2	McKee Run Generating Plant, No. 6 Well, Dover	----	----	93.0	----
Id55-1	White Oak Road Observation Well, Dover	50.8	1/70	77.0	26.2
If42-1	Port Mahon	118.0	5/69	----	----
Jd14-12	Division Street Observation Well, Dover	62.0	1/70	88.2	26.2
Jd14-15	Treatment Plant Well, Dover	54.0	1/70	----	----
Jd15-5	East Dover Elementary School Well, Dover	48.3	1/70	72.4	24.1
Jd34-18	Rodney Village Well, Dover	47.8	1/70	----	----
Jd43-5	Camden Water Authority Well, Camden-Wyoming	46.0	5/69	78.0	32.0

TABLE 4 (continued)

WELL NUMBER	NAME AND LOCATION	MEASURED WATER LEVEL (FEET BELOW MEAN SEA LEVEL)	MEASURED DATE	MEASURED WATER LEVEL FOR DECEMBER 21, 1974 (FEET BELOW MEAN SEA LEVEL)	HEAD DECLINE (DRAWDOWN) FOR 5-YEAR PERIOD
Jd45-7	Dover Air Force Base Housing Observation Well, Lebanon	-----	-----	66.6	-----
Je12-13	Horsepond Road Well, Dover	-----	-----	73.6	-----
Je32-4	Dover Air Force Base Observation Well, near Dover	49.1	1/70	73.9	24.8
Jf51-1	Kitts Hummock	<sup>1</sup> 20.0	9/69	-----	-----
Kc31-1	USGS/DGS Observation Well, near Petersburg	-----	-----	<sup>2</sup> 37.9	-----
Kd13-1	Kent County Vocational Technical High School, Woodside	-----	-----	71.5	-----
Kd51-1	Felton	-----	-----	51.9	-----
Nc13-1	USGS/DGS Observation Well, Greenwood	6.1	1/70	10.5	4.4

<sup>1</sup>Estimated from reported water level for date shown.<sup>2</sup>First measured 2/20/75.

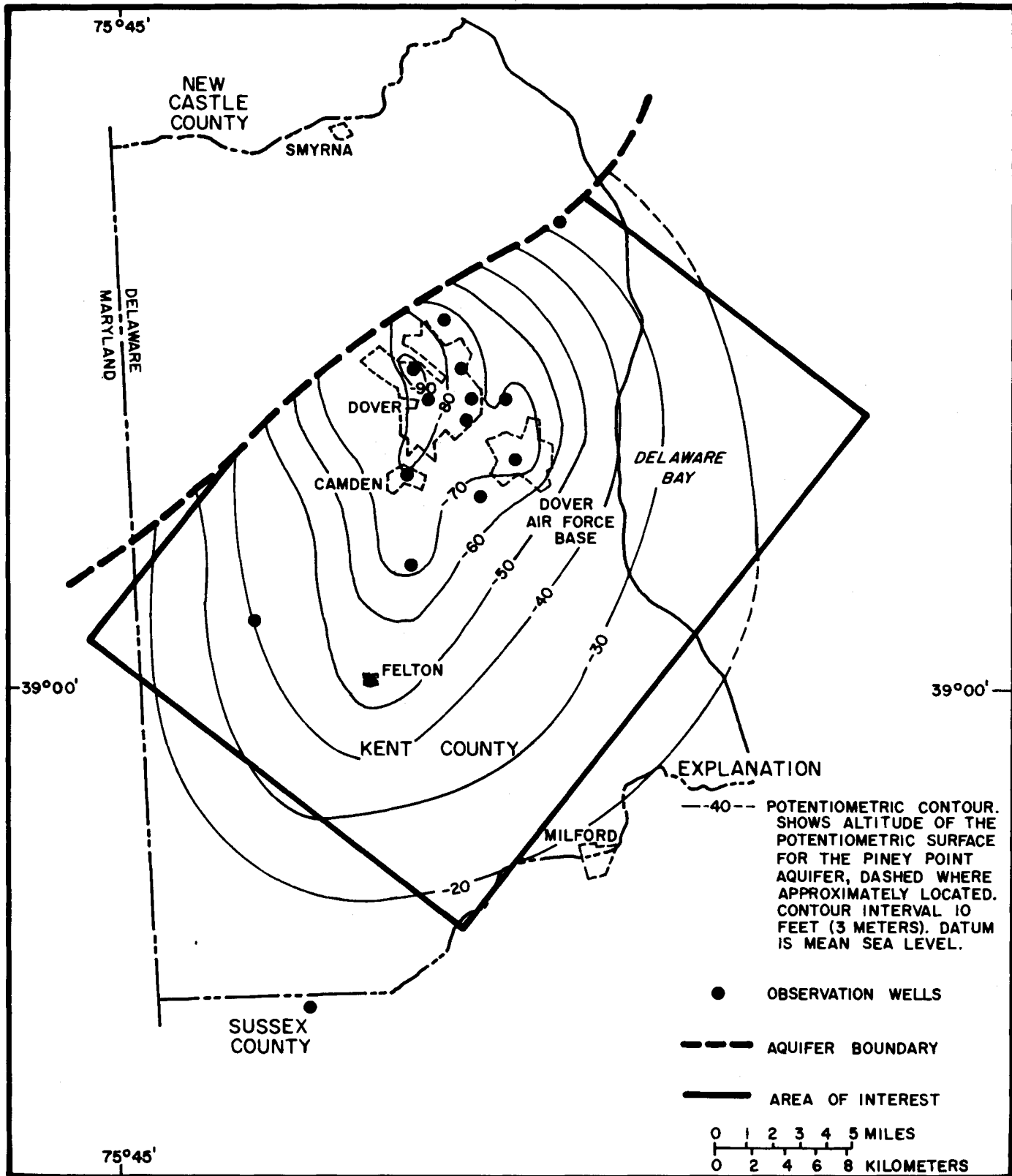


FIGURE 7  
 POTENTIOMETRIC SURFACE OF THE PINEY POINT AQUIFER  
 FOR JANUARY, 1975.

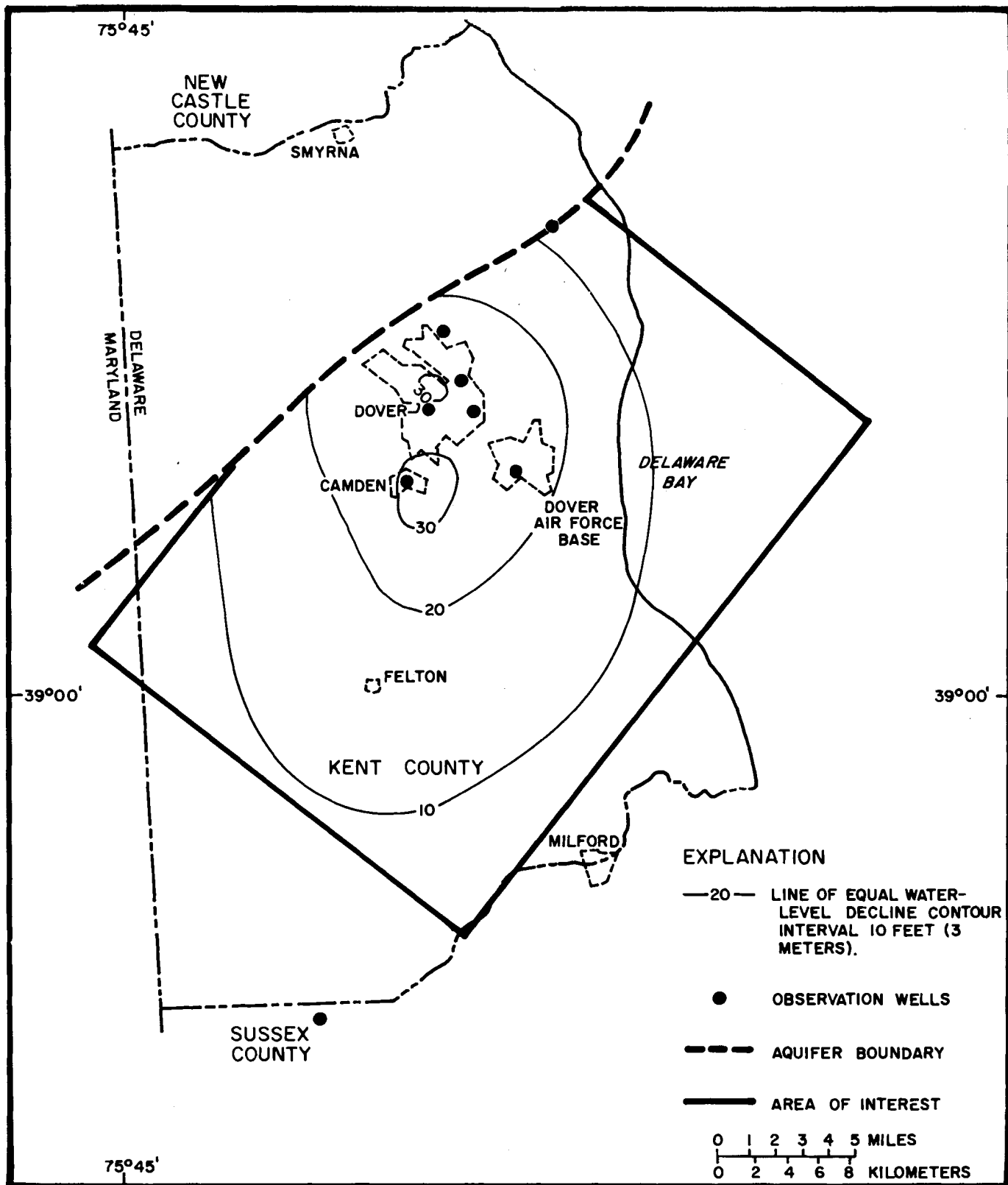


FIGURE 8  
 WATER-LEVEL DECLINE IN THE PINEY POINT AQUIFER, 1970 TO 1975.

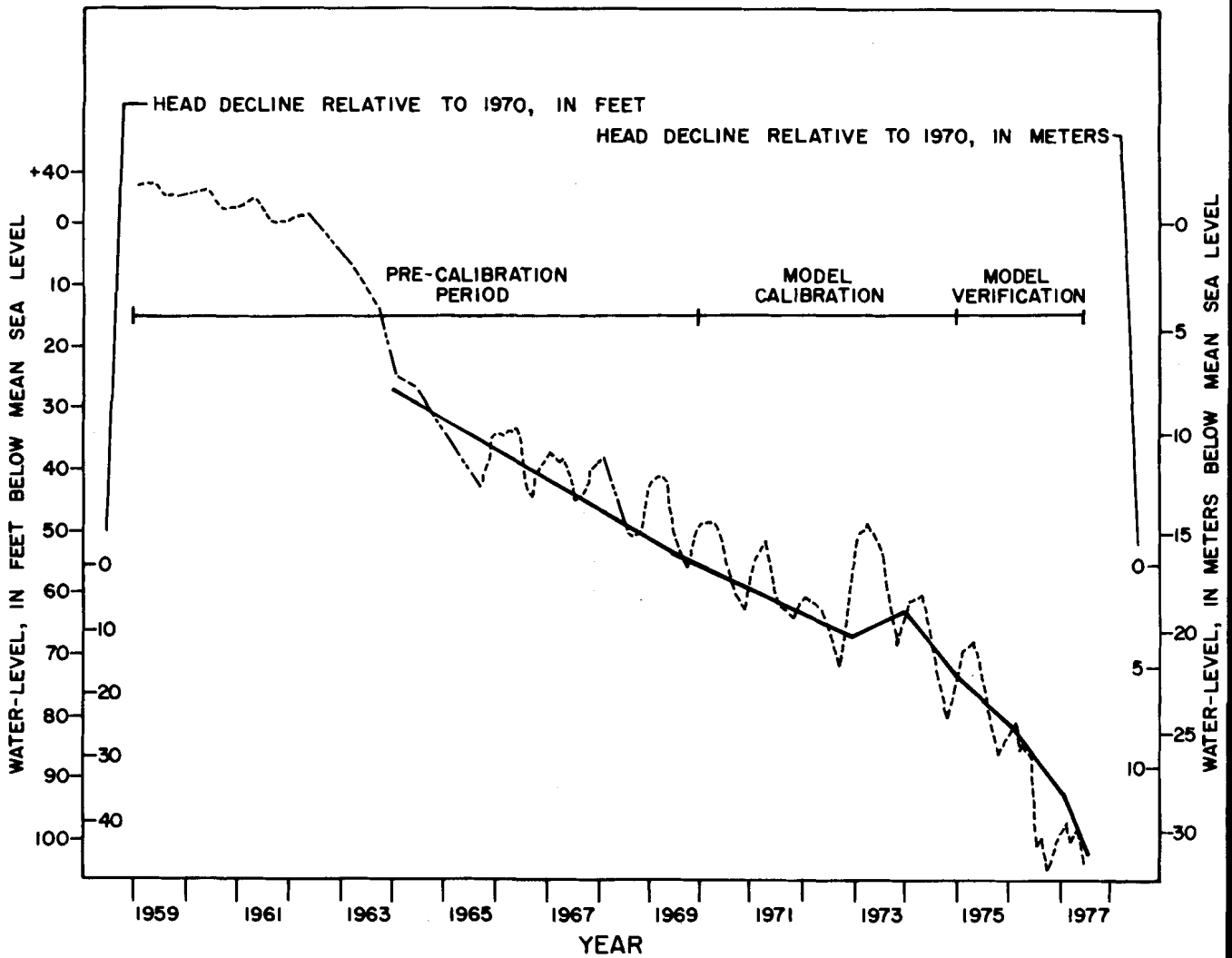


FIGURE 9

SIMULATED AND MEASURED WATER-LEVEL DECLINE FOR OBSERVATION WELL Je32-4 AT DOVER AIR FORCE BASE.

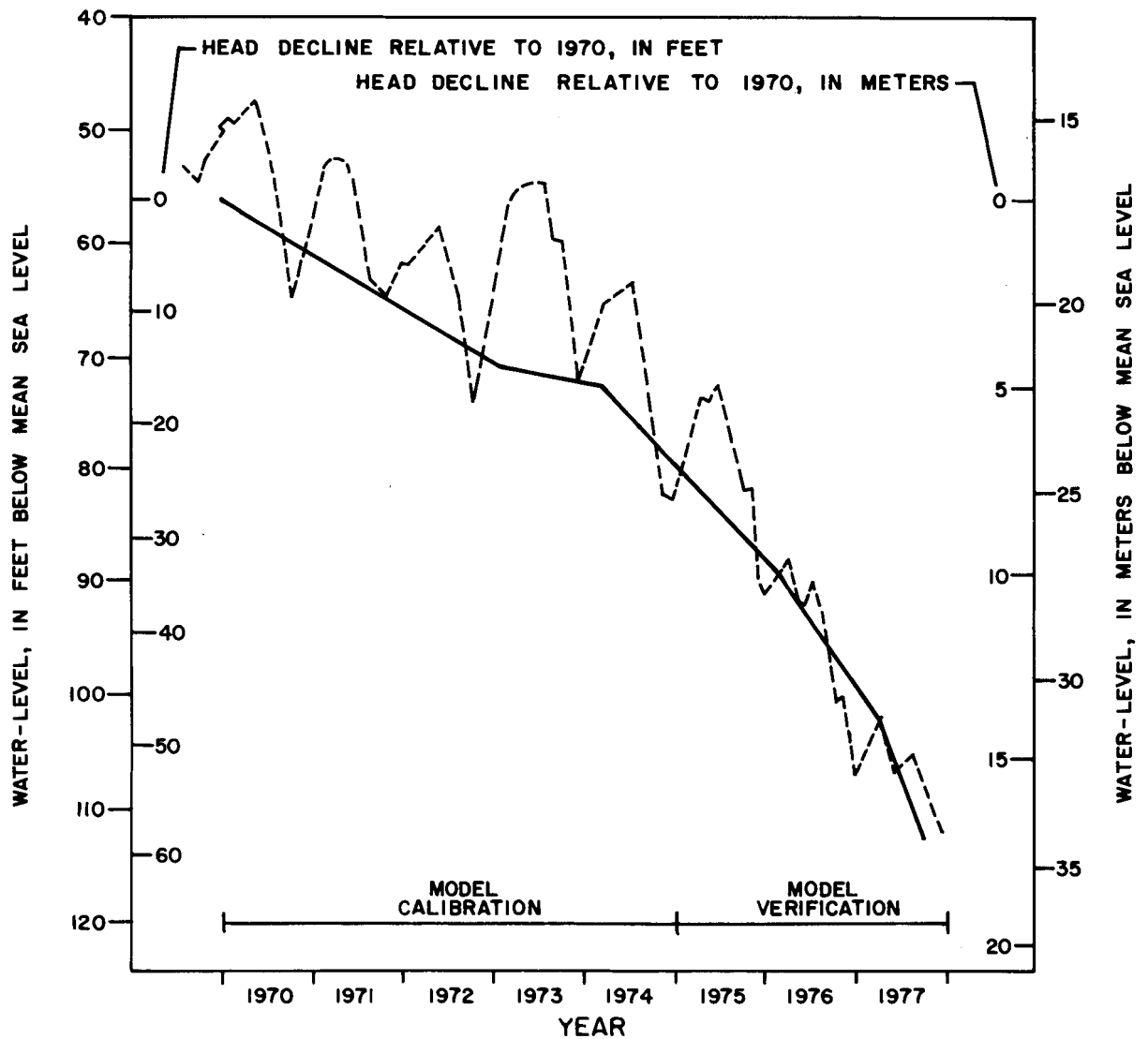
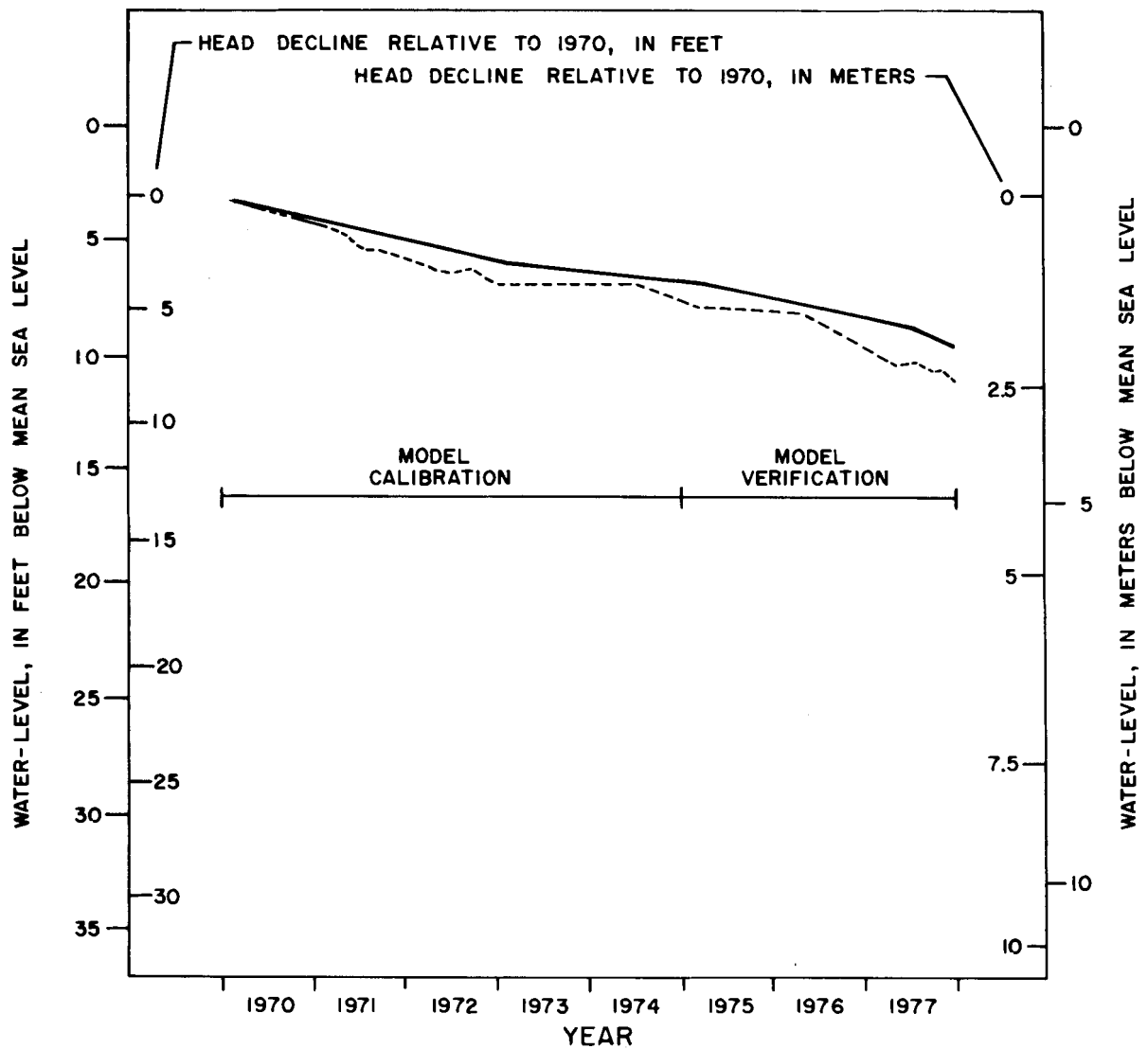


FIGURE 10  
SIMULATED AND MEASURED WATER-LEVEL DECLINE FOR OBSERVATION WELL 1d55-1 AT WHITE OAK ROAD, CITY OF DOVER.



**EXPLANATION**

- OBSERVED HEAD DECLINE
- SIMULATED HEAD DECLINE
- NO AVAILABLE DATA

**FIGURE 11**  
**SIMULATED AND MEASURED WATER-LEVEL DECLINE FOR OBSERVATION WELL Nc13-3 NEAR GREENWOOD, DELAWARE.**



13 mi (21 km) from the nearest pumping well. Water-level records have been maintained on a continuous basis for this well since it was drilled in the fall of 1970. The observed water-level response of Nc13-3 is unaffected by seasonal variations in withdrawal rates (Figure 11).

Water levels in observation wells Je32-4 and Id55-1 have declined at approximately the same rates, 24.8 ft (7.6 m) and 26.2 ft (8.0 m) respectively from January 1970 to January 1975. From 1970 through 1972 levels declined 5 to 7 ft (1.5 to 2.1 m) per year. During 1973 the Dover Air Force Base production well (Je32-5) was removed from service and water-levels in observation wells Id55-1 and Je32-4, recovered 2 to 4 ft (0.6 to 1.2 m). From 1974 to 1975, withdrawals from the Piney Point again increased, causing water levels to decline approximately 10 ft (3.0 m) per year. Water-levels declined about 1 ft (0.3 m) per year in observation well Nc13-3 at Greenwood during the entire 5-year period from 1970 to 1975.

