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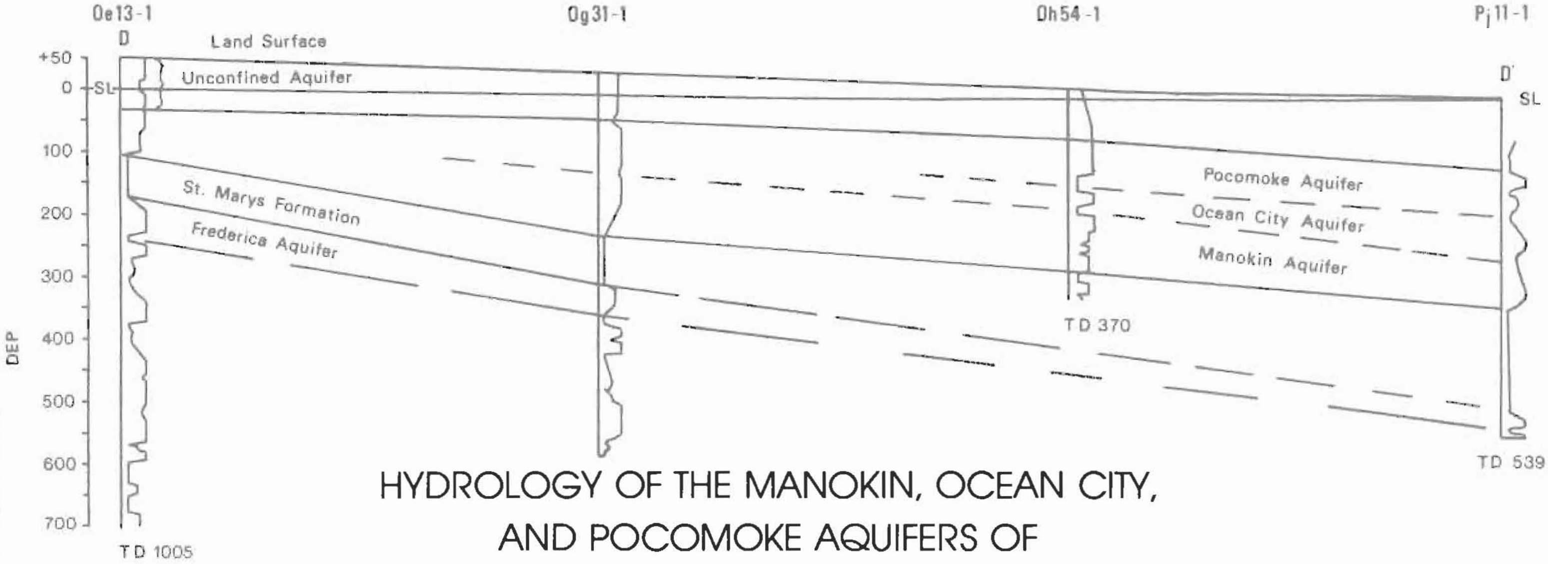
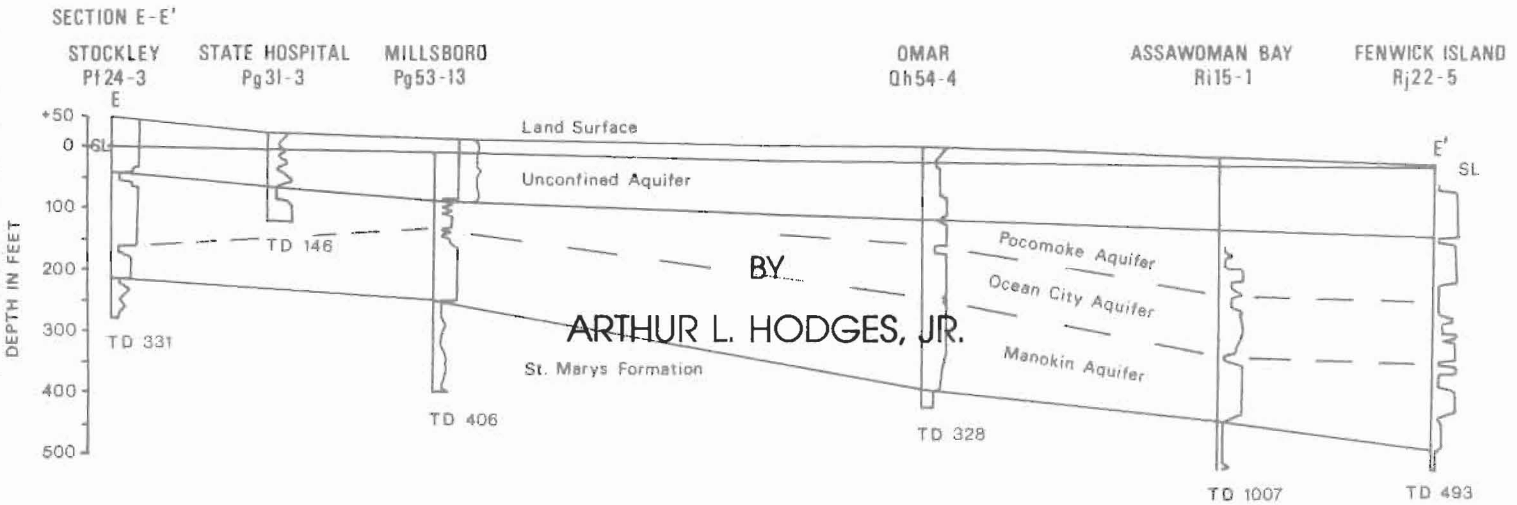


HYDROLOGY OF THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS OF SOUTHEASTERN DELAWARE



BY

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STATE OF DELAWARE

NEWARK, DELAWARE

JANUARY 1984

HYDROLOGY OF THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS OF SOUTHEASTERN DELAWARE

by

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HYDROLOGY OF THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS OF SOUTHEASTERN DELAWARE

ABSTRACT

Population and accompanying water use are expected to increase by 34 percent in southeastern Delaware between 1975 and 2000. To assess the capability of the aquifers in that area to supply the required amount of ground water, a study of those aquifers was started in 1976. Interpretation of geologic sections developed from drilling and geophysical data showed that the confining beds between the Manokin, Ocean City, and Pocomoke aquifers of Neogene age are thin and discontinuous in some parts of the area. Possible fault zones coinciding with deep tectonic features may also contribute to interconnection of these aquifers. Hydrographs of water levels in the aquifers show differential drawdown during periods of heavy pumping, but levels return to a common altitude during unstressed periods. Because of these characteristics, the Manokin, Ocean City, and Pocomoke aquifers are considered to be a single confined aquifer, in most places.

A digital model of this confined system was developed which included the overlying unconfined aquifer (Pleistocene age), the underlying confined aquifer (middle Miocene age), and the confining beds between these aquifers. The model was calibrated under both steady-state and transient (1976-79) conditions using historical pumpage and water-level data.

The unconfined aquifer was modeled as a constant-head source of recharge to the underlying Manokin, Ocean City, and Pocomoke aquifers. Where the confining bed between these aquifers is very thin or absent, water levels in the Manokin, Ocean City, and Pocomoke system approach the constant-head value specified for the unconfined aquifer. This precluded matching simulated water levels to observed water levels in these subcrop areas, and therefore the model is considered to be untested and uncalibrated where the two aquifers are connected.

The calibrated model was used to simulate the effect that increased pumpage would have on water levels in the Neogene age sands for the period 1980-2004. A maximum decline in water level of 2.60 feet resulting from projected increases in pumpage during this period is predicted to occur at Lewes. The decline would induce movement of saltwater toward the Lewes well field beginning about 1989.

The model suggests that there is little potential for upward movement of water through the underlying confining bed (St. Marys Formation) from deeper units as a result of projected pumpage in the Manokin, Ocean City, and Pocomoke aquifers.

INTRODUCTION

Ground water is the sole source of potable water for domestic, municipal, and industrial use in southeastern Delaware. It is also used for agricultural irrigation and livestock watering. Most of this water is taken from the shallow unconfined aquifer which is continually recharged by precipitation.

However, immediately along the coast, most municipal supplies are developed in one of three deeper sands because of the threat of saltwater intrusion directly from the ocean into shallow ground-water sources. These sands lying beneath the unconfined aquifer are locally separated by fine-grained layers, and are known informally as the Manokin, Ocean City, and Pocomoke aquifers (bottom to top). In this study, they are treated as a single confined unit because of the discontinuous nature of the confining beds between them.

Continued growth of residential and industrial communities in southeastern Delaware and the resort communities along Delaware's Atlantic coast will result in increased demands for water and associated development of ground-water resources. It is therefore necessary to assess the availability of additional water supplies and the effect that projected increases in withdrawals will have on water levels in the aquifer system.

Purpose and Scope

The study area (Figure 1) includes that part of southeastern Delaware bounded on the north by the town of Milton, on the west by U.S. Highway 13, on the south by the Delaware-Maryland State line, and on the east by Delaware Bay and the Atlantic Ocean. The area encompasses 675 square miles (mi^2) within Sussex County.

The purpose of this study was to assess the capability of the Manokin, Ocean City, and Pocomoke aquifers in southeastern Delaware to supply the projected increase in demand for water through the year 2004, and to determine the effect of this increased pumpage on the hydrologic system. This was done by a digital model designed to simulate the ground-water flow of these aquifers in an area of 3,776 mi^2 in southeastern Delaware and adjacent Maryland. This extended model area permits the analysis of stresses outside the study area and minimizes error introduced by the arbitrarily chosen model boundaries of the study area. Modeling can also be used to refine estimates of hydrologic coefficients in those areas where field data are lacking, and to forecast water-level declines in areas of hypothetical ground-water withdrawals. The results of this study are presented in the accompanying maps and tables that show both observed and predicted water levels and drawdowns.

Previous Investigations

Noteworthy publications pertaining to the geology of the area during the last 20 years include those of Jordan (1962, 1963, 1964, and 1967); Spoljaric and Jordan (1966); Kraft and Maisano (1968); and Brown and others (1972). Reports on the hydrology of the area published during the same period include those of Rasmussen

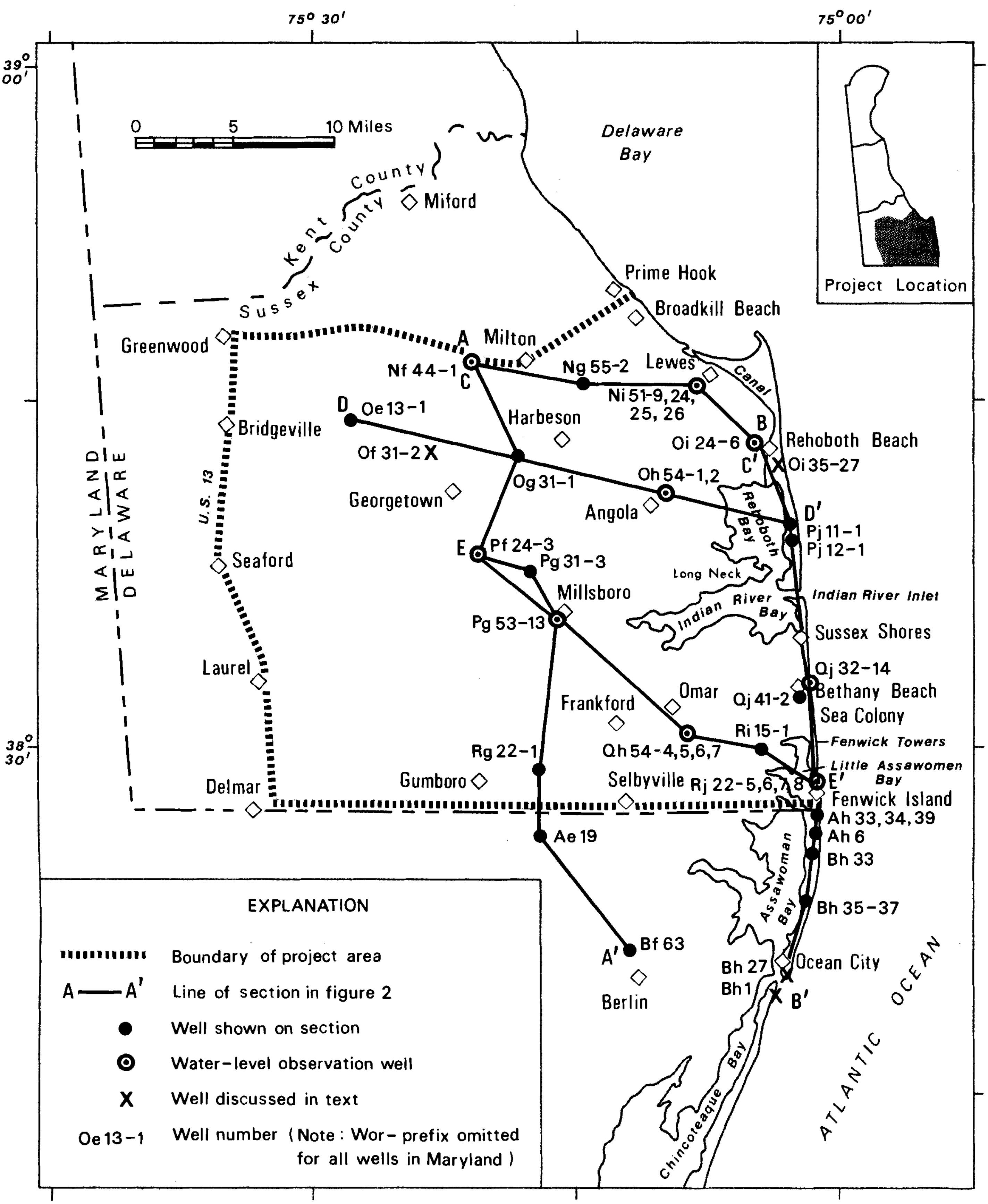


FIGURE 1.—LOCATION OF STUDY AREA, OBSERVATION WELLS, AND GEOHYDROLOGIC SECTIONS.

and others (1960); Parker and others (1964); Baker and others (1966); Rasmussen, Odell, and Beamer (1966); Sundstrom and Pickett (1969 and 1970); Miller (1971); Cushing and others (1973); and Johnston (1973, 1976, and 1977). Earlier investigations of the geology and hydrology of the area are fully referenced in these reports.

Methods of Investigation

Previous investigations provided general geologic and hydrologic knowledge of the study area; however, data on ground-water levels in the confined aquifers were sparse. For the study described here, an observation-well network was started in 1976 using four unused wells, and initial geologic sections were constructed using drillers' and geophysical logs. These sections were used to estimate the thickness and extent of the aquifers modeled in this study.

A preliminary digital model of the study area was designed treating the Manokin, Ocean City, and Pocomoke aquifers as a single confined aquifer using estimated and published geologic and hydrologic coefficients. The purpose of the preliminary model was to refine estimates of transmissivity of this confined aquifer and the vertical hydraulic conductivity of the overlying confining bed.

Additional geologic information was obtained from test holes drilled at five sites. These holes were converted to monitoring wells to provide water-level and chemical-quality data on one or more aquifers at each site. Geologic sections of the study area were refined as information became available from these test holes and from commercial water wells. The final step in the investigation was the design and calibration of a fine-grid model of southeastern Delaware and the surrounding area which was used to compute future water levels in the confined aquifer system in response to hypothetical withdrawals.

Population and Water Use

Forecasts of population growth in Sussex County are found in Rives and Brown (1975); Rives (1974); Delaware State Planning Office (1972); and Ratledge, Stapleford, and Tannian (1977). Percentage increase in population forecasts for 1970-95 range from 26.2 percent (Delaware State Planning Office, 1972) to 65.0 percent (Rives and Brown, 1975). Ratledge and others (1977) forecasted population growth in coastal Sussex County in terms of both permanent population and transient population, which consists mainly of summer visitors to seashore resort communities (Table 1). The permanent population during 1975-95 is estimated to increase 23.7 percent, and the transient population 30.3 percent. These percentage increases were used to project an equivalent percentage increase in ground-water use during 1980-2000.

Robertson (1977) reports all ground water used in coastal Sussex County in 1976, including municipal, industrial, agricultural and domestic supply (Table 2). Municipal and industrial water-use data for 1976 and 1977 collected during this study, also shown in Table 2, generally agree with Robertson's figures. It was assumed that all rural water is supplied from the unconfined aquifer, and Robertson's estimated rural water use is presented in Table 2 for comparison.

TABLE 1. ESTIMATED INCREASE IN POPULATION AND WATER USE IN COASTAL SUSSEX COUNTY, DELAWARE, 1975-2000

Population In Coastal Sussex County, Delaware

	1975	1980	1985	1990	1995
PERMANENT	41,276	44,207	46,306	48,570	51,068
TRANSIENT 1/	125,096	134,123	142,801	152,045	163,016
TOTAL	166,372	178,330	189,107	200,615	214,084

From Ratledge, Stapleford and Tannian, 1977, Table 25.

Percent Change In Population And Water Use Relative To 1975, Calculated From Above Figures And Extended To Year 2000 By Straight-Line Projection

	1975	1980	1985	1990	1995	2000
PERMANENT	0	7.1	12.2	17.7	23.7	29.6
TRANSIENT 1/	0	7.2	14.1	21.5	30.3	37.9
WATER USE 2/	0	7	13	20	27	34

1/ June through August.

2/ Averaged and rounded to nearest whole number.

TABLE 2. AVERAGE DAILY WATER USE IN COASTAL SUSSEX COUNTY, DELAWARE

	1976		1977		
Municipalities	Robertson (1977) Tables 2,3,5,6,7 (gal/d)	This study (gal/d)	This study (gal/d)	Values used for calibration (gal/d)	(ft^3/s)
Bethany Beach	103,500	101,000	108,400	108,400	0.1678
Dagsboro 1/ 2/	50,900	-	-		
Fenwick Island 1/	54,000	-	-	54,000	0.0835
Fenwick Towers	-	13,600	13,600	13,600	0.0210
Frankford 2/	86,000	-	85,300		
Georgetown	432,000	328,800	328,800	328,800 893,800 3/	0.5088 1.3830 3/
Lewes	1,125,000	1,000,000	1,345,700	1,345,700	2.0824
Millsboro 2/	105,000	235,600	235,600		
Millville 1/ 2/	30,000	-	-		
Milton 2/	200,000	-	185,600		
Ocean City, Md.	-	3,463,800	-	3,463,800	5.3600
Ocean View 1/ 2/	56,000	-	-		
Rehoboth Beach 2/	707,600	708,500	987,600		
Sea Colony	94,000	93,800	93,800	93,800	0.1454
Selbyville 2/	-	282,900	295,600		
South Bethany 1/ 2/	65,000	-	-		
Sussex Shores	98,000	88,500	75,400	75,400	0.1167
Industries					
Dagsboro 2/	40,000	-	-		
Georgetown	565,000	-	-	565,000	0.8740
Harbeson	1,350,000	-	-	1,350,000	2.0888
Millsboro 2/	3,295,000	3,287,700	3,287,700		
Milton 2/	2,200,000	1,728,800	1,728,800		
Prime Hook	90,000	-	-	90,000	0.1393
Rural					
Mobile Homes & Camp Grounds 2/	1,818,300				
Agricultural 2/	1,753,900				
Irrigation 2/	800,000				

1/ No municipal system.
2/ All pumpage from unconfined aquifer.
3/ Combined municipal-industrial.

Acknowledgments

The staff of the Delaware Geological Survey, under the direction of Dr. Robert R. Jordan, provided hydrologic and geologic assistance in this study. Kenneth D. Woodruff and John H. Talley ran geophysical logs in several of the test holes drilled for the program.

The author also thanks his U.S. Geological Survey colleagues, P. Patrick Leahy and Mary M. Martin, for their assistance in reprogramming digital ground-water flow models to meet the requirements of the Burroughs computer at the University of Delaware, which was used in this study.

GEOLOGY AND HYDROLOGY

The geology of Delaware in general, and Sussex County in particular, is discussed in detail in the reports cited previously. A variety of names has been applied to the units modeled in this study resulting in some confusion in the literature. The nomenclature used here is given in Table 3. The use of the terms Manokin, Ocean City, and Pocomoke as informal aquifer names is consistent with previous usage in both Maryland (Weigle, 1974) and Delaware (Jordan and Smith, 1983). The names refer to those sandy units of probably Neogene (Late Miocene to Pliocene) age in the upper part of the Chesapeake Group underlying the coastal areas of southeastern Delaware and nearby Maryland. One or more of the units may be present at any one location.

Locations of interpretive geohydrologic sections of the study area are given in Figure 1 and the sections are shown in Figure 2.

