SIMULATED GROUND-WATER FLOW IN THE POTOMAC AQUIFERS, NEW CASTLE COUNTY, DELAWARE

By Mary M. Martin

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U.S. GEOLOGICAL SURVEY

Dallas L. Peck, Director

For additional information write to:

District Chief
U.S. Geological Survey
208 Carroll Building
8600 LaSalle Road
Towson, Maryland 21204

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FACTORS FOR CONVERTING INCH-POUND UNITS TO METRIC UNITS SI

Multiply inch-pound unit	by	To obtain SI
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]
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)	0.0929	square meter per day (m^2/d)
gallon per minute (gal/min)	0.06309	cubic meter per second (m^3/s)
gallon per minute per foot [(gal/min)/ft]	0.207	square meter per second (m^2/s)
inch (in)	25.4	millimeter (mm)
million gallons (Mgal)	3785	cubic meters (m^3)
million gallons per day (Mgal/d)	3785	cubic meters per day (m^3/d)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

NOTE REGARDING VERTICAL DATUM

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

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ABSTRACT

Flow in three aquifers and intervening confining units of the Potomac Formation of Cretaceous age in New Castle County, Delaware, was simulated. The model was calibrated by comparing simulated and observed heads and head changes. Results of the calibration procedure show transmissivity values are lowest in the lower aquifer and highest in the upper aquifer. The maximum transmissivity of the lower aquifer is between 1,000 and 1,500 feet^2 per day. Maximum transmissivity of the middle aquifer is between 3,000 and 3,500 feet^2 per day. Maximum transimissivity of the upper aquifer is between 5,000 and 6,000 feet^2 per day. Values of vertical leakance for the three confining beds range between 1 x 10^{-8} per day and 1 x 10^{-2} per day. The highest values and greatest range of values are in areas near the subcrops. The lowest leakance values are in western Delaware and downdip areas. The smallest amount of lateral variability in hydraulic conductivity is in the confining bed overlying the upper aquifer. A storage coefficient of 5.6 x 10^{-4} was used in each of the aquifers. A specific storage value of 6 x 10^{-6} per foot was used for each confining bed. The storage coefficients were not changed during calibration.

The calibrated model was used to evaluate changes in water levels resulting from several scenarios of future pumpage. A reduction in pumpage at Amoco from 257 Mgal/yr to 12 Mgal/yr will cause a 120 foot local recovery of heads. Proposed pumpage in western Delaware of 683 Mgal/yr may cause drawdowns below the tops of the aquifers. Simulated increases in pumpage of 889 Mgal/yr in New Castle County would cause head decline, about 40 feet, in the lower aquifer at Getty. Water-levels generally will change less than 25 feet if there is no change in pumpage.

INTRODUCTION

The Potomac Formation of Cretaceous age is a major source of water for the towns and industries of New Castle County, Delaware. A steady increase in pumping since the mid-1900's has created both regional and local cones of depression centered about well fields in New Castle County (Sundstrom and others, 1967). Martin and Denver (1982) estimated 1980 pumpage to be 19.9 Mgal/d and documented water levels 200 ft below sea level. The decline of water levels in areas near brackish estuaries and man-made contamination has caused concern about future increased withdrawals from the Potomac aquifers. A multilayer digital model of the Potomac aquifers was made to simulate the flow system within the Potomac Formation, to quantify various aquifer characteristics, and to evaluate the effects of future withdrawals from the Potomac aquifers.

Purpose and Scope

The purpose of this report is to present: (1) the methodology and assumptions used in the development and calibration of the digital model; (2) the findings and conclusions made during the calibration and sensitivity analysis of the model; and (3) the results of simulations used to evaluate effects of future groundwater withdrawals from the Potomac aquifers.

This report is part of a 5-year study, requested by the Delaware Department of Natural Resources and Environmental Control and funded by the U.S. Army Corps of Engineers, to evaluate the effects of future pumpage from the Potomac aquifers. A hydrologic data report (Martin and Denver, 1982) containing data on water levels, pumpage, and aquifer characteristics used in developing the digital model described in this report was published previously as part of this study. Well-field names used in this report are the same as those used by Martin and Denver (1982, fig. 1) and are shown in figure 1.

Location and Extent of Model Area

The study area shown in figure 2 encompasses the portion of the Atlantic Coastal Plain in New Castle County, Delaware, in which the Potomac Formation contains potable ground water. The model is calibrated within the 330 mi^2 of the study area.

The modeled area of approximately 2,860 mi^2 extends from Camden, N.J., to Chestertown, Md. The boundaries of the modeled area are described in the following section on the model grid and boundaries. The model is considered to be uncalibrated outside the study area and cannot be used for evaluating the effects of future pumpage for areas in New Jersey and Maryland.

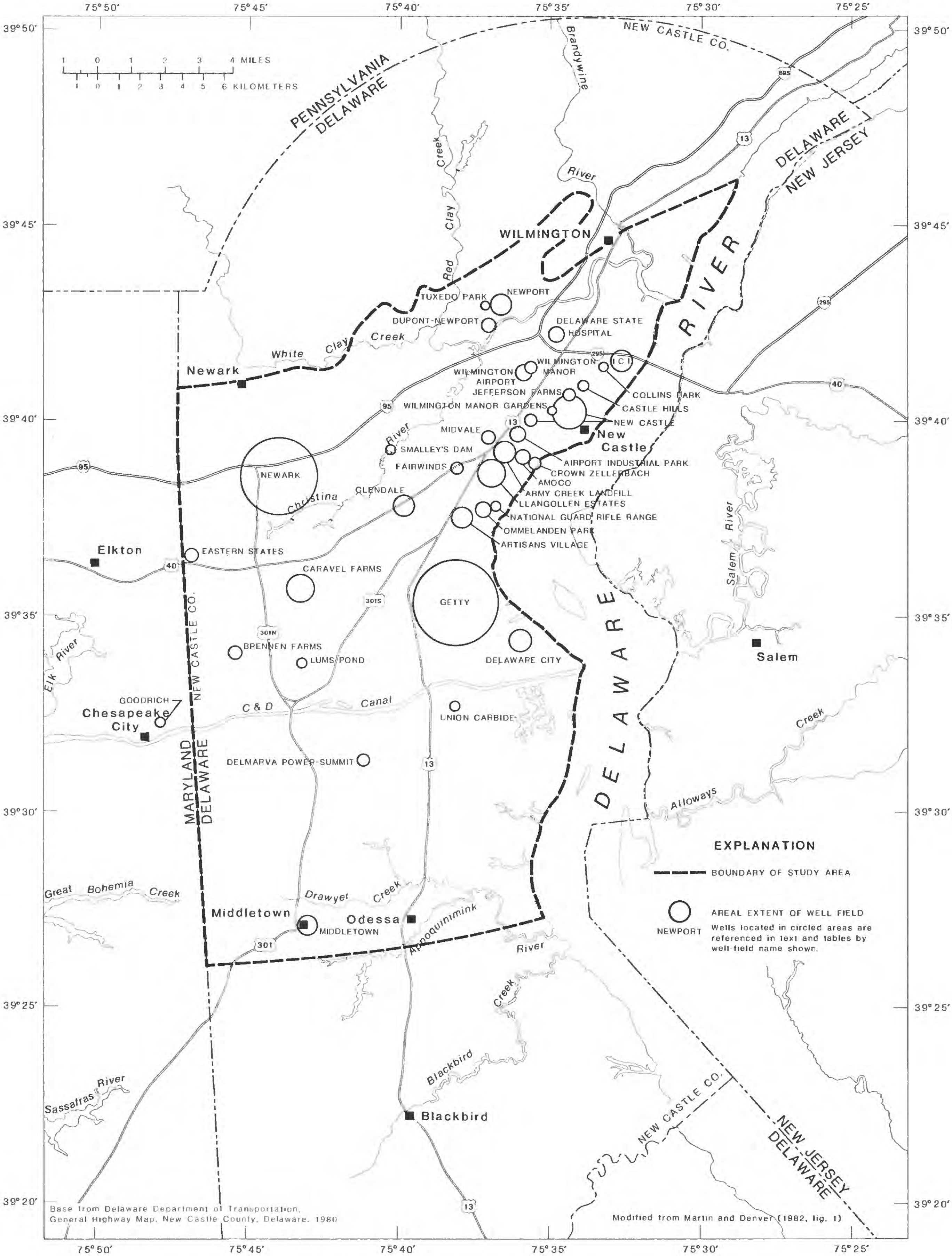


Figure 1.--Location of well fields in the Potomac Formation.