#### HYDROGEOLOGY OF THE CHESWOLD AQUIFER AND CONFINING BED

All recharge to the Piney Point aquifer has been assumed to occur as vertical leakage from the overlying confining bed and the Cheswold aquifer, and is dependent upon the hydraulic properties of the confining bed and the head gradient across the confining bed. The vertical head gradient is a function of heads in both the Piney Point and Cheswold aquifers. The potentiometric surface of the Cheswold aquifer and the hydraulic properties of the confining bed are discussed in the following sections.

#### Water Levels in the Cheswold Aquifer

The potentiometric surface of the Cheswold aquifer during August-September 1975 is shown in Figure 12. The Cheswold aquifer has been continuously pumped at Dover since 1893, causing an extensive cone of depression centered around the supply wells of the City of Dover and Dover Air Force Base. From 1965 to 1975 Cheswold pumpage remained relatively constant, averaging 6 to 7 Mgal/d (25,000 m<sup>3</sup>/d), as noted by Johnston and Leahy (1977). Comparison of 1975 water-levels (Figure 12) with those reported by Cushing, Kantrowitz, and Taylor (1973) for 1970 shows very little decline in water-levels from 1970 to 1975. Also, water-level measurements at

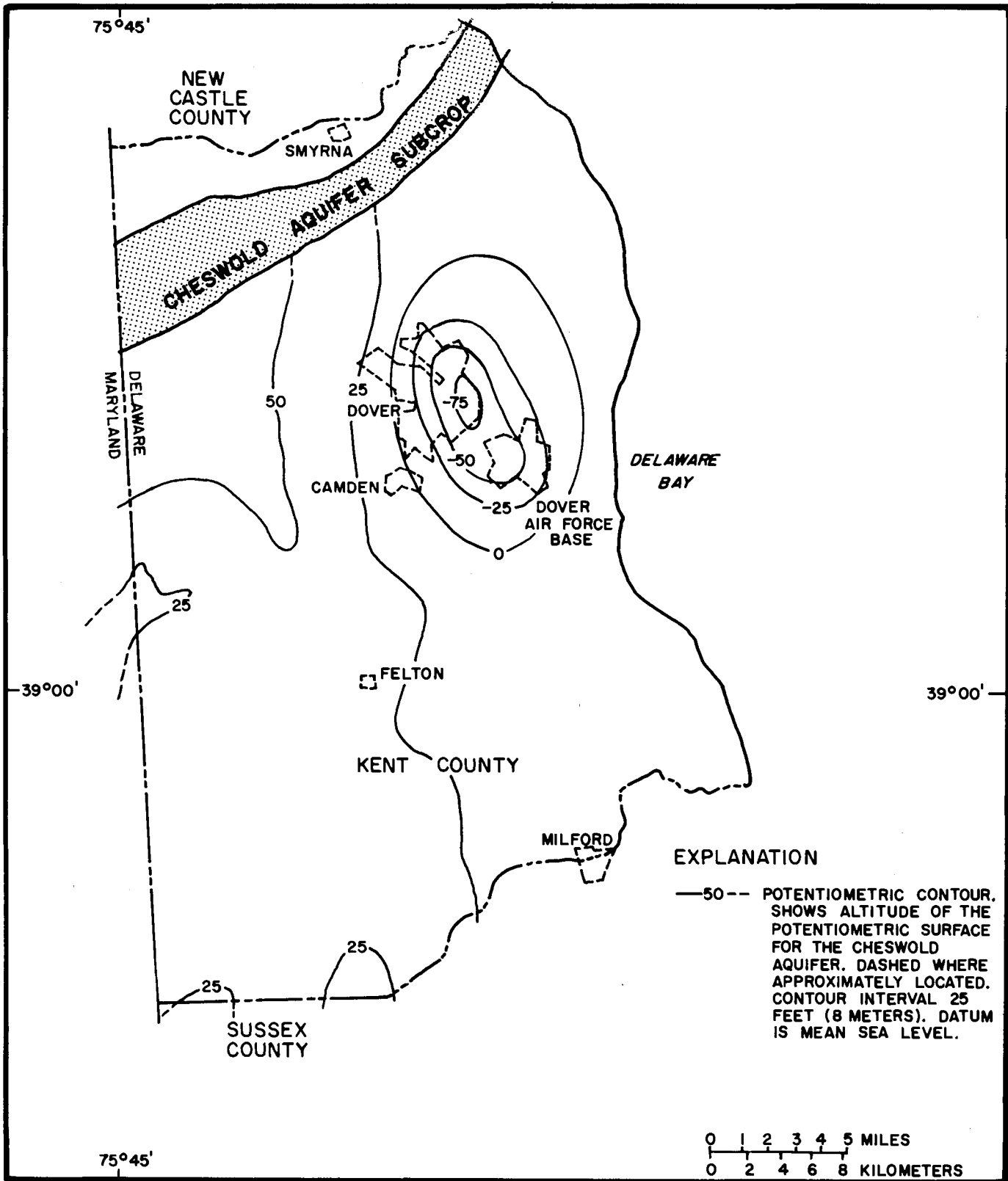


FIGURE 12  
 POTENTIOMETRIC SURFACE OF THE CHESWOLD AQUIFER,  
 AUGUST - SEPTEMBER, 1975.

an observation well screened in the Cheswold, Jd14-1, in the City of Dover, show little change for the period of record, 1972-1975. In this well, a 10-foot fluctuation in water level is caused by seasonal variations in Cheswold pumpage.

### Hydraulic Properties of the Overlying Confining Bed

An areally extensive confining bed (Miocene age) that trends across the Delmarva Peninsula and into southern New Jersey, separates the Piney Point and Cheswold aquifers. An isopach map of this unit in Kent County is shown in Figure 13. The confining bed dips southeastward and varies in thickness from approximately 160 ft (49 m) in northeastern Kent County to 60 ft (18 m) near Milford.

Few values of the hydraulic properties of the confining bed overlying the Piney Point aquifer have been determined. Nemickas and Carswell (1976) reported that values of vertical hydraulic conductivity, determined from four core samples taken about 20 mi (32 km) northeast of Dover in Cumberland County, New Jersey, range from  $2.0 \times 10^{-5}$  to  $5.2 \times 10^{-5}$  ft/d ( $6.0 \times 10^{-6}$  to  $1.6 \times 10^{-5}$  m/d). In Delaware a 23-day aquifer test was conducted near Dover to determine field values of both vertical conductivity and specific storage. Analysis of this test (Leahy, 1976) resulted in a range of values for vertical conductivity and specific storage. The vertical conductivity ranges from  $4.0 \times 10^{-5}$  to  $9.0 \times 10^{-5}$  ft/d ( $1.2 \times 10^{-5}$  to  $2.7 \times 10^{-5}$  m/d), and the specific storage from  $3.0 \times 10^{-6}$  to  $6.0 \times 10^{-6}$ /ft ( $1.0 \times 10^{-5}$  to  $2.0 \times 10^{-5}$ /m). On the Maryland side of the Delmarva Peninsula, a vertical conductivity of  $2.2 \times 10^{-4}$  ft/d ( $6.7 \times 10^{-5}$  m/d), was determined (J. F. Williams, oral commun., 1976) from a core sample taken near Preston, Maryland about 35 mi (56 km) southwest of Dover.

Field and laboratory determinations of vertical conductivity at a site may not accurately represent properties over a large area. However, the few reported values of vertical conductivity show a marked trend along the strike of the aquifer. Vertical conductivity values for the confining bed range from a minimum in New Jersey, increasing an order of magnitude southwestward across Delaware to a maximum reported value at Preston, Maryland. Grain-size analyses of core samples from New Jersey indicated the confining bed material ranged from silty clay to clayey silt (Nemickas and Carswell, 1976), whereas analyses of cores taken in Delaware indicated the material ranged from silty clay to clayey fine sand (Leahy, 1976).

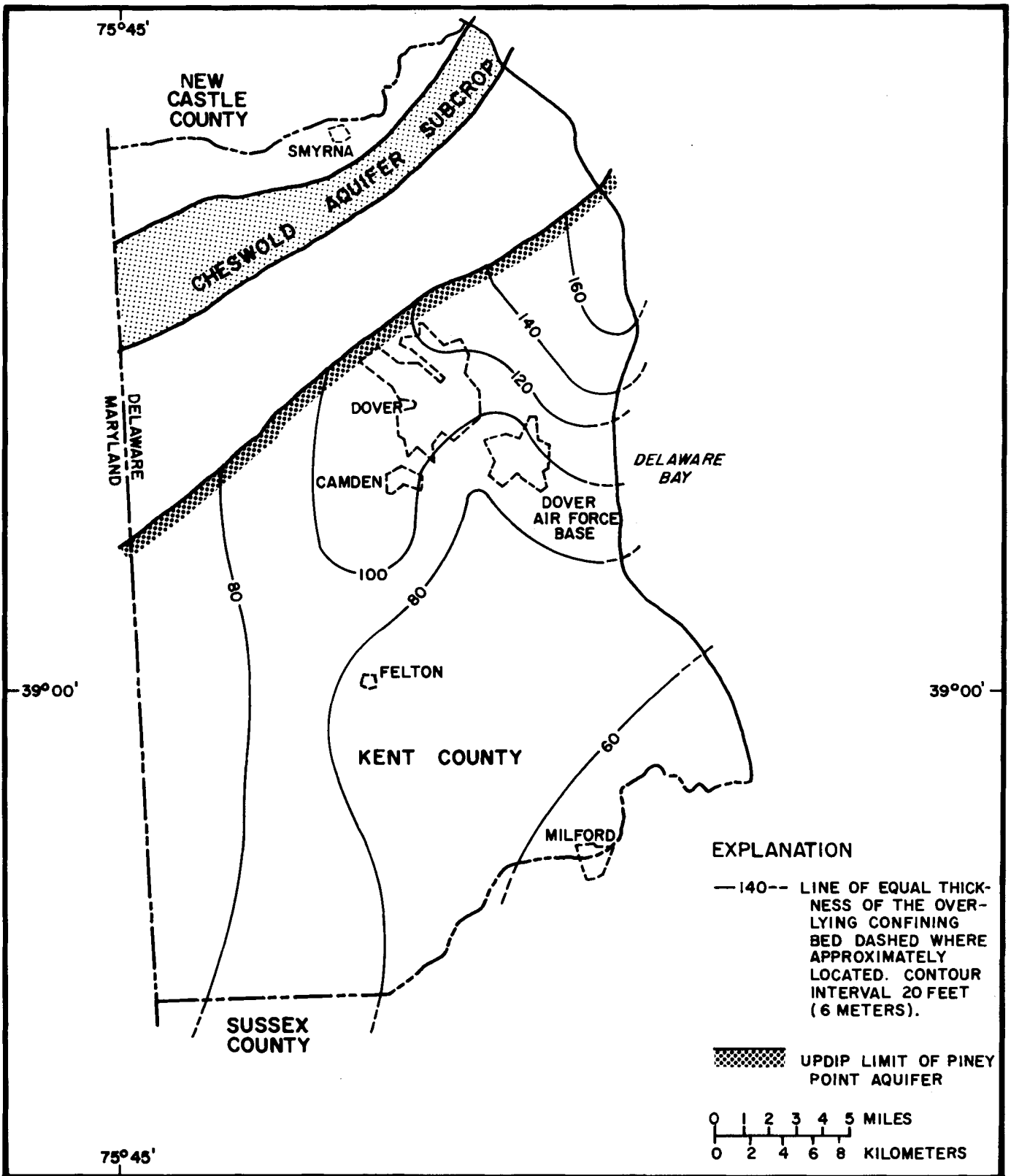


FIGURE 13  
THICKNESS OF THE CONFINING BED OVERLYING THE PINEY POINT AQUIFER.

# SIMULATION OF THE PINEY POINT AQUIFER

## The Digital Model

### Theory

Digital computers have made practical the development of various numerical techniques for the solution of partial differential equations. These techniques have been applied in the development of digital models of ground-water systems by other authors (e.g. Pinder, 1970; Prickett and Lonnguist, 1971; Pinder and Bredehoeft, 1968). The progress and ground-water model development by the U. S. Geological Survey has been reported by Appel and Bredehoeft (1976).

In this report, only the finite-difference aquifer model described by Pinder (1970) and modified by Trescott (1973) and Trescott, Pinder, and Larson (1976) will be discussed. Minor modifications of the model, primarily the addition of a statistical routine to aid in calibration, were made by the author for use in the simulation of the Piney Point aquifer.

The two-dimensional digital model, as applied in this study, simulates the response of a confined aquifer system to an imposed stress (pumping). The boundaries of the aquifer system vary spatially. Effects of steady and transient leakage from the overlying confining bed are included in the model. A time variation in pumping rates is represented by a sequence of pumping periods; pumping rates during each pumping period are constant, but may be changed from period to period. The information sought from the model is primarily hydraulic head, or changes in hydraulic head (draw-down) caused by pumping wells. The model is used to solve the two-dimensional ground-water flow equation. The flow equation is a form of the continuity equation (principle of conservation of mass) which states that:

Inflow - Outflow = Rate of accumulation or depletion.

For confined aquifer with purely two-dimensional flow, whose Cartesian coordinate axes are aligned with the principal components of the transmissivity tensor, the flow equation is as follows:

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

where,

$h$  is the hydraulic head (L);

$x$  and  $y$  are Cartesian coordinates (L);

$T$  is transmissivity ( $L^2/T$ );

$S$  is storage coefficient (dimensionless);

$t$  is time (T);

$W$  is the volumetric flux of sources and sinks in the aquifer, per unit surface area of the aquifer (L/T). In this study,  $W$  includes only pumpage and leakage through the overlying confining bed.

The finite-difference method is used as a means of obtaining approximate solutions to Equation 1. Basically, the method involves the substitution of finite-difference approximations for the partial derivatives in the flow equation (1). In order to apply the finite-difference technique, the aquifer must first be "discretized," that is, subdivided into rectangular elements or blocks in which the aquifer properties are assumed to be uniform. The point at the center of the block is called the node and is located by the indices  $i, j$ . The hydraulic head at a given node is assumed to be the average head over the area of the node. Time dependence of the hydraulic head is handled by dividing time into increments or steps; the head at a given node is treated as constant within the time step and is assumed to vary in stepwise fashion from one time step to the next.

Substitution of the finite-difference approximations for the derivatives in the flow equation (1) for a given time step, results in  $N$  equations in  $N$  unknown values of head, where  $N$  is the number of nodes representing the aquifer. At node  $(i, j)$  equation 1 may be approximated by the following finite-difference (algebraic) equation:

$$\frac{1}{\Delta x_j} \left[ T_{xx}(i, j+\frac{1}{2}) \frac{(h_{i, j+1, k} - h_{i, j, k})}{\Delta x_{j+\frac{1}{2}}} - T_{xx}(i, j-\frac{1}{2}) \frac{(h_{i, j, k} - h_{i, j-1, k})}{\Delta x_{j-\frac{1}{2}}} \right] +$$

$$\frac{1}{\Delta x_i} \left[ T_{yy}(i+\frac{1}{2}, j) \frac{(h_{i+1, j, k} - h_{i, j, k})}{\Delta y_{i+\frac{1}{2}}} - T_{yy}(i-\frac{1}{2}, j) \frac{(h_{i, j, k} - h_{i-1, j, k})}{\Delta y_{i-\frac{1}{2}}} \right] =$$

$$\frac{S_{i, j}}{\Delta t} (h_{i, j, k} - h_{i, j, k-1}) + W_{i, j, k} \quad (2)$$

where,

$h_{i,j,k}$  is the hydraulic head at time-level  $k$  for node  $(i,j)$  (L);

$T_{xx(i,j+\frac{1}{2})}$  is the transmissivity in the x-direction between node  $(i,j)$  and node  $(i,j+1)$  ( $L^2/T$ );

$S_{i,j}$  is the storage coefficient at node  $(i,j)$  (dimensionless);

$\Delta x_j, \Delta y_i$  are the space increment in the appropriate direction (L);

$\Delta t$  is the time increment (T);

$\Delta x_{j+\frac{1}{2}}$  is the distance between node  $(i,j)$  and node  $(i,j+1)$  (L);

$i$  is the index in the y-direction;

$j$  is the index in the x-direction;

$k$  is the time index.

Equation 2 is the finite-difference equation, which is solved by the digital model described by Trescott, Pinder, and Larson (1976). The ground-water flow equation (1) may be approximated by other finite-difference schemes, which are beyond the scope of this report. The interested reader is referred to Von Rosenberg (1969), Remson, Hornberger, and Molz (1971) or Bennett (1976) for a more rigorous mathematical discussion of finite-difference approximations.

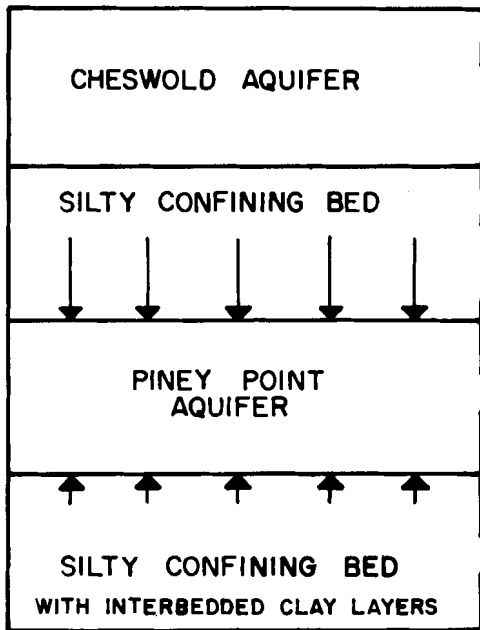
The system of  $N$  simultaneous (algebraic) equations generated by finite-difference equation (2) may be solved by many numerical techniques. The digital model used in this study, however, employs a numerical technique commonly referred to as the iterative-alternating direction-implicit (IADI) procedure. In this technique, a set of  $N$  equations for a given time step are solved by an iterative process in which the computations are processed alternately in the  $x$  and  $y$  directions. A more detailed discussion of the IADI technique is given by Trescott (1973) and Trescott, Pinder, and Larson (1976).

## The Conceptual Model, Boundary Conditions, and Data Requirements

A digital model is a mathematical approximation of a "real" physical system. As such, the physical system must be represented in mathematical terms by a conceptual model. A conceptual model of the Piney Point aquifer flow system, shown in Figure 14, was developed based on all available hydrologic data. Also, simplifying assumptions necessary in practice to describe the aquifer system mathematically were made. Some assumptions do not exactly represent the true physical situation. For example, the assumption of a distant no-flow boundary is probably not absolutely valid. However, the effect of such assumptions on results in the area of interest are negligible. The assumptions inherent in the conceptual model of the Piney Point aquifer are:

- (1) Heads in the Cheswold aquifer overlying the Piney Point aquifer are held constant throughout the entire simulation. During the calibration period (1970-1975) heads as well as withdrawals from the Cheswold aquifer remained essentially constant; however, this may not be the case during the period covered by the predictions.
- (2) Hydraulic properties of the aquifer are isotropic, and all flow in the Piney Point aquifer is horizontal and two-dimensional.
- (3) The aquifer is bounded laterally by no-flow boundaries on all sides, as shown in Figure 2. No-flow boundaries to the northeast, southeast, and northwest coincide with the physical limits of the aquifer. To the southwest, a no-flow boundary is positioned approximately parallel to the eastern shore of Chesapeake Bay. This boundary does not coincide with the true aquifer boundary, but, because this "effective" no-flow boundary is so distant, its location will have a negligible effect on simulated heads in the area of interest of the digital model.
- (4) As previously stated, the upper confining bed is silt, whereas the lower confining bed consists of silt and interbedded clay lenses. Therefore, vertical leakage to the aquifer is assumed to occur through the overlying confining bed only, because of the apparent very low conductivity of the confining unit underlying the Piney Point aquifer and





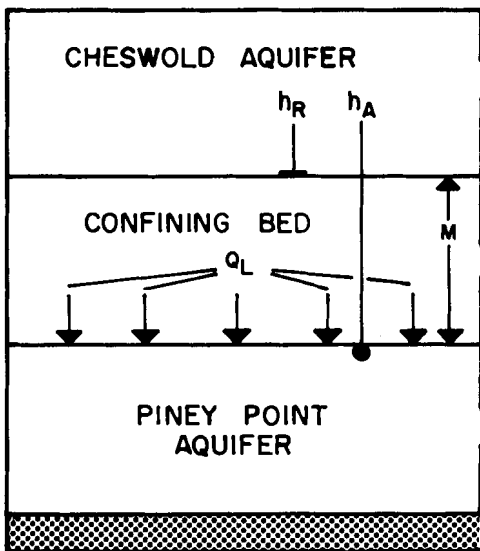
PUMPAGE OF 6-7 Mgal/d APPROXIMATE STEADY-STATE CONDITIONS INDICATED BY LITTLE CHANGE IN WATER LEVELS SINCE 1968-1977.

APPRECIABLE DOWNWARD LEAKAGE

LATERAL GROUND-WATER MOVEMENT TO PUMPING CENTERS

PROBABLY VERY LITTLE UPWARD LEAKAGE BECAUSE OF VERY LOW VERTICAL HYDRAULIC CONDUCTIVITY

A. NATURAL FLOW SYSTEM OF PINEY POINT AQUIFER



CONSTANT HEAD ( $h_R$ ) IN CHESWOLD AQUIFER

VERTICAL LEAKAGE ( $Q_L$ ) CONTROLLED BY HEAD GRADIENT ( $h_R - h_A$ ) AND VERTICAL CONDUCTIVITY ( $K_V$ ), SPECIFIC STORAGE ( $S_S$ ) AND THICKNESS ( $M$ ) OF CONFINING BED

LATERAL GROUND-WATER MOVEMENT

IMPERMEABLE BOUNDARY ( $K_V=0$ )

B. SIMULATED FLOW SYSTEM OF PINEY POINT AQUIFER

FIGURE 14  
CONCEPTUAL MODEL OF THE PINEY POINT AQUIFER FLOW SYSTEM.

the higher conductivity of the overlying confining bed. The base of the Piney Point aquifer is therefore treated as a no-flow boundary.

- (5) In the Piney Point aquifer, water is derived from the overlying Cheswold aquifer, storage in the confining bed, and storage in the aquifer itself. Release of water from confining bed storage is simulated using an approximation described by Bredehoeft and Pinder (1970).
- (6) Ground water is discharged by pumping and upward leakage where head gradients are favorable.