Tectonic and Depositional Setting

Woodruff (1977), reporting on the results of offshore seismic and magnetic studies, suggested the occurrence of a basement trough east of Indian River Inlet and noted an abrupt steepening of the basement surface east of Ocean City, Md. Several magnetic linear features were noted in the same general area of southeastern Delaware. Woodruff attributes these structures to a series of faulted blocks in the crystalline basement and suggests that the faults extend upward into the sediments of Cretaceous (?) age, which underlie the Miocene age units discussed in this report. Brown and others (1972), in a comprehensive study of tectonic structure and sedimentation along the central east coast of the United States, presented a regional mechanism of wrench-faulting and periodic rotational realinement of fault blocks. One of the primary hinge zones inferred in his study trends north-south along the Atlantic coast of Delaware and Maryland. Other hinge zones, or axes of deformation, trend northeast-southwest and northwest-southeast. These three axes of flexure coincide with the trend of the linear features described by Woodruff (1977). Section B-B' (Figure 2) suggests that these offshore structures continue landward and intersect the coast just north of Indian River Inlet (wells Pj11-1 and Pj12-1) and near the Delaware-Maryland border (wells Rj22-5 and Wor-Ah6). It is not known whether these structural features are narrow, sharply defined faults, or wide zones of monoclinally tilted sediments. Also, it is unknown whether faulting followed, or was contemporaneous with deposition of the

TABLE 3. NOMENCLATURE OF GEOLOGIC AND HYDROLOGIC UNITS

System	Series	Group	Geologic Unit 1/	Modeling or Hydrologic Unit
Quarternary	Holocene			Unconfined aquifer
	Pleistocene	Columbia Group	Omar Formation Beaverdam Formation	
	?		?	
Tertiary	Neogene (Mio-Pliocene) 2/	Chesapeake Group	Pocomoke aquifer Ocean City aquifer Manokin aquifer	Confining bed Manokin, Ocean City, Pocomoke aquifer system or confined aquifer
	?			
	Middle and Lower Miocene		Choptank Fm.: St. Marys Formation Frederica aquifer and unnamed sand	St. Marys Formation (lower confining unit) Frederica aquifer and unnamed sand
			Calvert Formation	

1/ Nomenclature used is that of the Delaware Geological Survey and may not necessarily agree with that of the U.S. Geological Survey.

2/ Age designations on basis of unpublished work by the Delaware Geological Survey.

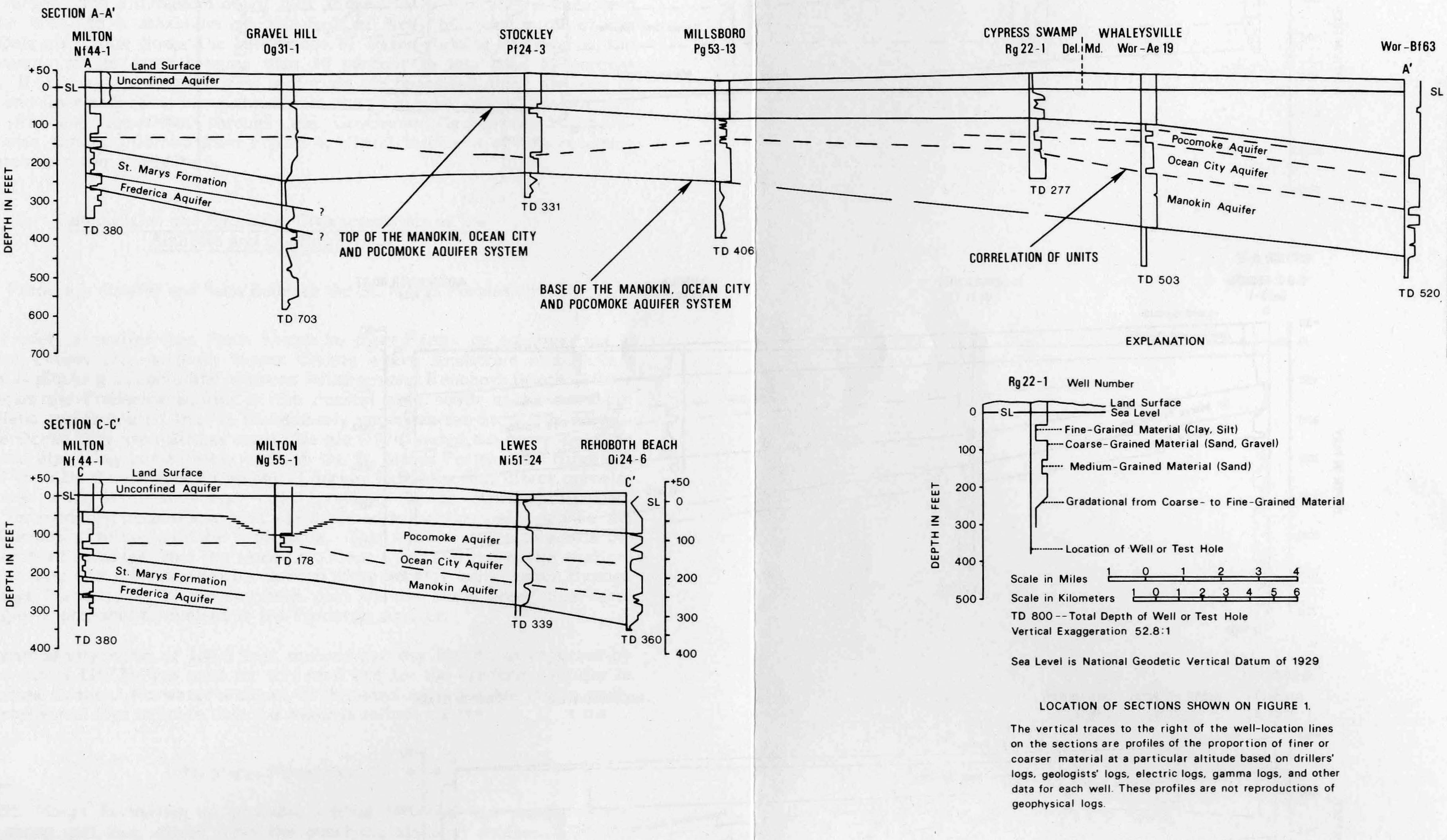
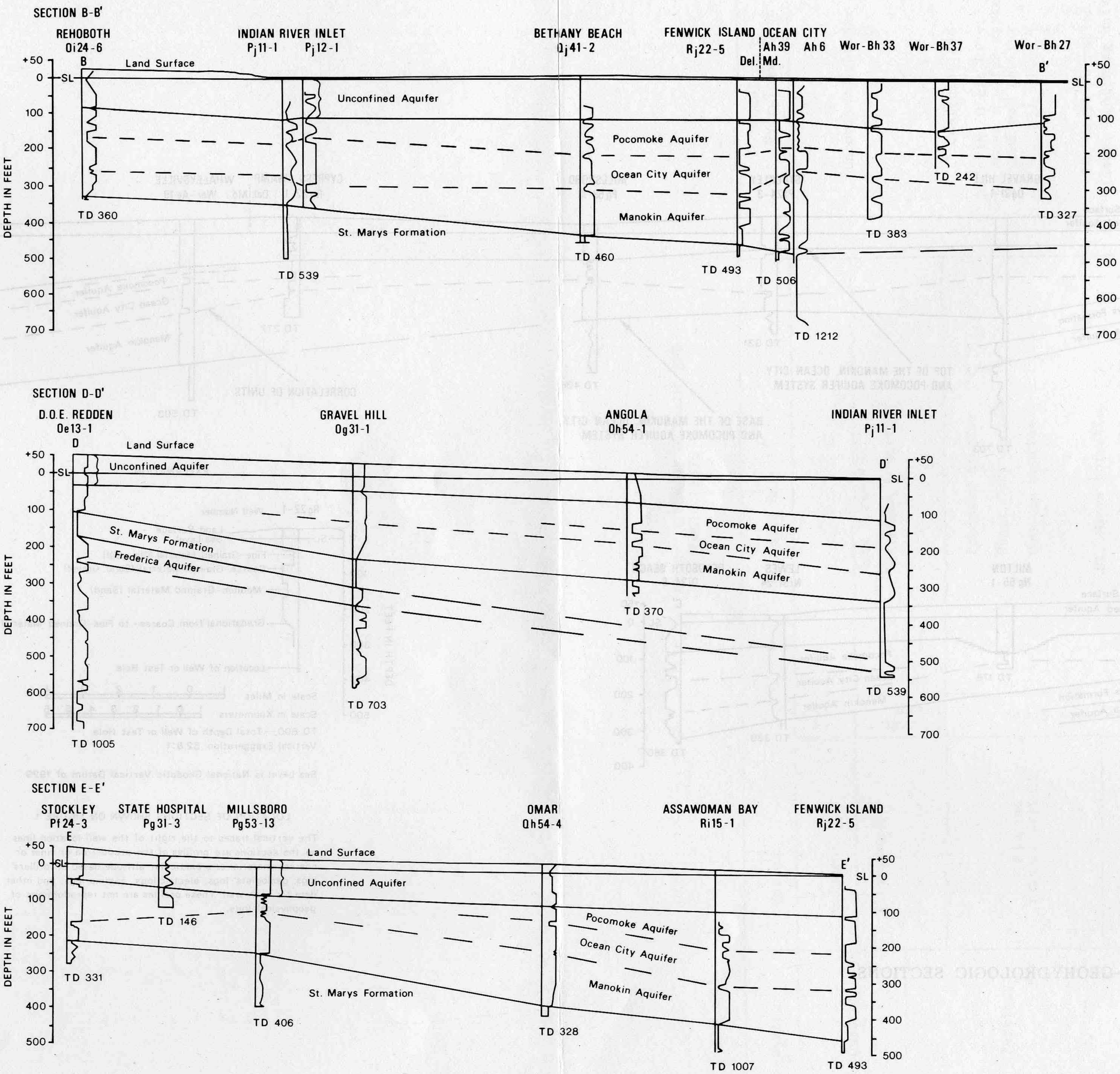


FIGURE 2.—GEOHYDROLOGIC SECTIONS.


SECTION B-B'
REHOBOTH
Oi24-6
INDIAN RIVER INLET
Pj11-1
Pj12-1
BETHANY BEACH
Qj41-2
FENWICK ISLAND
Rj22-5
OCEAN CITY
Ah39
Ah6
Wor-Bh33
Wor-Bh37
Wor-Bh27
Del.
Md.
B
B'
Land Surface
SL
Unconfined Aquifer
Pocomoke Aquifer
Ocean City Aquifer
Manokin Aquifer
St. Marys Formation
TD 360
TD 539
TD 460
TD 493
TD 506
TD 1212
TD 383
TD 242
TD 327
DEPTH IN FEET
SECTION D-D'
D.O.E. REDDEN
Oe13-1
GRAVEL HILL
Og31-1
ANGOLA
Oh54-1
INDIAN RIVER INLET
Pj11-1
D
D'
Land Surface
Unconfined Aquifer
St. Marys Formation
Frederica Aquifer
Pocomoke Aquifer
Ocean City Aquifer
Manokin Aquifer
TD 1005
TD 703
TD 370
TD 539
DEPTH IN FEET
SECTION E-E'
STOCKLEY
Pf24-3
STATE HOSPITAL
Pg31-3
MILLSBORO
Pg53-13
OMAR
Qh54-4
ASSAWOMAN BAY
Ri15-1
FENWICK ISLAND
Rj22-5
E'
Land Surface
Unconfined Aquifer
Pocomoke Aquifer
Ocean City Aquifer
Manokin Aquifer
St. Marys Formation
TD 331
TD 146
TD 406
TD 328
TD 1007
TD 493
DEPTH IN FEET

sediments. For the purposes of this study, however, it is assumed that the structural features noted above contribute to areal connection of the aquifers above the St. Marys Formation either through offset of confining beds, or as a result of stretching, thinning, and segmentation of those beds.

Thickness of the Neogene age sediments above the St. Marys Formation (Figure 3) ranges from a minimum of 70 feet at well Oe13-1 in the northeastern part of the area, to a maximum of 360 feet at Wor-Ah6, just south of the Maryland-Delaware State line. The percentage of water-yielding material within these sediments ranges from greater than 80 percent to less than 50 percent (Figure 4). If it is assumed that coarse materials are deposited along the axis of deposition and finer sediments along the flanks, then a curved axis of late Miocene and early Pliocene deposition through the Greenwood-Georgetown-Millsboro-Selbyville area can be inferred from Figure 4. Total thickness of this resulting aquifer system is shown in Figure 5.

Composition and Hydraulic Characteristics of the Aquifers and Confining Beds

Frederica Aquifer and Sand Beneath the St. Marys Formation

The Frederica aquifer (see Table 3) can be traced from its subcrop area in central Kent County into northern Sussex County where Sundstrom and Pickett (1969) show it pinching out on a line between Millsboro and Rehoboth Beach. Miller (1971) extends the Frederica aquifer in the coastal area south as far as about Fenwick Island and indicated that it immediately underlies the St. Marys Formation. In the Ocean City area further south, Weigle (1974) noted the presence of an unnamed sand also lying immediately beneath the St. Marys Formation. However, unpublished work by the Delaware Geological Survey indicates that direct correlation of these units is tenuous and would probably be an oversimplification. Therefore, for modeling purposes, a sand was assumed to continuously underlie the St. Marys Formation throughout the study area. This was necessary to assess the possible effects of pumpage from the Manokin, Ocean City, and Pocomoke aquifers on this lower sand and the potential for upward movement of saline water through the St. Marys Formation. In the northern part of the study area, this basal modeling layer is probably equivalent to the Frederica aquifer.

A transmissivity value of 1,400 feet squared per day (ft^2/d), as reported by Cushing and others (1973), was used for this sand and for the Frederica aquifer in northern Sussex County. No water analyses of this sand are available in the study area, but geophysical logs indicate that the water is saline.

St. Marys Formation

The St. Marys Formation of probable middle Miocene age separates the underlying sandy unit (see above) from the overlying Manokin aquifer. The St. Marys Formation ranges in thickness and composition from 70 feet of alternating clay and sand at Milton (well Nf44-1; Figures 1 and 2) to 180 feet of clay with minor layers of silt in an observation well (Wor-Ah6) at Ocean City, Md. (Figure 1). The decreasing permeability and increasing thickness of the St. Marys Formation to

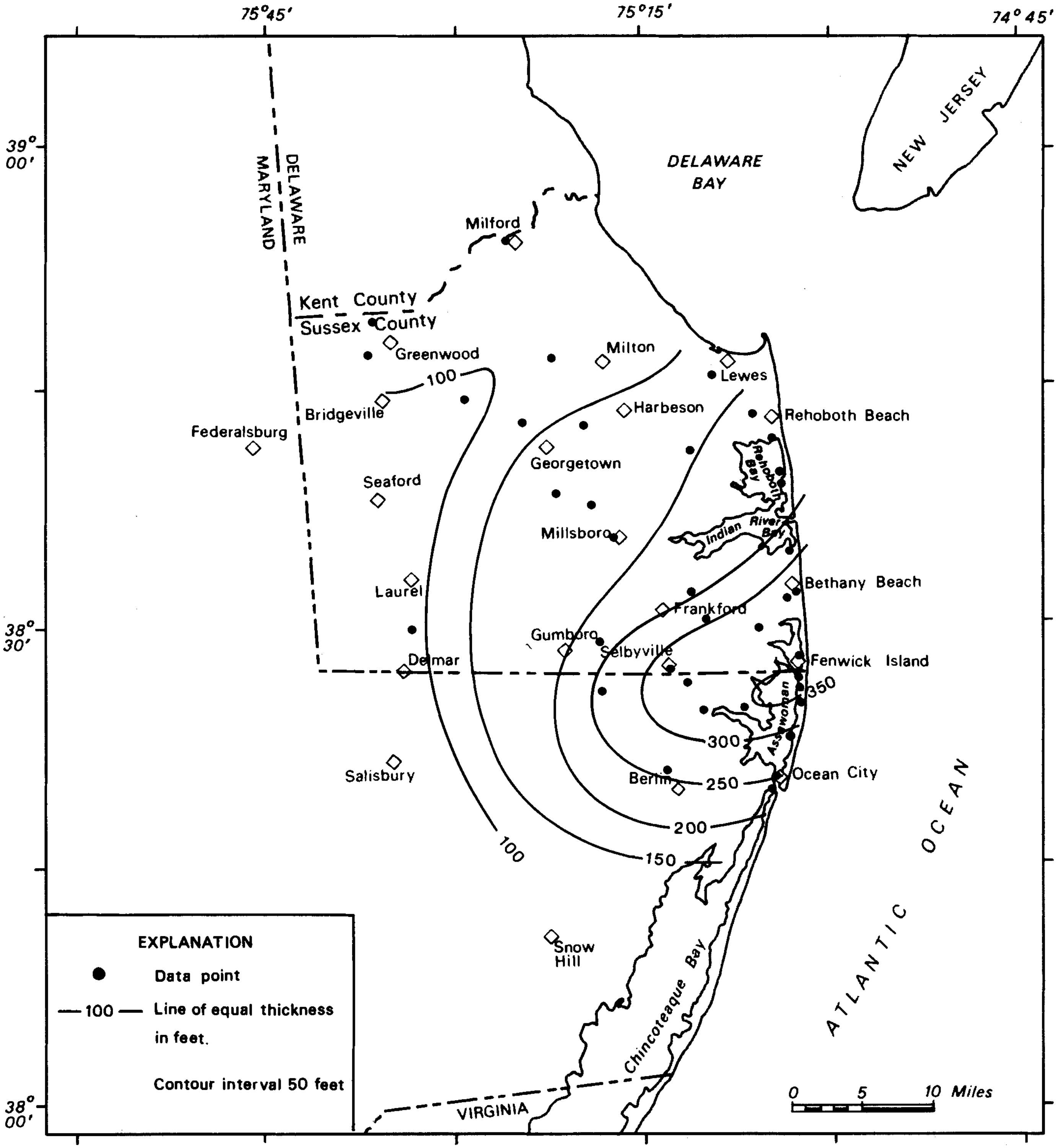


FIGURE 3.—THICKNESS OF NEOGENE AGE SEDIMENTS ABOVE THE ST. MARYS FORMATION.

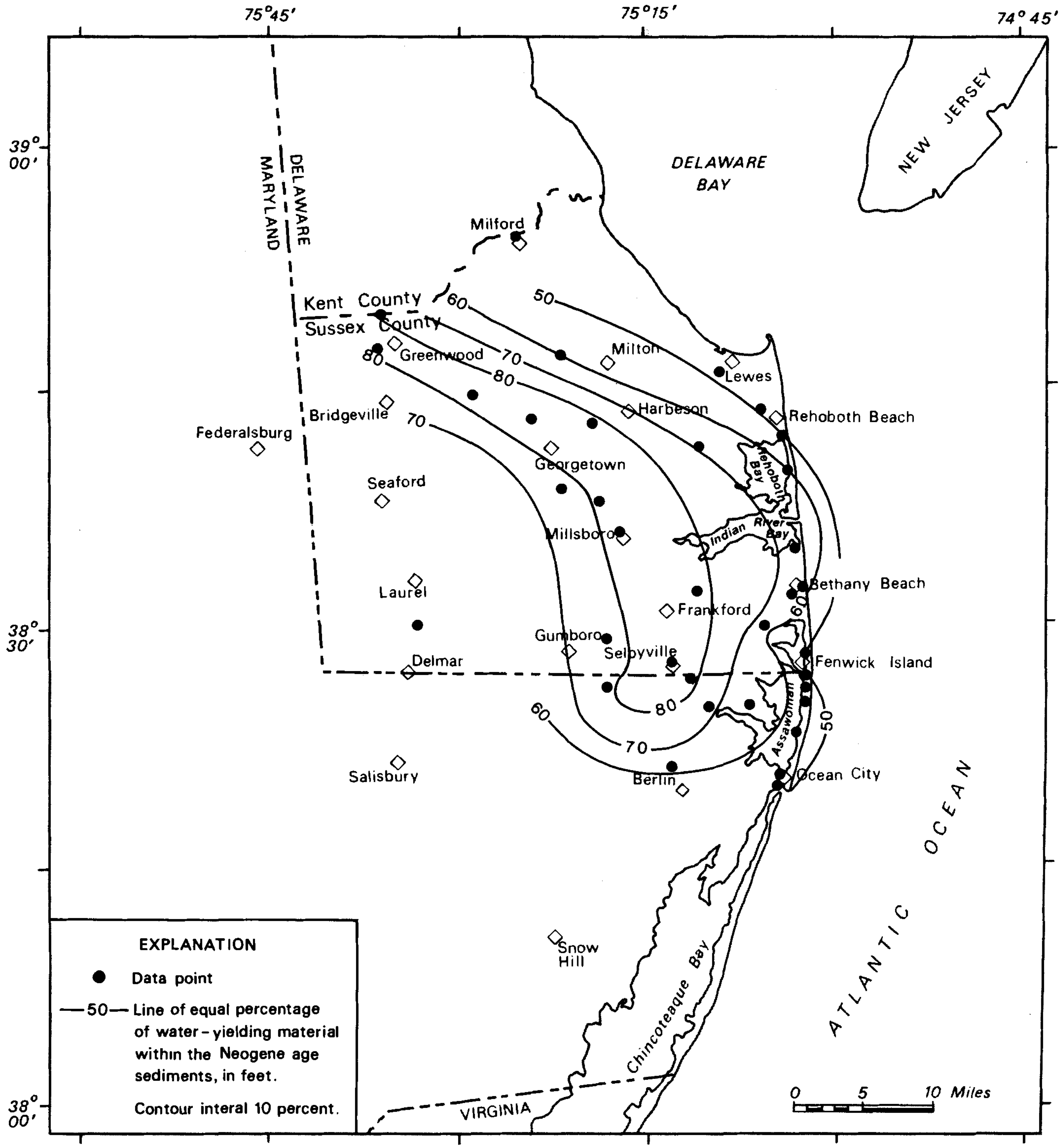


FIGURE 4.—PERCENTAGE OF SAND WITHIN NEOGENE AGE SEDIMENTS ABOVE THE ST. MARYS FORMATION.