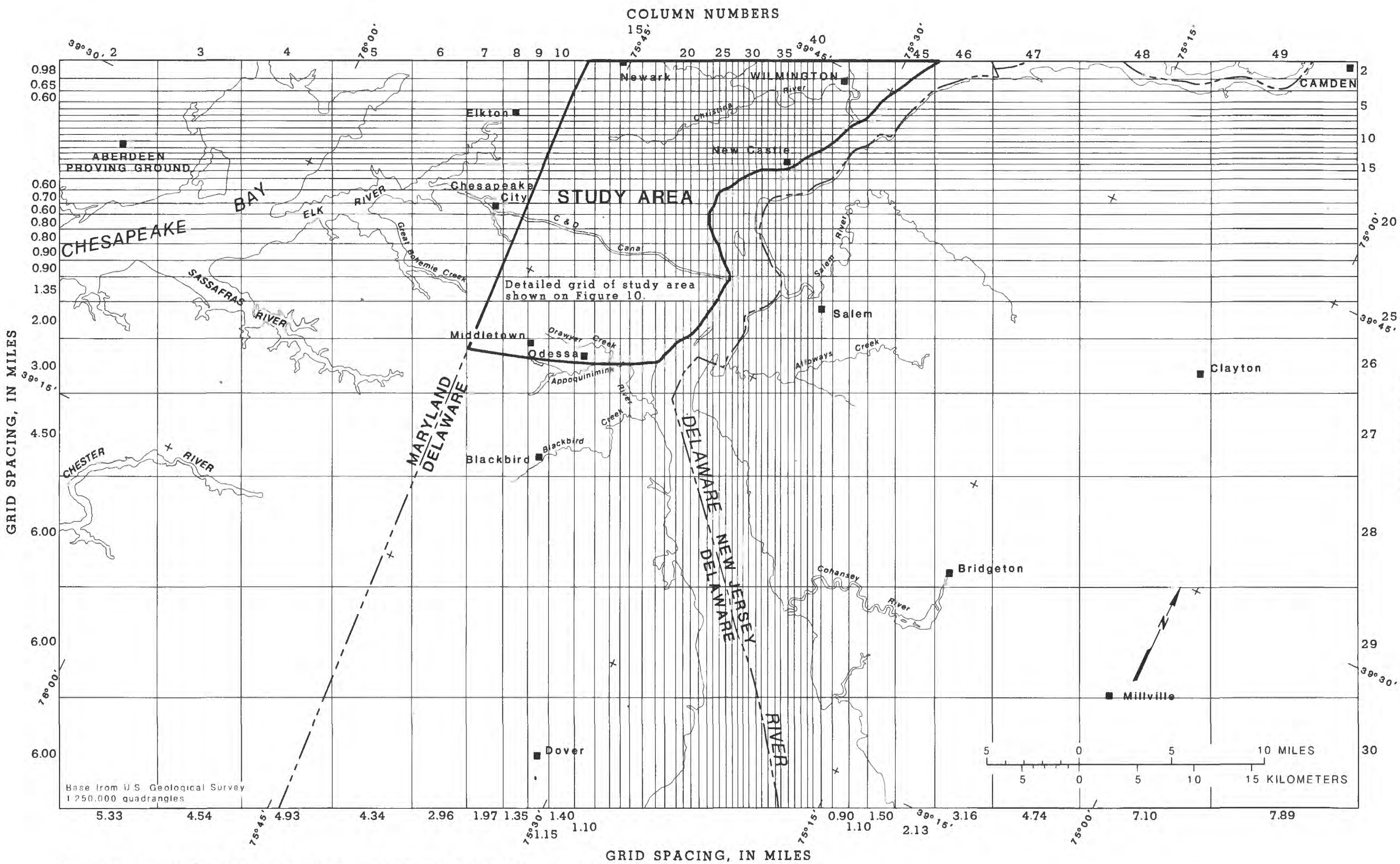


Figure 2.--Location of study area and grid boundaries.

Acknowledgments

Thanks are given to the U.S. Army Corps of Engineers and the Delaware Department of Natural Resources and Environmental Control for their cooperation and assistance during this study. Thanks are also given for the assistance of the Delaware Geological Survey. Special thanks are given to the many municipalities and industries for their cooperation with the Delaware Department of Natural Resources and Environmental Control, Delaware Geological Survey, and the U.S. Geological Survey in supplying valuable pumpage and water-level information.

CONCEPTUAL HYDROGEOLOGIC MODEL OF THE POTOMAC FORMATION

Extent of the Potomac Aquifers and Confining Beds

A summary of the geologic framework of New Castle County is given by Martin and Denver (1982, p. 3-9). The Potomac Formation is described as elongated sand bodies within a fine-grained clay and silt matrix by Sundstrom and others (1967, p. 18). Jordan (1962, p. 6) states that lithologic variability in both vertical and horizontal directions is characteristic of the Potomac Formation.

Although sand bodies within the Potomac Formation are limited in lateral extent, the formation was divided into two hydrologic zones with an intervening clay layer by Sundstrom and others (1967, p. 21). Rasmussen and others (1957, p. 111-115) described three aquifers within the Potomac Formation. Such units were considered to be areas of relatively high sand content and separate hydrologic units.

For the purpose of modeling, the Potomac Formation was divided into three aquifers with intervening confining beds. The extent of the aquifers and confining beds was determined from geophysical logs of holes in New Castle County, Delaware, in eastern Maryland, and in western New Jersey. Locations of the boreholes are shown in figure 3. Also shown are the location of geohydrologic cross sections that appear on plate 1.

Each of the hydrogeologic units shown on plate 1 is composed of various amounts of interbedded sand, silt, and clay. Units that are predominantly clay are referred to as confining units. The aquifers illustrated on plate 1 are not considered to be continuous sand bodies. Each aquifer is predominantly sand with interbedded silt and clay layers. Locally, sand bodies within the aquifers are discontinuous and are separated vertically and horizontally by intervening silts and clays. The aquifers are separated by confining units that are predominantly clay and are relatively continuous. Flow is generally horizontal within the aquifers and vertical within the confining units because of the contrast in the hydraulic conductivities of the aquifers and confining beds.

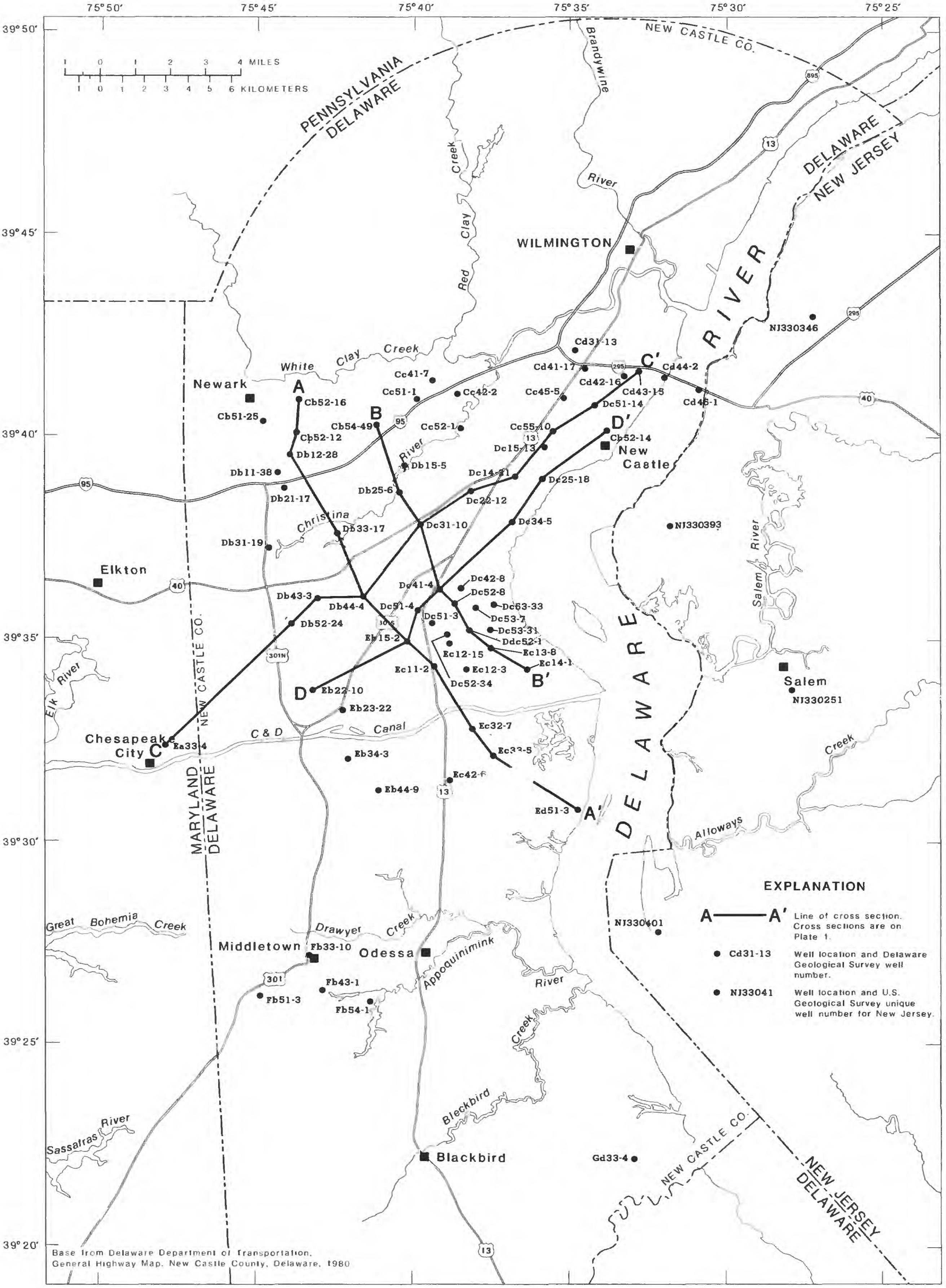


Figure 3.--Location of selected wells with geophysical logs and geohydrologic cross sections.

The aquifers and confining units generally thicken downdip and are approximately parallel to the bedrock surface. Each unit is variable in lithology and thickness and is assumed to extend throughout the modeled area, although geophysical data are limited outside the area of interest. Structure contour and thickness maps of the three aquifers and confining units are shown in figures 4 to 9.

Each of the aquifers and confining units is assumed to subcrop beneath the overlying unconfined aquifer. As modeled, the unconfined aquifer includes the Columbia Formation (Jordan, 1962, p. 32), recent alluvial deposits, and in limited areas, exposed portions of the Potomac Formation that are part of the soil zone. In southern New Castle County and most of New Jersey, the Potomac Formation is overlain by formations of Cretaceous to Quaternary age. These units are identified by Martin and Denver (1982, table 1) and are represented in the model as part of the confining bed overlying the upper Potomac aquifer.