A two-dimensional finite-difference model was assumed to be adequate to simulate the effects of pumping on the Piney Point aquifer. The use of this model is valid because (1) the Cheswold aquifer is currently in a near steady-state condition and (2) a very large percentage of the vertical flow to the aquifer is believed to occur as leakage through the overlying confining bed. The digital model used in the study is described by Trescott, Pinder, and Larson (1976). It requires certain geohydrologic information in order to simulate the effects of pumping on the Piney Point aquifer. The digital model uses geohydrologic data that are defined at each model node and are considered representative for the whole grid block. The data arrays necessary for simulation of the Piney Point aquifer are as follows:

- (1) a 30 x 36 rectangular grid (Figure 2) with variable nodal spacing (used to give the highest node density in the area of interest);
- (2) initial head distribution in the Piney Point aquifer (1970) derived from the results of the pre-calibration simulation;
- (3) distribution of water level changes or drawdowns (1970 to 1975) for the Piney Point aquifer;
- (4) transmissivity of the Piney Point aquifer;
- (5) storage coefficient of the aquifer: a constant value of  $3.0 \times 10^{-4}$ ;
- (6) thickness of the overlying confining bed;
- (7) hydraulic conductivity of the overlying confining bed;

- (8) potentiometric surface of the overlying Cheswold aquifer;
- (9) specific storage of the overlying confining bed: a constant value of  $6 \times 10^{-6} \text{ ft}^{-1}$  ( $2 \times 10^{-5} \text{ m}^{-1}$ ); and,
- (10) location and pumping rates of all wells tapping the Piney Point aquifer in the model area.

### Model Calibration and Verification

A digital model of an aquifer system cannot be used for prediction until it has been calibrated. Calibration involves adjusting input data until the model can closely describe the hydrologic history of the aquifer. Calibration consisted of simulating the known history of pumping and comparing the drawdowns computed by the model with actual drawdowns. The calibration of the model was further verified by simulating 1975-1977 pumpage and comparing computed and observed head declines (drawdowns) at three long-term observation wells in Delaware.

### Drawdown Simulation

The model simulated pumpage for the 15-year period from Jan. 1, 1959 to Jan. 1, 1975. A "pre-calibration" simulation from Jan. 1, 1959 to Jan. 1, 1970 was made to insure that the effects of previous pumping would be included in the results obtained for the calibration simulation. Initial or starting heads (Jan. 1, 1959) in the aquifer were set equal to the heads in the overlying aquifer (Cheswold) to provide an initial equilibrium or steady-state condition. The results obtained for the pre-calibration period were used as the initial conditions for the model of the calibration period. Thus, the drawdowns computed by the model for calibration were relative to these Jan. 1, 1970 results. Water levels in the Cheswold aquifer may have declined slightly in the pre-calibration period due to minor increases in pumping from the Cheswold aquifer. However, it was assumed that (1) the Cheswold head changes were small and rather localized because most of the Cheswold development occurred prior to the pre-calibration period; and (2) the declines had little effect on computed drawdowns during the calibration period.

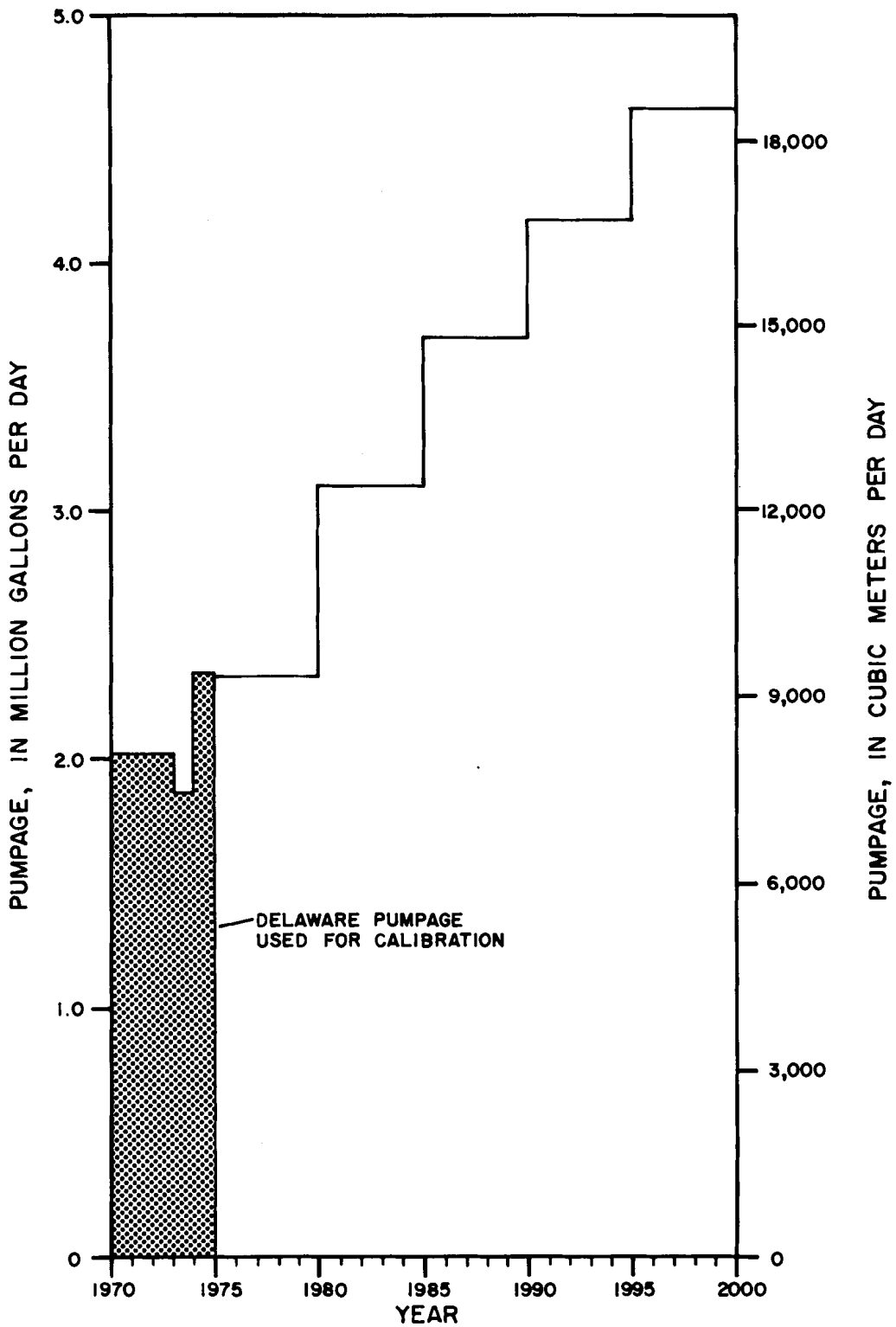
The 5-year period from Jan. 1, 1970 to Jan. 1, 1975 was chosen as the calibration period for the Piney Point model. More data on pumpage, water-levels, and drawdown were available

for these 5 years than for any other period. The period was broken down into three pumping periods of different duration as shown in Figure 15. The initial pumping period is 3 years long, lasting from January 1970 to January 1973. Pumping rates at most wells during this period changed only slightly and a 3-year average was considered adequate. The other two periods were one year each. During the second pumping period, January 1973 to January 1974, average daily pumpage from Dover Air Force Base well Je32-5 was substantially reduced from 0.5 Mgal/d (1,890 m<sup>3</sup>/d) to 0.19 Mgal/d (720 m<sup>3</sup>/d). Pumping rates increased slightly at other production wells in the Dover area, but the net effect was a decrease in total withdrawals from the Piney Point aquifer. During the third and final pumping period, pumpage from Dover Air Force Base well Je32-5 increased to a daily average of 0.5 Mgal/d (1,890 m<sup>3</sup>/d).

The model was calibrated by simulating actual withdrawals from 1970 to 1975. Nodal values of hydraulic head change resulted from these simulations and drawdown maps for the aquifer were constructed from the results. The procedure used in calibrating the model consisted of:

- (1) Comparison of nodal values of drawdown computed by the model for Jan. 1, 1970 to Jan. 1, 1975 with a drawdown array based on actual field measurements for the same period;
- (2) comparison of computed and observed drawdowns at several control points;
- (3) comparison of hydrographs computed by the model with hydrographs from long-term observation wells; and,
- (4) adjustment of the hydrologic parameters used in the model until adequate matches of 1, 2, and 3 above were achieved.

The computer program was altered so that an array of drawdowns based on field data could be used by the program for calibration. The drawdown array was compared with nodal values of drawdown calculated by the program. This was done by subtracting, node by node, the computed drawdown from the drawdown based on the field data. This calculation resulted in a drawdown-error or calibration matrix. Use of the calibration matrix speeded up the calibration process, and removed the bias inherent in visually comparing contoured drawdown maps.



**FIGURE 15**  
**DELAWARE PUMPAGE USED FOR CALIBRATION, 1970-75 AND ESTIMATED CITY**  
**OF DOVER PUMPAGE FOR THE PERIOD 1975-2000.**

In the process of calibrating the model, adjustment of some of the hydrologic parameters was necessary. These parameters included the transmissivity of the aquifer, and the vertical conductivity and specific storage of the confining bed. After adjustment, the transmissivity values used in the model ranged from 7,350 ft<sup>2</sup>/d (683 m<sup>2</sup>/d) near Lebanon to zero at no-flow boundaries representing the updip and downdip limits of the aquifer. The transmissivity distribution determined by calibration of the model is shown in Figure 16. The transmissivity distribution is very similar to the pre-modeling distribution, which was based on field determinations of transmissivity. The calibrated and premodeling transmissivity maps are in general agreement because the pre-modeling transmissivity map was based on values determined from aquifer tests (Table 3) that were somewhat evenly spaced over a large part of the area of interest.

The position of the updip boundary (zero transmissivity contour) was moved during calibration until an adequate match of computed and observed drawdowns and hydrographs was achieved. Initially, the northeast-southwest trending updip boundary of the Piney Point aquifer was simulated as being approximately 2 mi (3 km) north of Dover. However, model calibration indicates that the boundary is probably closer to the northwest edge of Dover as shown in Figure 16.

Based on model calibration, the confining bed overlying the Piney Point aquifer in Kent County has a vertical hydraulic conductivity that ranges from 3.0 to  $10^{-5}$  to  $4.7 \times 10^{-5}$  ft/d ( $9.1 \times 10^{-6}$  to  $1.4 \times 10^{-5}$  m/d). These values are approximately the values reported by Leahy (1976). The specific storage of the confining bed used in the model was  $6.0 \times 10^{-6}$  /ft<sup>-1</sup> ( $2 \times 10^{-5}$ /m<sup>-1</sup>) (Leahy, 1976).

The model was calibrated emphasizing the area of interest in Kent County, Delaware (Figure 1). Mean error and standard deviation of the calibration matrix were calculated in this area of highest node density. For the 1970-1975 calibration period, the mean drawdown error of the 440 nodes shown in Figure 2 was found to be 0.7 ft (0.2 m). The standard deviation was  $\pm 2.2$  ft ( $\pm 0.7$  m). Water levels in Kent County fluctuate seasonally as a result of variable pumpage and it is not possible to simulate this seasonal fluctuation when pumping periods of a year or more are used. The values of mean error and standard deviation calculated by the model were within the seasonal fluctuation of Piney Point water levels, and continued refinement of the model was unnecessary. To further evaluate the calibration, simulated and observed drawdowns at several control points in Kent County were compared for (1) the total

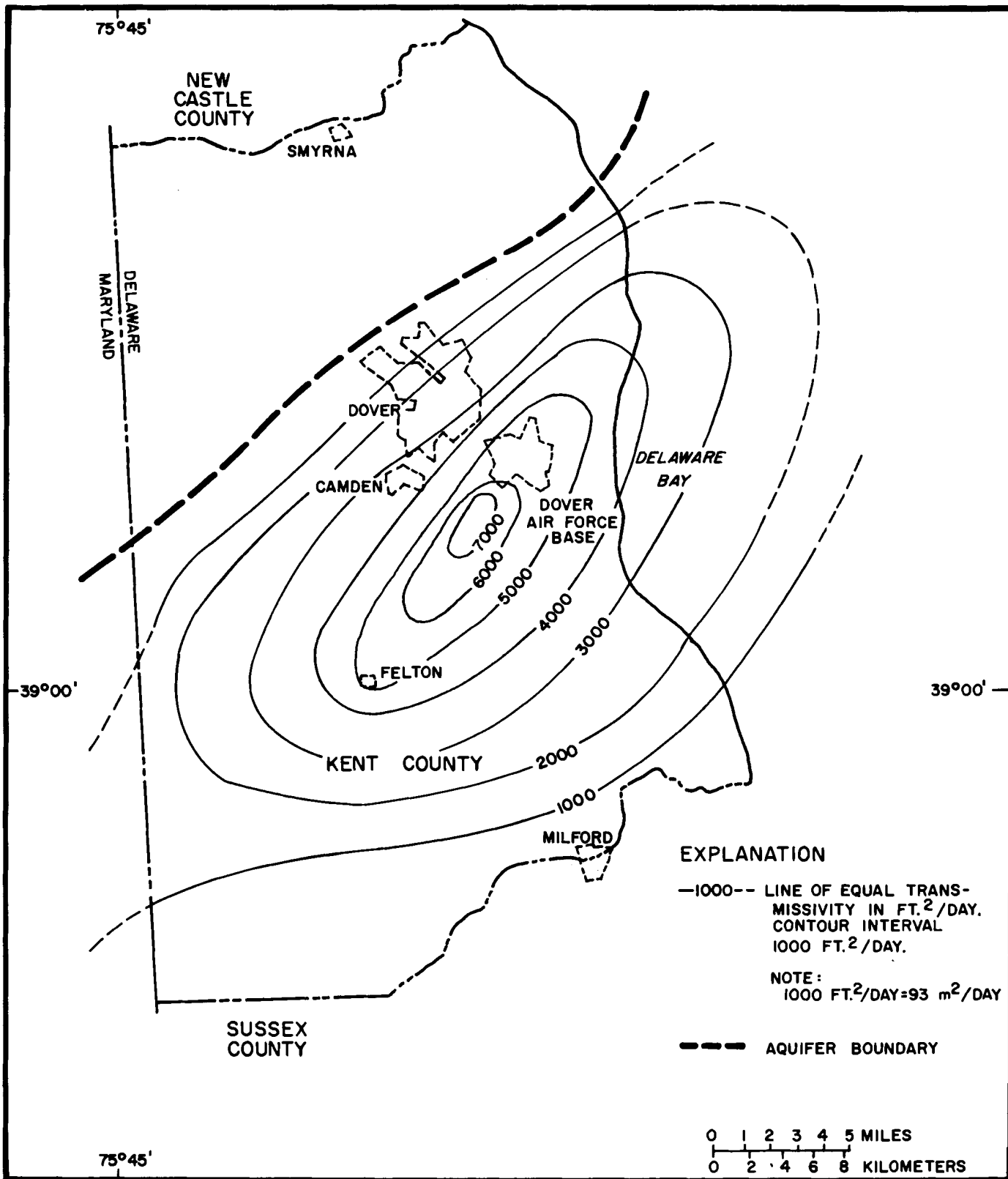


FIGURE 16  
TRANSMISSIVITY OF THE PINEY POINT AQUIFER BASED ON  
MODEL CALIBRATION.

simulation period from 1970-1975; (2) pumping period 2 from 1973-1974; and (3) pumping period 3 from 1974-1975. Results of these comparisons as well as the means and standard deviations of the differences between the observed and simulated head changes are shown in Table 5. Good agreement between the observed and simulated drawdowns for each of the periods is apparent.

Finally, values of drawdown calculated by the model were plotted against time and compared with hydrographs for the following three long-term observation wells:

- (1) Id55-1, White Oak Road, City of Dover,
- (2) Je32-4, Dover Air Force Base,
- (3) Nc13-3, near Greenwood, Delaware.

Figures 9, 10, and 11 show the close agreement of the simulated and observed drawdown for these observation wells. At the Dover Air Force Base observation well, Je32-4 water levels have been continuously recorded since 1959 (Figure 9). The simulated hydrograph matches the observed hydrograph for the precalibration period from Jan. 1, 1964 to Jan. 1, 1970. In the 1959-63 period the simulated hydrographs did not accurately match the observed hydrograph. The differences in the hydrographs probably were due to (1) uncertainties in the amount and distribution of pumpage used in the model for this early time period; and (2) variations from the assumed steady-state conditions at the beginning of the pre-calibration period. These initial inaccuracies were not considered to have a significant effect on model results for the calibration, verification, and predictive simulations.

#### Model Verification

The calibration of the model was verified by simulating withdrawals from Jan. 1, 1975 to June 1, 1977 and comparing computed and observed drawdowns at the three long-term observation wells in the study area. Input parameters used for the drawdown simulation were identical to the parameters determined through calibration of the model with the exception that (1) the Jan. 1, 1975 to June 1, 1977 pumpage figures were used and (2) initial head conditions for the simulation were derived from the calibration simulation.

The pumpage from 1975 to 1977 was divided into three pumping periods of the following duration: (1) 1 year from Jan. 1, 1975 to Jan. 1, 1976; (2) 1 year from Jan. 1, 1976 to



TABLE 5. Comparison of Simulated and Observed Head Changes (Drawdown) at Control Points.

WELL NUMBER	WELL NAME AND LOCATION	SIMULATED HEAD CHANGES IN FEET			OBSERVED HEAD CHANGES IN FEET			DIFFERENCE BETWEEN OBSERVED AND SIMULATED HEAD CHANGES IN FEET		
		TOTAL SIMULATION 1970-1975	PUMPING PERIOD 2 1973-1974	PUMPING PERIOD 3 1974-1975	1970-1975	1973-1974	1974-1975	1970-1975	1973-1974	1974-1975
He52-2	Bombay Hook Wildlife Refuge Obs. Well, Bombay Hook	13.7	1.0	4.0	9.4	---	---	-4.3	---	---
Id45-1	Persimmon Tree Lane Obs. Well, Dover	22.6	1.6	7.4	21.3	2.0	8.0	-1.3	0.4	0.6
Id55-1	White Oak Road Obs. Well, Dover	25.4	1.8	8.6	26.2	+1.5	10.0	0.8	3.3	1.4
Jd14-12	Division Street Obs. Well, Dover	28.6	2.6	9.0	26.2	0.0	11.0	-2.4	-2.6	2.0
Jd15-5	East Dover Elementary School Obs. Well, Dover	24.8	1.1	9.0	24.1	+1.0	11.4	-0.7	2.1	2.4
Jd43-5	Camden Water Authority Well, Camden-Wyoming	29.6	0.7	7.8	32.0	---	---	2.4	---	---
Jd45-7	Dover AFB Housing Obs. well, Lebanon	20.8	+0.5	7.7	---	---	11.2	---	---	3.5

TABLE 5 (continued)

WELL NUMBER	WELL NAME AND LOCATION	SIMULATED HEAD CHANGES IN FEET			OBSERVED HEAD CHANGES IN FEET			DIFFERENCE BETWEEN OBSERVED AND SIMULATED HEAD CHANGES IN FEET		
		TOTAL SIMULATION 1970-1975	PUMPING PERIOD 2 1973-1974	PUMPING PERIOD 3 1974-1975	1970-1975	1973-1974	1974-1975	1970-1975	1973-1974	1974-1975
Je32-4	Dover AFB Obs. Well, near Dover	19.6	+4.7	12.1	24.8	+4.0	13.2	6.2	0.7	1.1
Kc31-1	USGS/DGS Obs. Well, near Petersburg	10.9	0.3	2.4	---	---	15.0	---	---	2.6
Nc13-3	USGS/DGS Obs. Well, near Greenwood	4.0	0.4	1.4	4.4	0.1	1.0	0.4	-0.3	-0.6
						Mean Difference		0.1	0.6	1.8
						Standard Deviation (in Feet)		±3.2	±2.0	±1.0

<sup>1</sup>Estimated

Jan. 1, 1977; and, (3) 151 days from Jan. 1, 1977 to June 1, 1977. The simulated and observed hydrographs for the 2½-year verification period are shown in Figures 9, 10, and 11 for Je32-4, Id55-1, and Nc13-3 respectively. As expected, the simulated hydrographs closely match the observed hydrographs.

## The Model as a Predictive Tool

### Future Withdrawals

Once the model has been calibrated it can be used with limitations as a management tool to predict future water levels caused by changes in ground-water withdrawals. The accuracy of the predicted water levels depends partly on the accuracy of estimated future ground-water pumpage. The estimates of future pumpage used in the model were prepared from information supplied by City of Dover and Kent County officials for the period from 1975 through 2000. Pumpage from the Piney Point aquifer estimated by City of Dover officials is shown in Figure 15. For modeling purposes, pumpage was assumed to increase step-wise where each step is a 5-year period. City officials estimated that average Piney Point pumpage would increase from 2.45 Mgal/d (9,270 m<sup>3</sup>/d) during 1975-80 to 4.95 Mgal/d (18,740 m<sup>3</sup>/d) during 1995-2000. Included in Dover's plan was an additional well in the Moore's Lake area a mile south of Dover (Figure 17) and the use of a new well, Jel2-13, at Horsepond Road a mile east of Dover (Figure 4).

Five-year estimates of Piney Point pumpage for Kent County's proposed water authority are shown in Figure 18. These estimates show an increase of 0.5 Mgal/d (1,890 m<sup>3</sup>/d) during 1975-80, to 4.3 Mgal/d (16,280 m<sup>3</sup>/d) during 1995-2000. Locations of proposed production wells for two plans are shown in Figure 17. In County Plan 1, four wells would be spaced along a 5.5 mi (8.8 km) line parallel to Delaware Route 10. County Plan 2 proposes five wells concentrated south of Dover between Delaware Route 10 and U. S. Route 113. Estimated pumpage used in the predictive simulations were divided equally between the wells in both County plans.