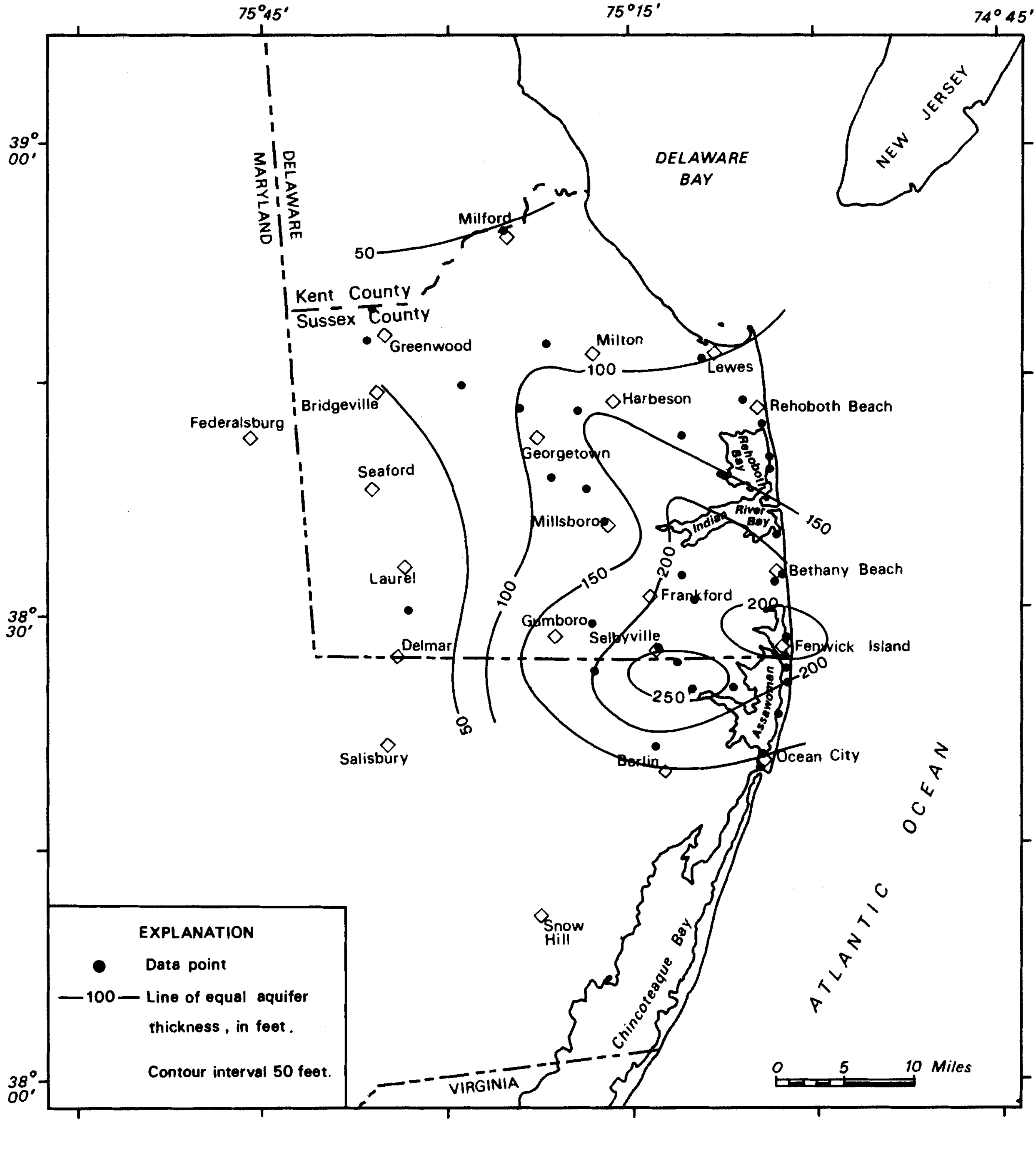


FIGURE 5.—THICKNESS OF THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS.

the southeast is a significant factor in retarding the upward movement of saline water into the Manokin, Ocean City, and Pocomoke aquifers in southeastern Delaware and adjacent coastal Maryland (Weigle, 1974). Several thin sandy layers within the St. Marys Formation supply sufficient water for domestic wells in the northwestern part of the study area. Well Of31-2, located just northwest of Georgetown, is a domestic well screened in one of these sandy zones. Hydraulic conductivity of the St. Marys Formation was not determined in this study; however, values of vertical hydraulic conductivity (Kv) reported for Neogene age confining beds in Delaware, Maryland, and New Jersey (Table 4) range from $2x10^{-5}$ to $1.6x10^{-3}$ feet per day (ft/d). Wolff (1970), in a study of vertical hydraulic conductivity of a confining bed near Salisbury, Md., made laboratory determinations of this property on seven samples at loads corresponding to overburden thicknesses of approximately 61 and 122 feet. The Kv of the samples tested under the pressure equivalent to 61 feet of overburden ranged from $6.2x10^{-3}$ to $4.2x10^{-5}$ ft/d, and averaged $1.3x10^{-3}$ ft/d. Vertical conductivity of the same samples tested under the pressure equivalent to 121 feet of overburden ranged from $1.6x10^{-3}$ to $2.8x10^{-5}$ ft/d and averaged $5.0x10^{-4}$ ft/d. Thus, vertical hydraulic conductivity decreased as the thickness of simulated overburden increased. Estimated Kv of the St. Marys Formation is 10^{-3} ft/d in the western (updip) part of the study area, and 10^{-5} or 10^{-6} ft/d in the eastern (downdip) part of the modeled area. A conservative average value of $1x10^{-4}$ ft/d was used in the models.

Leahy (1976) made the only two measurements of specific storage for Neogene age (Miocene?) confining beds in Delaware (Table 4). A specific storage value of $1x10^{-6}$ per foot (ft^{-1}) was used for the St. Marys Formation in this study.

Manokin, Ocean City, and Pocomoke Aquifers

The Manokin, Ocean City, and Pocomoke aquifers in southeastern Delaware were modeled as a single aquifer because they are hydraulically connected locally where the confining beds between them are discontinuous.

Manokin aquifer.--This is the lowermost aquifer currently used for municipal water supply in southeastern Delaware. The Manokin ranges in thickness from 30 feet near Milton to about 150 feet at Fenwick Island, Del. It is composed of fine and medium gray sand with occasional layers of coarse sand to fine gravel. The contact between the Manokin aquifer and the underlying St. Marys Formation is gradational in most places. Layers of gray clay increase in number and thickness with depth. This transition zone is generally about 25 feet thick, but is as much as 60 feet thick at well Og31-1 (Figure 1). The Manokin aquifer does not crop out, but receives recharge through vertical leakage from overlying aquifers. The confining layer that separates the Manokin from overlying aquifers ranges from a thin silty zone at well Og31-1 to a 10-foot clay at Bethany Beach.

Ocean City aquifer.—This aquifer was originally considered as part of the Manokin (Rasmussen and Slaughter, 1955), but was later recognized as a separate unit and named by Weigle (1974). It is a fine to coarse light-gray sand with occasional fine gravel and supplies much of the water for Ocean City, Md. The Ocean City aquifer can be traced from Ocean City northward along the coast to Rehoboth Beach, as shown in Figure 2, section B-B', and, in Delaware, reaches a

TABLE 4. PROPERTIES OF NEOGENE AGE CONFINING BEDS IN THE DELAWARE-NEW JERSEY-MARYLAND AREA

Area	Depth sampled (ft)	Age (Period)	Vertical Conductivity (ft/d)	Specific Storage (ft^{-1})	Reference
Dover, Del.	289-308	Miocene?	4×10^{-5}	3×10^{-6}	
			9×10^{-5}	6×10^{-6}	Leahy (1976)
New Jersey	Unknown (Kirkwood Fm)	Miocene	2×10^{-5}	--	
			5.2×10^{-5}	--	Nemickas and Carswell (1976)
Maryland	?	Miocene	2.2×10^{-4}	--	Leahy (1976)
Maryland	82-88	Miocene?	1.6×10^{-3}	--	
			5.3×10^{-4}	--	Wolff (1970)

maximum thickness of 120 feet near Indian River Inlet. Sections C-C', D-D', and E-E' on Figure 2 show the thinning and eventual absence of the confining bed between the Ocean City aquifer and the overlying Pocomoke aquifer to the north and west of the Atlantic Coast.

The Ocean City aquifer overlies the Manokin aquifer east of a line from Gumboro to Lewes (Figure 6). West of this line a single aquifer, assumed here to be the Pocomoke, overlies the Manokin aquifer.

Pocomoke aquifer.--East of the Gumboro-Lewes line this aquifer has a maximum thickness of 90 feet at Bethany Beach. It is composed of gray to white, fine to coarse sand and some fine gravel, and locally contains one or more silt or clay layers. Along the Gumboro-Lewes line, the Pocomoke and Ocean City aquifers appear to merge into a single unit which thins rapidly to the north and west.

Transmissivity data for the Manokin, Pocomoke, and Ocean City aquifers are sparse. Values determined from individual aquifer tests are presented in Table 5.

In order to model the aquifer system adequately, it was necessary to assign values of transmissivity for the entire thickness of the system throughout the study area. This was done by first determining the total thickness of aquifer material that occurs between the top of the St. Marys Formation and the base of the unconfined aquifer (Figure 5). This thickness of aquifer material was multiplied by a hydraulic conductivity of 50 ft/d, which is representative of a medium-grained sand (Lohman, 1979), the predominant constituent of the aquifer. The values obtained were adjusted to reflect pumping test data in Delaware and estimates by Achmad and Weigle (1979) in Maryland. Lines of equal transmissivity within the aquifer are shown in Figure 7.

The coefficient of storage of an aquifer is dependent on the compressibility characteristics of the aquifer and the expansion of the confined water in that aquifer. These factors are assumed to vary only slightly within the study area. An average coefficient of storage value of 3.57×10^{-4} was calculated using values determined from aquifer tests (Table 5). This value was used to represent the storage coefficient for the entire Manokin, Ocean City, and Pocomoke aquifer system modeled in this study.

Confining Bed Between the Aquifers of Neogene Age and the Unconfined Aquifer

The confining bed that separates the Neogene age sands from the unconfined aquifer in much of the study area ranges from silty fine sand to clay, and in thickness from 0 to 55 feet. The altitude of the top of the confining bed decreases from 20 feet below sea level in the northwestern part of the study area, to as much as 150 feet below sea level along the southern boundary of the modeled area. The values for Kv determined by Wolff (1970) would indicate a decrease in this value, due to compaction, from 1×10^{-3} to about 7×10^{-4} ft/d from northeast to southwest. A value of 1×10^{-3} ft/d was used for the vertical conductivity of the first confining bed beneath the unconfined aquifer in the model.

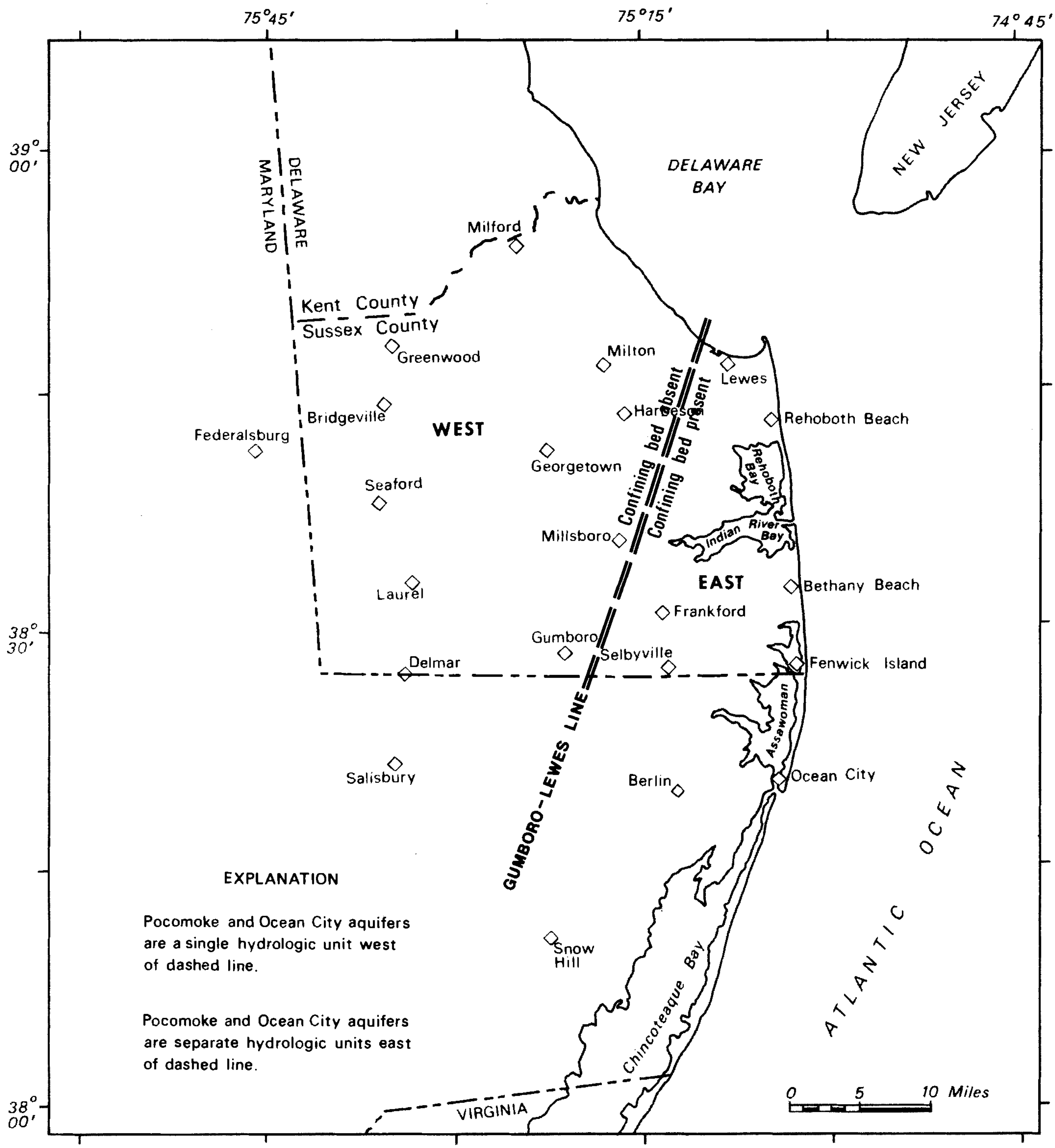


FIGURE 6.—AREAL EXTENT OF THE CONFINING BED BETWEEN THE POCOMOKE AND OCEAN CITY AQUIFERS.

TABLE 5. TRANSMISSIVITY AND STORAGE COEFFICIENTS OF NEOGENE AGE AQUIFERS

(Locations are shown in Figure 1.)

Well	Location	Transmissivity (ft^2/d)	Storage Coefficient (dimensionless)	Analysis by	Date
Oi24-6	Rehoboth Beach	3300	-	Leahy	1975
Oi35-27	Dewey Beach	2500	3.2×10^{-4}	Hodges and Leahy	1976
Pg53-13	Millsboro	6800	7.7×10^{-4}	Hodges	1979
Qj32-12	Bethany Beach	8000	-	Sundstrom and Pickett	1969
Qj32-16	Bethany Beach	8000	-	Hodges and Leahy	1976
Qj41-3	Bethany Beach	4900	3.3×10^{-4}	Hodges and Martin	1979
WorAh-33	Ocean City, Md.	14,000	-	Weigle	1974
WorAh-34	Ocean City, Md.	14,800	-	Weigle	1974
WorBh-1	Ocean City, Md.	3500	1×10^{-5}	Rasmussen and Slaughter	1955
WorBh-35	Ocean City, Md.	5500	-	Weigle	1974
Average value of storage coefficient			3.57×10^{-4}		

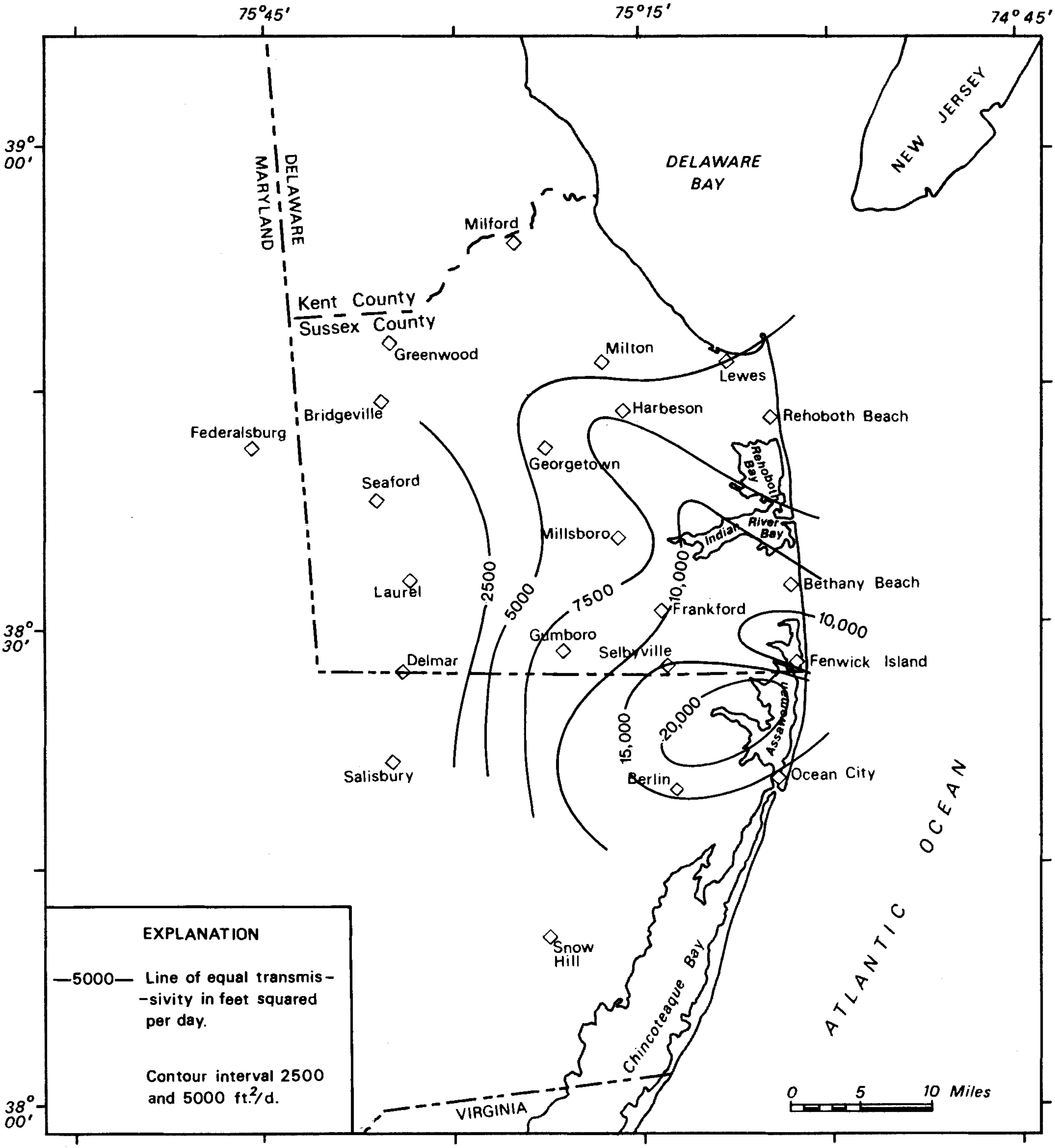


FIGURE 7.—TRANSMISSIVITY OF THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS.

Unconfined Aquifer

The unconfined aquifer of Pleistocene age is the uppermost aquifer throughout the study area. It is equivalent to the Omar and Beaverdam Formations in southeastern Delaware (Table 3; Pickett, 1980), but as both units function as a single hydrologic unit, no differentiation between the formations was made in this study. The aquifer is composed of fine to coarse, white to brown sands locally containing layers of silt, clay, and gravel.

Transmissivity of the unconfined aquifer in the study area ranges from 2,100 ft^2/d at Selbyville to 20,000 ft^2/d in the Broadkill Beach area (Johnston, 1977). Transmissivity values of 15,000 ft^2/d from Rehoboth Beach southwestward to Indian River Inlet east of Millsboro, parallel the Gumboro-Lewes line mentioned above, along which the underlying Ocean City aquifer merges with the Pocomoke aquifer.

The average ground-water discharge from the unconfined aquifer was estimated by Johnston (1973, p. 45) to be 0.550 $(Mgal/d)/mi^2$. This discharge may also be considered as recharge available to, but unused by, deeper aquifers. On the basis of Johnston's work, approximately 370 Mgal/d is available to recharge the lower aquifers in the study area. Ground-water pumpage in 1976 from all sources, including the unconfined aquifer and pumpage from Ocean City, Md., was equivalent to approximately 5 percent of the volume of unused recharge available to the lower aquifers. This surplus of available water means that the unconfined aquifer can be modeled as a constant-head source of water for the underlying units.