Source and Movement of Ground Water

Under prepumping conditions, the Potomac aquifers were recharged by vertical leakage from the unconfined aquifer in subcrop areas. Small amounts of vertical leakage through overlying confining beds also occured. With no pumpage discharge, most water in the Potomac aquifers discharged to streams in updip subcrop areas. Small amounts of recharge from the overlying unconfined aquifer entered the aquifers in the subcrop areas and through overlying confining beds. Water then moved downdip in the aquifers and discharged to overlying beds and nearby bays. The prepumping Potomac flow system in New Castle County was part of a larger regional flow system that extended into Maryland and New Jersey. A ground-water divide between the Delaware River and Chesapeake Bay existed near the Maryland and Delaware border. Ground water in eastern Maryland and in extreme western Delaware flowed toward the Chesapeake Bay. Ground water flowed from the subcrop area in northern New Castle County to the Delaware Bay and to discharge areas in New Jersey along the Delaware River.

Pumping from the Potomac aquifers is now the major source of discharge and has caused the development of both regional and local cones of depression. Water levels in most areas react quickly to changes in pumping stress. The Potomac aquifers are still recharged by vertical leakage from the unconfined aquifer in the subcrop areas and through overlying confining beds. However, decline in water levels has increased recharge by inducing infiltration in the updip areas and has decreased discharge to streams in the updip supcrop areas and to overlying units in downdip areas. Decline in water levels has also caused a decrease in the amount of water in aquifer and confining bed storage. Pumpage has locally changed the location of the ground-water divide between the Delaware River and the Chesapeake Bay. Ground water in eastern Maryland and extreme western Delaware flows to local cones of depression and towards the Chesapeake Bay. Ground water flows from

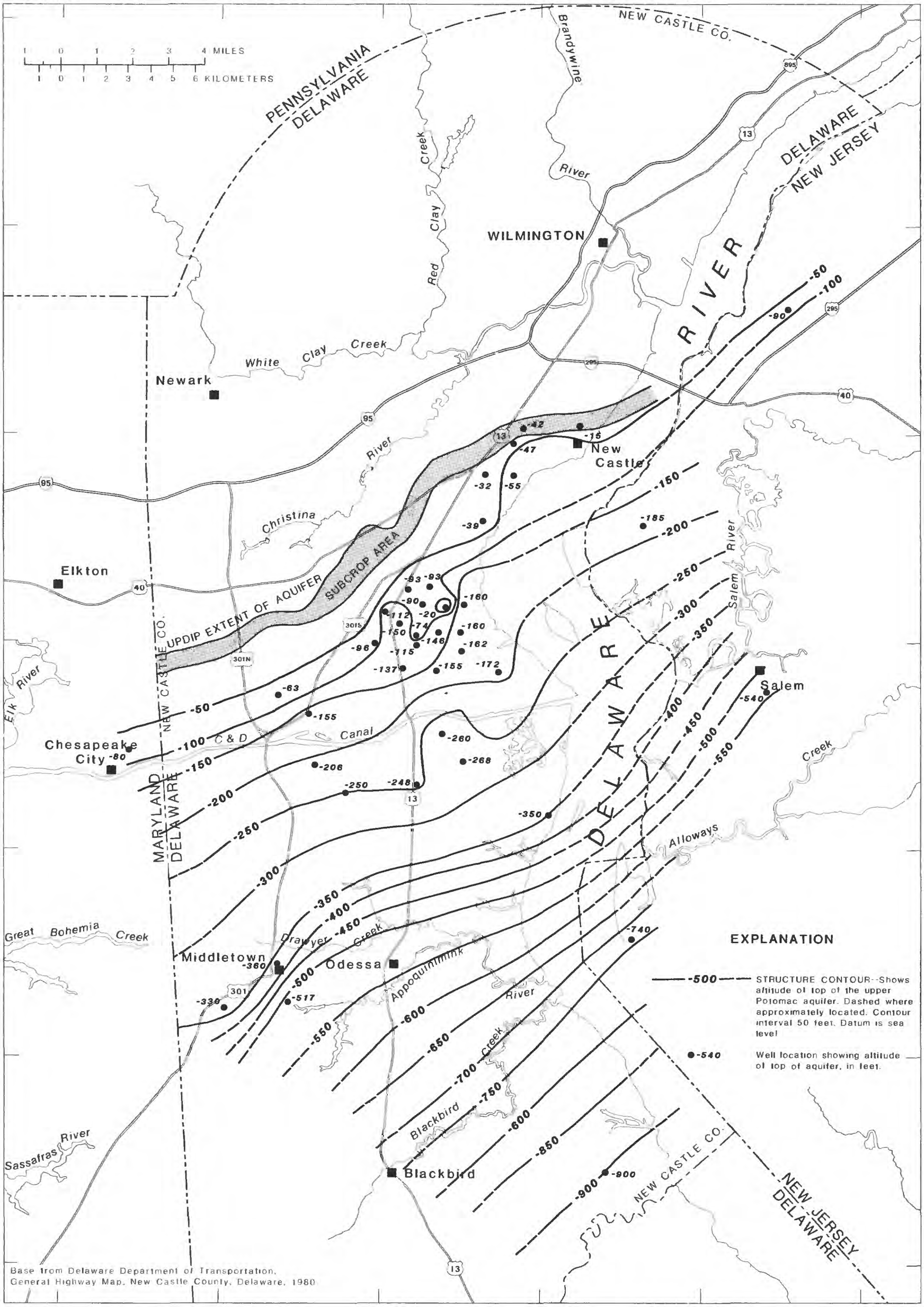


Figure 4.--Structure contours on top of the upper Potomac aquifer.

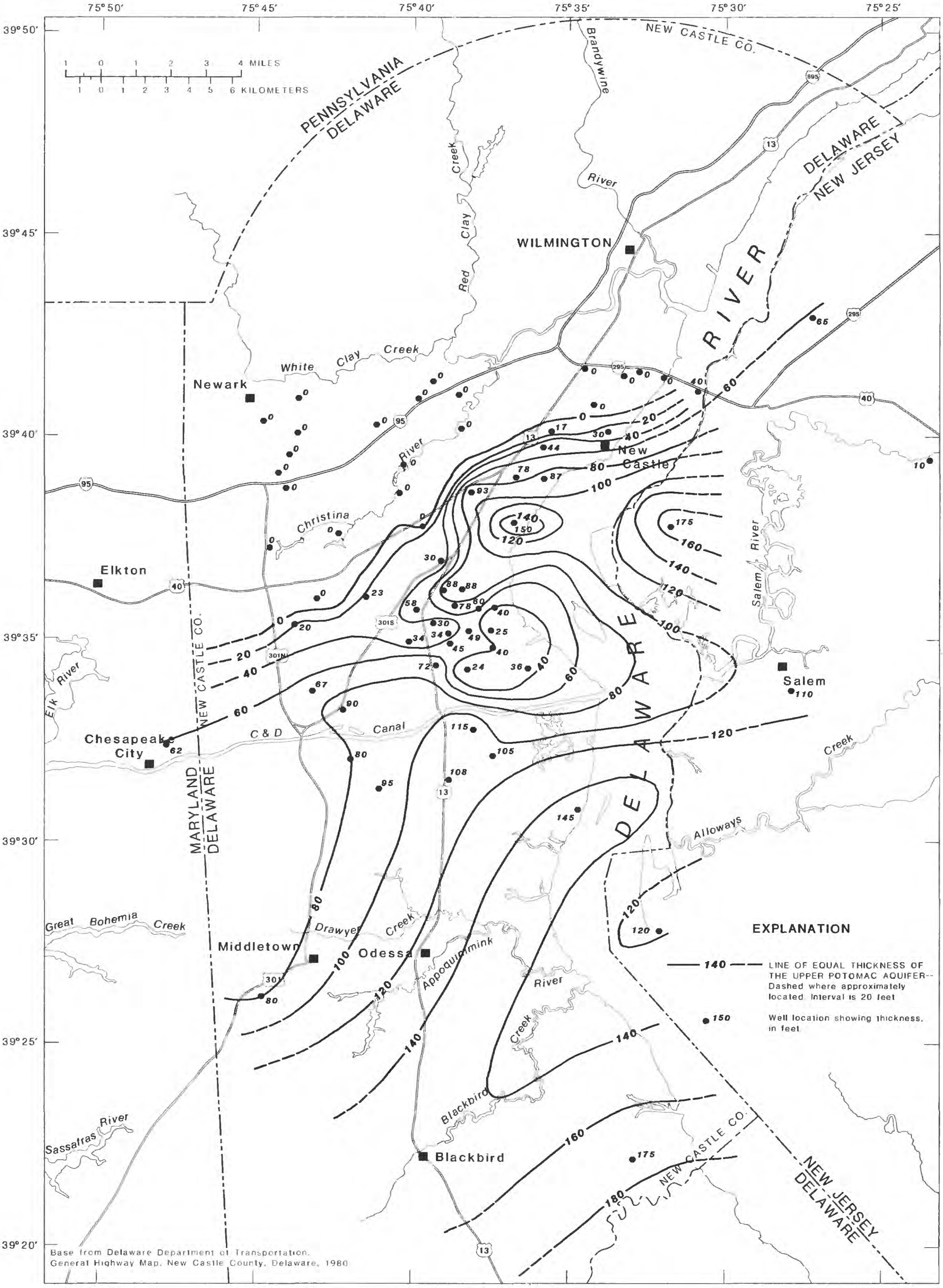


Figure 5.--Thickness of the upper Potomac aquifer.