### Predictions

The calibrated model was used to simulate the response of water levels in the Piney Point aquifer to estimated pumpage during 1975-2000. The potentiometric surface and

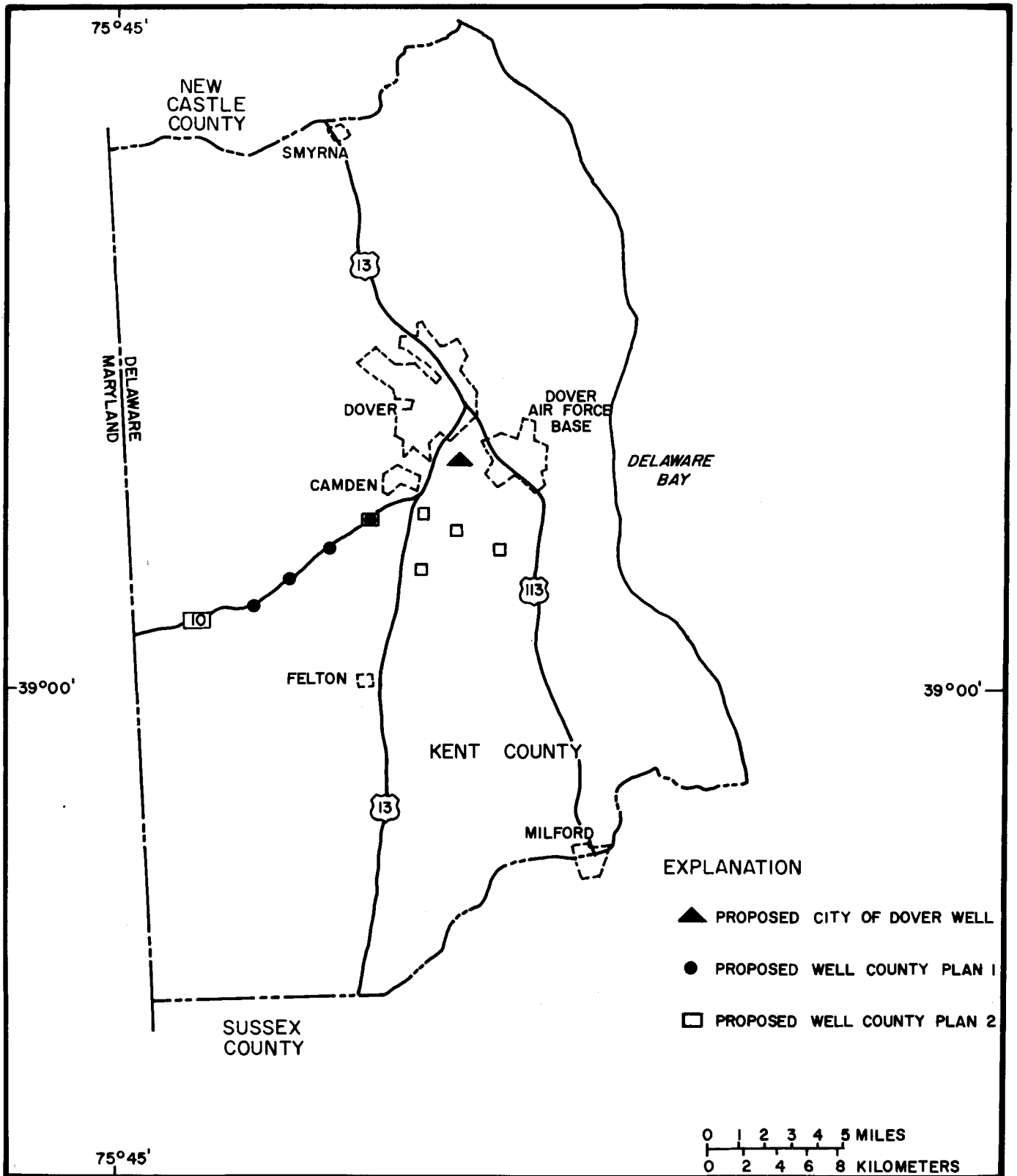


FIGURE 17  
 LOCATIONS OF PROPOSED WELLS USED FOR SIMULATING  
 INCREASED PUMPAGE.

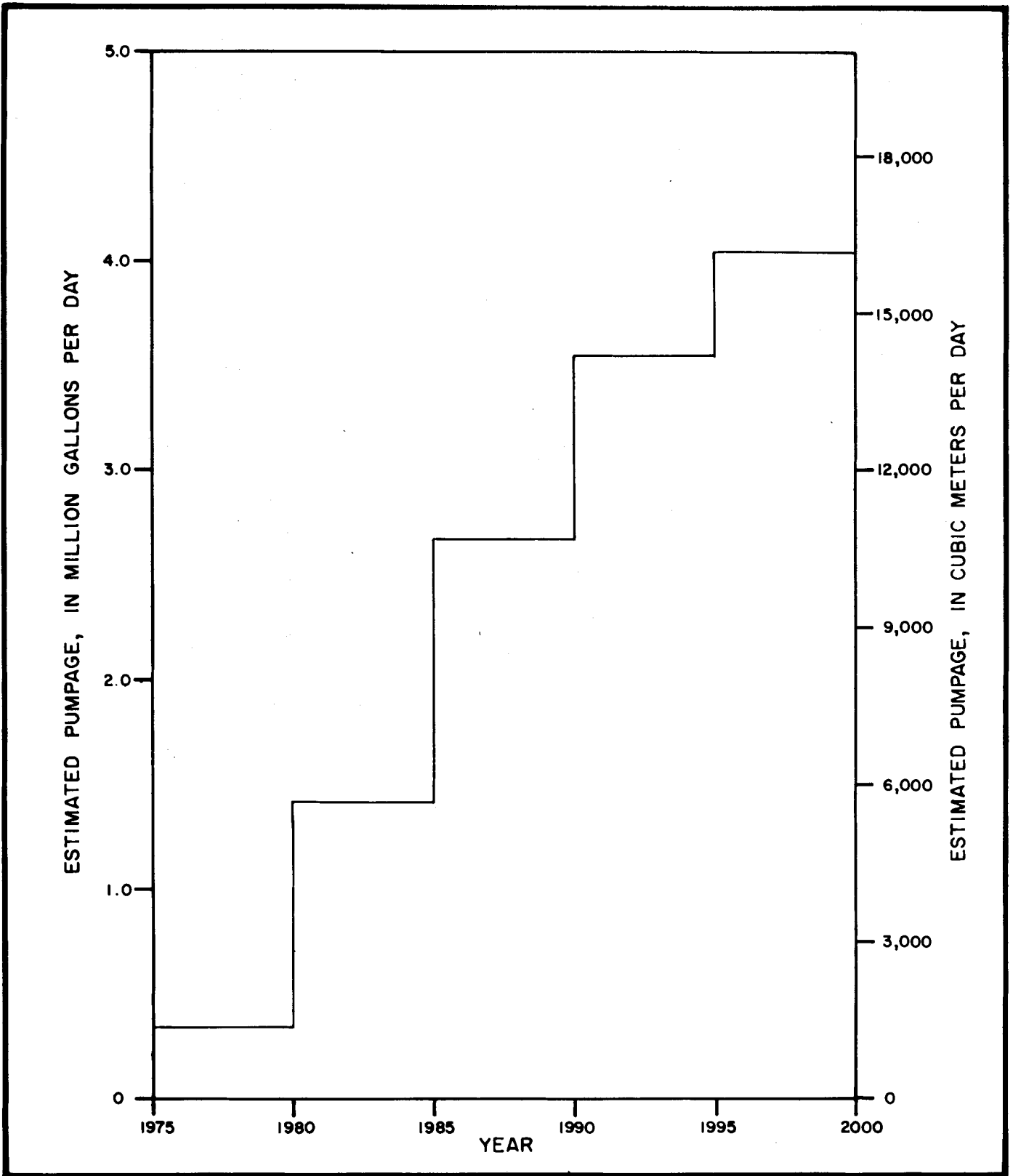


FIGURE 18  
ESTIMATED PUMPAGE BY PROPOSED KENT COUNTY WATER  
AUTHORITY.

withdrawals from the Cheswold aquifer were assumed to remain constant for the period. Also, withdrawals from the Piney Point aquifer by users in Maryland, 5.03 Mgal/d (19,040 m<sup>3</sup>/d), by smaller communities and industries in Kent County, 1.2 Mgal/d (4,580 m<sup>3</sup>/d), and by Dover Air Force Base, 0.53 Mgal/d (2,010 m<sup>3</sup>/d), were assumed to remain constant at the 1974-75 value for the predictive period. Various combinations of the withdrawal plans proposed by both Kent County and the City of Dover were used in the predictive simulations. The following two types of predictive runs were made:

- (1) transient runs, in which the changes in drawdown are computed at the end of a specified time, and
- (2) steady-state runs, which show the changes in drawdown necessary for the aquifer to achieve equilibrium with the applied pumping.

The drawdowns computed by the model are average values for the node. Drawdowns at individual pumping wells would be much greater than these computed values. Table 6 shows the type of simulation, the pumpage, the withdrawal plan simulated and the number of the figure where the results of the predictive run are presented.

A steady-state simulation of the 1975 pumping stress of 2.68 Mgal/d (10,140 m<sup>3</sup>/d) is shown in Figure 19. The simulation shows that water levels would decline at the center of the Dover cone an additional 12 ft (4 m) before reaching equilibrium. Comparison of this figure with the map showing the drawdown available to the top of the Piney Point aquifer as of 1975 (Figure 20), indicates that approximately 163 ft (50 m) of additional drawdown is available in the center of the Dover cone. Figure 21 is the result of a steady-state simulation of a withdrawal of 5.1 Mgal/d (19,300 m<sup>3</sup>/d). Additional pumpage is distributed according to the City plan and represents the 1985-90 withdrawal estimate. Drawdowns in the deepest part of the Dover cone are shown stabilized at 80 ft (24 m) below the 1975 potentiometric surface. Therefore, increasing the 1975 pumpage by 2.42 Mgal/d (9,160 m<sup>3</sup>/d) will cause an increase in head decline of 80 ft (24 m). Also, comparison of the predicted drawdown with the available drawdown (Figure 20) shows that approximately 100 ft (30 m) of drawdown will be available in the Dover area.

Figures 22 and 23 show model results for Jan. 1, 1980 and 1985, respectively, of a transient simulation of the City's pumpage plan. As with the previous simulations, Delaware pumpage included a constant 1.2 Mgal/d (4,540 m<sup>3</sup>/d), representing

TABLE 6. Type of Simulation and Total Delaware Pumpage from the Piney Point Aquifer used for Predictions.

Figure Number	Type of Simulation	Total Pumpage Simulated in Delaware (Mgal/d)	Additional Pumpage Distributed According to Plan	Date of Results	Remarks
19	Steady-State	2.7	---	(1)	Includes 1974 Delaware pumpage with an additional 0.2 Mgal/d for the Dover Air Base Housing well which started pumping in 1975.
21	Steady-State	5.1	City of Dover	(1)	Pumpage simulated was the 1985-90 estimate.
22	Transient	Variable	City of Dover	1/1/80	Pumpage was 3.7 Mgal/d from 1975-80.
23	Transient	Variable	City of Dover	1/1/85	Pumpage was 3.7 Mgal/d from 1975-80, and 4.5 Mgal/d from 1980-85.
24	Steady-State	5.5	County Plan 1	(1)	Pumpage used was the 1985-90 estimate.
25	Steady-State	5.5	County Plan 2	(1)	Pumpage used was the 1985-90 estimate.
26	Transient	Variable	County Plan 1	1/1/85	Pumpage was 3.2 Mgal/d from 1975-80, and 4.3 Mgal/d from 1980-85.
27	Transient	Variable	County Plan 2	1/1/85	Same pumpage as Figure 24.
28	Steady-State	6.0	Combined City and County Plan 1	(1)	Pumpage used was the 1980-85 estimate.
29	Steady-State	6.0	Combined City and County Plan 2	(1)	Pumpage simulated was the 1980-85 estimate.

1 See footnote at end of table, p. 49.

TABLE 6 (continued)

Figure Number	Type of Simulation	Total Pumpage Simulated in Delaware (Mgal/d)	Additional Pumpage Distributed According to Plan	Date of Results	Remarks
30	Transient	Variable	Combined City and County Plan 1	1/1/80	Pumpage simulated 4.2 Mgal/d from 1975-80.
31	Transient	Variable	Combined City and County Plan 1	1/1/85	Pumpage simulated 4.2 Mgal/d 1975-80, and 6.0 Mgal/d from 1980-85.
32	Transient	Variable	Combined City and County Plan 1	1/1/2000	Pumpage simulated was 4.2 Mgal/d 1975-80, 6.0 Mgal/d 1980-85, 7.9 Mgal/d 1985-90, 9.4 Mgal/d 1990-95, and 10.5 Mgal/d from 1995-2000.
33	Transient	Variable	Combined City and County Plan 2	1/1/80	Same pumpage as Figure 30.
34	Transient	Variable	Combined City and County Plan 2	1/1/85	Same pumpage as Figure 31.
35	Transient	Variable	Combined City and County Plan 2	1/1/2000	Same pumpage as Figure 32.
39	Transient	Variable	City of Dover	1/1/85	Same pumpage as Figure 21. Cheswold aquifer head reduced 11 feet areally.

<sup>1</sup>Steady-state simulations are not time dependent.



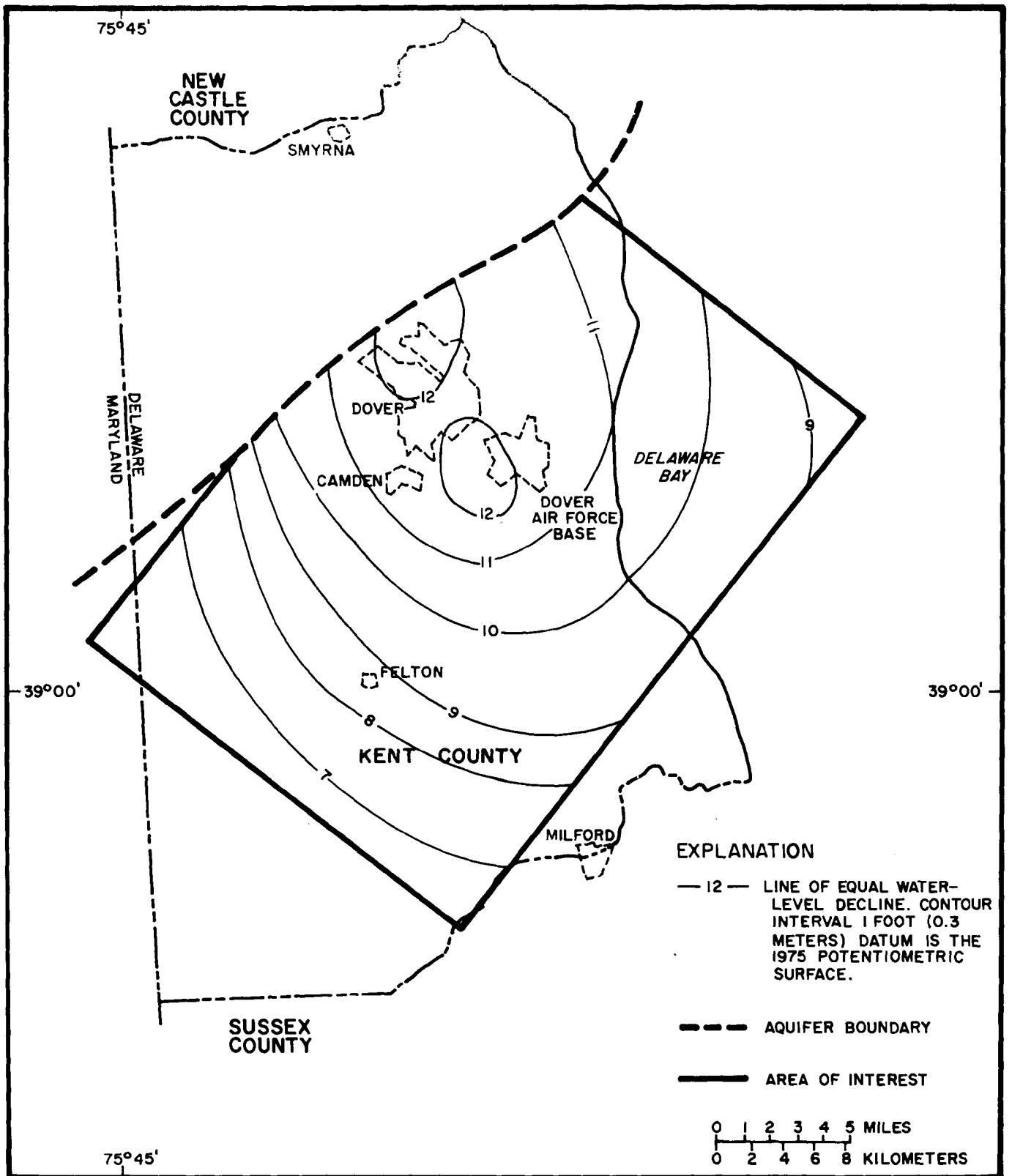


FIGURE 19

PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--STEADY-STATE SIMULATION USING 1975 DELAWARE PUMPAGE OF 2.68 Mgal/d (10,140 m<sup>3</sup>/d).

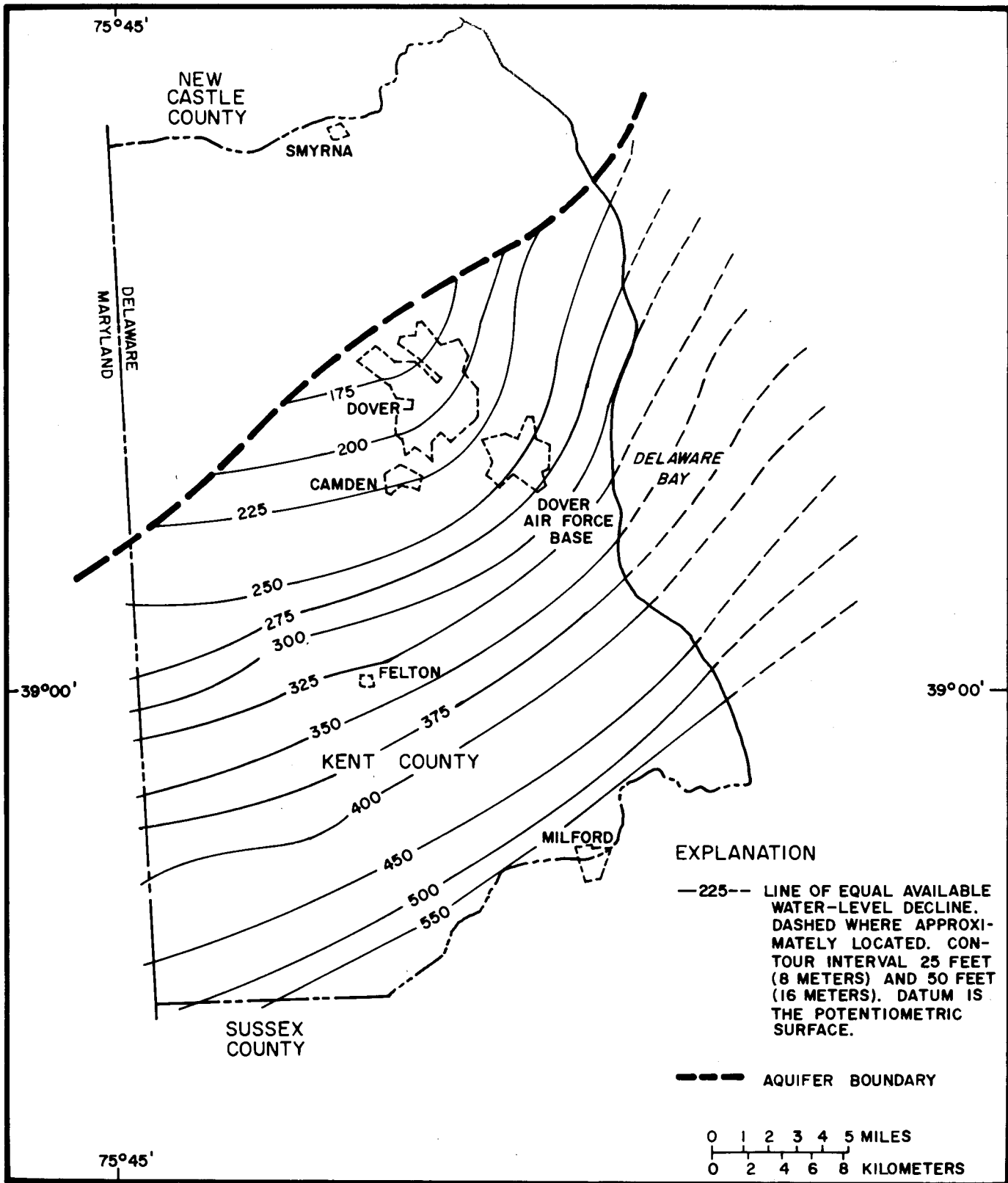


FIGURE 20  
 DRAWDOWN AVAILABLE TO THE TOP OF THE PINEY POINT  
 AQUIFER IN 1975.

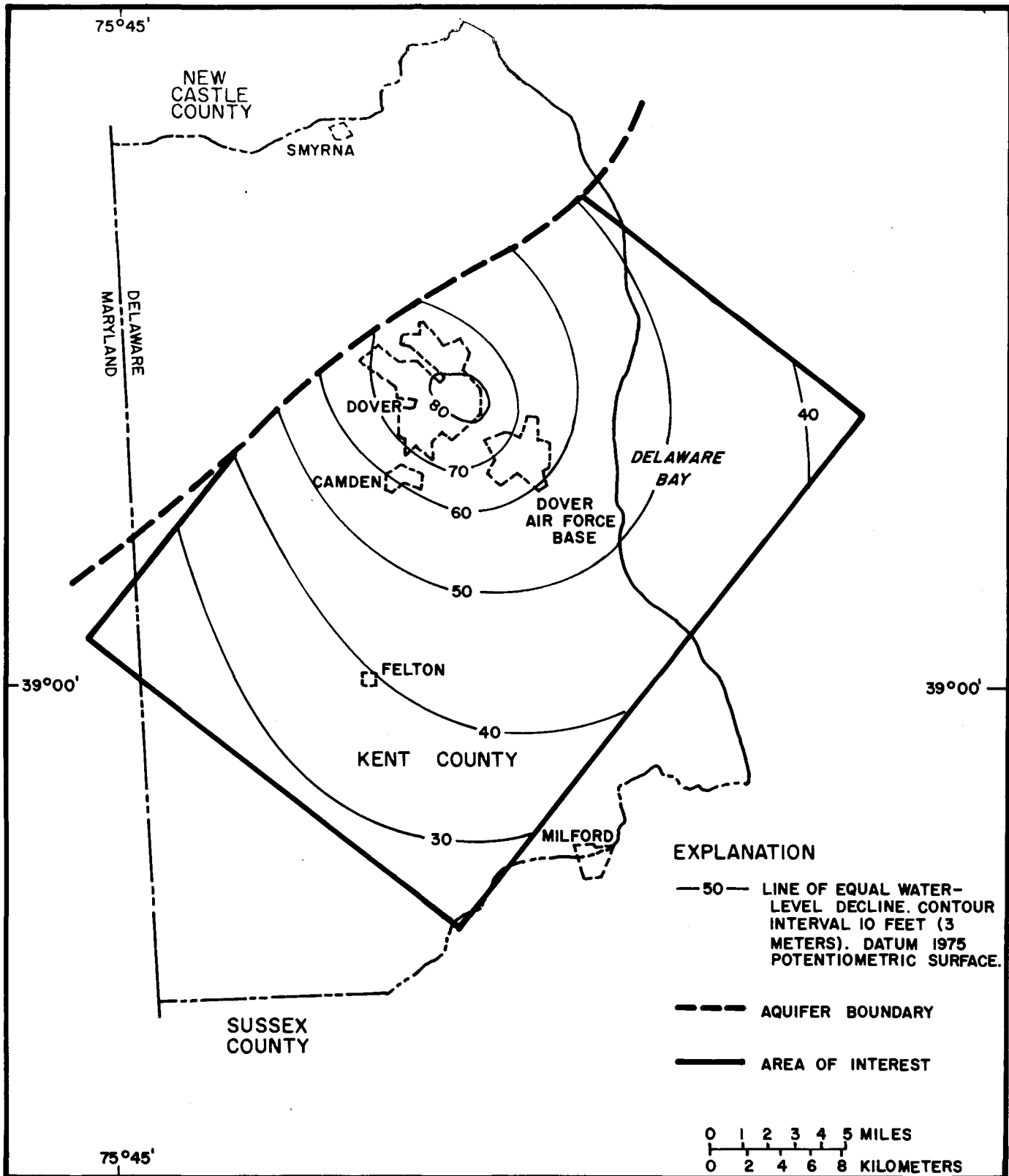


FIGURE 21

PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE-- STEADY-STATE SIMULATION USING 1985-90 DELAWARE PUMPAGE OF 5.1 Mgal/d (19,300 m<sup>3</sup>/d) DISTRIBUTED ACCORDING TO CITY OF DOVER PUMPAGE ESTIMATES.