Ground-Water Levels

Hydrographs of water levels in 17 observation wells are shown in Figure 8; the locations of these wells are shown in Figure 1. Nine of these wells are in the Manokin aquifer, four are in the Pocomoke aquifer, and two each are in the Ocean City and unconfined aquifers. A graph of monthly precipitation at Milford, Del., on the northern edge of the study area, is also included as part of Figure 8 so that changes in water levels can be compared with the time and magnitude of precipitation events.

The maximum annual fluctuation of record, about 8 feet in well Rj22-5, occurs mainly in response to increased pumpage from the Manokin aquifer during the summer in nearby Ocean City, Md. Water levels in most wells fluctuate seasonally in response to the combined influence of recharge, natural discharge, and pumpage. The effects of pumpage are quite evident on the hydrographs for wells Rj22-6 and 7.

Well Rj22-8, in the unconfined aquifer, is located on a highly permeable barrier beach island about 1,400 feet wide near Fenwick Island, between the Atlantic Ocean and Little Assawoman Bay. Water levels in this well respond to diurnal tidal fluctuations, ocean storm tides, and precipitation. There is no local pumpage from the aquifer because the water is salty, and, consequently, there is no seasonal water-level fluctuation caused by pumping. The three water-level highs during 1978 (Figure 8) were caused by major coastal storms.

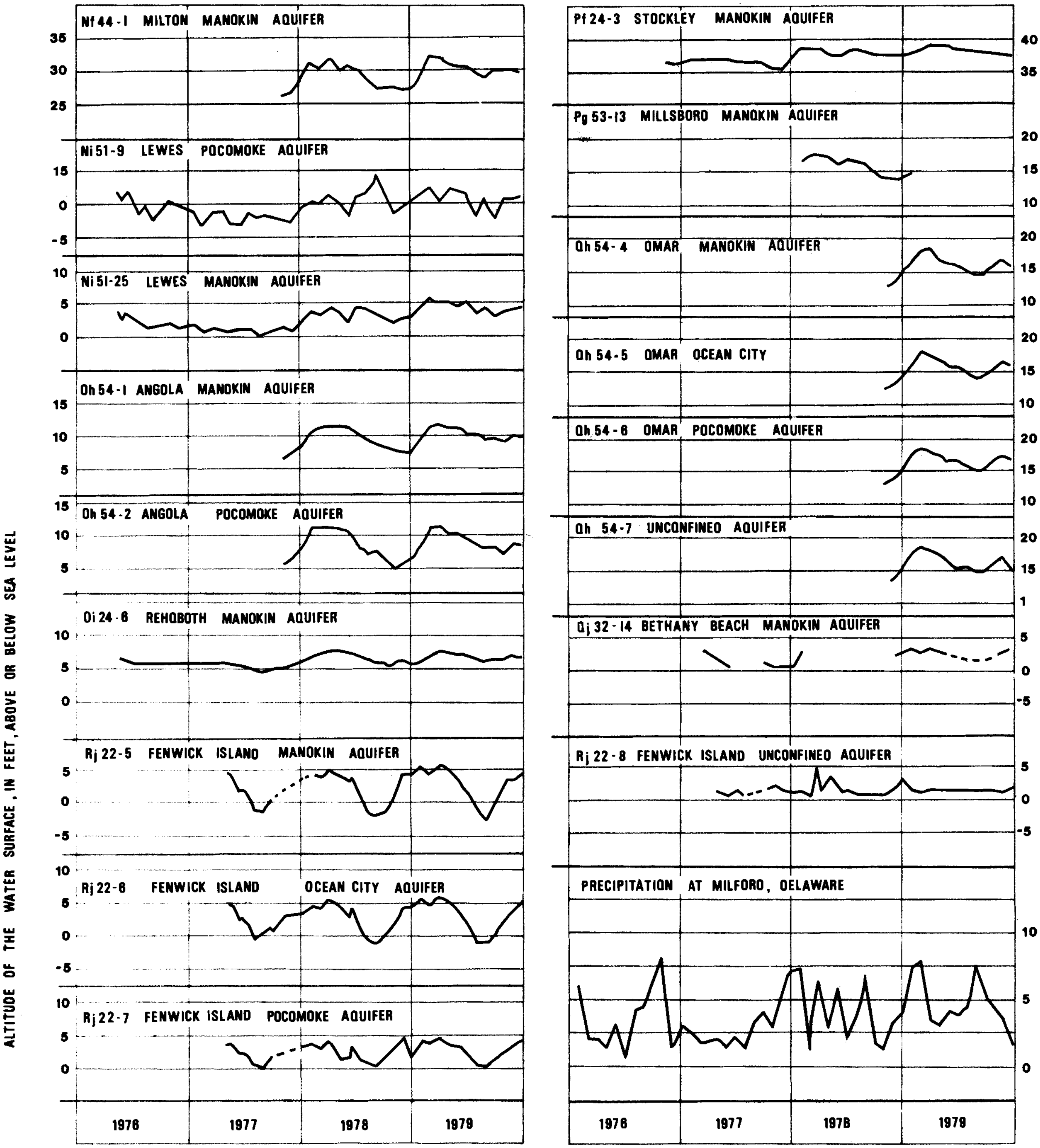


FIGURE 8.—WATER-LEVEL FLUCTUATIONS IN OBSERVATION WELLS, AND PRECIPITATION, 1976-79.

Ground-Water Quality

Chemical analyses of water from the 17 wells shown in Figure 1 are given in Table 6. Areal trends in water quality are difficult to assess from this small number of wells; however, comparison of analyses from two sites--the first near Omar, and the second near Fenwick Island--indicates that differences exist in water quality among the aquifers.

At the first site (wells Qh54-4, 5, 6, and 7), dissolved solids, carbon dioxide, hardness, bicarbonate, alkalinity, sodium, and chloride all decrease with depth. Other constituents show no apparent trend.

At the second site (wells Rj22-5, 6, 7, and 8), water from the Ocean City aquifer contains the lowest concentration of dissolved solids, hardness, chloride, sodium, sulfate, calcium, magnesium, potassium, and phosphorous, and also has the lowest pH. The high concentration of chemical components in the water from well Rj22-8, which is screened in the unconfined aquifer, is attributed to the inundation of Fenwick Island during coastal storms, most recently in November 1964, which caused seawater to infiltrate into the unconfined aquifer.

The variability in the concentration of chemical components of ground water from the Neogene age aquifers of coastal Delaware is evident in the analyses shown in Table 6. Back (1966), who discussed the chemical relationship between ground water and the materials that make up the aquifers, described the water from Miocene sediments in Virginia (p. A31) as characteristically a calcium bicarbonate type. He also noted, in relation to water from the "Miocene age" formations of Maryland on the Delmarva Peninsula, that "Slight changes in the hydrologic environment cause pronounced changes in the chemical character . . . of the water."

Ground water containing elevated concentrations of chloride occurs in parts of the confined aquifers along the coast from Indian River Inlet to Ocean City, Md. Brackish water was reported by the driller of well Pj11-1 at 300 feet and 530 feet below land surface. Several wells on Long Neck, west of Indian River Inlet, are reported to have been abandoned because of salinity, and chloride content of the Bethany Beach municipal well in the Manokin aquifer increases with long-term pumping. Weigle (1974) reports salty water in the bottom few feet of the Manokin aquifer in Ocean City, Md., and discusses the possible sources of the saline water. The scope of this project did not permit a detailed investigation of the chemical quality of the water in the Manokin, Ocean City, and Pocomoke aquifers; however, there is sufficient evidence available to indicate that caution should be used in planning for utilization of the Manokin aquifer along the Delaware coast south of Dewey Beach, Del.

TABLE 6. CHEMICAL ANALYSES OF GROUND WATER IN SOUTHEASTERN DELAWARE
(Well locations are shown in Figure 1.)

		Well Number						
Well data/constituent	Units	Nf 44-1	Ni-51-26	Oh 54-1	Oh 54-2	Oi 35-27	Pf 24-3	Pg 53-13
Aquifer name	-	Manokin	Pocomoke	Manokin	Pocomoke	Manokin	Manokin	Pocomoke
Sample date	-	11/22/77	03/18/77	11/22/77	11/22/77	10/15/76	11/05/76	01/31/78
Depth, top of sample interval	ft	116	106	280	179	208	168	160
Depth, bottom sample interval	ft	121	156	290	189	248	178	250
Total Depth of Hole	ft	121	157	290	290	250	331	406
Elevation of land surface	ft	40	22	18	18	18	5	22
Pumping rate	gal/min	25	1030	10	25	200	50	68
Temperature	°C	16.5	14.0	17.5	17.0	14.5	14.5	14.0
Color	Pt-Co units	4	0	23	12	1	300	60
Specific conductance	umho/cm at 25°C	244	135	462	220	169	90	115
pH	-	6.1	5.5	8.0	5.9	5.2	5.7	6.4
Solids, dissolved	mg/L	59	57	205	60		72	95
Solids, residue at 180°C	mg/L	57	77	265	79	108	83	82
Sodium Adsorption Ratio	-	0.5	1.2	8.4			0.8	1.2
Carbon dioxide, dissolved	mg/L	34	51	3.0		141	125	29
Nitrogen, NO_2+ NO_3	mg/L	0.00	4.9	0.01	.44	0.01	0.01	.02
Hardness, as $CaCO_3$	mg/L	19	16	12	12		20	21
Hardness, noncarbonate	mg/L	0	8	0	0		0	0
Carbonate as CO_3	mg/L	0	0	0		0	0	0
Bicarbonate as HCO_3	mg/L	27	10	190	21	14	39	45
Alkalinity as $CaCO_3$	mg/L	22	8	160	17	11	32	37
Chloride	mg/L	4.1	15	10	7.8	37	5.2	5.8
Fluoride	mg/L	0.0	0.0	0.4	.0	0.0	0.1	0.1
Silica	mg/L	20	16	16	22	23	27	32
Sulfate	mg/L	7.1	3.2	6.6	6.3	9.0	1.1	3.4
Calcium	mg/L	5.9	2.9	2.1	3.5		4.8	5.4
Iron, dissolved	ug/L	770	10	2100	320		3200	9200
Iron, total recoverable	ug/L	790	80	4700	790	4300	6000	9300
Magnesium	mg/L	1.0	2.1	1.6	.8		1.9	1.8
Manganese, dissolved	ug/L	50	10	30	40		130	260
Manganese, suspended	ug/L	0	0	10			0	0
Manganese, total recoverable	ug/L	50	10	40	40	40	110	260
Phosphorus	mg/L	0.00	0.00	0.96	.01	0.03	0.13	0.16
Potassium	mg/L	1.6	1.5	6.0	1.4		1.4	2.0
Sodium, dissolved	mg/L	5.2	11	66	7.7		8.0	13
Sodium, percent	-	35	57	88			45	55

Well Number									
Qj 32-8	Qh 54-4	Qh 54-5	Qh 54-6	Qh 54-7	Qj 41-2	Rj 22-5	Rj 22-6	Rj 22-7	Rj 22-8
Unconfined	Manokin	Ocean City	Pocomoke	Unconfined	Manokin	Manokin	Ocean City	Pocomoke	Unconfined
02/23/56	11/03/78	11/03/78	11/03/78	11/03/78	08/05/71	05/11/77	05/11/77	05/11/77	05/11/77
	324	229	144	104		450	290	180	110
70	328	232	148	108	366	455	295	185	115
	424	424	424	424		493	493	493	493
7	28	28	28	28	5	5	5	5	5
	11	50	20	33		50	5.0	0.33	50
	15.5	15.0	15.0	15.0		18.0	17.5	22.5	16.0
	1000	1000	500	1300	70	30	80	50	0
445	360	209	211	309	306	1720	230	420	23000
6.7	6.3	6.3	6.3	6.3	7.9	7.0	6.3	6.8	6.7
	229	208	146	136		1060	156	276	17700
	246	222	154	144	196	1010	144	263	17200
	1.1	0.4	0.6	0.7		12	1.1	2.2	38
	112	112	60	55		34	67	38	2.2
	0.00	0.00	0.00	0.00		0.00	0.05	1.8	0.04
	100	110	54	44		150	63	110	4000
	0	0	0	0		0	0	0	4000
	0	0	0	0		0	0	0	0
127	140	140	75	68	133	210	83	150	7
	110	110	62	56		170	68	120	6
63	33	15	14	13	29	460	21	60	9500
	0.1	0.1	0.0	0.0	.1	0.2	0.1	0.2	0.0
	33	45	36	32	51	26	35	33	29
.5	9.2	7.7	8.3	8.3	0	54	4.4	8.0	1300
	29	42	19	14	32	26	18	24	440
	18000	14000	17000	20000		3100	8700	4600	130000
	17000	13000	17000	20000	9100	3000	8900	4600	120000
	7.6	2.4	1.7	2.2	3.9	21	4.4	11	710
	170	190	140	140		60	150	140	1300
	0	0	0	0		0	0	0	0
	160	180	120	140	130	60	150	110	1100
	0.32	0.15	0.19	0.21		0.41	0.16	0.17	0.58
	4.2	1.5	1.5	2.1	3.3	18	3.5	9.5	80
	26	11	11	11	21	350	20	52	5500
	34	17	30	34		81	39	49	74

AQUIFER SIMULATION

Digital Models

Digital models used by Johnston (1977) and Leahy (1979A), and the models used in this study, were developed by Trescott, Pinder, and Larson [1979 (two-dimensional model)] and by Trescott [1975 (three-dimensional model)]. Both a two-dimensional model and a modified three-dimensional model, termed a "quasi three-dimensional model," were used in this study.

A two-dimensional model, which simulates flow in an individual aquifer, assumes that all flow within the modeled aquifer is horizontal and that heads in adjacent aquifers remain constant with time.

A three-dimensional model simulates flow in confining beds as well as aquifers and simultaneously computes head distributions in all layers in three dimensions.

The quasi three-dimensional model used in this study simulates flow in all confining beds and aquifers on the system, and simultaneously computes head distribution in all layers. Even though two components of flow are considered in aquifers, only the vertical component of flow is considered in confining beds, which decreases the number of equations that need to be solved in a simulation. The quasi three-dimensional model used in this study contains modifications made by Posson and others (1980), which enable the model to consider both steady-state and transient leakage through and from the confining beds. Steady-state conditions are those that are reached in a modeled system when it is in equilibrium with applied pumping. Transient conditions are those that are computed at the end of a specific time during the equilibration process while the modeled system is reacting to applied pumping.

Leahy (1979B) compared the theory, mathematics, and method of solution of the two-dimensional, three-dimensional, and quasi three-dimensional finite-difference models used in Delaware ground-water studies. The reader is referred to this work for specific details of each model.

Conceptual Model of the Flow System

For a digital model to represent a real flow system, the physical system must be described by a conceptual model that reduces the complexity of the physical system and relates hydrologic properties of this system to equivalent mathematical terms of the digital model. The conceptual model of the flow system is shown in Figure 9. Ground-water movement in the natural flow system (Figure 9A) moves downward from the unconfined aquifer to recharge underlying aquifers, and laterally to discharge areas along streams and the ocean. Water levels in the unconfined aquifer vary seasonally, but can be considered to act as a constant-head source of recharge to underlying aquifers. Ground-water movement in the confined aquifers modeled in this study is predominantly lateral, moving downdip toward discharge areas off the coast. Vertical movement of water from these aquifers occurs as a result of pumpage and differential head across overlying or underlying confining beds. Vertical movement of ground water through confining beds at the offshore interface between freshwater and saltwater is controlled by aquifer head, confining-bed thickness, and vertical conductivity.

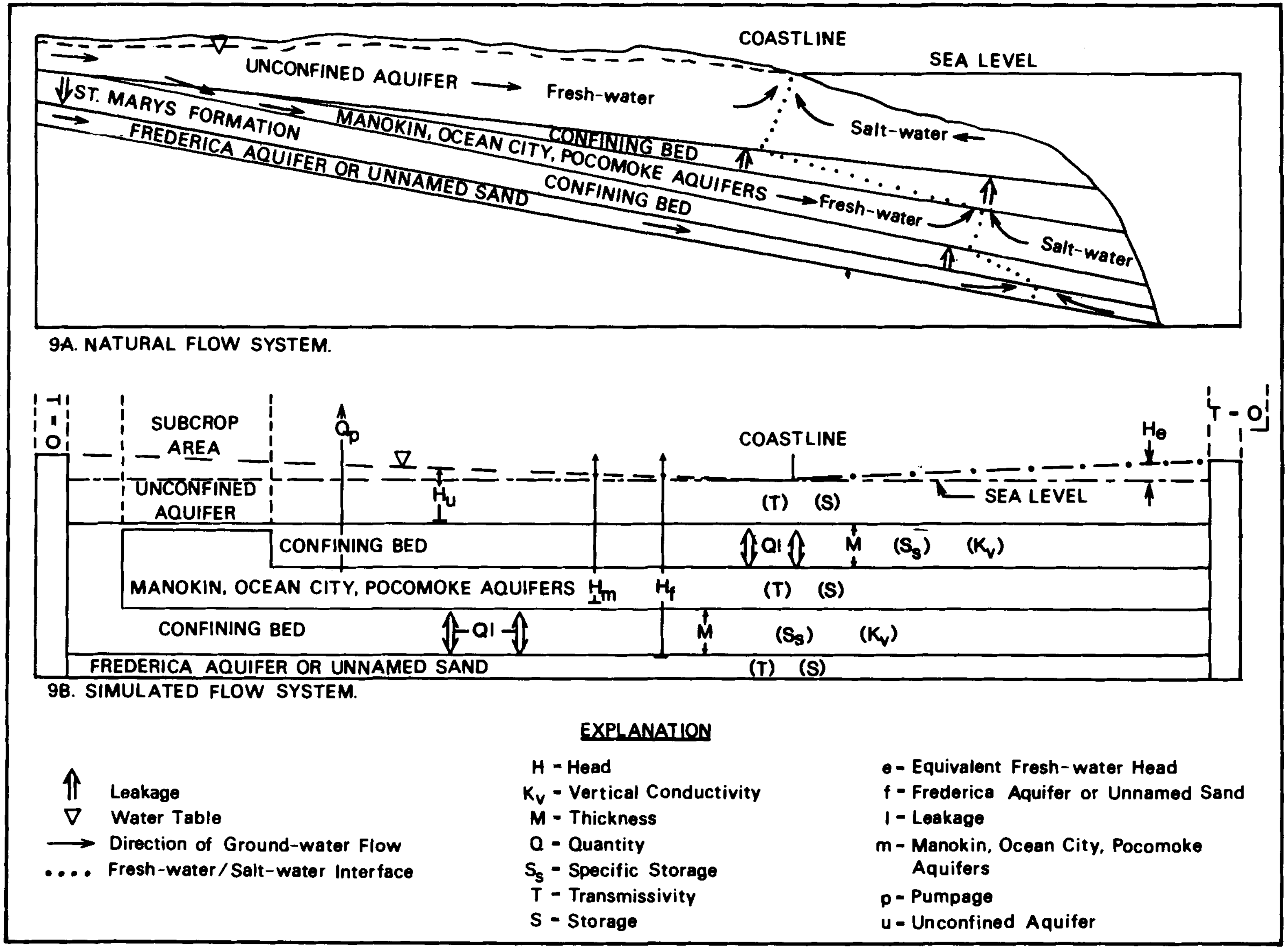


FIGURE 9. CONCEPTUAL MODEL OF THE FLOW SYSTEM.

FIGURE 9.—CONCEPTUAL MODEL OF THE FLOW SYSTEM.

The density of seawater is 1.025 times that of freshwater; thus, the weight of a 40-foot column of seawater is equivalent to that of 41 feet of freshwater. The maximum depth to the ocean floor below sea level in the modeled area is 150 feet, equivalent to 153.7 feet of freshwater; therefore, as much as 3.7 feet of head was added to offshore sea level to compensate for differences in freshwater-saltwater density. The freshwater-saltwater interface is the point at which freshwater head in the aquifer is equal to saltwater head.

A schematic diagram of the natural flow system as used in the model is shown in Figure 9B. The unconfined aquifer is a constant-head source of water throughout the modeled area. Onshore head in the unconfined aquifer is determined from average annual water-table altitudes, and offshore heads are determined from sea level plus additional head (He) equivalent to the salt-freshwater differential discussed above. In those areas where the confining bed between the unconfined aquifer and the immediately underlying aquifers is thin or absent, the head in the underlying aquifers (Hm) approaches the constant-head value (Hu) in the unconfined aquifer.

The direction and quantity of ground-water leakage through confining beds (Ql) is determined by head differences in adjacent aquifers (Hu, Hm, and Hf) and the thickness (M), specific storage (S), and vertical conductivity (Kv) of the confining bed. Leakage in the unstressed system near the coast is generally upward because of higher heads in deeper aquifers. This may be reversed, however, by withdrawals (Qp) from an aquifer.

Two-Dimensional Digital Model

A two-dimensional model of the coastal aquifer system was developed early in the study to provide realistic estimates of aquifer coefficients for both the Neogene sands and the confining bed between these sands and the unconfined aquifer.