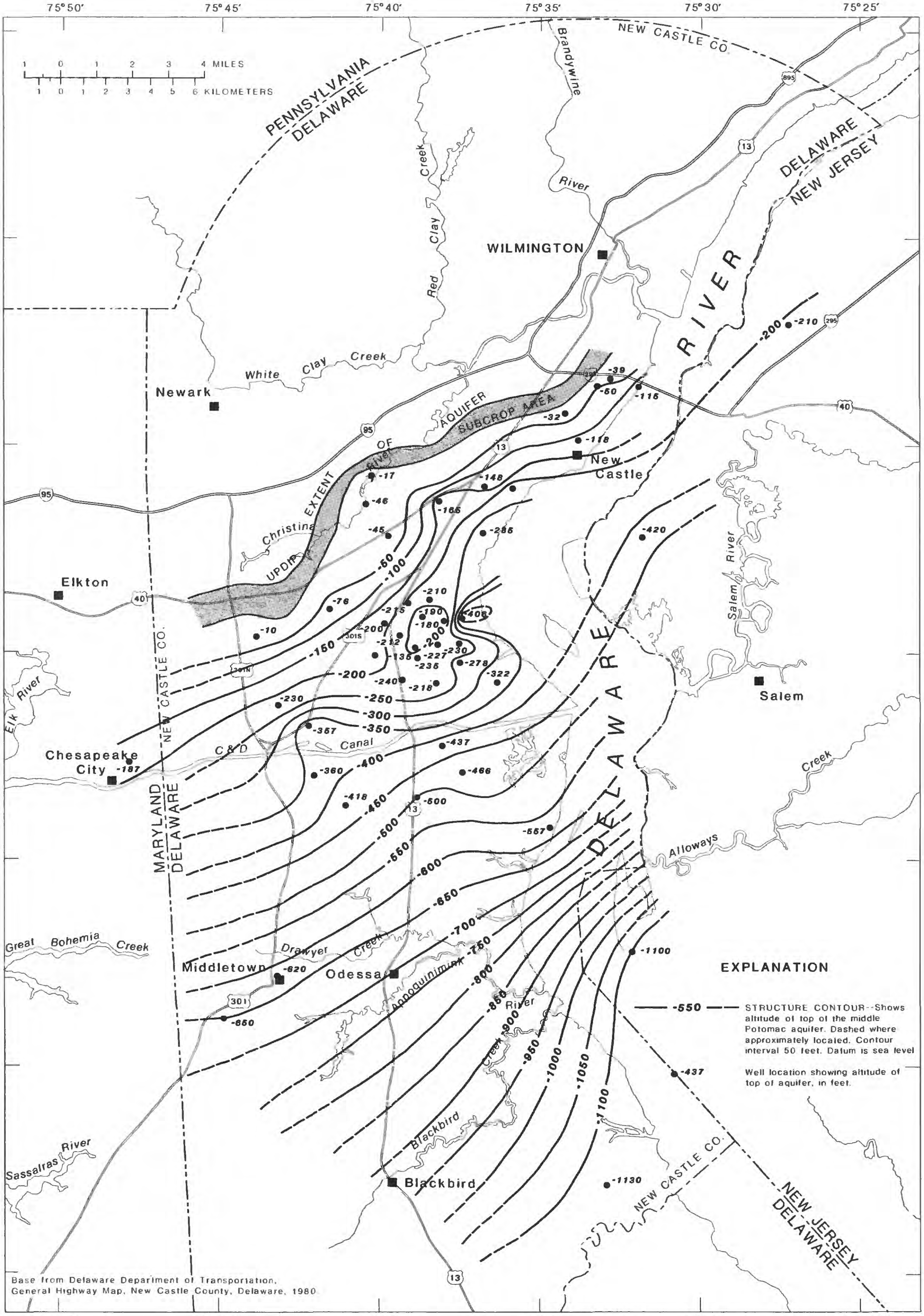


Figure 6.--Structure contours on top of the middle Potomac aquifer.

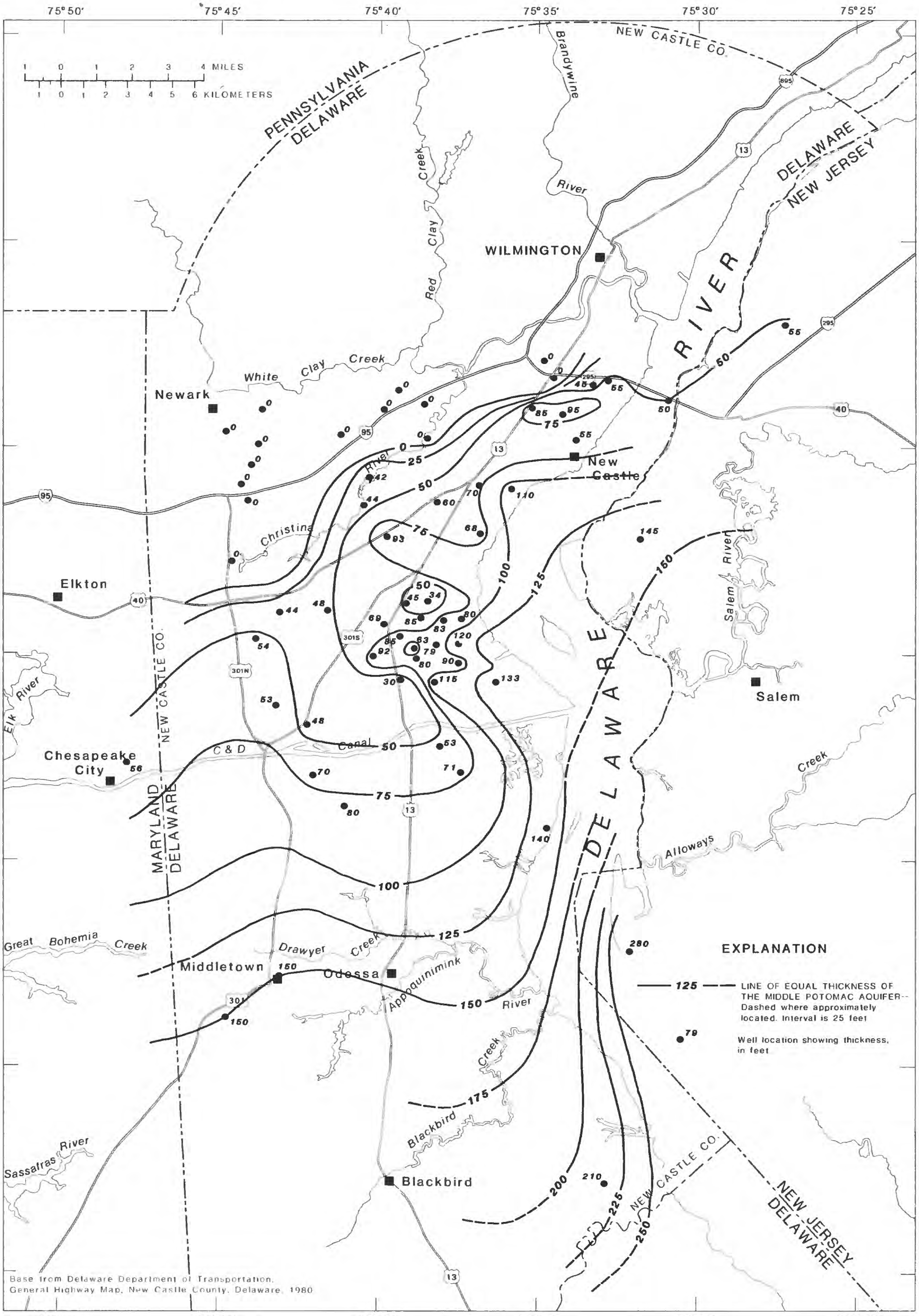


Figure 7.--Thickness of the middle Potomac aquifer.

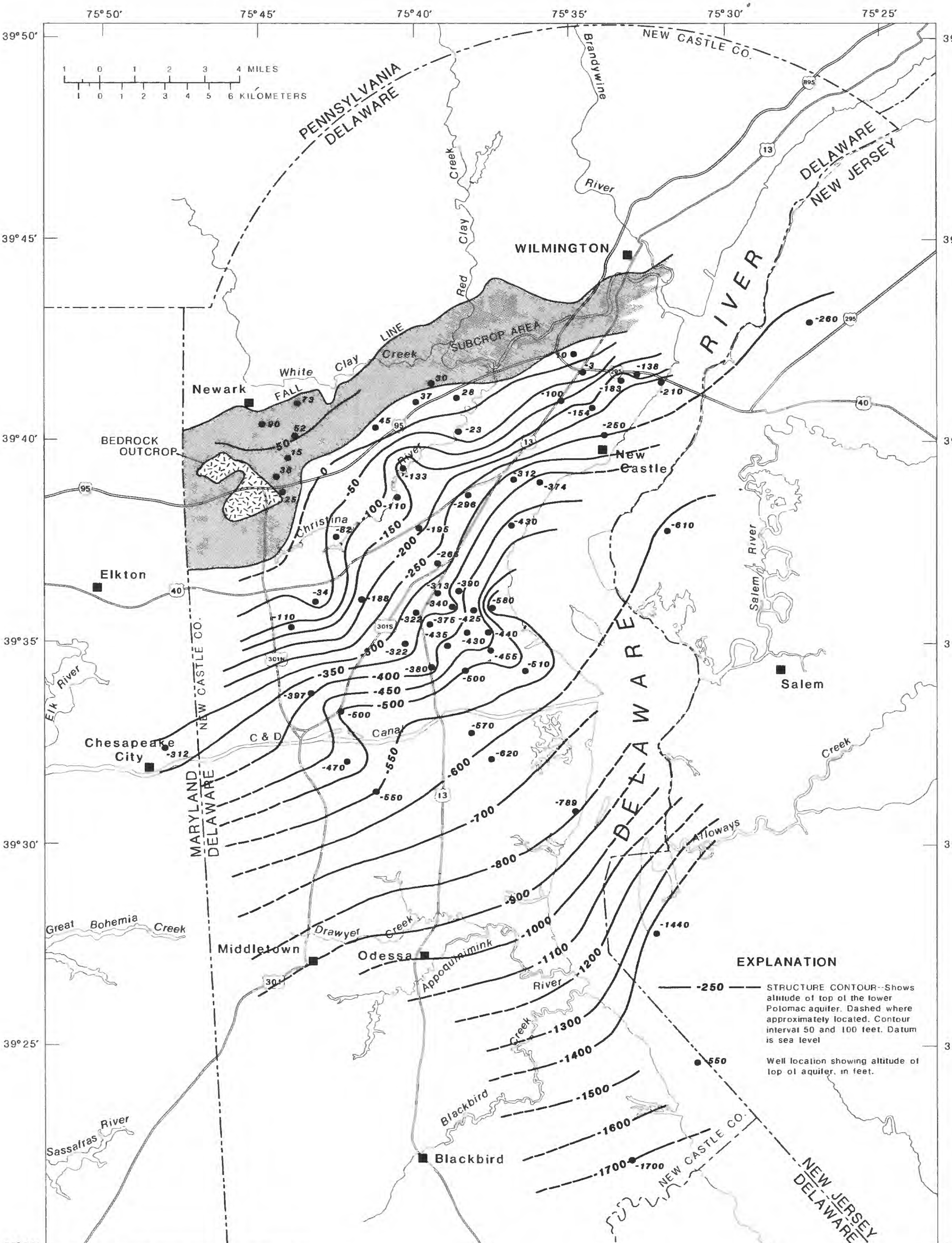


Figure 8.--Structure contours on top of the lower Potomac aquifer.