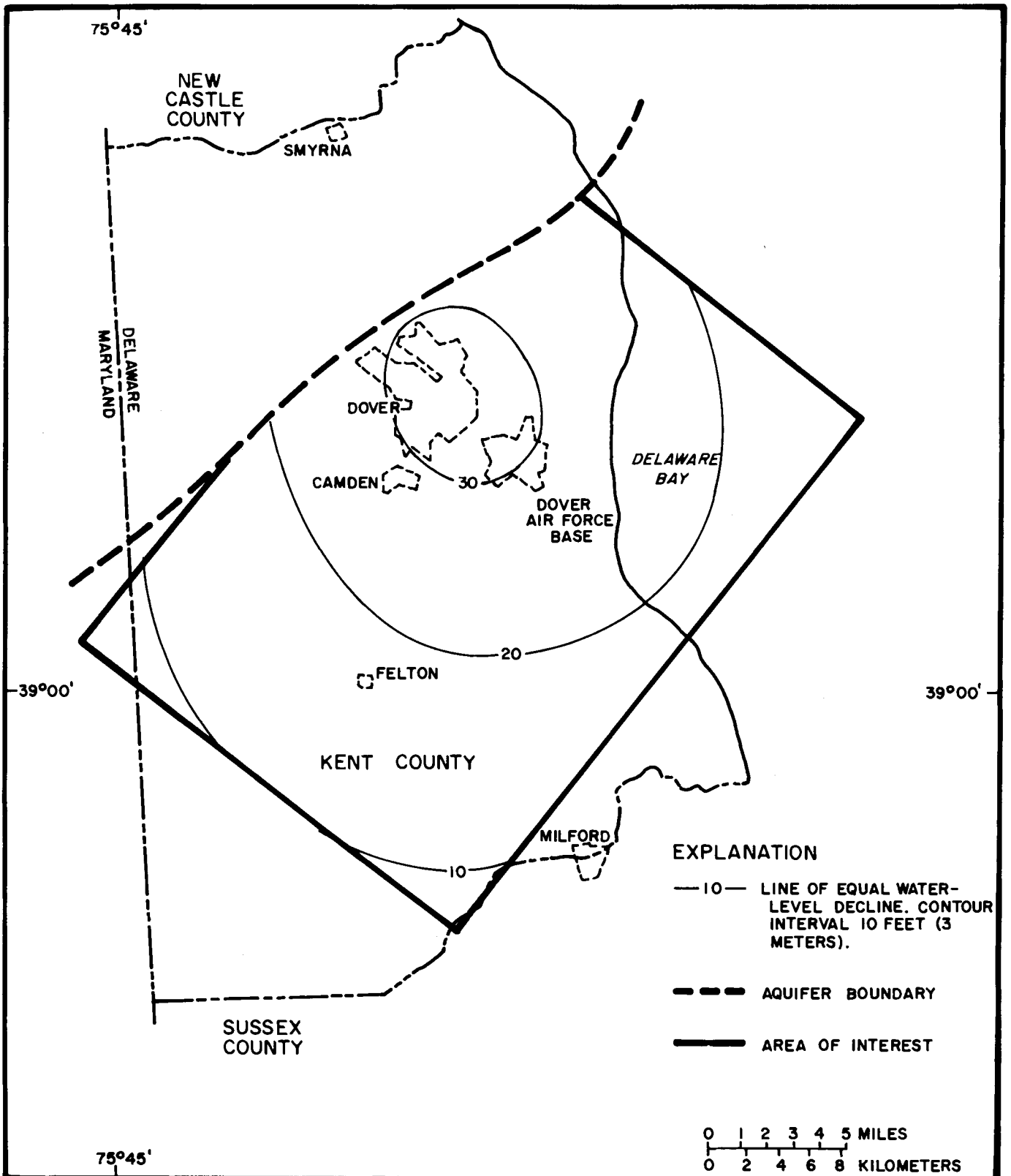
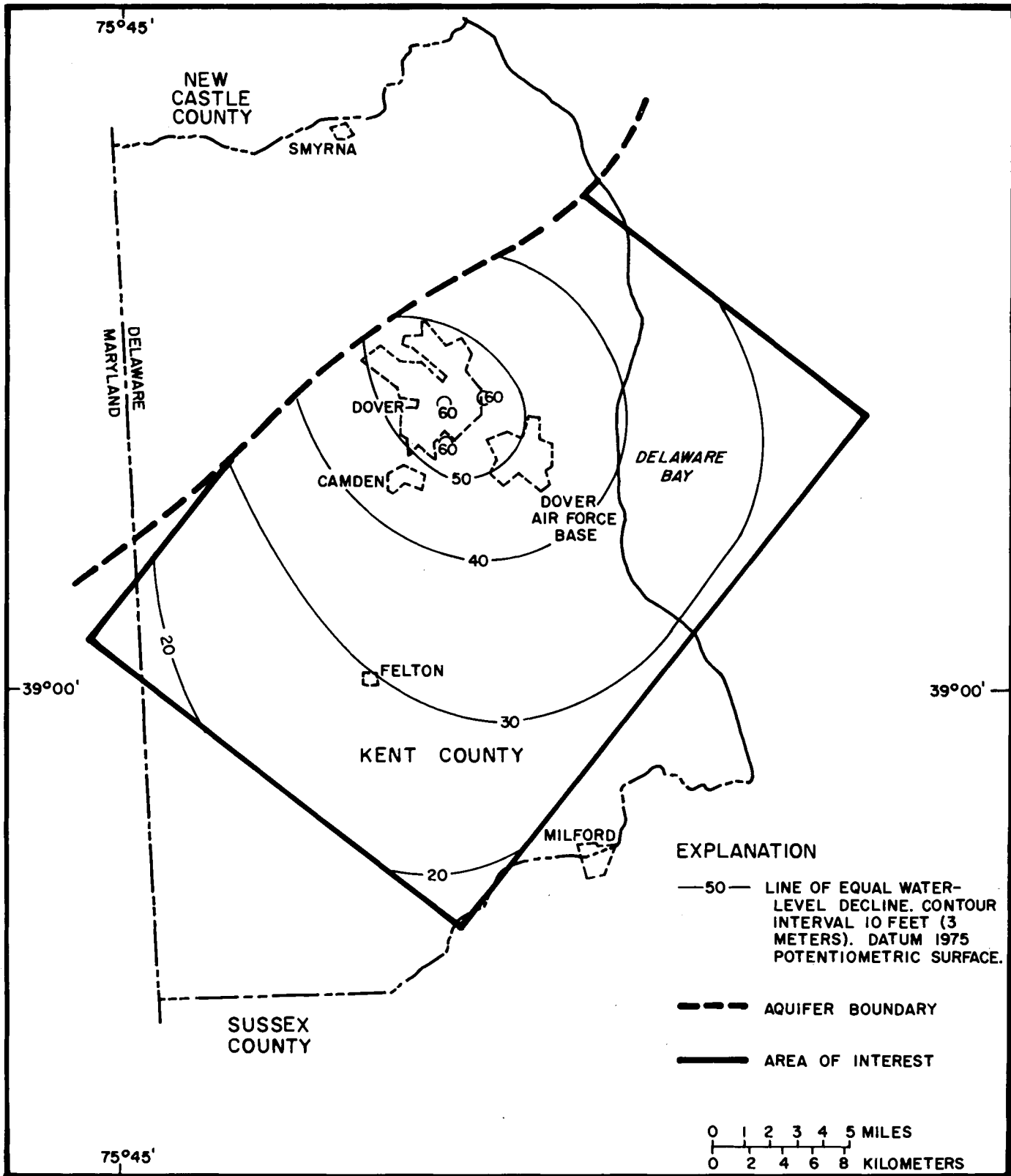


FIGURE 22

PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--TRANSIENT SIMULATION FOR JANUARY 1, 1980 USING CITY OF DOVER PUMPAGE ESTIMATES.



**FIGURE 23**  
**PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--**  
**TRANSIENT SIMULATION FOR JANUARY 1, 1985 USING CITY OF DOVER PUMPAGE**  
**ESTIMATES.**

minor industrial and municipal use in Kent County. The draw-downs computed for January 1980 show the deepest point of the Dover cone at about 30 ft (9 m) below the 1975 water level, leaving approximately 140 ft (42 m) of available drawdown. The total Delaware pumpage was increased in 1980 from 3.6 Mgal/d (13,630 m<sup>3</sup>/d) to 4.5 Mgal/d (17,030 m<sup>3</sup>/d), and remained constant during the 5-year simulation period, 1980-85. Figure 23 shows the drawdown below the 1975 level as of Jan. 1, 1985. The deepest point of the Dover cone is 60 ft (18 m) below the 1975 water level, leaving approximately 120 ft (37 m) to the top of the aquifer. The simulations predict that if withdrawals from the aquifer increase according to City of Dover estimates, water levels will decline 30 ft (9 m) in the center of the cone from Jan. 1, 1980 to Jan. 1, 1985.

Steady-state simulations using a total Delaware pumpage of 5.5 Mgal/d (20,820 m<sup>3</sup>/d) are shown in Figures 24 and 25. The pumpage used in these runs is the 1985-90 withdrawal estimate proposed by both County plans. In both plans, the City of Dover and the minor industrial and municipal pumpage was assumed to remain at 1.5 Mgal/d (5,680 m<sup>3</sup>/d) and 1.2 Mgal/d (4,540 m<sup>3</sup>/d), respectively. In Plan 1, additional County pumpage (Figure 18) was spread along a 5.5 mi (8.9 km) line beginning approximately 5 mi (8 km) southwest of Dover; however, Plan 2 called for additional development to be concentrated 3 to 5 mi (5 to 8 km) south of Dover (Figure 17), where development of the aquifer is already significant.

Drawdowns (Figure 24) resulting from simulation of County Plan 1 show water levels in the Dover area stabilizing at approximately 50 to 60 ft (15 to 18 m) below the 1975 level. In contrast, the declines (Figure 25) resulting from simulation of County Plan 2 indicates water levels would reach equilibrium at approximately 60 to 70 ft (18 to 21 m) below the 1975 level in the Dover area. A comparison of Figures 24 and 25 illustrates that when pumping is concentrated in a small area, the center of the resulting drawdown cone will be deeper than when the pumpage is spread over a large area. Comparison of the predicted drawdowns with the available draw-down map indicates that at least 115 ft (35 m) of additional drawdown will be available. Simulation results of the Plan 1 pumpage show this minimum located about 4 mi (6 km) southwest of Dover. In contrast, results using Plan 2 show the minimum located in or very near the City of Dover.

Figure 26 and 27 show results for Jan. 1, 1985 of transient simulations of County Plans 1 and 2. Estimated total Delaware pumpage used in both plans was 3.2 Mgal/d (12,110 m<sup>3</sup>/d)

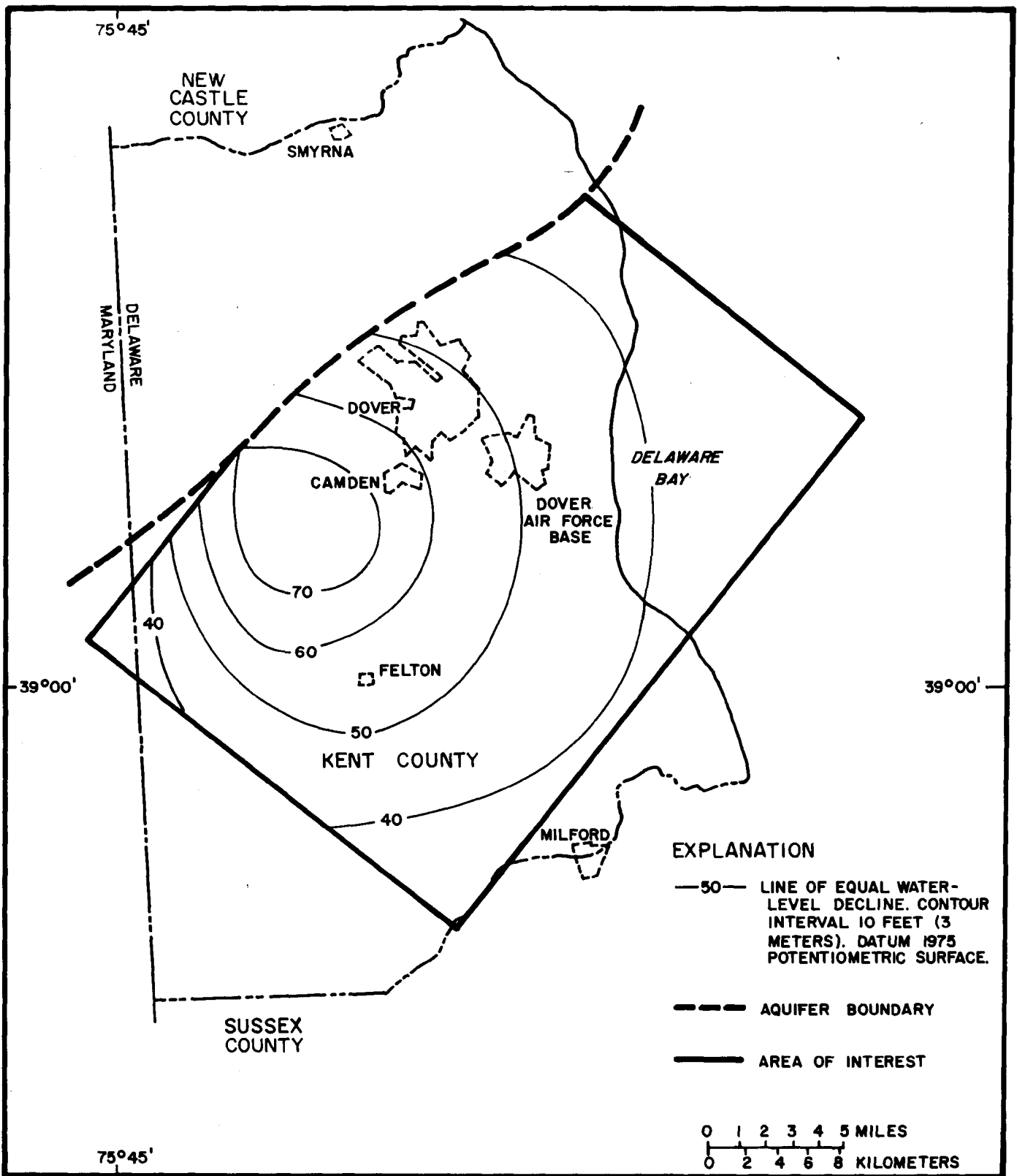


FIGURE 24

PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE-- STEADY-STATE SIMULATION USING 1985-90 DELAWARE PUMPAGE OF 5.5 Mgal/d (20,820 m<sup>3</sup>/d) DISTRIBUTED ACCORDING TO COUNTY PLAN I PUMPAGE ESTIMATES.

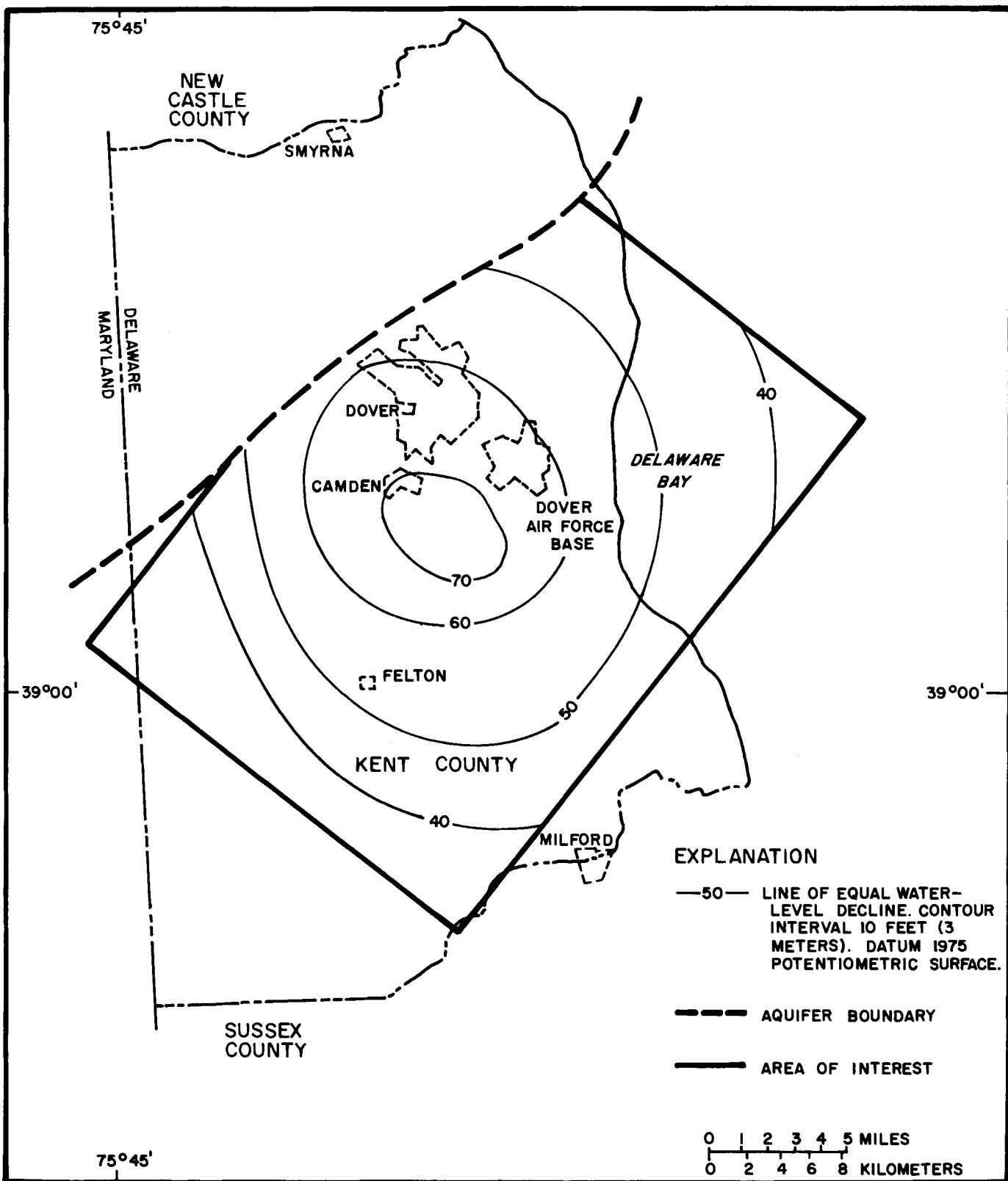


FIGURE 25

PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE-- STEADY-STATE SIMULATION USING 1985-90 DELAWARE PUMPAGE OF 5.5 Mgal/d (20,820 m<sup>3</sup>/d) DISTRIBUTED ACCORDING TO COUNTY PLAN 2 PUMPAGE ESTIMATES.



during 1975-80 and 4.25 Mgal/d (16,090 m<sup>3</sup>/d) during 1980-85. The additional pumpage was distributed differently in each County plan (Figure 17). Figures 26 and 27 show the cones centered southwest and south of Dover, respectively. Drawdown in the deepest part of the cones will reach about 40 ft (12 m) below the 1975 level by 1985. The cones are approximately the same, except that they are centered near the respective additional development.

Figures 28 and 29 show the predicted declines needed for the aquifer to reach steady-state with an estimated 1980 to 1985 average Delaware pumpage of 6.0 Mgal/d (22,710 m<sup>3</sup>/d). The pumpage is distributed according to City Plan and County Plan 1 or County Plan 2, respectively. Drawdown will stabilize at about 80 ft (24 m) below the 1975 level (Figure 28) using the City Plan and County Plan 1 estimates of future pumpage. This leaves approximately 95 ft (29 m) of available drawdown to the top of the aquifer in the Dover area. Similarly, the simulation in which the City Plan and County Plan 2 estimates were used (Figure 29) indicates that water levels will stabilize at approximately 90 ft (27 m) below the 1975 water level at the center of the Dover cone, leaving a minimum of about 90 ft (27 m) of available drawdown in Dover.

Figures 30, 31, and 32 show transient changes in drawdown for Jan. 1, 1980; Jan. 1, 1985; Jan. 1, 2000, respectively, predicted by simulation of a combined City Plan and County Plan 1 pumpage estimates. The total Delaware pumpage used in the simulation consisted of: (1) 4.2 Mgal/d (15,900 m<sup>3</sup>/d) during 1975-80; (2) 6.0 Mgal/d (22,710 m<sup>3</sup>/d) during 1980-85; (3) 7.9 Mgal/d (29,900 m<sup>3</sup>/d) during 1985-90; (4) 9.4 Mgal/d (35,589 m<sup>3</sup>/d) during 1990-95; and (5) 10.5 Mgal/d (39,740 m<sup>3</sup>/d) during 1995-2000. The 1980 map (Figure 30) shows water-level decline in the center of the Dover cone reaching about 40 ft (12 m) below the 1975 level. In contrast, the 1985 map (Figure 31) shows drawdowns in Dover of 80 ft (24 m) below the 1975 level; and by 2000 (Figure 32) drawdowns are predicted to be 180 ft (55 m) below the 1975 level.