Initial transmissivity values used for the Manokin, Ocean City, and Pocomoke aquifer system were those given by Sundstrom and Pickett (1969, 1970), Weigle (1974), and Rasmussen and Slaughter (1955). Thickness of the confining bed between the confined system and the unconfined aquifer was estimated from preliminary geologic sections and data from Weigle (1974).

Calibration of the model was done by assessing the drawdown at 7 observation wells in southeastern Delaware caused by pumping at 12 wells in Delaware and Ocean City, Md., during a 6-month period in 1976. Each modeled pumping period was 30 days. At the end of each pumping period, observed water levels were compared with predicted water levels at that location. Adjustments were made to the transmissivity of the aquifer and to the hydraulic conductivity and specific storage of the confining bed, until predicted water levels approximated those measured at the observation wells. The difference between simulated and observed drawdown for five of the wells averaged 1.54 feet. Observed and measured water levels could not be closely matched at the other two wells because of close proximity of high-capacity pumping wells to the observation well relative to the grid spacing of the model.

Quasi Three-Dimensional Model

The quasi three-dimensional model of southeastern Delaware was constructed with an expanding grid containing 1,575 blocks. This grid represents a 782-mi^2 area of 1-mile-square blocks (Figure 10). The overall size of the modeled area is 64 mi north to south and 59 mi east to west, which covers a total of 3,776 mi^2.

Assumptions and Boundary Conditions

The following simplifying assumptions were made in the quasi three-dimensional model:

1. The unconfined aquifer is a constant-head source of recharge to all underlying aquifers in the modeled area. Johnston (1977, p. 10) reported that annual withdrawals from the unconfined aquifer in southern Delaware compared to natural rates of recharge and discharge to streams result in long-term steady-state conditions in the unconfined aquifer. Therefore, this aquifer was not modeled as an active layer in this report.

2. The Manokin, Ocean City, and Pocomoke aquifers function as a homogenous and isotropic hydrologic unit. This assumption is based on examination of hydrographs from wells Rj22-5, 6, and 7 (Figure 8). Although water levels are affected to different degrees by pumpage from the several aquifers underlying southeastern Delaware and Maryland, all three aquifers return to approximately the same water level during late winter when the aquifer is not being stressed by heavy pumpage. Water levels in wells Oh54-1 and Oh54-2 show not only different summer drawdowns, but different time responses to this stress. Water levels in both wells, however, return to approximately 11 feet above sea level during winter.

3. Manokin, Ocean City, Pocomoke aquifer boundaries are no-flow boundaries. A no-flow boundary (Figure 10) required by the model surrounds the aquifer system on all four sides. A no-flow boundary is also approximated along the western and northwestern boundary of the modeled area where the confined aquifer system is absent. Aquifer transmissivity is reduced to the value of the St. Marys Formation in these areas, approximating the flow in a confining bed. In the subcrop area of the Manokin, Ocean City, and Pocomoke aquifers shown in Figure 10, a confining bed with a thickness of 0.01 feet is assumed for modeling purposes to be present between the confined and unconfined aquifers. In this area therefore, head values in the confined aquifer approximate the constant head of the unconfined aquifer. The perimeter no-flow boundary on the eastern edge of the model simulates the freshwater-saltwater interface boundary discussed earlier. The north, east, and south boundaries are positioned arbitrarily at sufficient distances from the center of the grid so that they will have negligible effect on simulated heads calculated by the model in the study area.

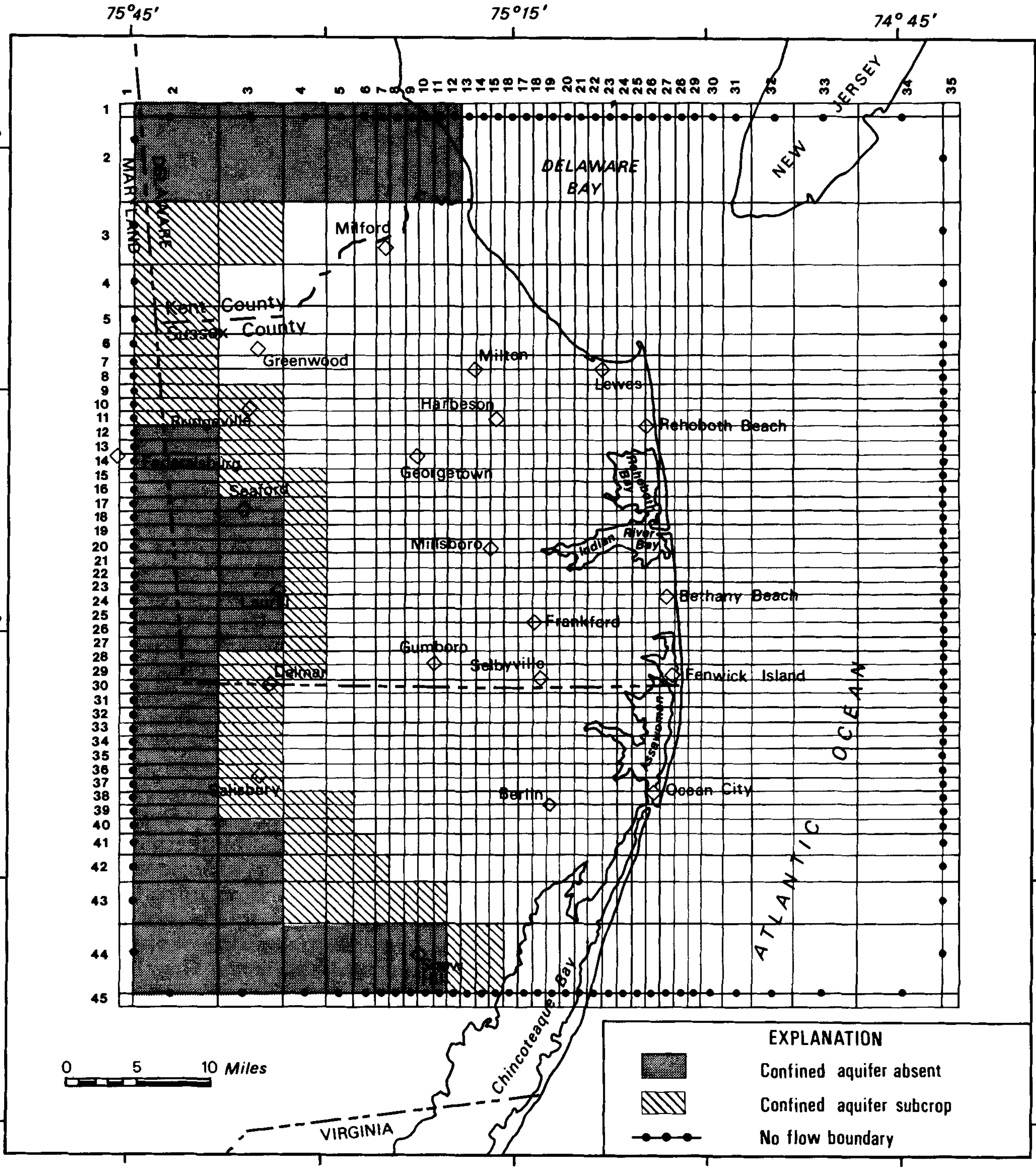


FIGURE 10.—QUASI THREE-DIMENSIONAL MODEL GRID AND SUBCROP AREA OF THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFER SYSTEM.

4. The St. Marys Formation, which underlies the Manokin, Ocean City, and Pocomoke aquifers has constant thickness and vertical hydraulic conductivity throughout. Data are insufficient to determine areal variability of these properties. An average value of 100 feet for the thickness of the formation and an average Kv of 10^{-4} ft/d was assumed throughout the area.

5. The Frederica aquifer, which underlies the St. Marys Formation, has constant transmissivity throughout the area. Again, data on this aquifer are sparse in the modeled are. Although a value of 1,400 ft^2/d was reported by Cushing, Kantrowitz, and Taylor (1973), 1,000 ft^2/d was assumed to more realistically reflect the general thinning of the aquifer in the study area.

6. The sand beneath the St. Marys Formation is bounded on all sides by no-flow boundaries that coincide with the four sides of the modeled area. This aquifer extends to the west and north and probably to the south and east beyond the imposed boundaries. However, the combined thickness of the overlying confining bed, the absence of coastal pumpage, and the distance of the boundaries from the primary area of interest should allow the model to adequately predict the relatively small amount of stress in this sand imposed by pumping the overlying confined aquifers. The sand beneath the St. Marys Formation was not modeled in detail, but, rather, was included in the model to avoid specifying the base of the Manokin, Ocean City, Pocomoke aquifer system as an arbitrary no-flow boundary.

7. All pumpage is constant during a pumping period. Given this assumption, the model will produce a simulated aquifer head that will represent the water level at a particular node at the end of that pumping period.

8. All ground-water flow in confined aquifers is horizontal, and all flow in confining beds is vertical.

9. No movement of water occurs across the freshwater-saltwater interface.

Input Data

Several types of data are required by the model in order to generate the desired information. In addition to scalar parameters, including model instructions and pumpage information, the model requires data for each hydrologic property of each layer included in the computations. Values used in these hydrologic data matrices are:

1. Starting head.—Altitude of the water table in the unconfined aquifer (Figure 11) was taken from Sundstrom and Pickett (1969, 1970), Weigle (1974), and Cushing, Kantrowitz, and Taylor (1973). Starting heads in the confined aquifers were developed during steady-state calibration, discussed below.

   Starting head in the offshore part of the unconfined aquifer was increased by as much as 3.7 feet in order to compensate for the additional head generated by the difference in density between freshwater and saltwater.

2. Storage coefficient.—The unconfined aquifer was modeled as a constant head; therefore, a storage value was not used for this aquifer. The storage value of the Manokin, Ocean City, and Pocomoke aquifers is $1x10^{-4}$, and that of the sand beneath the St. Marys Formation is $1x10^{-5}$.

3. Transmissivity.—A value of 10,000 ft^2/d was used throughout the modeled area for the transmissivity of the unconfined aquifer. Transmissivity of the Manokin, Ocean City, and Pocomoke aquifers (Figure 7) was supplied in matrix form to reflect areal changes in this property caused by changing lithology and thickness. Transmissivity of the sand beneath the St. Marys Formation, as noted above, was assumed to be 1,000 ft^2/d throughout the modeled area.

4. Confining-bed thickness.—The thickness of the confining bed between the unconfined aquifer and the immediately underlying confined aquifer system (Figure 12) was estimated from the geologic sections shown in Figure 2. Thickness of the St. Marys Formation was assumed to be 100 feet throughout the modeled area.

5. Vertical hydraulic conductivity of the confining beds.—The vertical hydraulic conductivity of the confining beds was adjusted during calibration (discussed below). The final value used in the predictive model is $1x10^{-4}$ ft/d for the St. Marys Formation and $1x10^{-3}$ ft/d for the confining bed between the unconfined aquifer and underlying Manokin, Ocean City, and Pocomoke aquifer system.

6. Specific storage of the confining beds.—The specific storage value used for both confining beds is $1x10^{-6}$ ft^{-1}.

Calibration of the Quasi Three-Dimensional Model

To reliably predict the effect of future changes in stress on an aquifer system, the hydrologic coefficients must be adjusted until the model closely simulates historic water levels. This process of adjustment, called calibration, is continued until simulated water levels are equal or nearly equal to measured water levels.

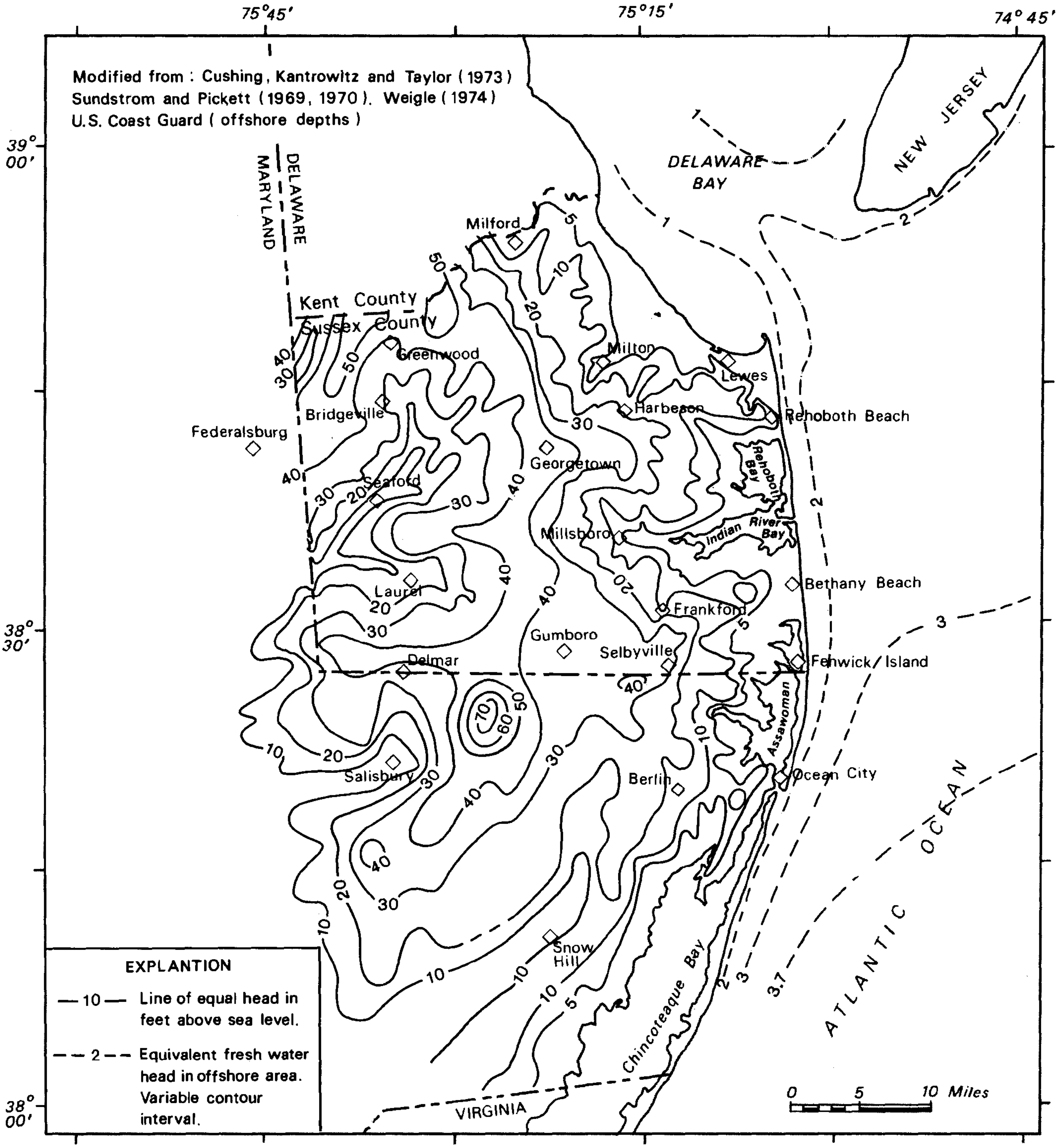


FIGURE 11.—POTENTIOMETRIC SURFACE OF THE UNCONFINED AQUIFER.

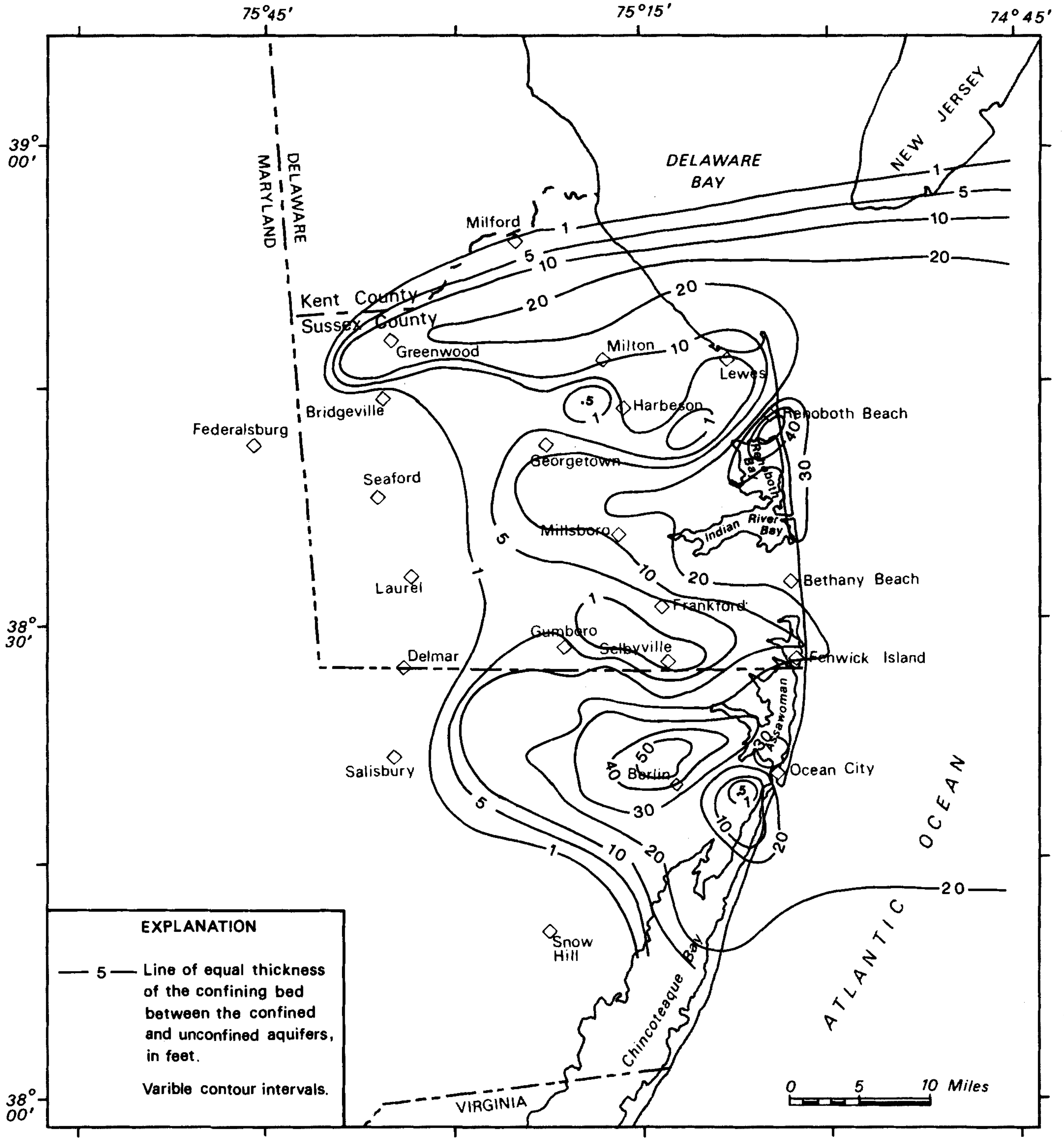


FIGURE 12.—THICKNESS OF THE CONFINING BED BETWEEN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFER SYSTEM AND THE UNCONFINED AQUIFER.

Calibration of the quasi three-dimensional model was complicated by the hydraulic connection between the confined and the unconfined aquifer. Stresses on the aquifers, both natural and man-made, cause water levels to decline during summer. Decrease of the stress during the winter allows water levels to rise in both aquifers. Head values simulated by the model in areas where the confining bed between the unconfined and confined aquifers is thin or absent approach the yearly average water level of the unconfined aquifer which was specified as the starting head in that node. Logs of well Oh54-1 in Angola show almost no confining bed between the aquifers (Figure 2). Calibration values at that node (Figure 8) therefore reflect the average water level of the unconfined aquifer rather than the effects of regional pumpage from the Manokin, Ocean City, and Pocomoke aquifers. In areas where the confining bed between the unconfined and confined systems is thick, calibration values simulated by the model show the effects of pumpage from the confined system.

The quasi three-dimensional model was calibrated by simulating both steady-state and transient-state conditions. Steady-state conditions were simulated first, using 1977 average pumpage. Aquifer and confining-bed coefficients were adjusted until computed water levels matched water levels observed at a particular node. Transient response of the system during 1976-79 was then simulated and minor adjustments were made to aquifer parameters until simulated water-level fluctuations reproduced those observed in observation wells. The final step in model calibration involved a series of simulations in which the transmissivity values of the confined aquifer and conductivity of the confining bed were changed to assess the sensitivity of the model to these properties. The model was then used to determine the areal drawdown configuration caused by pumping from the Manokin, Ocean City, and Pocomoke aquifers during 1975-79 and the potential effects of the increase in pumpage projected to occur between 1980 and 2004.

Steady-State Calibration

Steady-state water levels in the confined aquifer systems (Figures 13 and 14) were simulated by the model using 1977 pumpage data, a known head distribution in the unconfined aquifer, and estimated aquifer properties of the sand beneath the St. Marys Formation. Adjustments were made in the transmissivity of the Manokin, Ocean City, and Pocomoke aquifer system, the vertical hydraulic conductivity of the confining beds, and the thickness of the confining bed beneath the unconfined aquifer until the simulated water levels matched the average water level observed at each of 14 observation wells during 1976-79. Because land surface altitude at each observation well was estimated from topographic maps, the observed water levels may be in error by as much as 5 feet. Steady-state calibration water levels are noted on the left side of hydrographs in Figure 8 and are contoured in Figure 14. No water-level data in the Frederica aquifer of coastal Delaware or the sand beneath the St. Marys Formation are available, and therefore the model is not calibrated for this aquifer. Simulation results for this deeper sand are included so that the effects of pumping from the overlying Neogene age sands can be estimated.