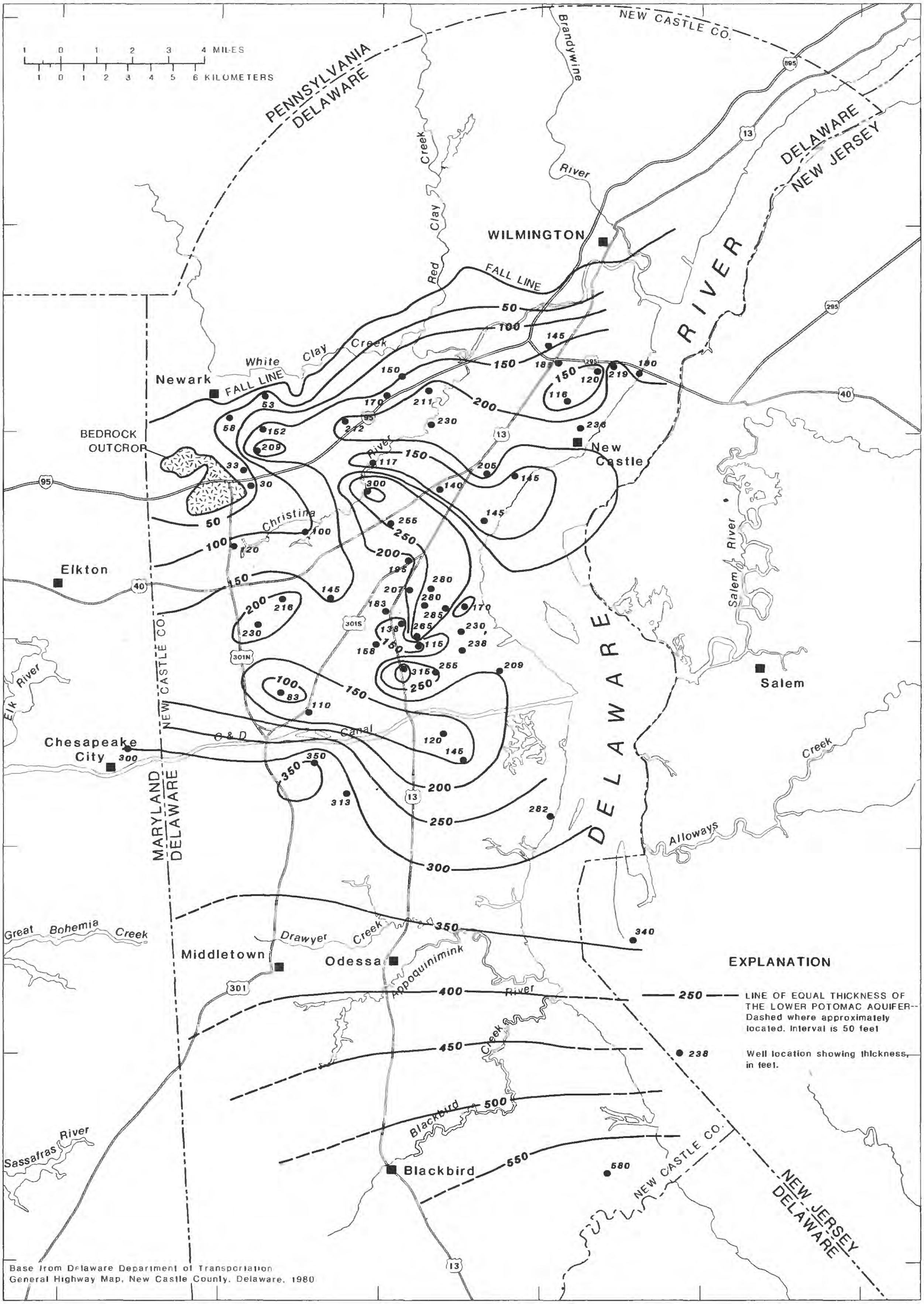


Figure 9.--Thickness of the lower Potomac aquifer.

northern New Castle County to local and regional cones of depression in Delaware, to the Delaware Bay, and towards areas of pumpage discharge in New Jersey.

DIGITAL SIMULATION OF THE POTOMAC AQUIFERS

The Digital Model

Flow within the Potomac Formation was modeled using the program documented by Trescott (1975). The program simulates the flow of ground water in three dimensions by using a finite difference approximation to the following ground-water flow equation (Posson and others, 1980, p. 6):

$$\frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(T_y \frac{\partial h}{\partial y}\right) = S \frac{\partial h}{\partial t} + bW\ (x,y,z,t) + Q_L\ (x,y,z,t) \quad (1)$$

in which

T_x, T_y	are the transmissivities in the x and y direction (L^2T^{-1});
h	is the hydraulic head (L);
S	is the storage coefficient (dimensionless);
b	is the thickness of the hydraulic unit (L);
W	is the volumetric flux per unit volume (T^{-1});
Q_L	is the volumetric flux per unit area from the confining beds (LT^{-1});
x,y	are the horizontal directions;
z	is the vertical direction;
t	is time.

A quasi three-dimensional approach was used to model flow within the Potomac Formation. Confining beds were not simulated as a layer of nodes. The left-hand side of equation (1) includes two-dimensional flow in the aquifers and the right-hand side includes one-dimensional flow through the confining beds (Q_L).

The program can: (1) calculate the changes in hydraulic head or drawdown caused by pumping; (2) simulate one or more units that may be heterogeneous, anisotropic, and have irregular boundaries; and (3) simulate the effects of transient leakage from confining beds and time-varying pumpage. Posson and others (1980, p. 6-13) discuss the simulation of transient leakage from confining beds. Program modifications to incorporate transient leakage are shown in Leahy (1982). Utilizing a block-centered, finite-difference grid, the program solves the system of simultaneous algebraic approximations for each node using the strongly implicit procedure (SIP) algorithm.

Finite-Difference Grid and Boundaries

The grid spacing in the area of interest is based on the location of both production and observation wells. A variable grid spacing is used to locate wells as close as possible to a node. A node is a point in the center of an area bounded by two adjacent grid lines in the row direction (southwest to northeast) and two adjacent lines in the column direction (northwest to southeast). The grid for the area of interest is shown in figure 10. Nodal areas in the area of interest range from 0.1 mi^2 to 9 mi^2. Outside the area of interest the grid spacing is much larger as shown in figure 2.

Each of the model boundaries is described below. The assumptions made in selecting the boundaries are discussed in a following section on assumptions. The lateral model boundaries are shown in figure 1. The northern boundary approximates the Fall Line and the limit of Coastal Plain sediments in New Castle County. The eastern boundary in New Jersey approximates a ground-water discharge area and flow line as shown by Back (1966, fig. 3) and Luzier (1980, p. 46). This boundary is perpendicular to the Fall Line and intersects Camden, New Jersey. The western boundary approximates a similar discharge area in Maryland and intersects Chestertown, Maryland. The southern boundary roughly approximates the occurrence of 10,000 mg/L chloride concentrations within the Potomac Formation as shown by Meisler (1980, fig. 4). These four boundaries are modeled as no-flow boundaries.

The lower model boundary represents the top of the crystalline basement below the Coastal Plain sediments and is a no-flow boundary. The top boundary is the potentiometric surface of the water table. Water-table altitudes were compiled as discussed in the following section on data input. The top boundary is modeled as a constant head and serves as the source of recharge to the underlying Potomac aquifers. Figure 11 is a schematic representation of the model boundaries and layers.

Data Requirements and Input

Average thickness for each node for each aquifer and confining unit was estimated by overlying the grid on the thickness map of the unit. In the model, the thickness of the confining unit overlying the upper Potomac aquifer includes the thickness of all formations present between the unconfined aquifer and the upper Potomac aquifer.