Comparison of the predicted drawdown maps (Figures 30, 31, and 32) with Figure 20, indicates that the minimum drawdown available in the Dover area will be about 140 ft (43 m) on Jan. 1, 1980; 100 ft (30 m) on Jan. 1, 1985; and 10 ft (3 m) on Jan. 1, 2000. Comparison of the steady-state (Figure 28) and transient simulations (Figure 31) shows that on Jan. 1, 1985, water levels in the center of the Dover cone will be approximately 10 ft (3 m) above the stabilized water levels. The results of a predictive run using the combined City Plan and County Plan 2 pumpage is shown in Figures 33, 34, and 35. The pumpage estimates are the same as the estimates used in

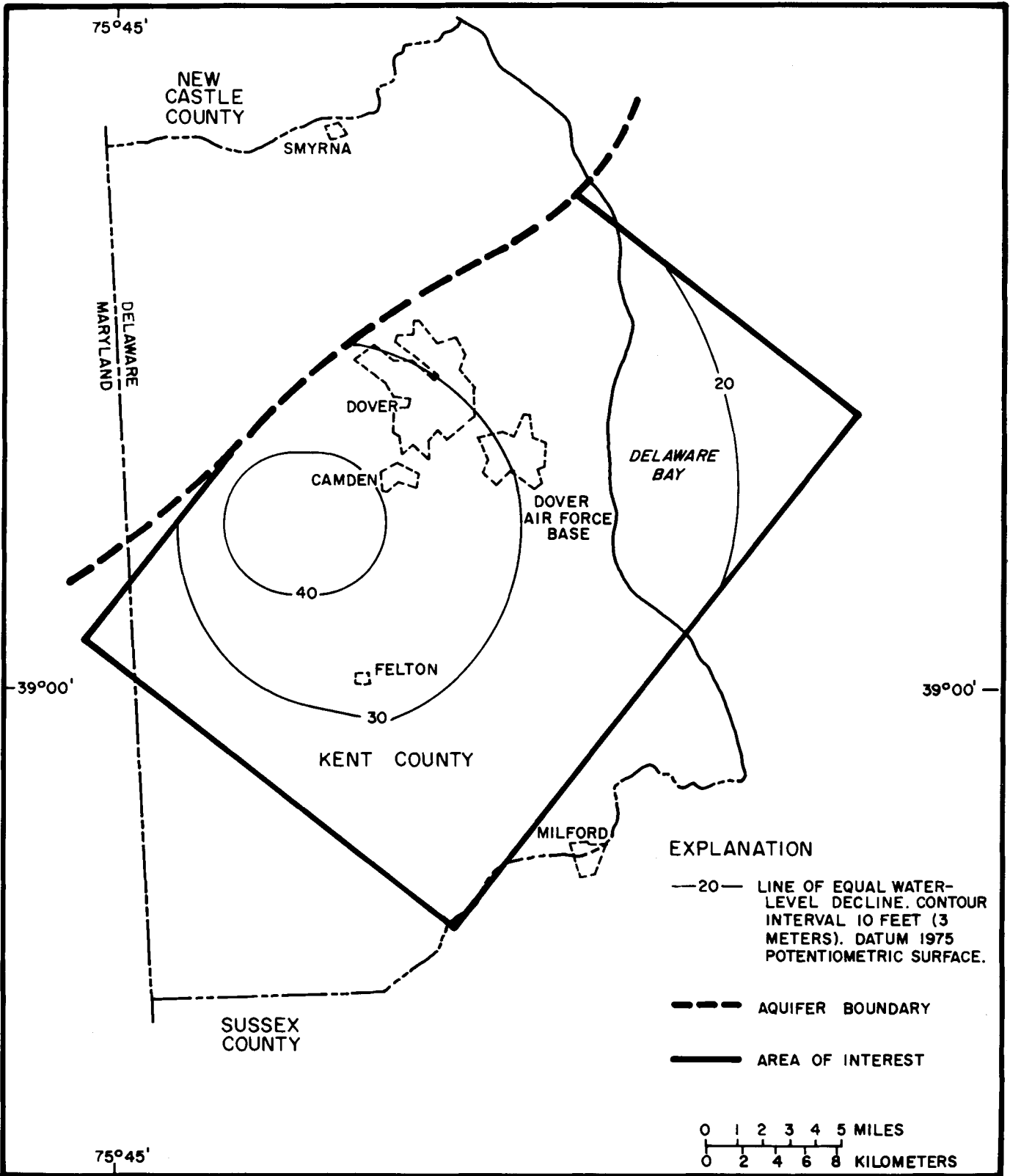


FIGURE 26  
 PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--  
 TRANSIENT SIMULATION FOR JANUARY 1, 1985 USING COUNTY PLAN I PUMPAGE  
 ESTIMATES.

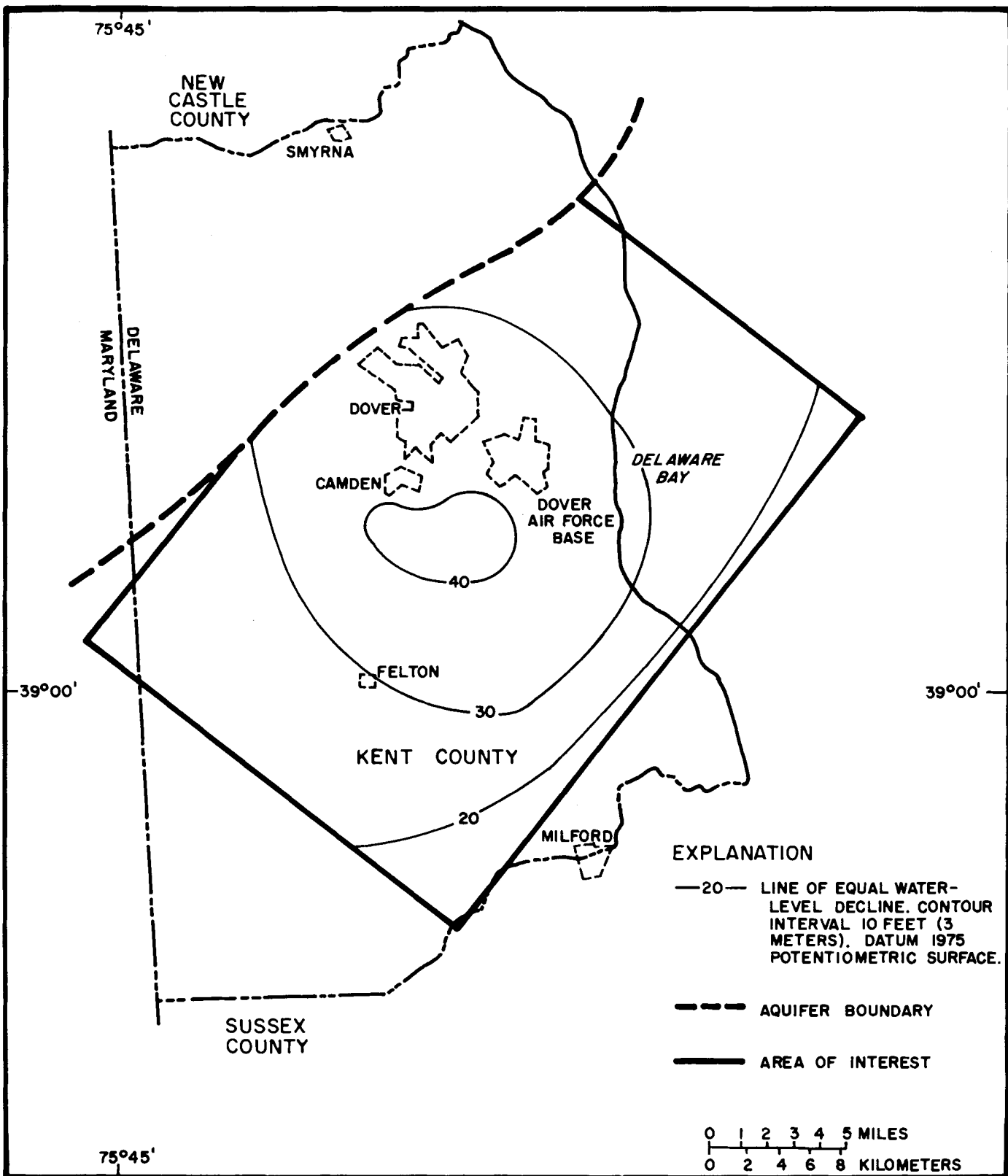
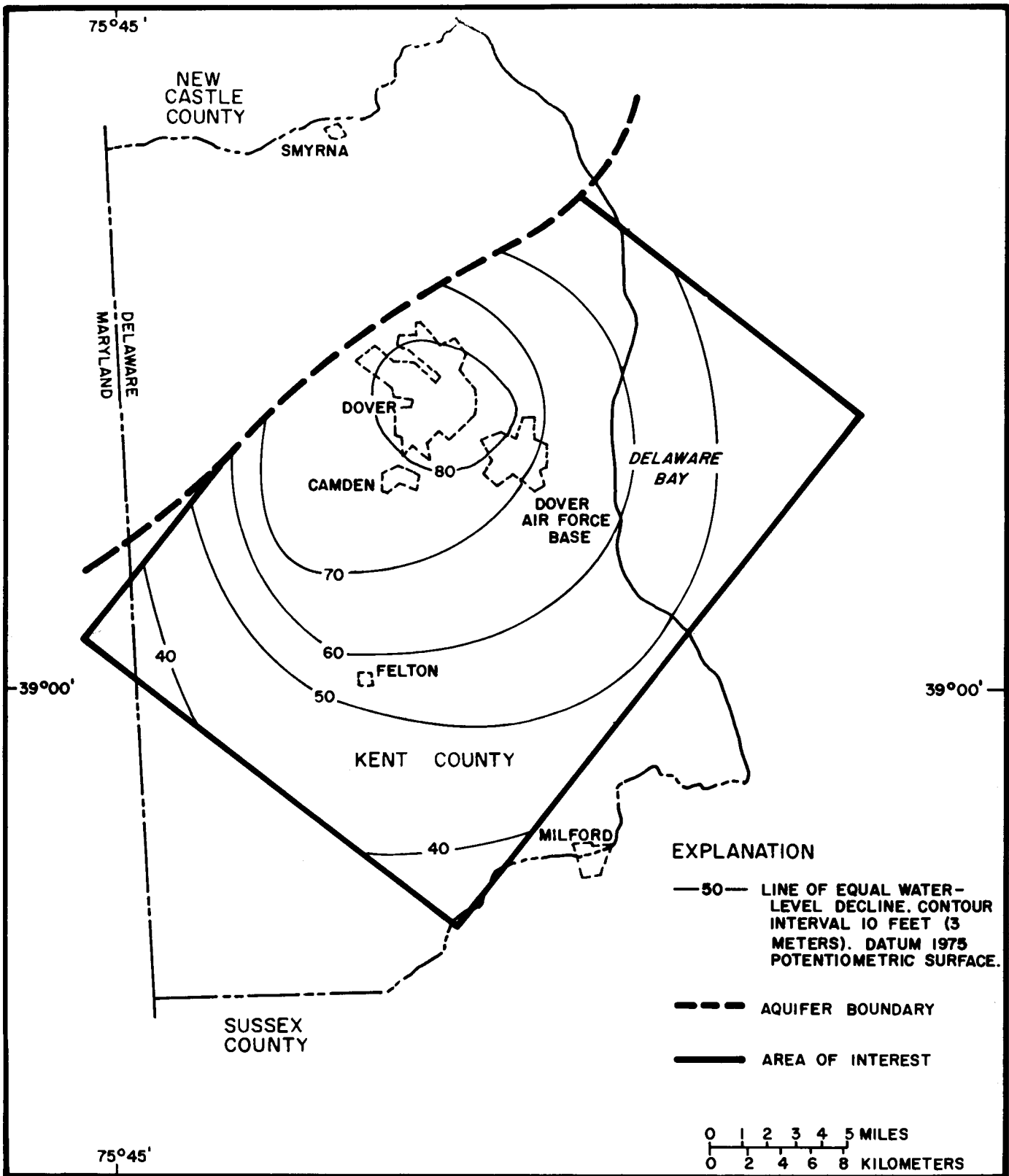


FIGURE 27

PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE-- TRANSIENT SIMULATION FOR JANUARY 1, 1985 USING COUNTY PLAN 2 PUMPAGE ESTIMATES.



**FIGURE 28**  
**PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--**  
**STEADY-STATE SIMULATION USING 1980-85 DELAWARE PUMPAGE OF 6.0 Mgal/d**  
**(22,710 m<sup>3</sup>/d) DISTRIBUTED ACCORDING TO CITY OF DOVER PLAN AND COUNTY**  
**PLAN 1.**

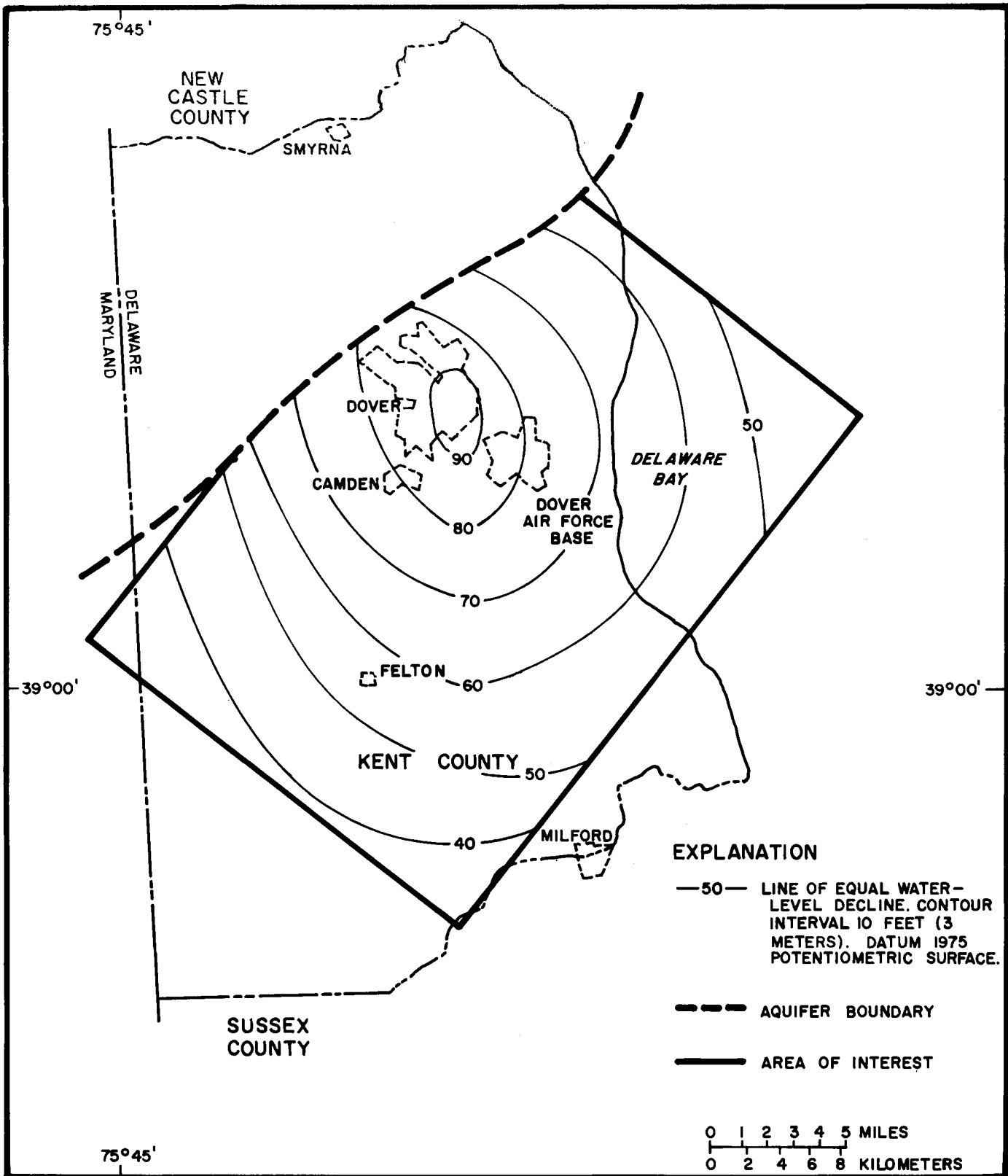


FIGURE 29

PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--  
 STEADY-STATE SIMULATION USING 1980-85 DELAWARE PUMPAGE OF 6.0 Mgal/d  
 (22,710 m<sup>3</sup>/d) DISTRIBUTED ACCORDING TO CITY OF DOVER PLAN AND COUNTY  
 PLAN 2.

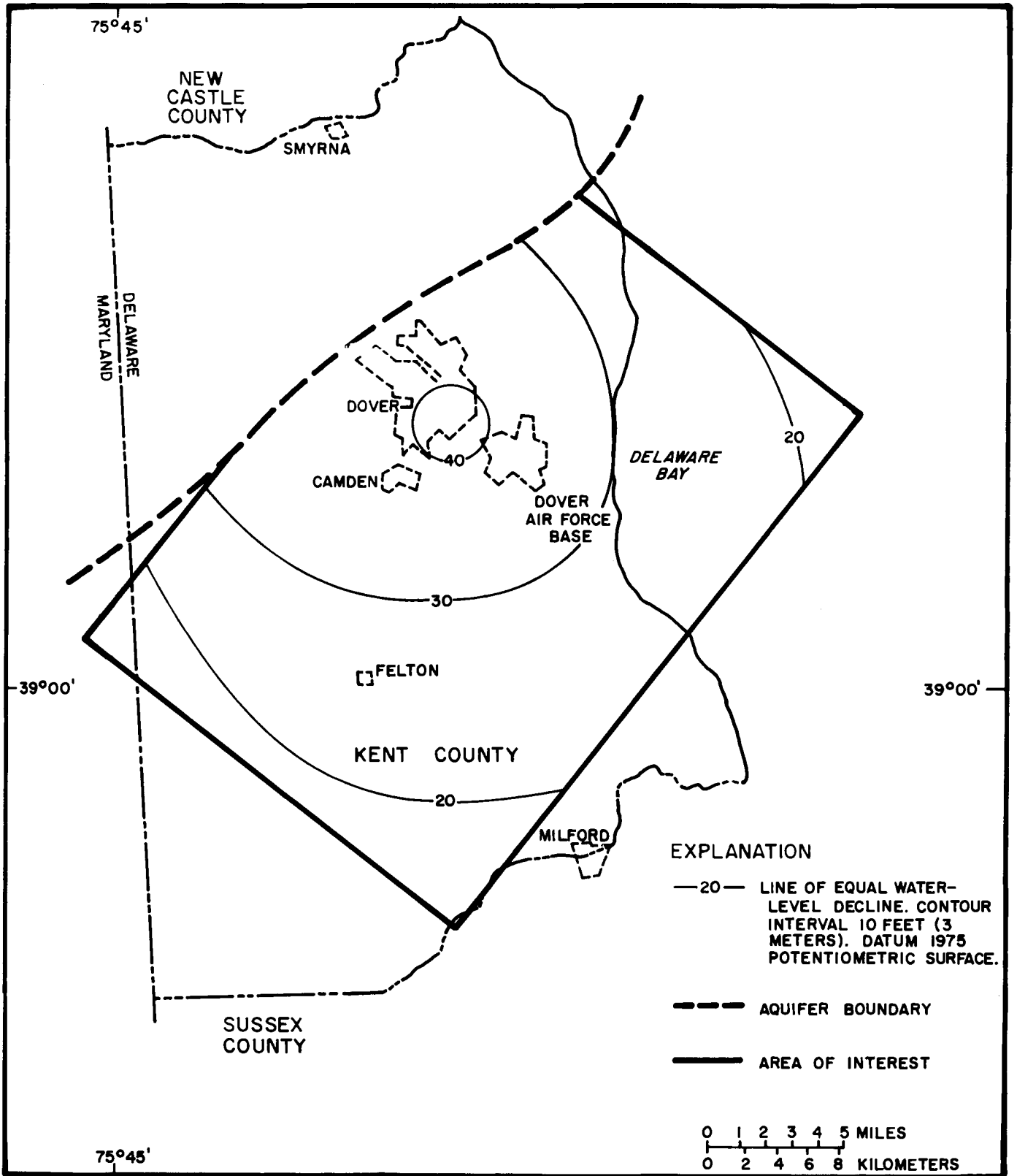
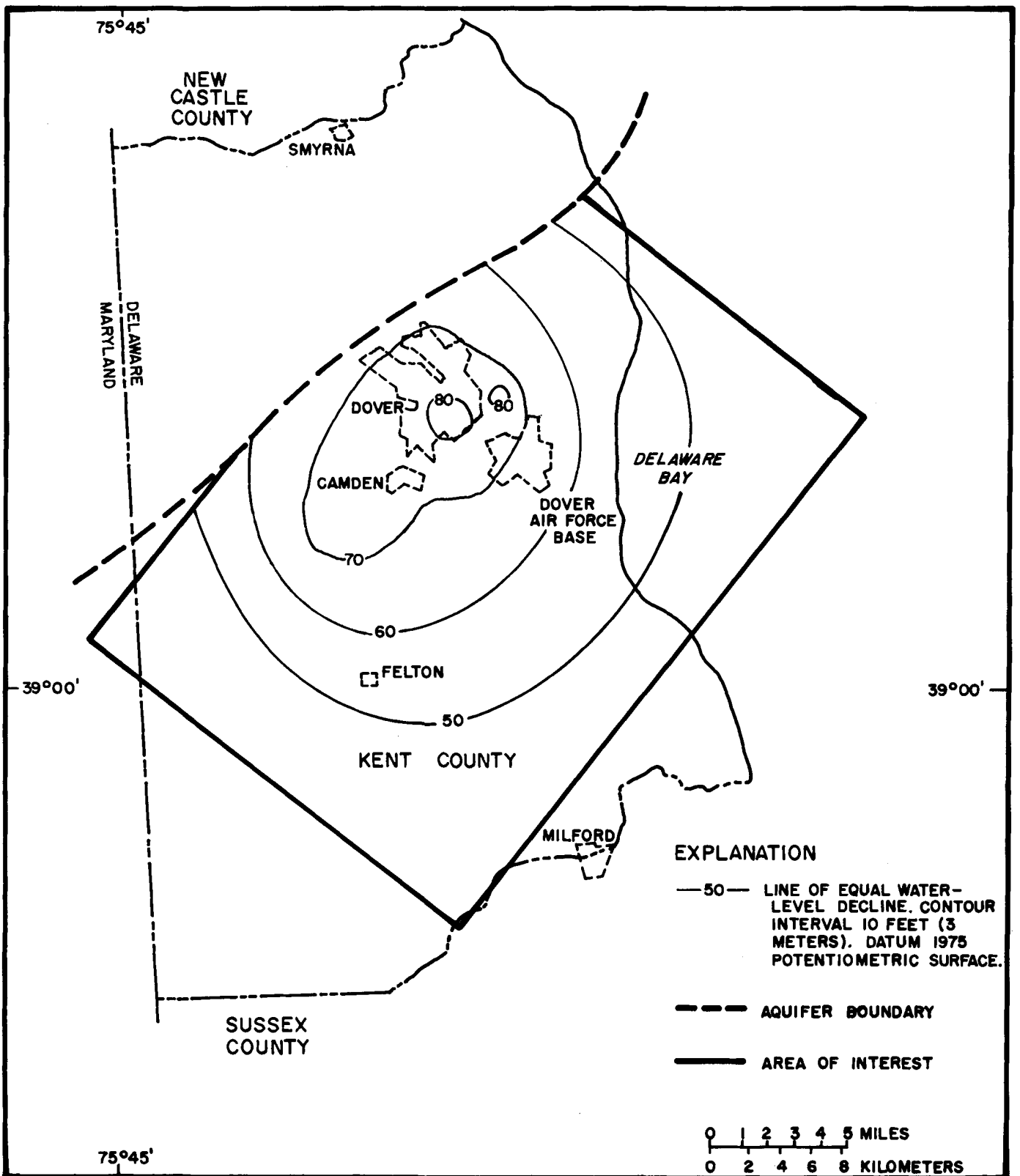


FIGURE 30  
 PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--  
 TRANSIENT SIMULATION FOR JANUARY 1, 1980 USING CITY OF DOVER AND  
 COUNTY PLAN I PUMPAGE ESTIMATES.