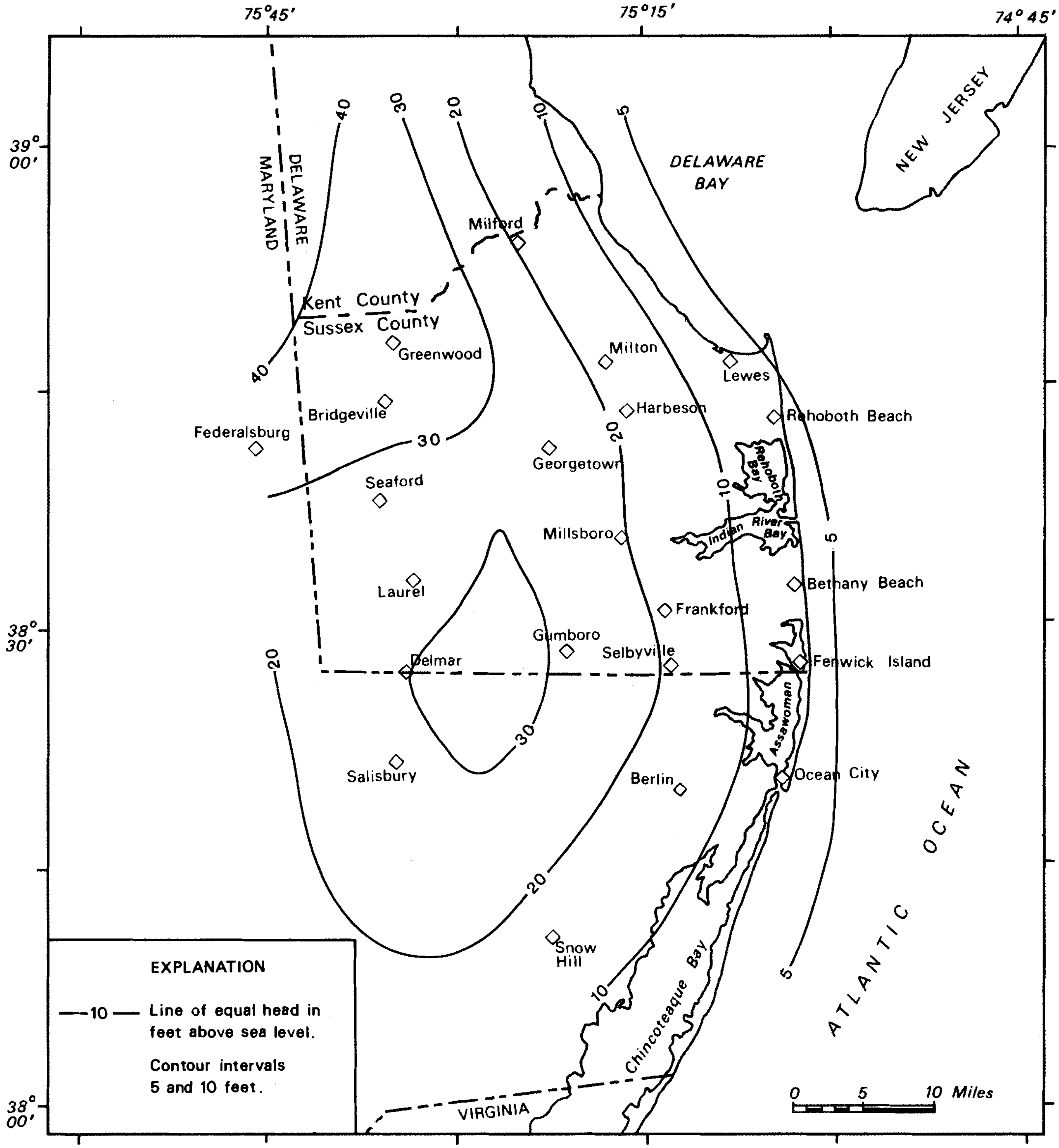


FIGURE 13.—UNCALIBRATED STEADY-STATE HEAD IN THE SAND BENEATH THE ST. MARYS FORMATION, 1977.

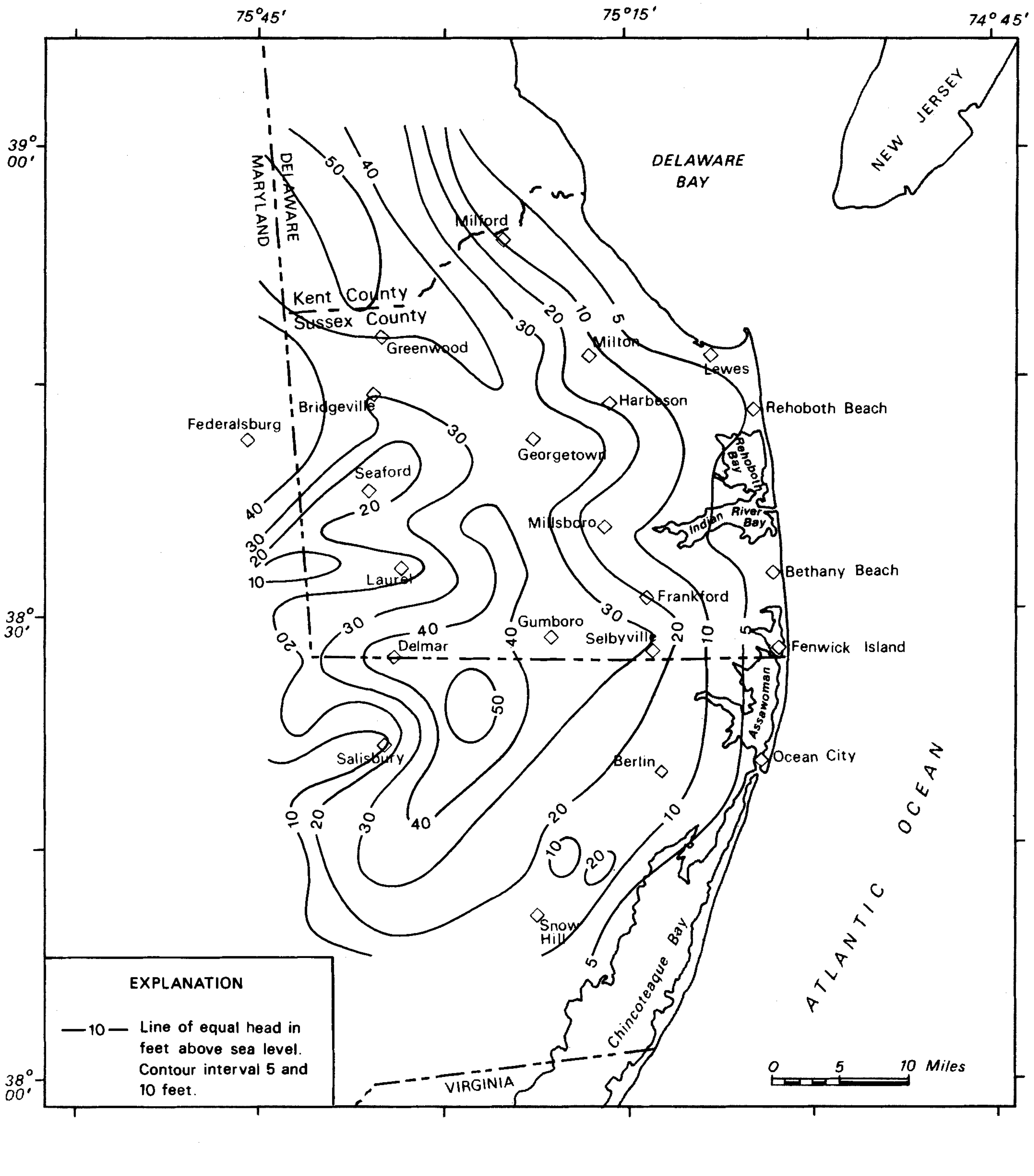


FIGURE 14.—STEADY-STATE HEAD IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFER SYSTEM, 1977.

Transient Calibration

The second phase of model calibration checked the response of the model to transient changes in the hydrologic system. These changes include seasonal variations in pumpage and the effects of storage in confining beds. Starting head values for all of the confined aquifers were those developed by steady-state calibration (above). Pumpage values for 1976-79 (Table 7) were grouped into nine pumping periods, which represented average pumpage from September through May, and June through August for each year of the simulation. Head values simulated by the model were compared with observed water levels in the Manokin, Ocean City, and Pocomoke aquifers as shown in Figure 15. Model results generally agree with observed water levels, except at Lewes. Constant pumpage from the aquifer system subcrop near well Ni51-9 results in a fairly constant head difference between the Pocomoke and Manokin aquifers at this location. Measurements made in August 1978, following a decrease in pumpage that began in May 1978, indicate that when stress is removed, water levels in both aquifers become similar.

Transient calibration values simulated by the model at the node containing observation wells Rj22-5, 6, and 7 at Fenwick Island are reproduced on the hydrograph for each observation well. Simulated water levels at Bethany Beach generally follow those measured in an observation well that corresponds to that node. Only those measurements taken when an adjacent production well was not being pumped are shown on the hydrograph. Water levels in wells Nf44-1 and Pf24-3, which are adjacent to the subcrop area, and in wells Oh54-1, Oh54-2, Oi24-6, Qh54-4, Qh54-5, and Qh54-6, where the confining bed immediately beneath the unconfined aquifer is thin or missing, reflect the water level specified for the unconfined aquifer as discussed above. Sensitivity of the calibrated model to values of aquifer transmissivity and vertical conductivity of the confining bed underlying the unconfined aquifer was analyzed by running the model at 2 times and 10 times calibration values of these properties. Results of this analysis are shown in Figure 16. Increasing the value of either property causes both positive and negative head changes in the modeled area, with a maximum rate of divergence occurring near the calibration values. Sensitivity to change in T or K values decreases with proximity to the ocean, which verifies the influence of constant head at the ocean boundary.

Use of the Calibrated Model

To evaluate the areal effects of pumping, a starting head of zero was specified in all aquifers, and the same pumpage values and time increments were specified as those used in the transient calibration for 1976-79. The results of this simulation are shown in Figures 17A-17I. Changes in water level caused by increased or decreased pumpage are the same in both the transient calibration and the zero starting head models for each of the nine time steps. Maximum drawdown in the sand beneath the St. Marys Formation during this period occurred during summer 1977 in Ocean City, Md., in response to pumping from the overlying aquifer system. This simulation is based on uncalibrated data for the Frederica aquifer, and the values shown should be regarded as trend indicators only.

Simulated drawdown (Figures 17A-17I) in the Manokin, Ocean City, and Pocomoke aquifers due to pumping during 1976-79 indicates that the cones of depression caused by pumping at Georgetown, Harbeson, and Lewes are localized,

TABLE 7. TRANSIENT CALIBRATION PUMPAGE, 1976-1979

LOCATION	Pumpage, (gal/d)								
	1976			1977		1978		1979	
	JAN-MAY	JUNE-AUG	SEPT-MAY	JUNE-AUG	SEPT-MAY	JUNE-AUG	SEPT-MAY	JUNE-AUG	SEPT-DEC
Prime Hook	90,000	90,000	90,000	90,000	6,000	18,000	6,000	18,000	6,000
Georgetown	863,000	1,054,000	840,000	1,054,000	840,000	1,054,000	840,000	1,054,000	811,000
Harbeson	1,350,000	1,350,000	1,350,000	1,350,000	1,016,000	1,016,000	1,016,000	1,016,000	1,016,000
Lewes	1,270,000	1,610,000	1,257,000	1,610,000	1,262,000	1,323,000	1,196,000	1,356,000	1,213,000
Sussex Shores	41,000	216,000	36,000	141,000	39,000	180,000	39,000	181,000	39,000
Sea Colony	52,000	197,000	59,000	197,000	88,000	257,000	86,000	369,000	105,000
Bethany Beach	70,000	209,000	65,000	224,000	68,000	223,000	72,000	230,000	76,000
Fenwick Towers	3,000	33,000	7,000	33,000	10,000	39,000	13,000	45,000	16,000
Fenwick Island	20,000	139,000	25,000	139,000	32,000	142,000	39,000	162,000	45,000
Ocean City	207,000	6,999,000	2,938,000	8,407,000	2,179,000	8,609,000	2,412,000	8,257,000	2,938,000

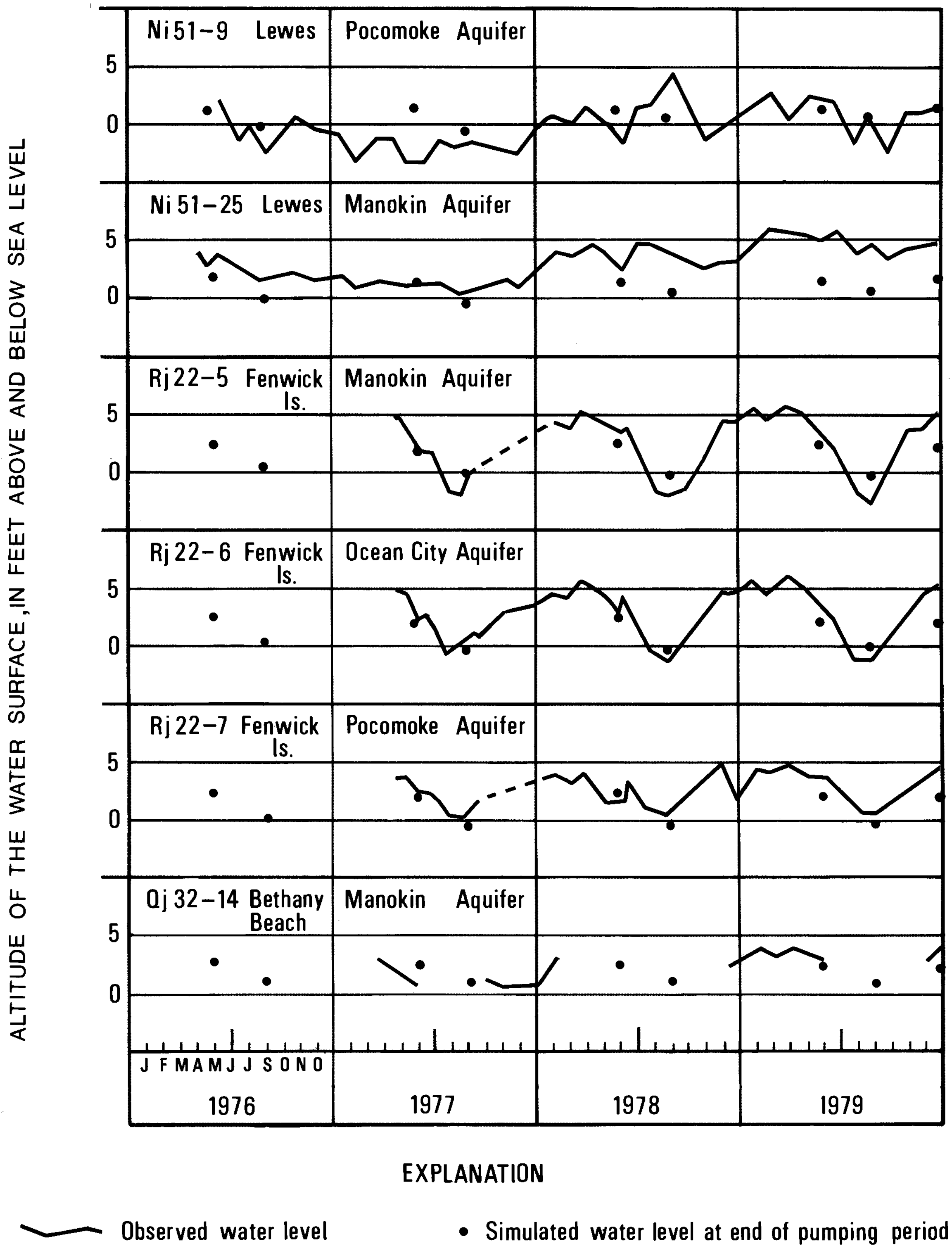


FIGURE 15.—TRANSIENT CALIBRATION, 1976-79; OBSERVED VERSUS SIMULATED WATER LEVELS.

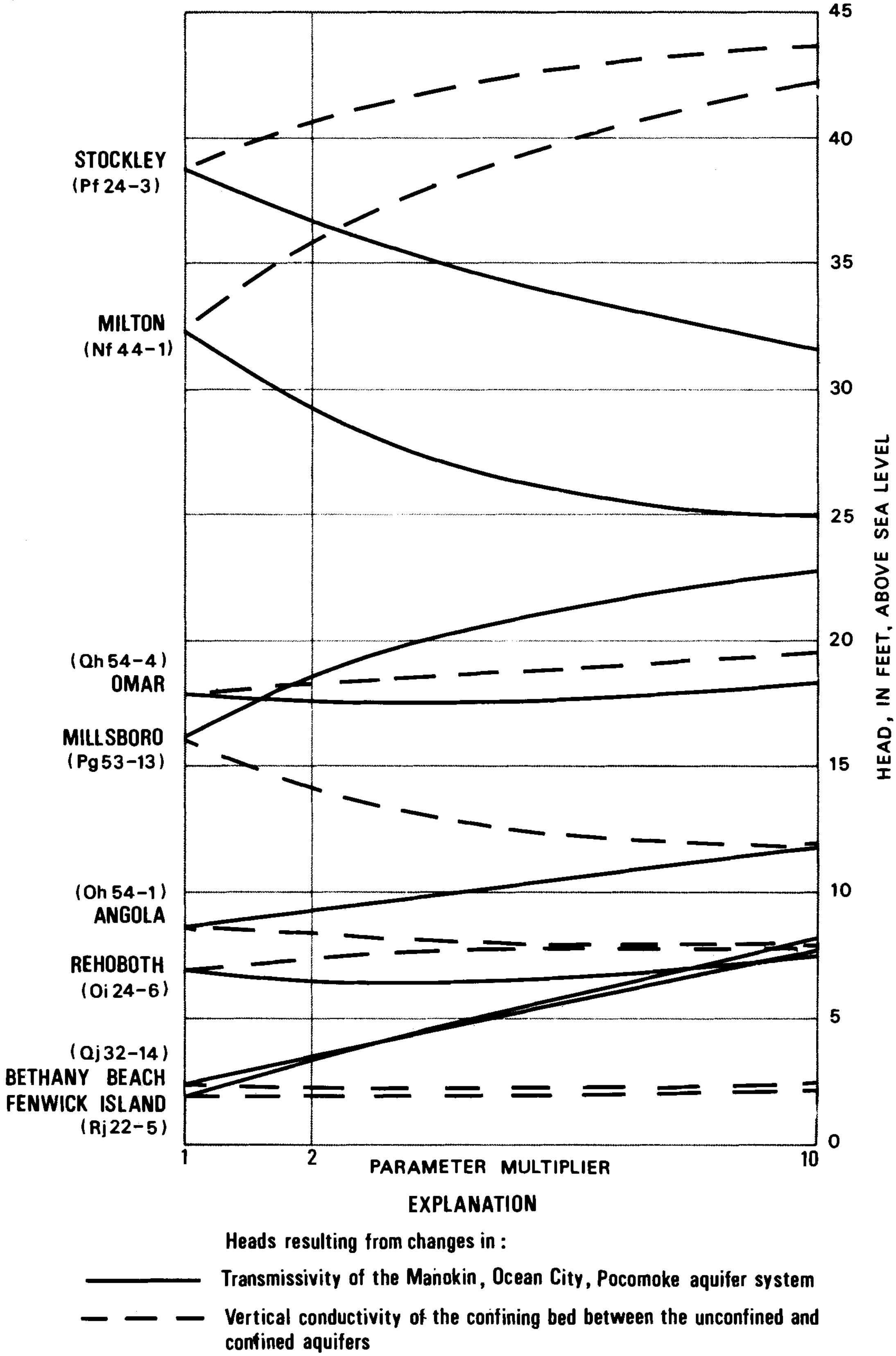


FIGURE 16.—SENSITIVITY ANALYSIS OF THE STEADY-STATE MODEL.

and do not coalesce. Drawdown due to pumping at Ocean City, Md., however, extends northward into Delaware and merges with a drawdown cone produced by pumping at Fenwick Island and Bethany Beach. Maximum drawdown in this aquifer occurs from June to August at Ocean City, Md. During winter months, however, the residual effect of this stress is just over 1 foot in southeastern Delaware.

Forecasting with the Quasi Three-Dimensional Model

Water-level values developed by the steady-state model were used as starting heads in the predictive model. Pumpage at 14 nodes was increased in a series of six steps representing average pumpage for 5-year periods (Table 8). The first period used 1977 pumpage, and was included to assure model stability under transient conditions. At the end of this period, pumpage was increased to that projected for 1980-84. The other four pumping periods covered 1985-89, 1990-94, 1995-99 and 2000-04. Pumpage values used in this simulation were derived from the percentage increase in water use shown in Table 1.