Altitude of the water table was compiled from a series of hydrologic atlases of New Castle County. In Maryland and New Jersey, water-table altitudes were obtained from unpublished data compiled by the U.S. Geological Survey for other modeling projects in those states. The hydrologic atlases for New Castle County show a water table that is assumed to be several feet above average because the water-level measurements were made during a period of above average precipitation. An average potentiometric surface was

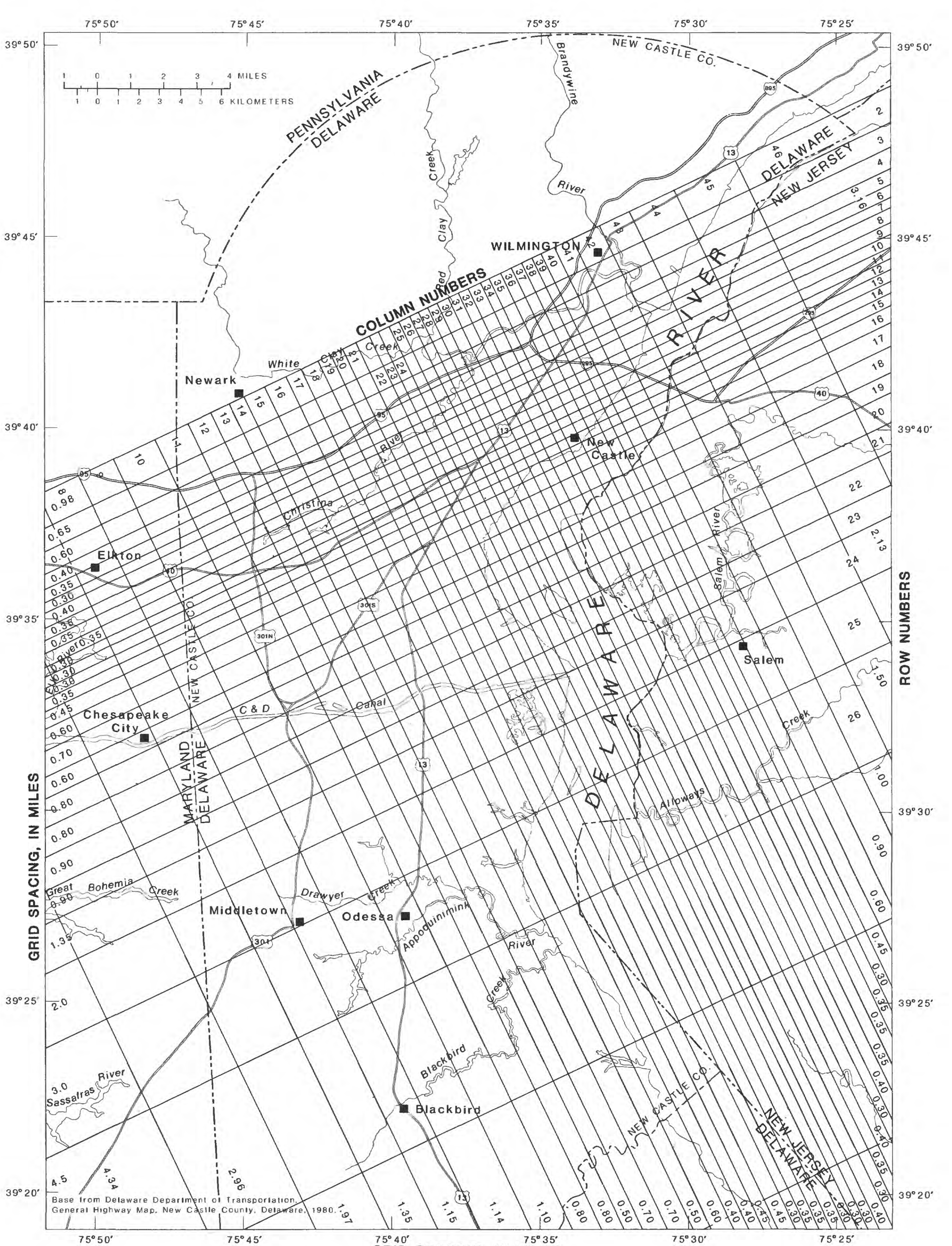


Figure 10.--Finite-difference grid in the study area.

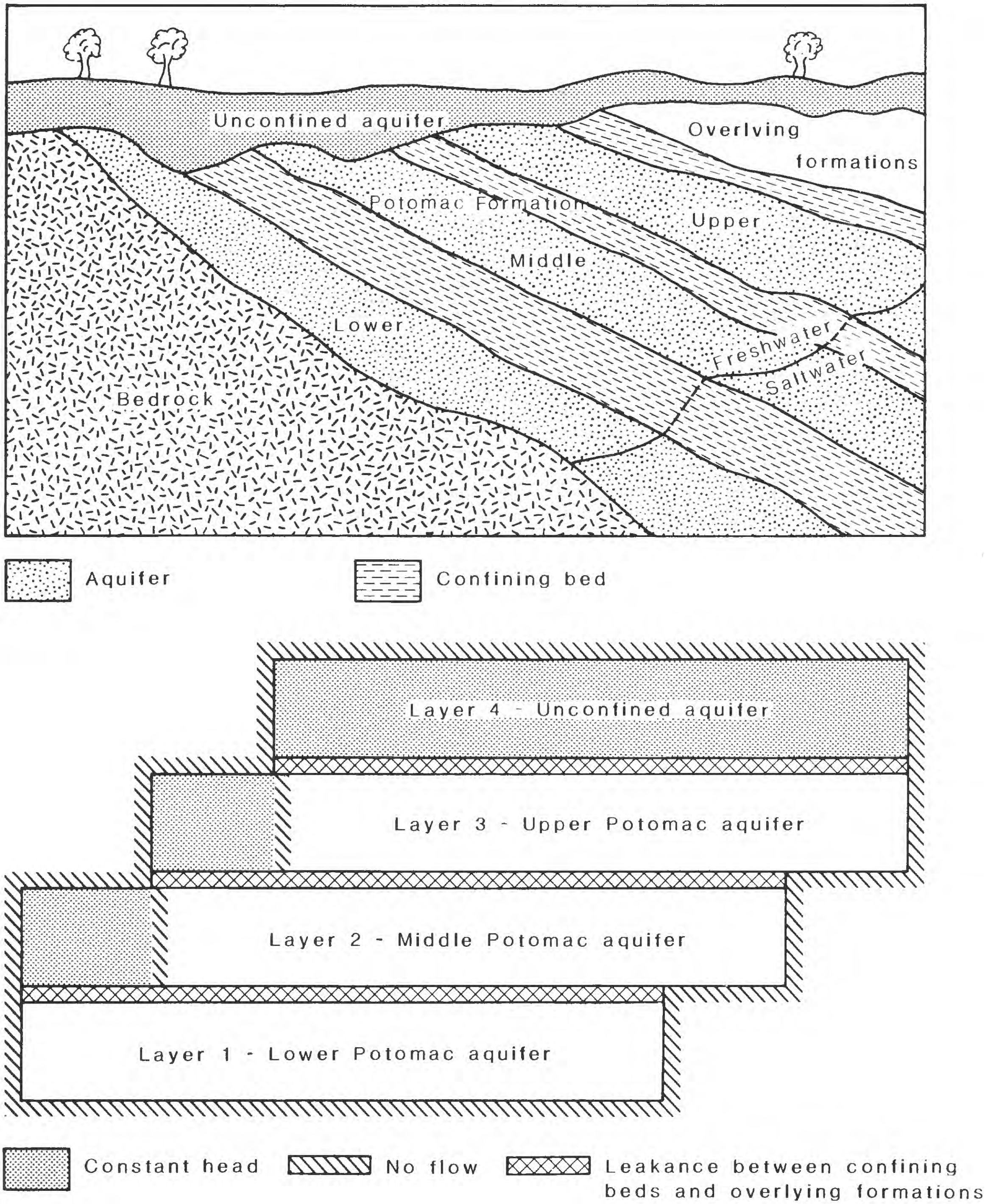


Figure 11.--Generalized geohydrologic cross section (top) and schematic representation of model layers and boundaries (bottom).

estimated to be 0 to 5 ft below the surface given in the hydrologic atlases. This estimate was based on the examination of available hydrographs of wells screened in the unconfined aquifer. Figure 12 shows the altitude of the water table for the Coastal Plain in New Castle County that is shown in the hydrologic atlases.

The average storage coefficient of the Potomac aquifers was calculated to be 5.6×10^{-4} (Martin and Denver, 1982, p. 13). This value was used for each of the Potomac aquifers and was not changed during calibration, because it was similar to earlier estimates of storage coefficients by Sundstrom and others (1967, p. 43-47).

Few values of transmissivity from aquifer test analyses are available. However, a wide range of transmissivity values are reported by Martin and Denver (1982, table 1). The wide range of values reflects the variable character of Potomac sands over short distances. Because of the limited number of transmissivity values and the variable character of the aquifers within each node, average values of hydraulic conductivity for each aquifer were used to calculate initial transmissivity values. Average hydraulic conductivity was calculated using the above mentioned transmissivity values and an additional 55 specific-capacity values calculated from unpublished data on production well drawdowns. Although individual estimates of hydraulic conductivity from specific capacity are fairly rough, an average of many values is considered usable.

A relationship between hydraulic conductivity and depth of sand or distance from subcrop could not be found. The mean hydraulic conductivity of the lower aquifer is significantly lower than the mean hydraulic conductivity of the middle and upper aquifers. The hydraulic conductivities of the middle and upper aquifers are not significantly different. Initially, a hydraulic conductivity of 15 ft/d was used for the lower layer and 25 ft/d was used for the upper and middle layers. Transmissivity values were changed significantly during calibration and final values of aquifer hydraulic conductivity are much different than the initial estimates. However, because there is error in estimating both aquifer thickness and hydraulic conductivity, final results are discussed in terms of transmissivity, not hydraulic conductivity.