**FIGURE 31**  
**PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--**  
**TRANSIENT SIMULATION FOR JANUARY 1, 1985 USING CITY OF DOVER AND COUNTY**  
**PLAN 1 PUMPAGE ESTIMATES.**

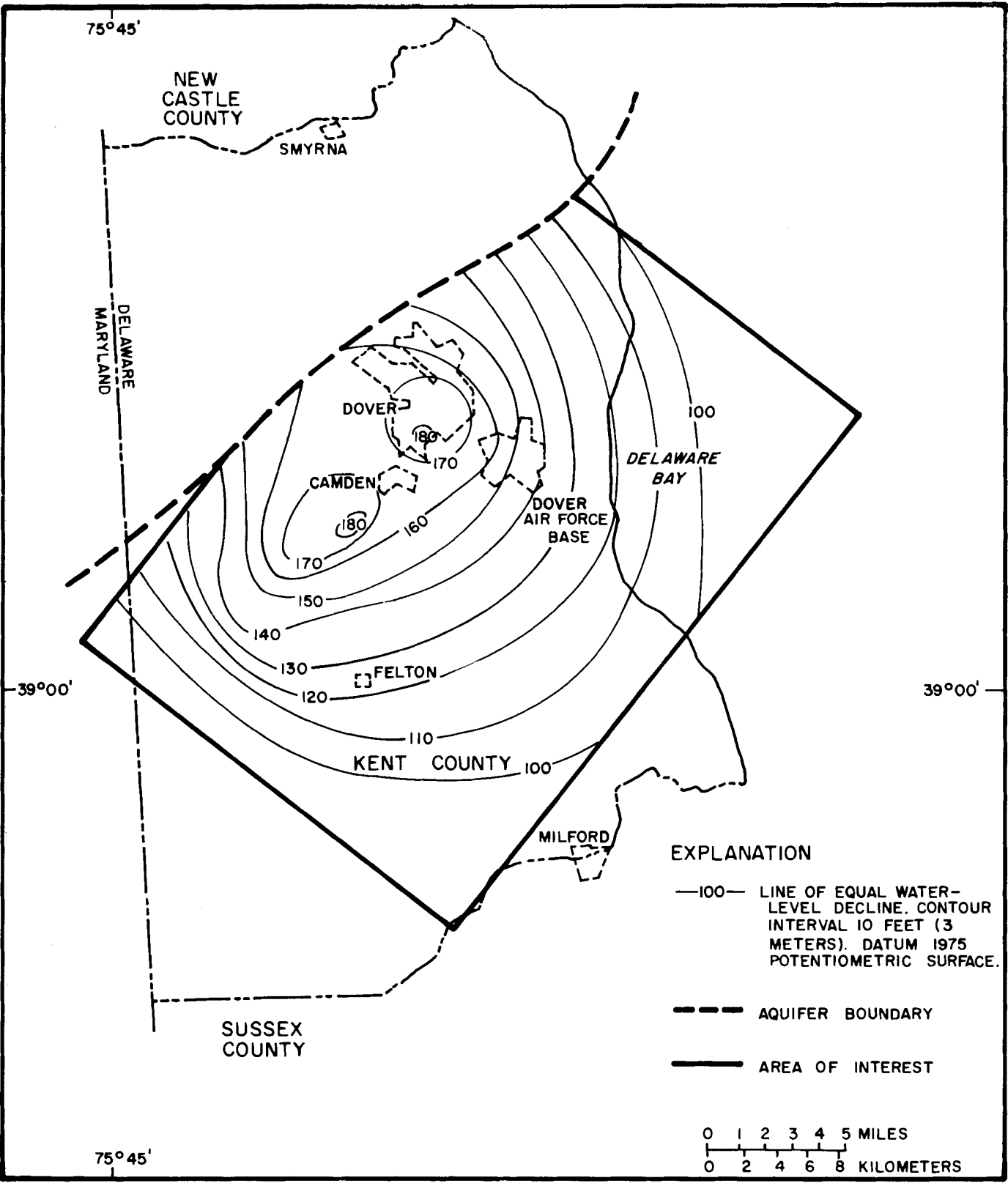


FIGURE 32  
 PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--  
 TRANSIENT SIMULATION FOR JANUARY 1, 2000 USING CITY OF DOVER AND  
 COUNTY PLAN 1 PUMPAGE ESTIMATES.



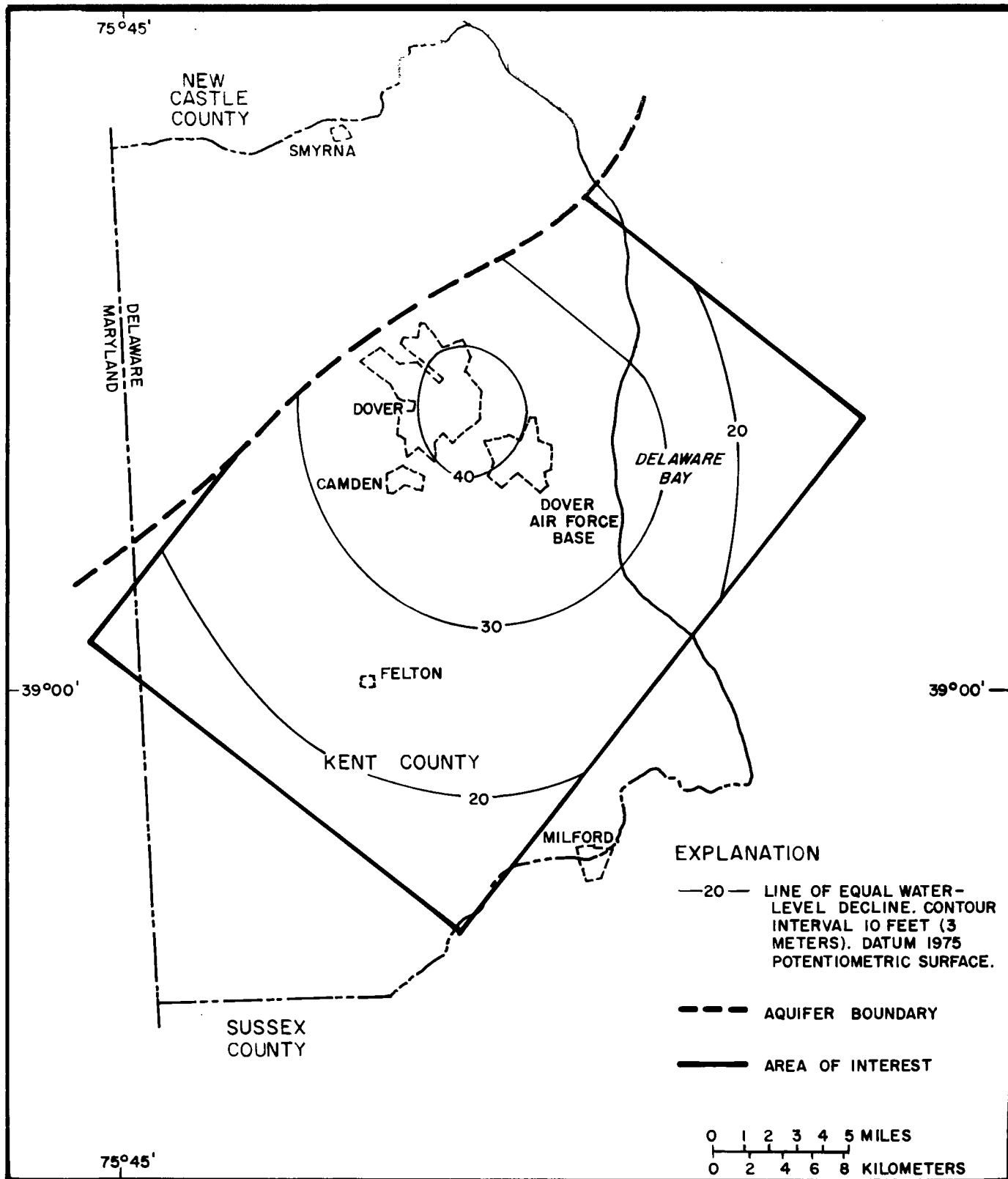
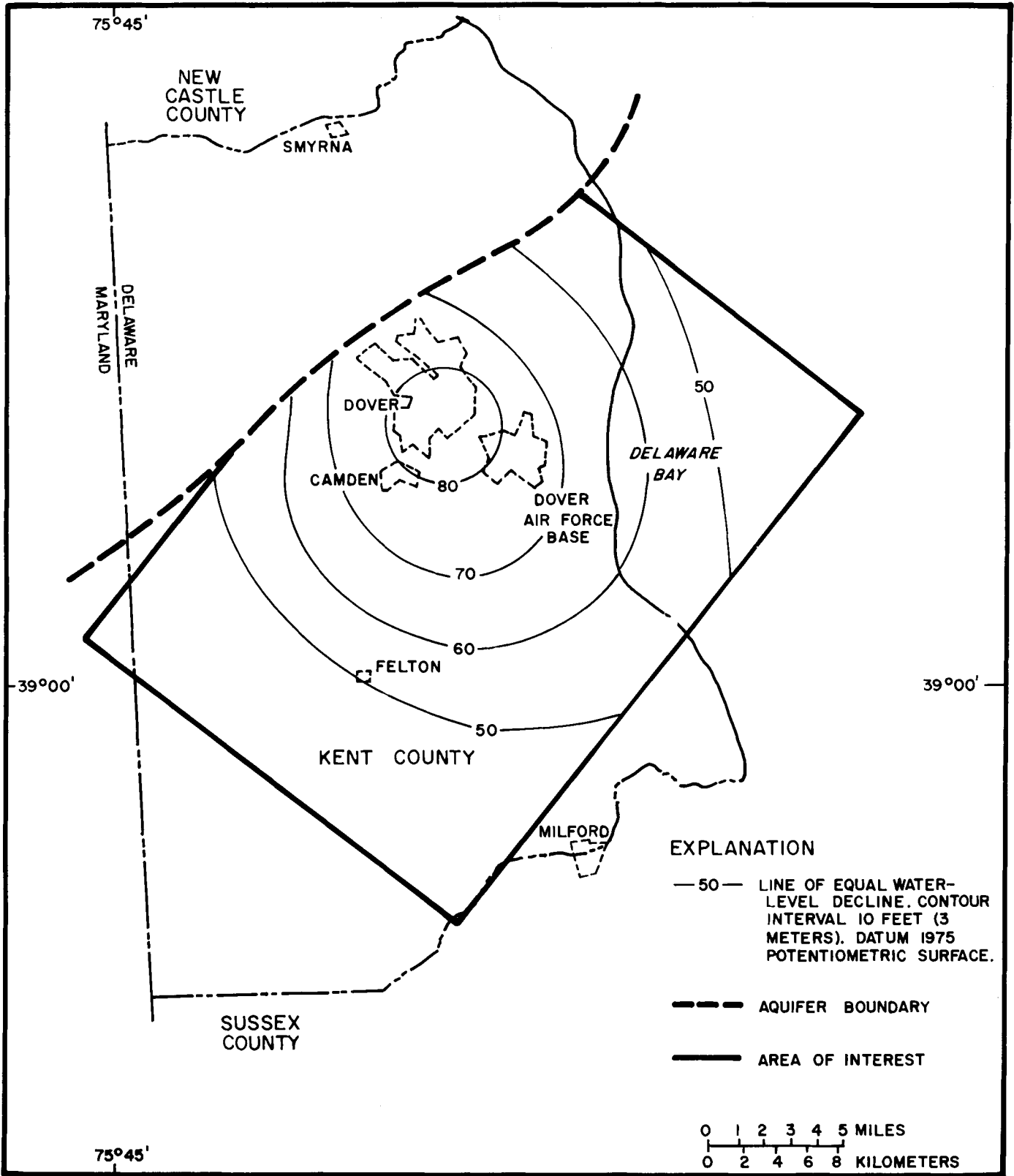
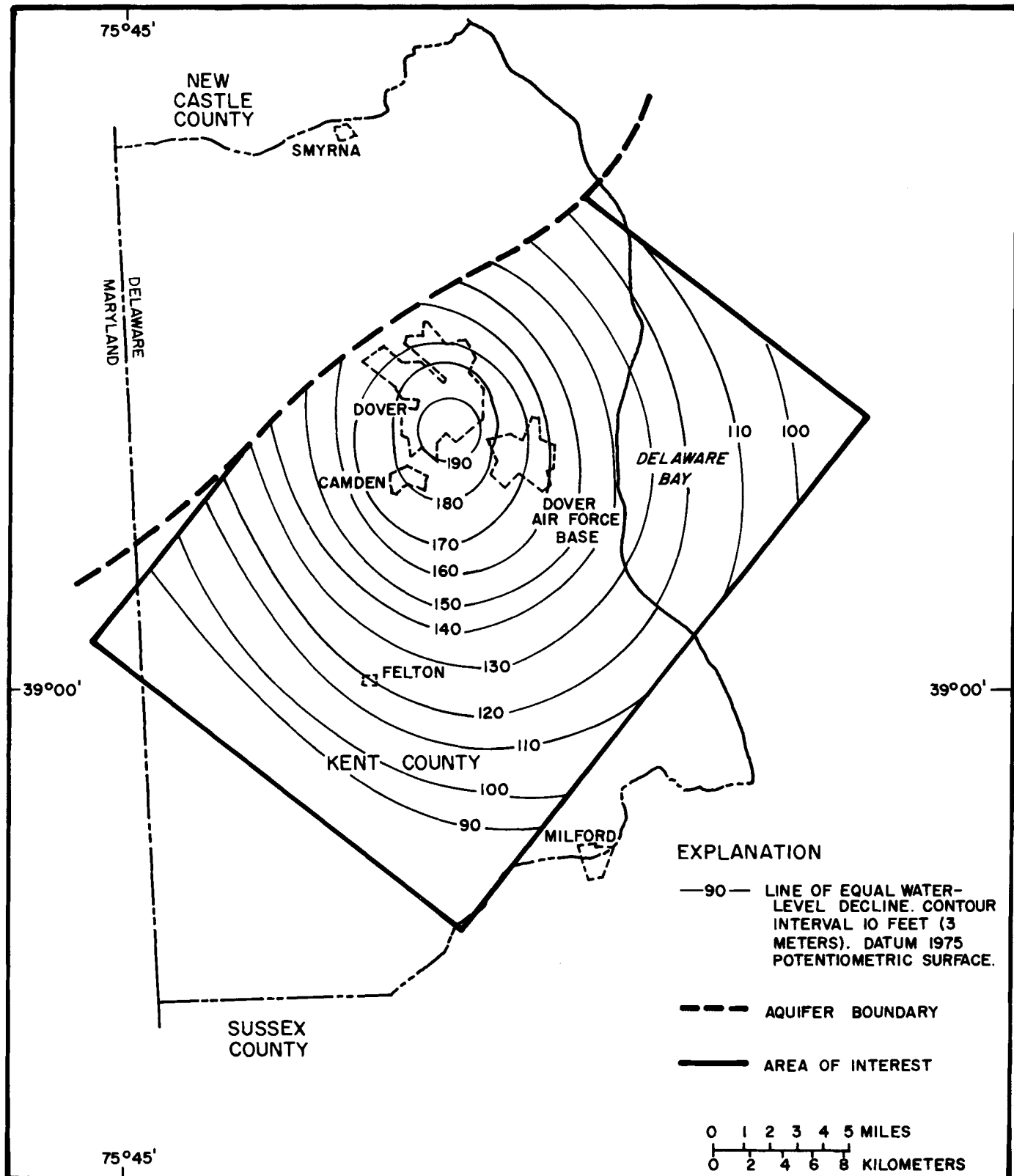


FIGURE 33  
 PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--  
 TRANSIENT SIMULATION FOR JANUARY 1, 1980 USING CITY OF DOVER AND COUNTY  
 PLAN 2 PUMPAGE ESTIMATES.



**FIGURE 34**  
**PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--**  
**TRANSIENT SIMULATION FOR JANUARY 1, 1985 USING CITY OF DOVER AND COUNTY**  
**PLAN 2 PUMPAGE ESTIMATES.**



**FIGURE 35**  
**PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE--**  
**TRANSIENT SIMULATION FOR JANUARY 1, 2000 USING CITY OF DOVER AND**  
**COUNTY PLAN 2 PUMPAGE ESTIMATES.**

the combined City Plan and County Plan 1 simulation. However, the distribution of County pumpage is different in each of the simulations. Figures 33, 34, and 35 show the drawdown maps for Jan. 1, 1980; Jan. 1, 1985; and Jan. 1, 2000, respectively. By 1980 (Figure 33) water-level declines of 40 ft (12 m) below the 1975 level in the center of the Dover cone are predicted. By 1985 (Figure 34) and 2000 (Figure 35) water-level declines of a maximum of 80 ft (24 m) and 190 ft (58 m) below the 1975 level are predicted. Comparison with predictions using the combined City Plan and County Plan 1 (Figures 30, 31, and 32) illustrates that: the early transient results (Figures 30 and 33) for both development proposals may appear somewhat similar, but as the simulation proceeds, the resulting drawdowns (Figures 31 and 34, 32 and 35) will become markedly different owing to differences in the distribution of pumpage.

Figures 36, 37, and 38 show hydrographs that were generated by the transient simulations for three long-term observation wells in Delaware. At the White Oak Road, City of Dover observation well Id55-1 (Figure 37), the predicted water levels, based on combined City Plan and County Plan 2 pumpage estimates had declined to within 21 ft (6 m) of the top of the aquifer by 2000. Also, the hydrographs, based on the two County plans, the combined City Plan and County Plan 1, and the combined City Plan and County Plan 2, showed significant declines. At the Dover Air Force Base observation well, Je32-4 (Figure 36), similar declines were predicted late in the simulation period. Because these hydrographs represent static water levels, expected pumping levels in production wells will be significantly lower. The hydrographs representing the combined City and County plans indicate that pumping levels in production wells near these two observation wells in the center of the Dover cone will probably fall below the top of the aquifer sometime in the latter part of the simulation.

The drawdown map shown in Figure 39 resulted from a simulation identical to the one shown in Figure 23, except that the heads in the overlying Cheswold aquifer were uniformly reduced by 11 ft (3 m). These comparison runs were made to illustrate the sensitivity of the model to the often unrealistic assumption that heads in the overlying aquifer remain constant throughout a simulation. The results of these simulations (Figures 23 and 39) indicate that during transient conditions an 11 ft (3 m) reduction in head in the Cheswold aquifer results in Piney Point aquifer heads that are reduced a maximum of 11 ft (3 m). This is also illustrated by the hydrographs in Figures 36, 37, and 38. An additional steady-state

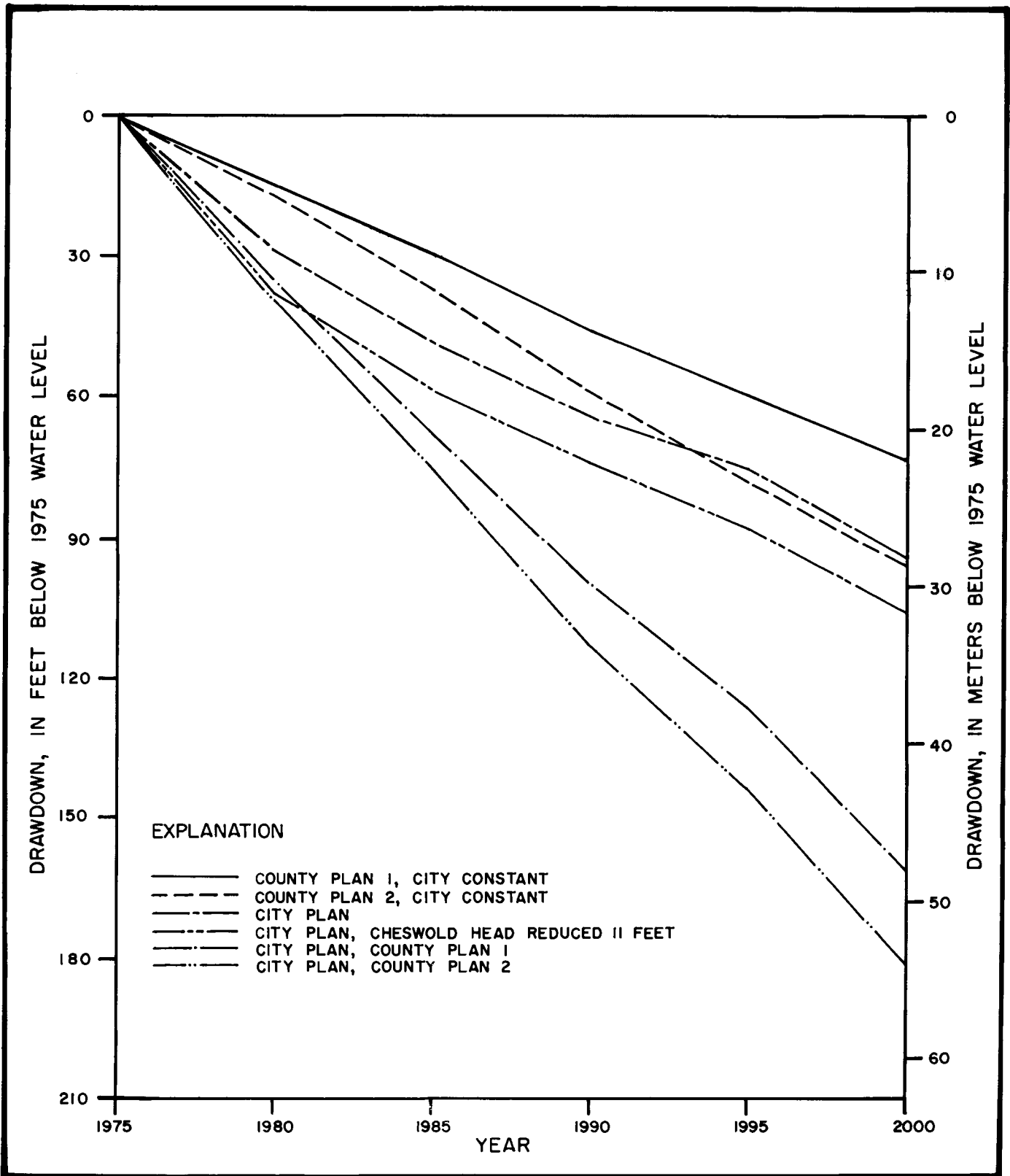


FIGURE 36  
 SIMULATED HYDROGRAPHS FOR OBSERVATION WELL Je 32-4 AT  
 DOVER AIR FORCE BASE FOR 1975-2000.