Predictive simulation results are given in Table 9. The estimated increases in pumpage through the year 2004 are predicted to have little effect on average yearly water levels at the major pumping centers in Delaware, except in the town of Lewes.

Most of the wells in the Lewes well field are screened in the Pocomoke and Ocean City aquifers. The confining bed between the unconfined aquifer and the Neogene aquifer at Lewes is thin and relatively permeable (Figure 2 C-C' and Figure 12), and a local clay layer between 10 and 20 feet below land surface is considerably less permeable than the confining bed below the unconfined aquifer. This will cause the unconfined, Pocomoke, and Ocean City aquifers to function as a single leaky hydrologic unit in the Lewes well field area. Pumping from the well field will lower the water level in the unconfined aquifer and, to a lesser extent, in the Manokin aquifer as noted above in the section on Transient Calibration. Increasing pumpage from the town well field will lower the average yearly water level below sea level during 1985-89. This may induce ground water to flow from Delaware Bay and the Lewes and Rehoboth Canal toward the well field, which may eventually cause chloride contamination of the Lewes water supply. Potential movement of saltwater toward the Lewes well field, based on a digital model of the unconfined aquifer, was also discussed Johnston (1977).

The predicted yearly decrease in average water levels in the aquifer system ranges from a maximum of 0.10 ft/yr at Lewes, to a minimum of 0.002 ft/yr at Rehoboth Beach. Rehoboth Beach now takes its water from the unconfined aquifer, but the above simulation indicates that if the underlying confined aquifer is developed there for additional municipal supply, interference from nearby pumpage will be minimal. The smallest increase in total pumpage during the predictive period will occur at Fenwick Island. Decrease in head, however, will be 0.03 ft/yr because of the effects of pumpage at Ocean City, Md. Maximum water-level changes in the sand beneath the St. Marys Formation will be less than 0.1 foot per node per 5-year period. This conclusion is based on an uncalibrated simulation, but suggests that in Delaware, little water from this sand will move upward toward the overlying aquifers as a result of future pumpage.

TABLE 8. PROJECTED PUMPAGE FROM THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS 1980-2004

LOCATION	Pumpage (gal/d)				
	1980-1984	1985-1989	1990-1994	1995-1999	2000-2004
Prime Hook	94,700	97,100	99,700	102,100	104,600
Georgetown	946,600	981,400	1,016,800	1,056,100	1,100,500
Harbeson	1,419,800	1,457,100	1,494,300	1,531,600	1,568,700
Lewes	1,441,900	1,520,700	1,601,400	1,682,100	1,816,700
Sussex Shores	80,800	85,200	89,800	94,300	101,800
Sea Colony	100,500	106,000	111,600	117,200	126,600
Bethany Beach	116,200	122,500	129,100	135,600	146,400
Fenwick Island	57,800	61,000	64,200	67,500	72,800
Fenwick Towers	14,500	15,300	16,200	17,000	18,400
Ocean City, Md.	3,711,500	3,914,100	4,121,900	4,329,700	4,676,100

TABLE 9. SIMULATED WATER LEVELS AT MAJOR WELL FIELDS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS 1977 - 2004

Location	Starting Head, Ft Above Sea Level 1977	Predicted Head, (Sea Level Datum)					Total Increase In Pumpage (ft^3/s) 1977-2004	Total Decline In Head (ft) 1977-2004	Decrease In Head (ft/year)
		1984	1989	1994	1999	2004			
Lewes	0.75	0.22	-0.22	-0.66	-1.11	-1.85	0.7287	2.60	0.10
Rehoboth Beach	6.85	6.84	6.83	6.82	6.81	6.79	0.5348	0.06	0.002
Georgetown	34.96	34.63	34.41	34.19	33.94	33.66	0.3197	1.30	0.05
Harbeson	14.99	14.65	14.47	14.30	14.12	13.94	0.3384	1.05	0.04
Sussex Shores	2.58	2.52	2.48	2.43	2.38	2.31	0.0408	0.27	0.01
Sea Colony	3.27	3.21	3.17	3.12	3.07	2.98	0.0508	0.29	0.01
Bethany Beach	2.36	2.29	2.24	2.18	2.12	2.02	0.0587	0.34	0.01
Fenwick Island	1.01	0.82	0.66	0.50	0.34	0.08	0.0292	0.93	0.03

SUMMARY

Confining beds between the Manokin, Ocean City, and Pocomoke aquifers are thin and discontinuous. Differential water levels may develop in these aquifers adjacent to pumping centers, but a common level is established when the stress is decreased. Because of this interconnection, these three aquifers were modeled as a single confined aquifer, referred to in this report as the Manokin, Ocean City, and Pocomoke aquifer system.

Total thickness of the system ranges from 50 feet along the north and west edges of the modeled area to 250 feet near Selbyville. Transmissivity values in the aquifer were estimated in untested areas by multiplying estimated aquifer thickness at each node by a hydraulic conductivity of 50 ft/d. Storage coefficient of the aquifer is 1×10^{-4}.

The St. Marys Formation, a predominantly clayey unit that underlies the confined aquifer system, generally increases in thickness from northwest to southeast, but an average value of 100 feet was used in the model. Values of vertical hydraulic conductivity and specific storage for this formation were 1×10^{-4} ft/d and 1×10^{-6} ft^{-1}, respectively.

The confining bed overlying the Manokin, Ocean City, and Pocomoke aquifer system is as much as 55 feet thick. A value of 1×10^{-3} ft/d was used for the vertical hydraulic conductivity, and 5×10^{-4} for specific storage of this confining bed.

The unconfined aquifer investigated by Johnston (1977), was not included as an active layer in this study, but was modeled as a constant source of water for the confined system.

A quasi three-dimensional model was calibrated through steady-state and transient simulations to compare simulated water-level fluctuations with observed values. However, where the intervening confining bed is thin or absent, water levels in the confined system approach the constant-head value specified for the overlying unconfined aquifer. This precluded matching simulated water levels to observed values, and the model is therefore considered to be untested and uncalibrated in these subcrop areas. The sand which underlies the St. Marys Formation was included in the model. Lack of water-level data precluded model calibration of this aquifer, but the simulations provide estimates of changes due to pumping the overlying Manokin, Ocean City, and Pocomoke aquifers.

Simulations for 1980-2004, based on assumed continuous increases in withdrawal during that period, indicated that the total decline in average water levels at eight major well fields would be 2.60 feet or less at each site. Water levels at Lewes, however, were predicted to fall below sea level during 1985-89. This would reverse the present direction of ground-water flow and induce movement of saltwater from Delaware Bay and the Lewes and Rehoboth Canal toward the Lewes well field. Pumpage from the Manokin, Ocean City, and Pocomoke aquifers will probably have little effect on deeper aquifers. Simulated heads below the St. Marys Formation changed less than 0.1 foot per 5-year pumping period at any node, which suggests little potential for upward movement of water through the St. Marys Formation.

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APPENDIX I

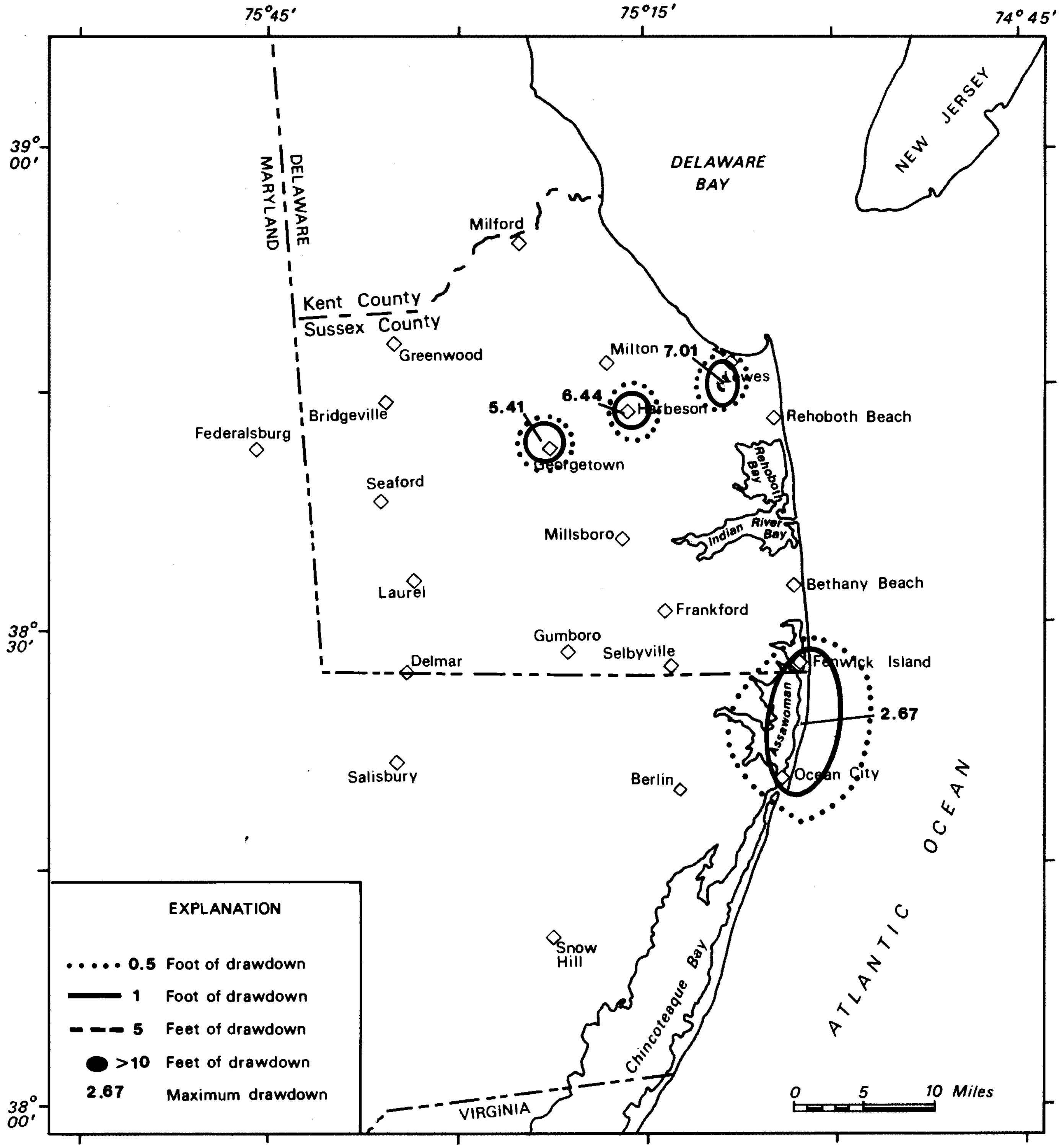

FIGURE 17A.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS FOR JANUARY-MAY 1976.

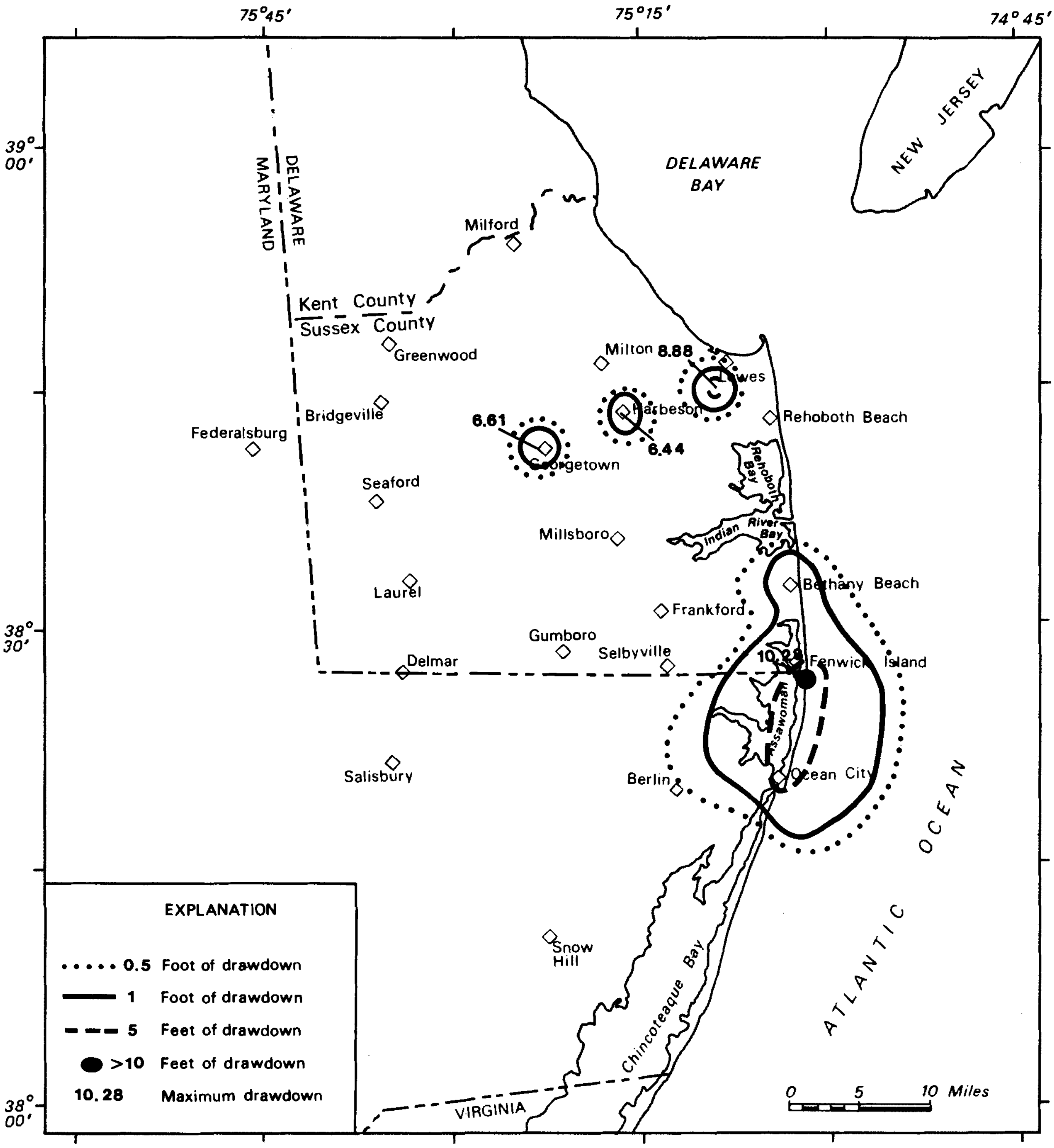

FIGURE 17B.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS FOR JUNE-AUGUST 1976.

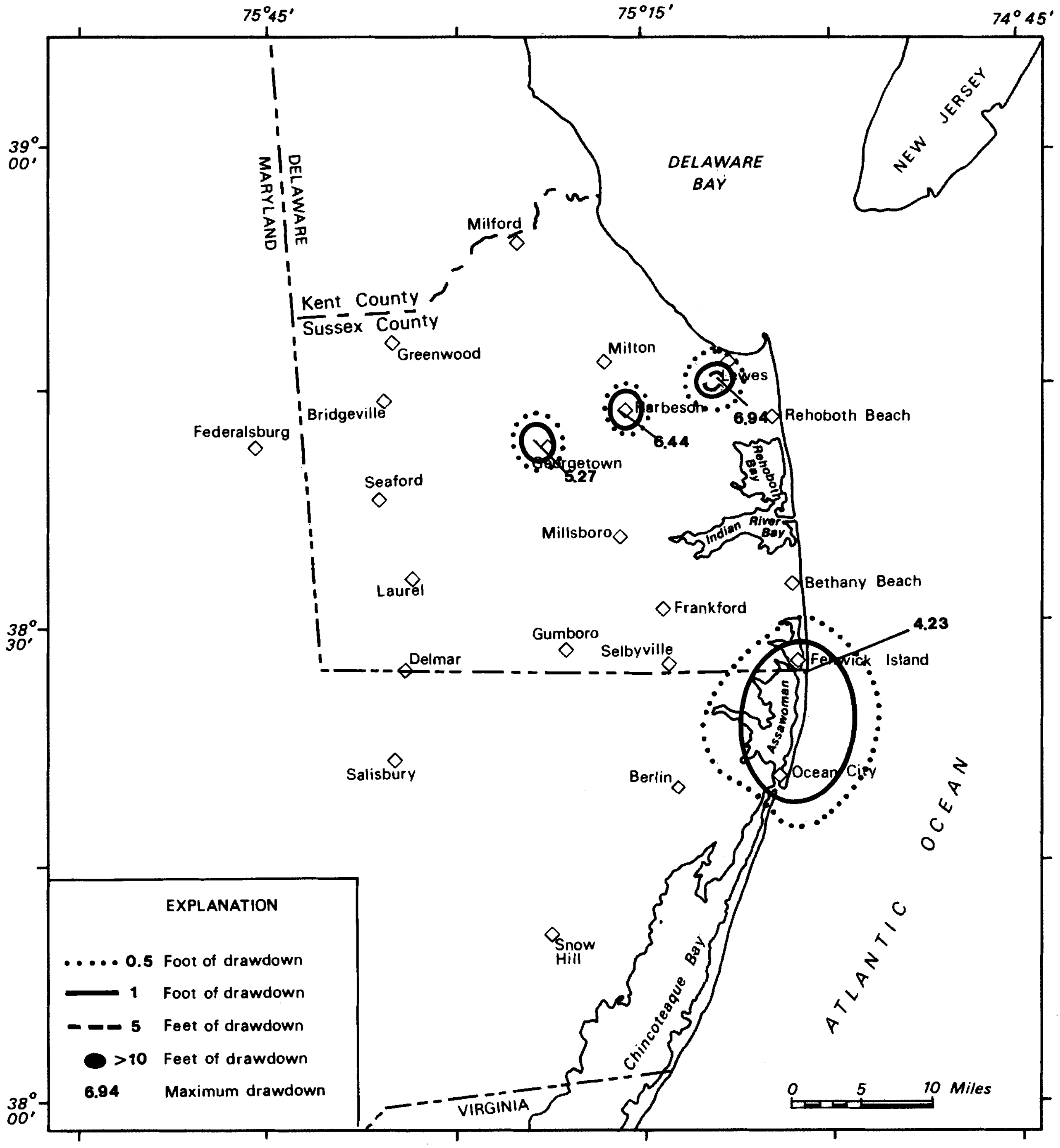

FIGURE 17C.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS FOR SEPTEMBER-MAY 1976-77.

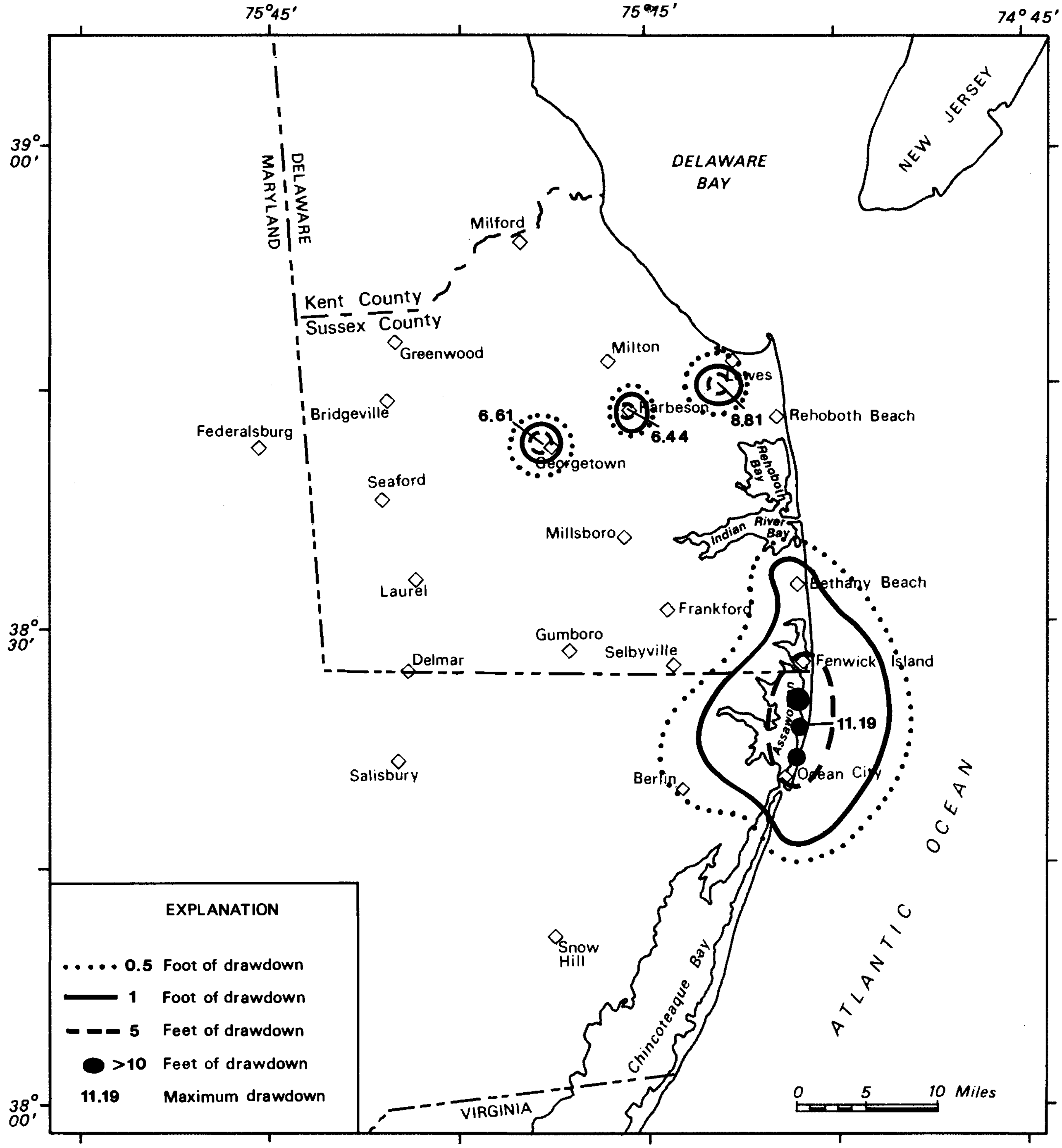

FIGURE 17D.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS FOR JUNE-AUGUST 1977.