Few values of vertical hydraulic conductivity of the confining beds within the Potomac are available. Therefore, initial estimates of the vertical confining bed hydraulic conductivities were partially based on hydraulic conductivity values from other areas and confining beds in other formations. Martin and Denver (1982, p. 13) report a range of vertical hydraulic conductivity values from 0.0083 ft/d to 3.2 ft/d for the study area. Sundstrom and others (1967, p. 55) reported coefficients of vertical permeability (hydraulic conductivity) of the intervening clayey zone in the Getty area ranging from 9×10^{-5} ft/d to 3×10^{-4} ft/d. Luzier (1980, p. 27) reports laboratory values for vertical

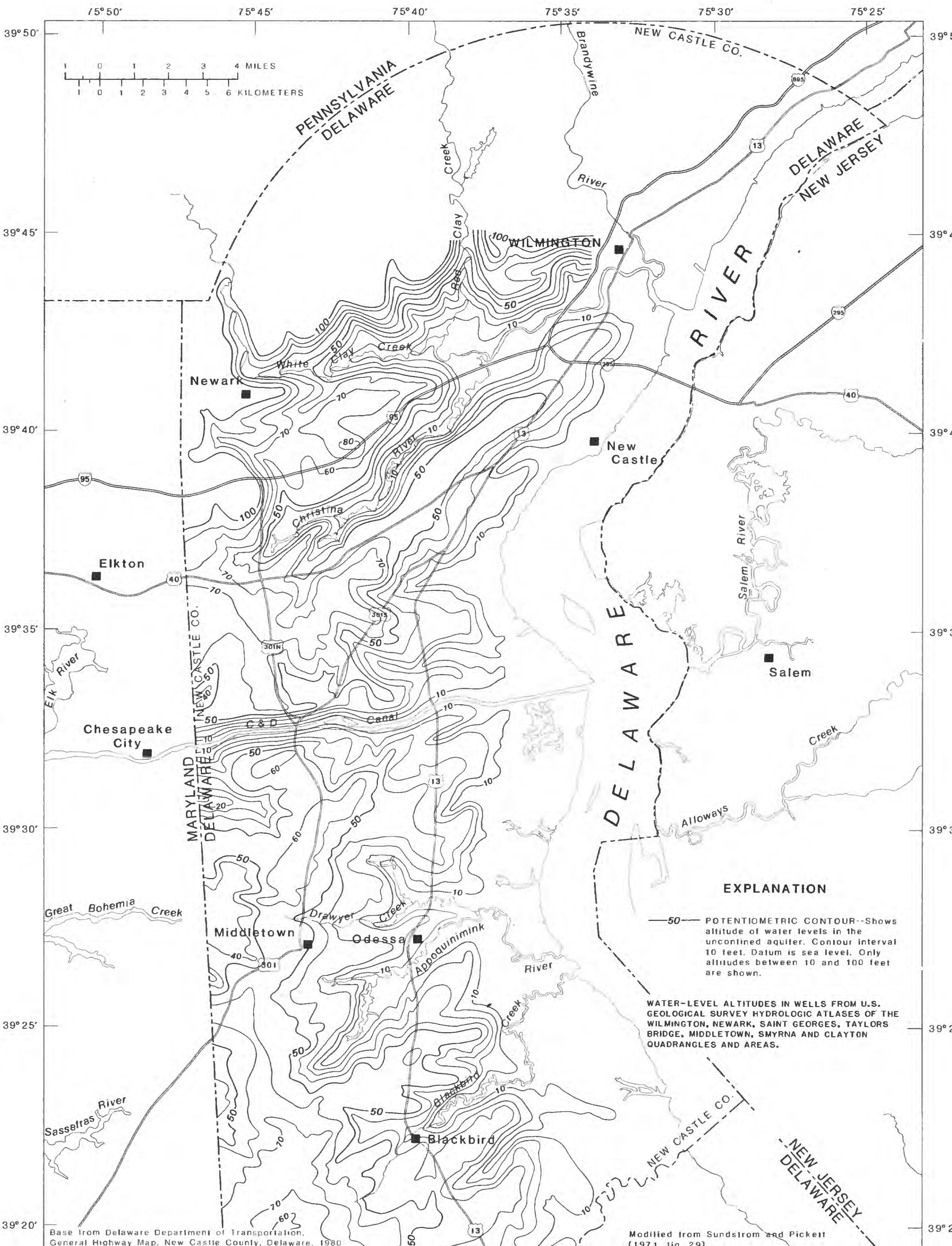


Figure 12.--Altitude of the water table in New Castle County.

hydraulic conductivity of the Merchantville Formation and Woodbury Clay in New Jersey ranging from 7.2 x 10^{-7} ft/d to 1.0 x 10^{-4} ft/d. Leahy (1976, p. 22) reports a vertical hydraulic conductivity range of 4 x 10^{-5} ft/d to 9 x 10^{-5} ft/d for the confining bed overlying the Piney Point aquifer in Kent County, Delaware.

The relatively large vertical hydraulic conductivity values reported by Martin and Denver (1982, table 1) are for wells near the subcrop area. The lower hydraulic conductivity values reported by Sundstrum and others (1967, p. 55) are for wells 5 mi from the subcrop and screened deeper than 100 ft. The initial hydraulic conductivity values used in the model decreased in the downdip direction. This distribution was similar to that used by Luzier (1980, p. 29) for the confining bed above the Potomac-Raritan-Magothy aquifer system in New Jersey. Initial estimates of vertical hydraulic conductivity ranged from 7.5 x 10^{-4} ft/d near the subcrop in Delaware to 5 x 10^{-6} ft/d near the southern boundary of the model. These values were changed significantly during calibration because values of confining bed leakance (hydraulic conductivity divided by thickness) were changed. Final values of leakance, not vertical hydraulic conductivity, are discussed in the following section on simulation results.

Specific storage values for the confining beds within the area of interest are not available. Leahy (1976, p. 22) reported a range of specific storage for the confining bed above the Piney Point aquifer in Kent County, Delaware as 3 x 10^{-6}/ft to 6 x 10^{-6}/ft. The model was tested for sensitivity to this parameter, but was found to be only slightly sensitive to specific storage. The initial estimate of 6 x 10^{-6}/ft was not changed during calibration.

Pumpage data were taken from the data report by Martin and Denver (1982). Average pumpage for each node for each pumping period was calculated. The length of each pumping period and the average total pumpage from Potomac Formation in New Castle County are shown in figure 13. Detailed pumpage values for each well field are shown in the data report. Production wells and their nodal location are listed in table 1. Pumpage values for areas in Maryland and New Jersey were obtained from unpublished records compiled by the U.S. Geological Survey for other modeling projects.

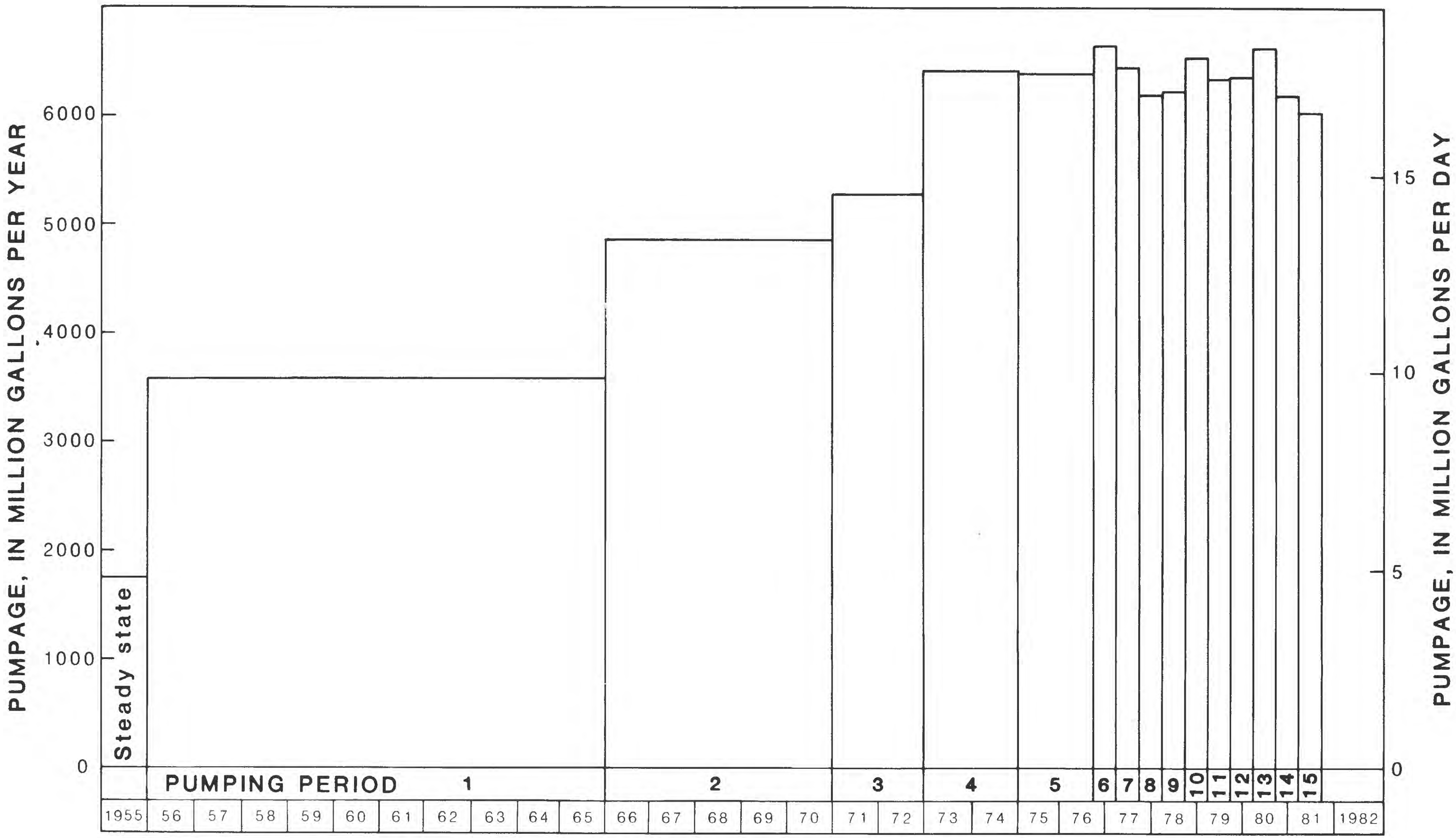


Figure 13.--Graph showing average pumpage from the Potomac Formation in New Castle County for each pumping period.

Table 1.--Production wells in New Castle County used in the model.

Well field: Locations shown in figure 1.
Well No.: Delaware Geological Survey numbering system.
Aquifer: U: upper Potomac aquifer, M: middle Potomac aquifer, L: lower Potomac aquifer.
Node: Indicates row, column. Slash indicates well is on grid line between two rows or colums. Pumpage is equally divided between nodes.