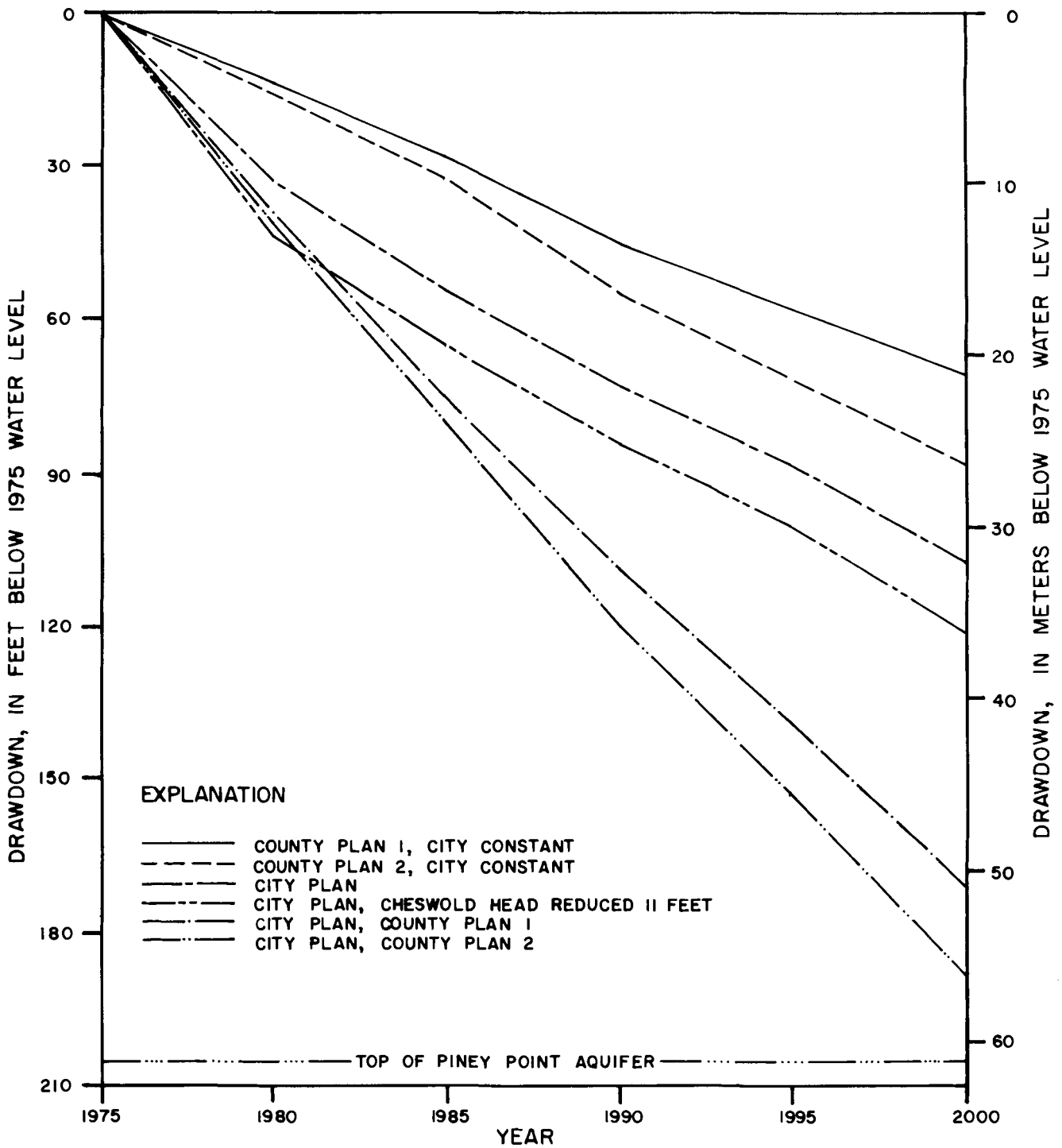


FIGURE 37  
 SIMULATED HYDROGRAPHS FOR OBSERVATION WELL Id55-1 AT  
 WHITE OAK ROAD FOR 1975-2000.

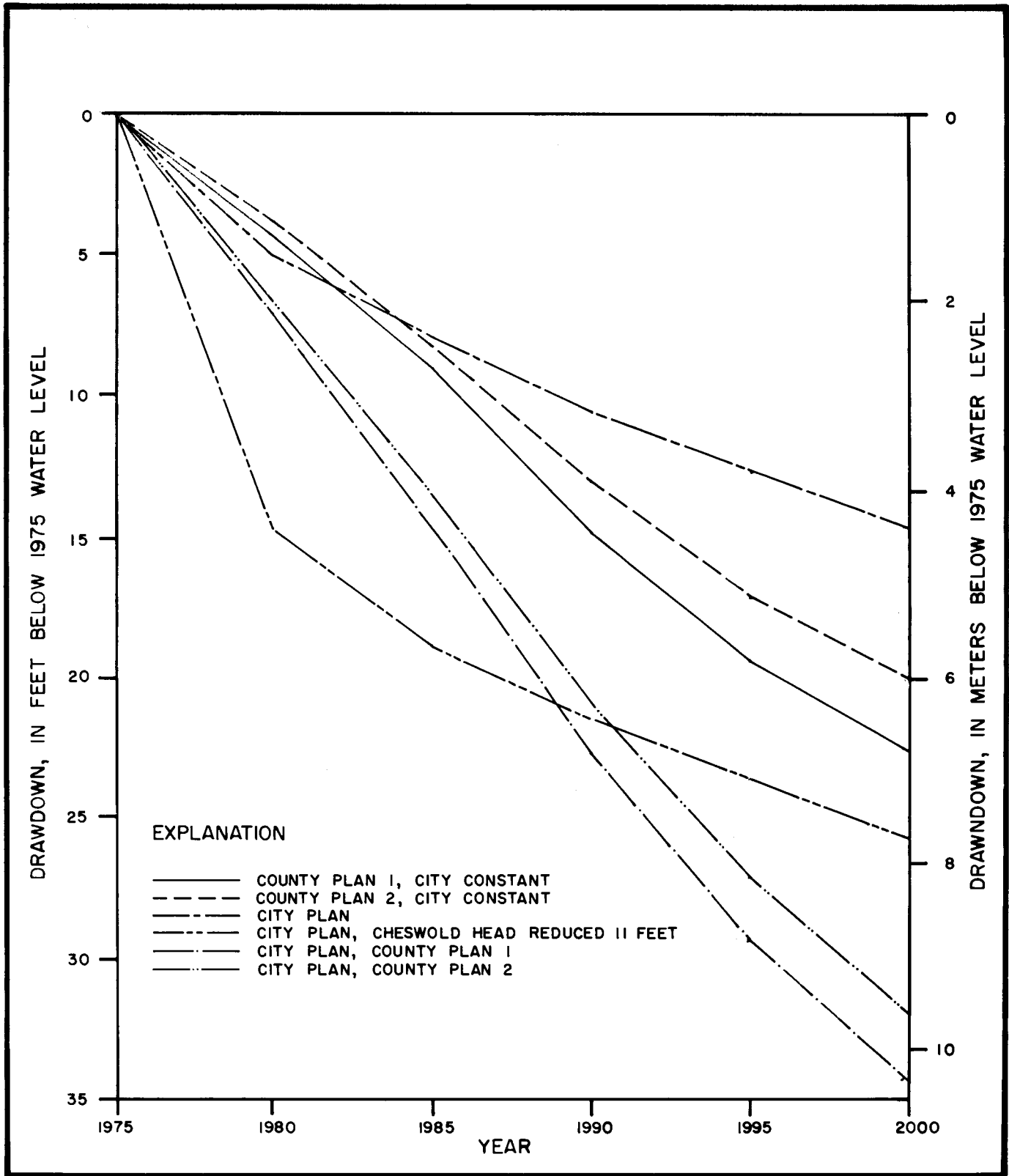


FIGURE 38  
 SIMULATED HYDROGRAPHS FOR OBSERVATION WELL Nc13-3 AT  
 GREENWOOD FOR 1975-2000.

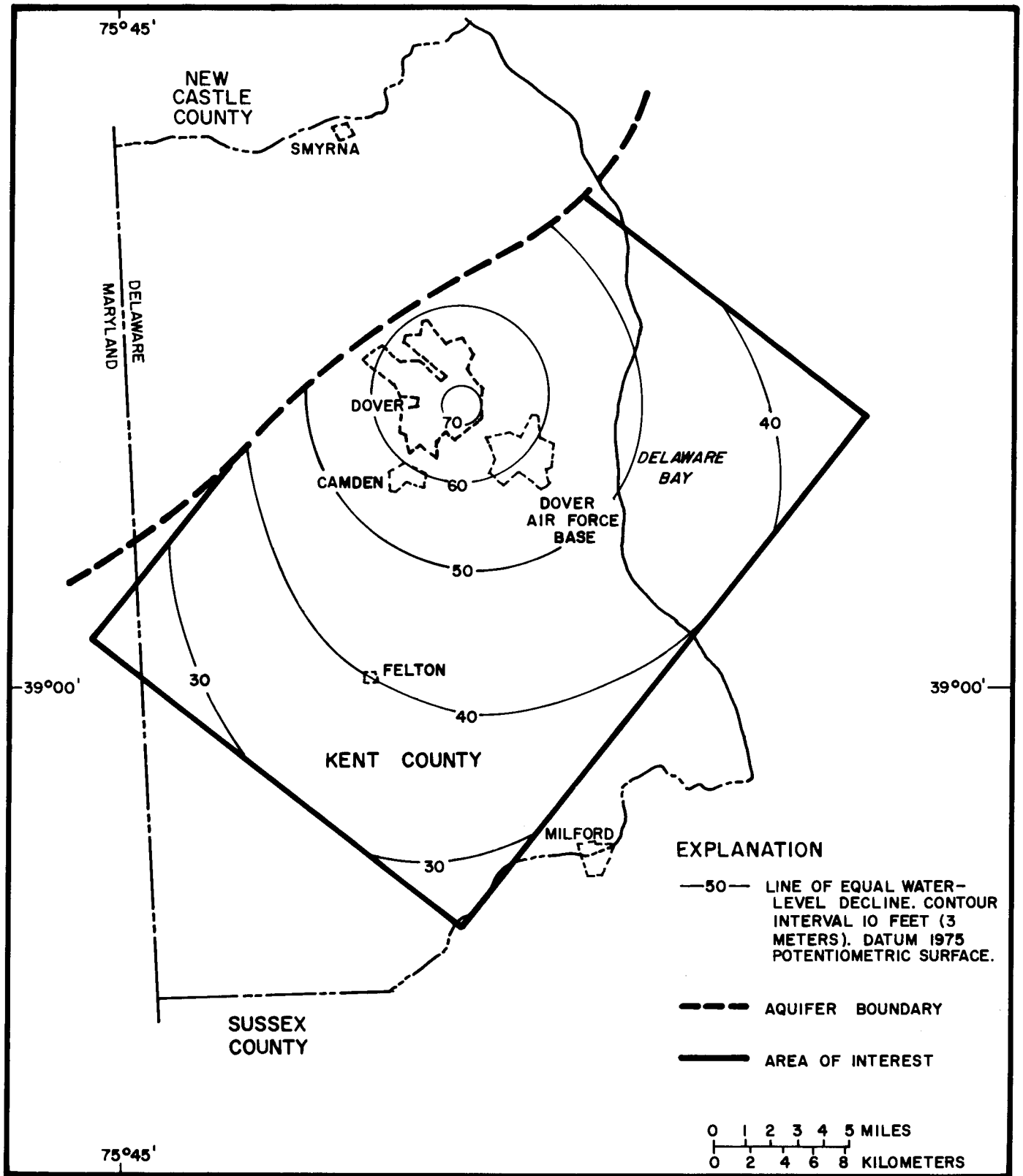


FIGURE 39

PREDICTED DECLINE OF THE POTENTIOMETRIC SURFACE BELOW THE 1975 SURFACE FOR JANUARY 1, 1985-- TRANSIENT SIMULATION USING THE CITY OF DOVER ESTIMATED PUMPAGE WITH THE CHESWOLD AQUIFER POTENTIOMETRIC SURFACE REDUCED AREALLY BY 11 FEET (3 METERS).



simulation was made using the same pumpage as that used for Figure 21, except that the heads in the Cheswold aquifer were areally reduced 11 ft (3 m). A comparison of this run with Figure 21 showed that when steady-state conditions are reached the 11 ft (3 m) reduction in the source bed (Cheswold aquifer) produces an identical 11 ft (3 m) reduction in the potentiometric surface of the Piney Point aquifer. Thus, the maximum error in predicted aquifer heads caused by not allowing heads in the source bed to change during a simulation is equivalent to the head change in the source bed itself.

### Model Limitations

Major limitations of a two-dimensional model of an aquifer in a multi-aquifer sequence are the assumptions that must be made concerning heads and development in underlying and overlying aquifers. These assumptions will affect the model predictions.

In developing the Piney Point aquifer model, it was assumed that the base of the aquifer could be considered a no-flow boundary, and that the Cheswold aquifer represented an overlying constant-head boundary. In order to treat the Cheswold aquifer as a constant-head boundary, it was necessary to assume that the Cheswold aquifer is in steady-state equilibrium, and that pumping from the Cheswold aquifer will not change during the prediction period. An additional assumption is that heads in the Cheswold do not respond to changes of head in the Piney Point. These assumptions limit the credibility of the model predictions. In an effort to improve the model predictions, additional runs (Figure 39) were made with the Cheswold aquifer head uniformly reduced 11 ft (3 m). Although the amount that Cheswold heads were reduced was arbitrarily chosen, the resulting predictions indicate the possible magnitude of variation in Piney Point aquifer heads introduced by changes in Cheswold head.

A more accurate representation of the Piney Point aquifer would require a three-dimensional model of the multi-aquifer system in which the heads, withdrawals, and hydraulic parameters of all the interactive aquifers are included. This type of model is currently (1978) being developed and will include the Magothy, Piney Point, Cheswold, and unconfined aquifers. Predictions based on the three-dimensional model will be more accurate because the true interactive nature of the aquifer system can be simulated.

## SUMMARY

The calibrated model of the Piney Point aquifer can be used to evaluate the aquifer's capabilities of meeting proposed ground-water withdrawals in Kent County. Although the modeled area consists of 3,150 mi<sup>2</sup> (8,360 km<sup>2</sup>) of the Delmarva Peninsula and includes the major pumping centers of Dover, Delaware and Cambridge, Maryland, the model is considered calibrated and useful for predictive purposes in most of the Kent County area.

The calibration period began with a January 1970 potentiometric surface. Simulation of 5 years of pumping produced drawdowns for January 1975. Calibration of the model consisted of matching drawdown values at each node in the model with a head change map based on field measurements. The mean error and standard deviation between the simulated and field surfaces in the study area is 0.7 ft (0.2 m) and  $\pm 2.2$  ft ( $\pm 0.7$  m) respectively. In general, there is good agreement between observed and simulated hydrographs for three observation wells.

The calibrated model was used to predict changes in the potentiometric surface of the aquifer, as it responded both to changes in the distribution of pumpage and to assumed increases in pumpage to the year 2000.

The model showed:

- (1) Under the present (1975) pumpage of 2.68 Mgal/d (10,140 m<sup>3</sup>/d), water levels would stabilize at about 12 ft (4 m) below the 1975 level near the center of the Dover cone, leaving approximately 163 ft (50 m) of available drawdown to the top of the aquifer in the Dover area.
- (2) Static water levels resulting from combined City and County withdrawal plans would decline to within 20 to 30 ft (6 to 9 m) of the top of the aquifer in Dover by 2000. Pumping levels in wells located in Dover will probably decline below the top of the aquifer.
- (3) By spreading the increased development of the aquifer southwest of Dover, a pumpage of 5.5 Mgal/d (30,820 m<sup>3</sup>/d) would result in the stabilized minimum water levels of 50 to 60 ft (15 to 18 m) below the 1975 level at Dover. About 125 ft (38 m) of available drawdown would remain to the top of the aquifer at Dover and slightly less updip. In contrast,

concentrating the development of 5.5 Mgal/d (20,820 m<sup>3</sup>/d) nearer Dover results in a stabilized water level near Dover of 60 to 70 ft (18 to 21 m) below the 1975 level.

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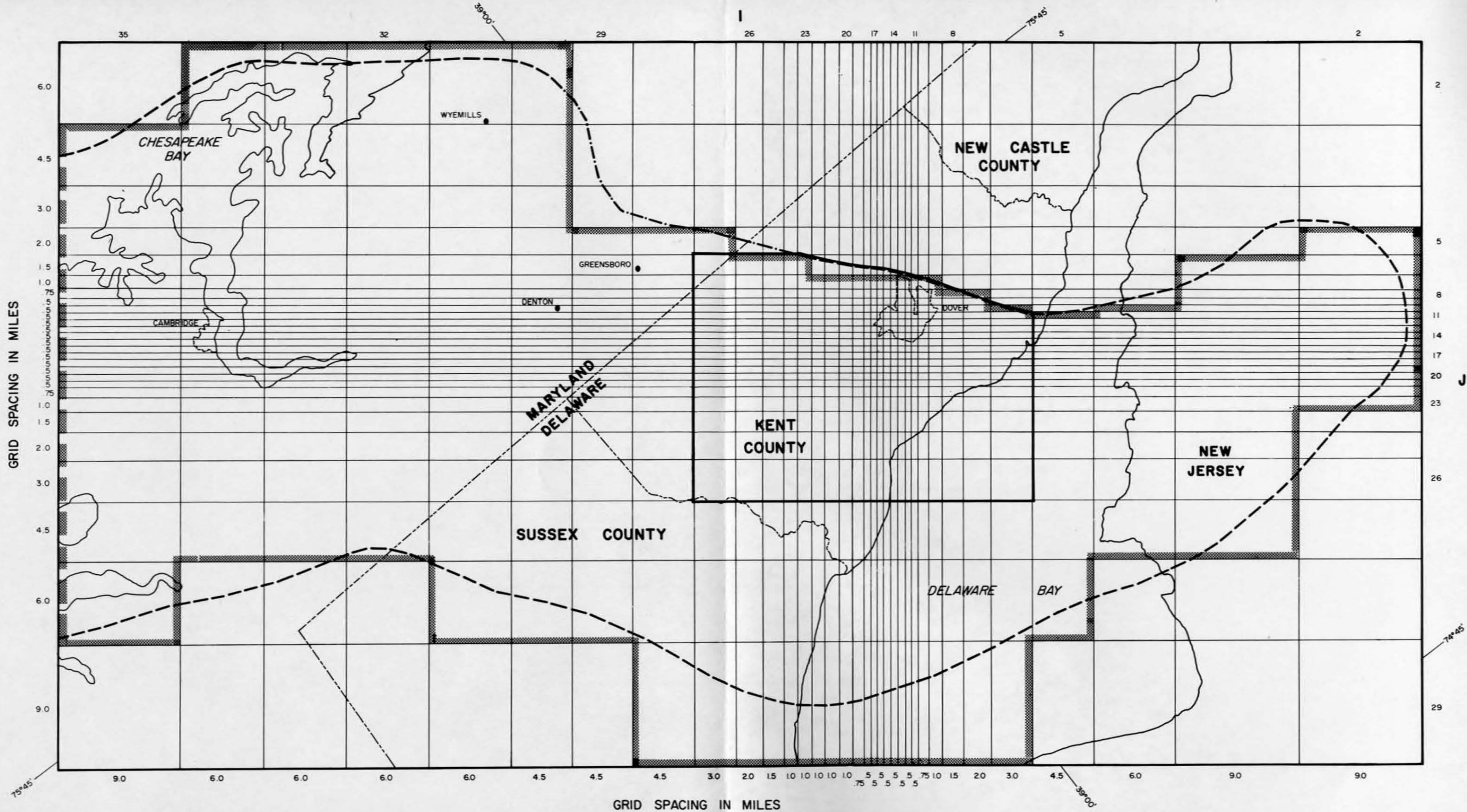
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## APPENDIX

### Conversion Factors







Factors for converting inch-pound units to metric units are shown to four significant figures. However, in the text the metric equivalents are shown only to the number of significant figures consistent with the values for the inch-pound units.

<u>Inch-pound unit</u>	<u>Multiply By</u>	<u>Metric Unit</u>
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
foot per day (ft <sup>2</sup> /d)	0.0929	meter per day (m <sup>2</sup> /d)
gallon per minute per foot [(gal/min)/ft]	0.207	liter per second per meter [(L/s)/m]
million gallon per day (Mgal/d)	3785	meter <sup>3</sup> per day (m <sup>3</sup> /d)
mile (mi)	1.609	kilometer (km)
per foot (ft <sup>-1</sup> )	3.281	per meter (m <sup>-1</sup> )
mile <sup>2</sup> (mi <sup>2</sup> )	2.590	kilometer <sup>2</sup> (km <sup>2</sup> )



**FIGURE 2**  
**MAP OF MODEL AREA SHOWING FINITE-DIFFERENCE GRID**  
**AND AQUIFER BOUNDARY**

**EXPLANATION**

-  FINITE-DIFFERENCE BLOCK
-  SIMULATED NO-FLOW AQUIFER BOUNDARY
-  ARTIFICIAL NO-FLOW BOUNDARY  
(DISTANT FROM AREA OF INTEREST)
-  AREA OF INTEREST
-  APPROXIMATE AQUIFER BOUNDARY
-  NO-FLOW BOUNDARY AQUIFER PINCHOUT
- I, J GRID NUMBERS