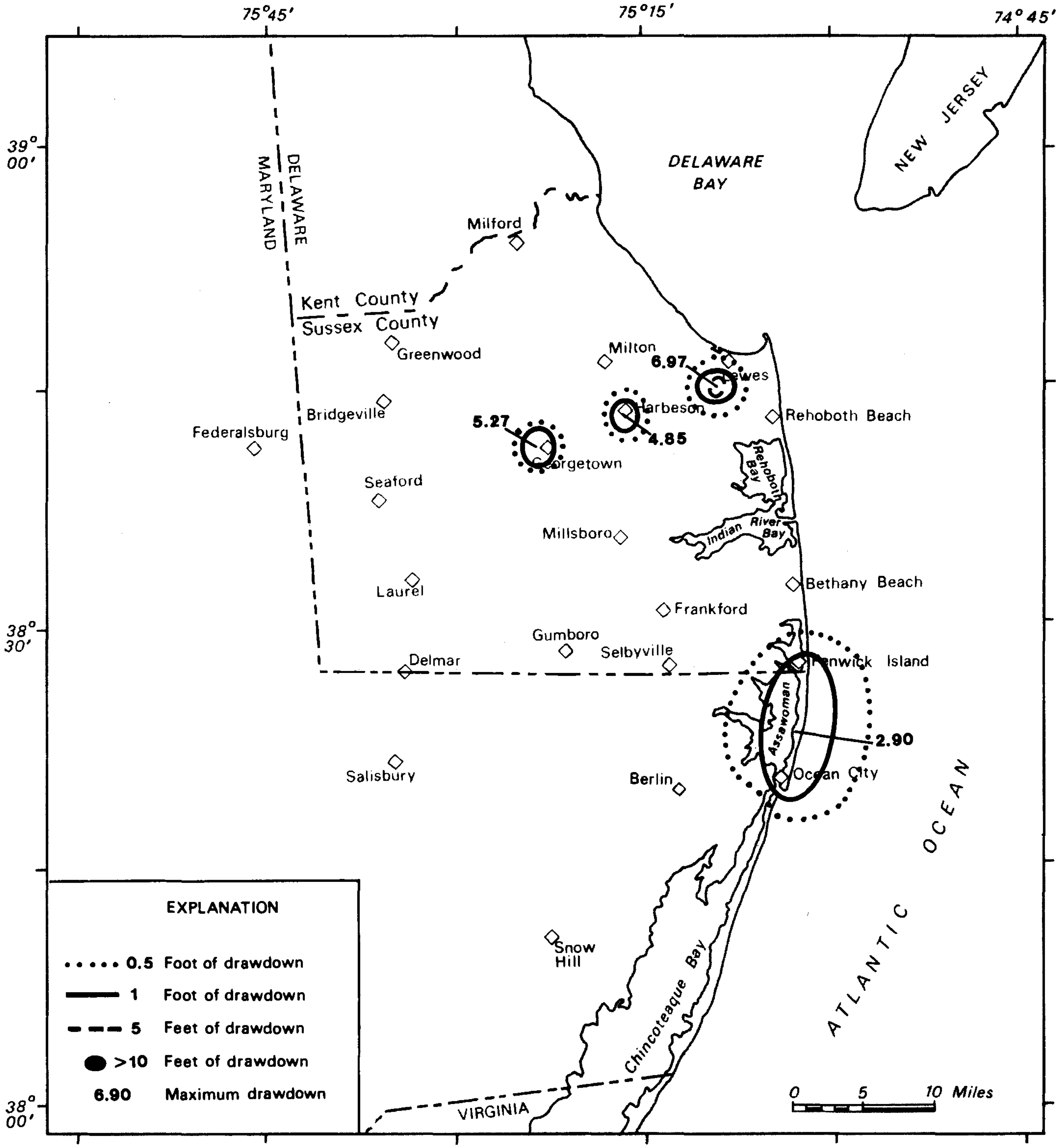

FIGURE 17E.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS FOR SEPTEMBER-MAY 1977-78.

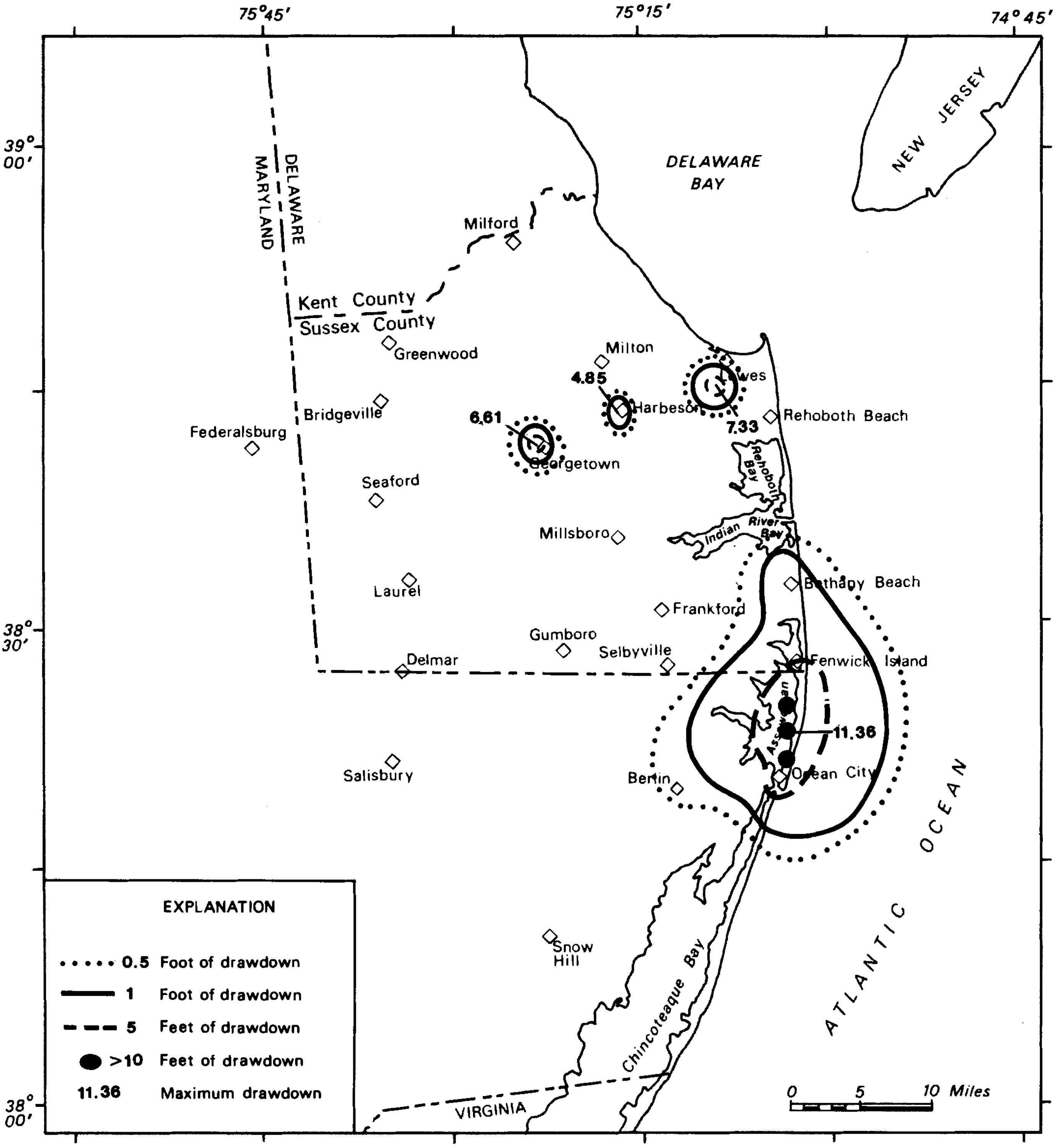

FIGURE 17F.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS FOR JUNE-AUGUST 1978.

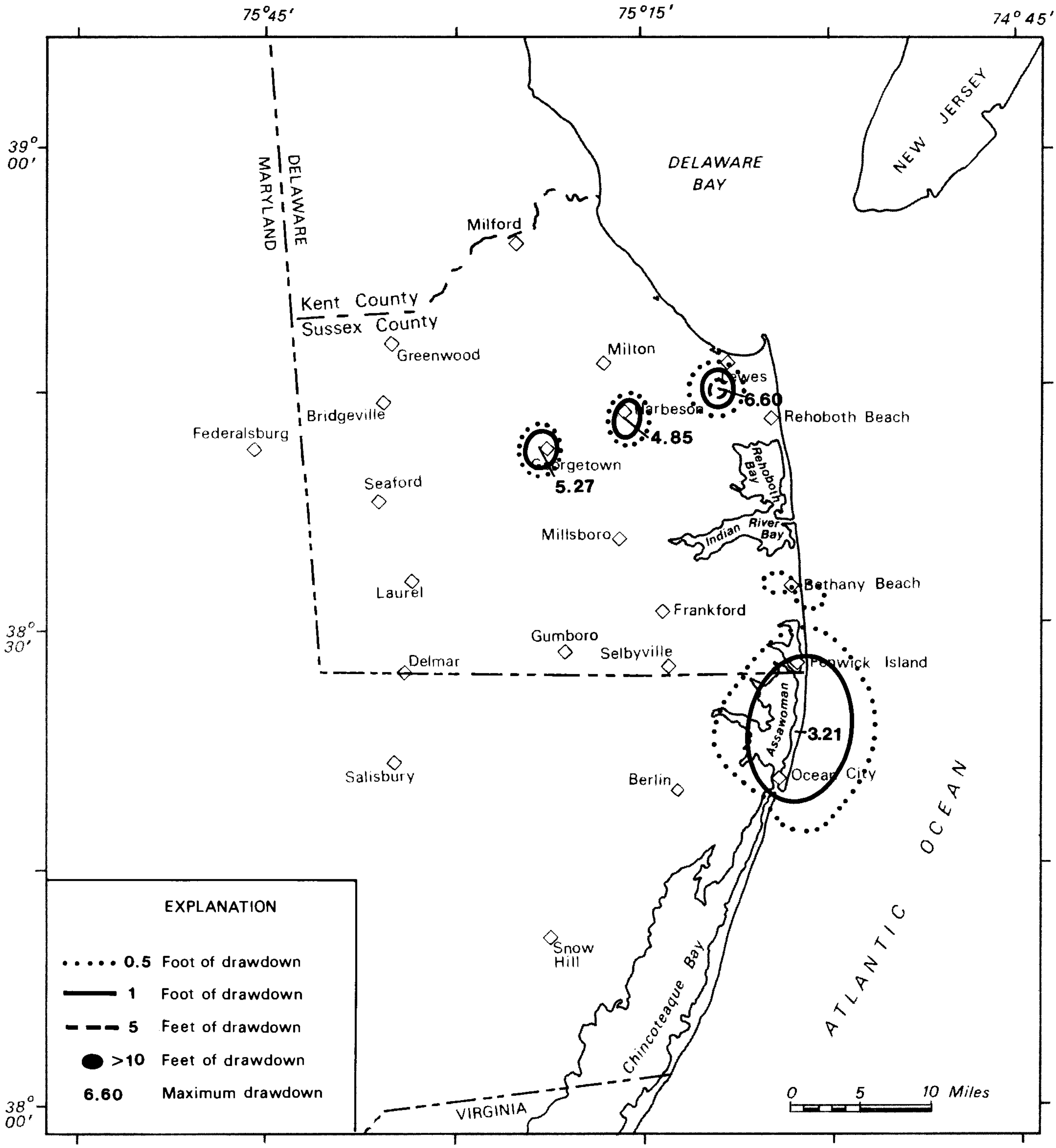

FIGURE 17G.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS FOR SEPTEMBER-MAY 1978-79.

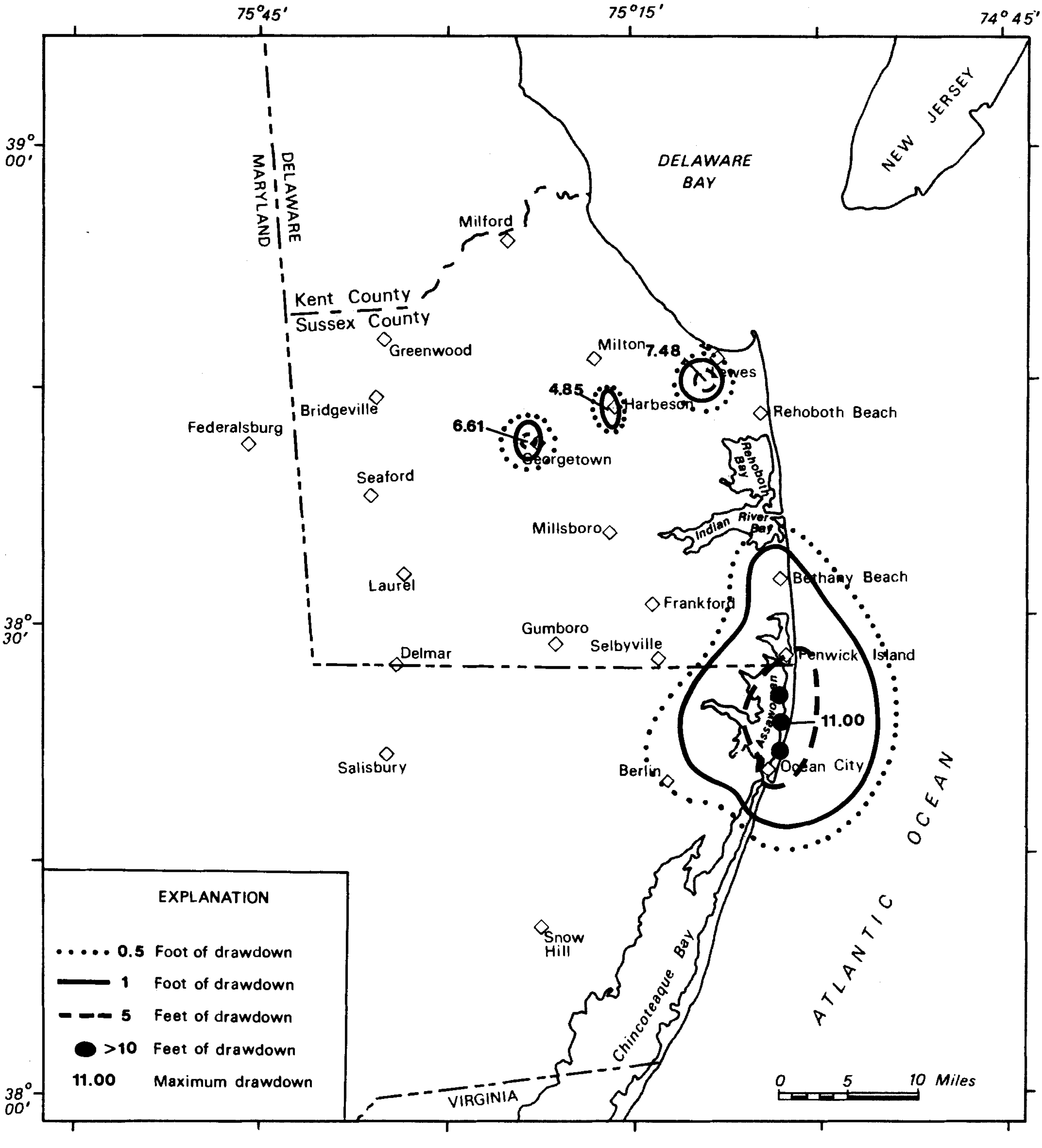

FIGURE 17H.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE AQUIFERS FOR JUNE-AUGUST 1979.

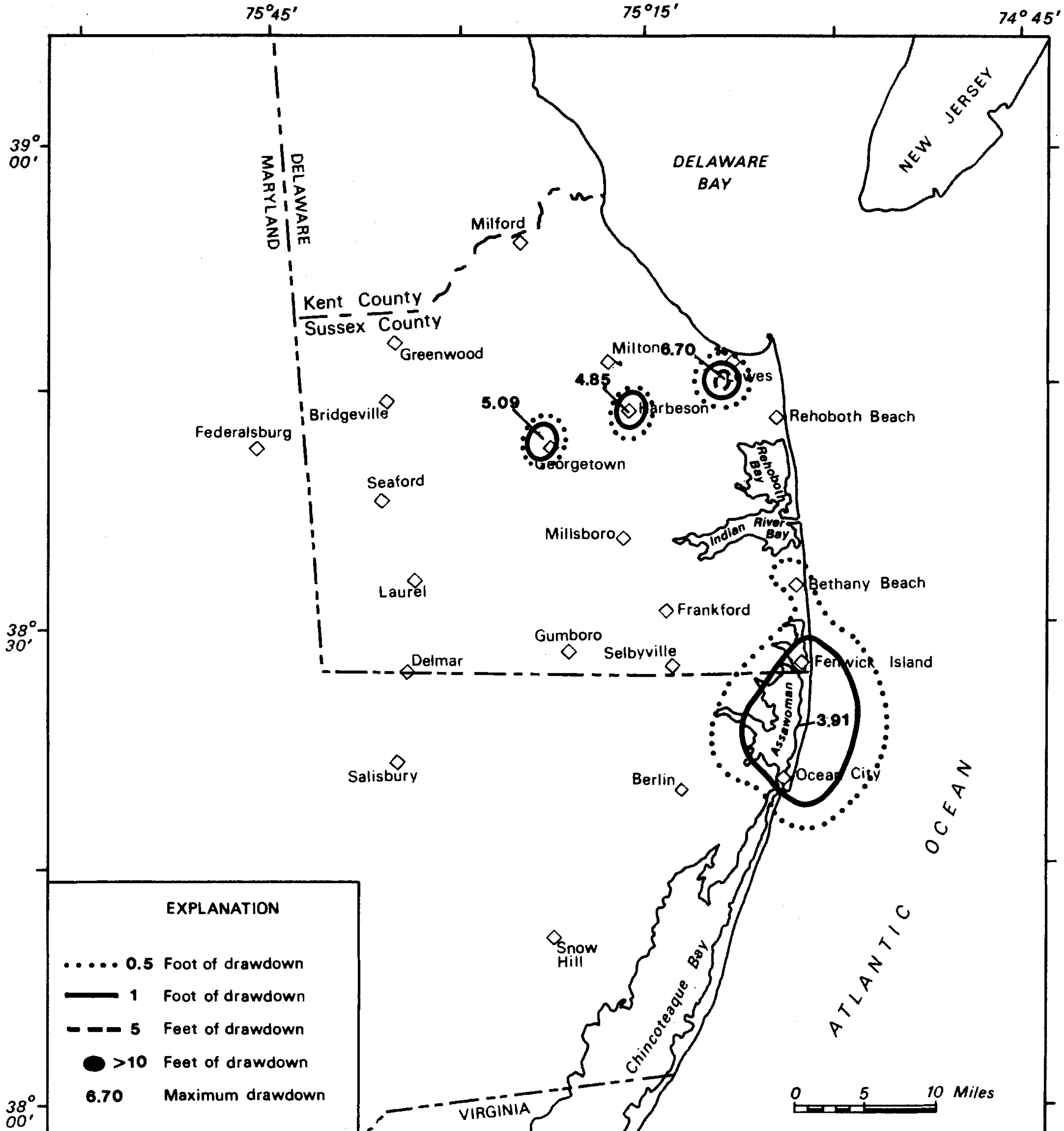

FIGURE 17I.—SIMULATED DRAWDOWNS IN THE MANOKIN, OCEAN CITY, AND POCOMOKE. AQUIFERS FOR SEPTEMBER-DECEMBER 1979.

APPENDIX II

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.

Multiply inch-pound units	by	To obtain SI units
foot (ft)	0.3048	meter (m)
foot per day (ft/d)	0.3048	meter per day (m/d)
square foot per day (ft^2/d)	0.09290	square meter per day (m^2/d)
gallon per minute per foot [(gal/min)/ft]	0.2070	liter per second per meter [(L/s)/m]
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

National Geodetic Vertical Datum of 1929 (NGVD of 1929): A geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called mean sea level. NGVD of 1929 is referred to as sea level in this report.