Well field and Well No.	Layer	Node
Amoco		
Dc15-9	U	14,30
Dc15-10	L	14,30
Dc25-17	L	14,29/30
Army Creek Landfill		
Dc14-30,34, 35,36	U	13,28
Dc14-47	U	14,29
Dc14-48	U	13,28
Dc14-50	U	12/13,27
Dc14-51	U	13,29
Dc24-36	U	13,27
Dc24-38	U	13,28
Artisans Village		
Dc33-7	U	15,23
Dc33-8	U	16,23
Caravel Farms		
Db52-27	M	15,12
Castle Hills		
Cd42-18	M	10,37
Cd52-15,28	M	10,37
Collins Park		
Cd42-1	M	9,39
Cd42-3	M,L	9,39
Cd42-4,5,9, 13,14, 15,17	M	9,39
duPont-Newport		
Cc34-14,15,19	L	3,33
Fairwinds		
Dc22-13	U	12,23
Dc22-14,24	U	12,24
Dc22-22,23	U	12,22
Dc22-24	U	13,22
Getty		
Dc41-4	L	17/18,18/19
Dc42-6	L	18,19
Dc51-7	L	18,17
Dc52-24	L	19,19
Eb15-4	L	19,16
Eb15-5	M,L	19,16
Ec12-20	L	21,18
Ec13-6	L	21,20
Ec14-7	L	22,21/22
Ec22-3	U	22,16
Glendale		
Dc31-10,21	M	13,19
Dc31-24	M	13,20
ICI		
Cd44-14	L	11,41
Jefferson Farms		
Cd51-14,15	M	10,36
Llangollen Estates		
Dc23-2,9,10,12	U	14,26

Table 1.--Production wells in New Castle County used in the model--Continued.

Well field and Well No.	Layer	Node	Well field and Well No.	Layer	Node
			Newport--continued		
Crown Zellerbach			Dc24-1,41	U	--
Dc25-1	M,L	15,30	Dc24-14	U	14,27
Dc25-2,5,6,27	U	15,30	Dc24-15	U	15,28
Dc25-3	M,L	15,30	Dc24-17	U	15,27/28
Dc25-4,7	M	15,30	Dc24-18,19	U	15,27
Midvale			Tuxedo Park		
Dc14-3,53	U	11,28	Cc23-1,24-2,3	L	2,33
Newark			Wilmington Airport		
Ca55-3,4,5,7	L	2,14	Cc45-1	L	7,33
Db11-49,12-27	L	4,15	Cc45-2	L	6,33
Db22-42	L	5,15	Cc55-1	L	8,33
Db32-16	L	8,15	Wilmington Manor		
New Castle			Cc 55-6,7	L	7,33
Cc55-17	U	11,32			
Cd51-8	U	11/12,33	Wilmington Manor Gardens		
Cd52-13,27	M	13,36	Cd51-1,11	L	11,33
Dc15-16	U	11,31	Cd51-12	L	11,34
Newport					
Cc34-2,3,4,5,6, 8,9,10,11, 34,35	L	3,33			

Major Assumptions

Numerous assumptions are made throughout the modeling procedure and some assumptions more than others limit the usefulness of the model. The major limiting assumptions discussed below include:

(1) a layered aquifer system,
(2) the location and extent of the aquifer subcrops,
(3) the selection of boundary conditions.

The existence of a layered aquifer system is assumed in the conceptual model. Although sand bodies within the Potomac Formation are discontinuous, a layered model is appropriate if flow within the sand bodies is predominately in the horizontal direction but limited in the vertical direction. This assumption is supported by the examination of geophysical logs and water levels for the Potomac. Examination of geophysical logs show the existence of thick clays between sandy zones. Sandy zones are essentially continuous although individual sand bodies are not continuous. Water levels in several well fields indicate that cones of depression are fairly widespread laterally, but not always apparent in overlying and underlying sand zones. The assumption of a layered system does not seriously limit the applicability of the model because vertical flow between aquifers can be controlled in the model by changing confining unit leakance values.

Another assumption concerning the geology is the existence and position of subcrops for each layer. Both clayey and sandy zones of the Potomac Formation are identified on geophysical logs in subcrop areas in northern New Castle County. These zones can be directly observed in outcrop areas. However, the hydrogeologic relationship of sandy subcrop areas to sandy zones identified in downdip areas is not exactly known.

For modeling purposes, the location and extent of the aquifer subcrops were estimated by locating the aquifer on geophysical logs near the subcrop and approximating the aquifer's updip intersection with the base of the overlying unconfined aquifer by assuming the aquifers were deposited approximately parallel to bedrock. These subcrop areas are shown in figures 4, 6, and 8.

In the model, high leakance values were used between the constant-head nodes of the water-table aquifer and the underlying aquifer subcrops. This allows the majority of recharge to the aquifers to occur in updip areas, and creates head gradients to cause downdip movement of water. In relation to the general ground-water flow system simulated by the model, the assumed location of the subcrops is not a serious limitation on model results, because the amount and distribution of recharge into the aquifers was controlled in the model by changing leakance values at the subcrop.

However, in simulating local flow patterns near the subcrop, particularly near producing well fields, the model's applicability is limited by the assumed location of the subcrops. Horizontal and vertical hydraulic connections between individual sand units is very important in simulating flows in these areas. True hydraulic connections are not known because of limited geophysical data and cannot be absolutely simulated because of nodal separation. Therefore, the connections between some well fields cannot be satisfactorily simulated. The effect of this limitation on certain well fields is discussed in the following section on model calibration.

The choice of boundary conditions was another major assumption made in developing the model. In the real ground-water flow system, absolute no-flow and constant-head boundaries do not exist. The northern and bottom no-flow boundaries approximate the flow from bedrock into the Coastal Plain sediments and are not considered to be limiting assumptions because of the small amount of flow across these boundaries even under stressed conditions.

The overlying constant-head boundary is based on the assumption that water-table altitudes do not change. Water-table altitudes vary several feet seasonally and decline several feet during extended periods of drought. However, no long-term change in average water-table altitudes can be observed in available hydrographs. Because the model was calibrated over a 25-year period, the use of an average water-table altitude as a constant-head boundary is not considered to be a limiting assumption. Although the constant nodes can provide an infinite amount of recharge, the recharge rate to the underlying aquifer nodes was controlled in the model by adjusting leakance values for the intervening confining bed. The use of a constant-head boundary to simulate the water-table aquifer is not considered to be limiting. Some error may exist in areas where declines in water-table altitude may have occurred but have not been documented. Such areas may include Airport Industrial Park and Glendale.

The use of no-flow boundaries for these southwestern and northeastern limits of the model is based on the assumption that in these two discharge areas, ground-water flow is along a flow line toward the Fall Line or the center of a cone of depression. Also, the flow direction does not change with time. Interpretation of water-level maps for Maryland and New Jersey indicates that although flow is generally northward along this boundary, there are probably small amounts of flow across these two boundaries. The boundary in New Jersey is defined by the large cone of depression centered near Camden. This cone was well developed by the start of the simulation period, and heads along this boundary are known to have declined during the calibration period. The head declines along the boundary were simulated by using only a percentage of the pumpage from wells along the boundary. The boundary in Maryland is defined by the natural flow system within the Potomac aquifers. Only minor amounts of pumpage occur near this boundary. There is no evidence to indicate that pumping during the calibration period has caused these boundaries to move laterally.

Although flow rates and direction at these boundaries are assumed to be fairly constant during the calibration period, some flow across these boundaries probably exists. The amount of flow is assumed to be small and could not be accurately determined, therefore no-flow boundaries are used in these areas. Also, these boundaries are considered to be far enough away from the study area to have minimal effect there.

The use of a no-flow boundary for the southern boundary assumes that the interface between the saltwater and freshwater systems is stationary, not diffuse, and can be accurately located. None of these assumptions is actually met. The interface is known to exist as a zone of intermixed saltwater and freshwater. The location of the interface can only be estimated based on limited data, and movement of the interface zone must occur as ground-water levels in downdip areas decline. Nevertheless, estimating a no-flow boundary at the 10,000 mg/L chloride concentration surface is considered to be acceptable because there is little evidence to indicate that this surface has moved large distances during the time period of the model simulations. Also, the 10,000 mg/L isochlor corresponds closely to the sharp interface for mean bay tide calculated by Henry (1964, p. 661) for a similar coastal plain aquifer in Florida. The model is limited by errors introduced in locating the interface, and in modeling ground water with chloride concentrations up to 10,000 mg/L as freshwater. The greatest error would occur if the interface moved large distances during the calibration period. The possible error of using a stationary boundary is discussed further in the following section on calibration.

Model Calibration

The model was calibrated by simulating the ground-water flow system using the parameters described in the data input section and comparing the calculated heads and head changes to observed data. Model calibration was done using a trial-and-error procedure. Hydraulic parameters of the aquifers and confining beds were adjusted within an acceptable range until the model results simulated observed data reasonably well.

Changes were made primarily in aquifer transmissivity and confining unit leakance. The model was most sensitive to these parameters; that is, model results varied greatest to changes in these parameters. Pumpage and the boundary conditions were considered to be known and were not changed during calibration. The model was tested for sensitivity to storage coefficients for the aquifers and confining beds early in the calibration procedure. The model did not appear sensitive to these parameters, and the original values discussed in the data input section were used throughout the calibration procedure.

The model was calibrated using both steady-state and transient-state simulations. Steady-state simulations were used to reproduce the flow system for a particular time when water levels were not changing and, therefore, storage of the aquifers or confining beds had no effect on water levels. In New Castle County, steady-state flow is considered to have existed before any pumping occurred (unstressed steady state) and after pumpage at a constant rate had occurred long enough for the system to reach equilibrium (stressed steady state). Unfortunately, such conditions existed for periods with little recorded water-level data which prevents a rigorous steady-state calibration. However, a preliminary calibration of the steady-state simulations was achieved by comparing model results to the expected flow patterns for unstressed and slightly stressed conditions and by comparing calculated heads to the limited data available. These steady-state simulations were useful in refining initial estimates of transmissivity and hydraulic conductivity for the entire model area or for relatively large areas. Consequently, the number of transient simulations needed for calibration was reduced.

Transient-state simulations were used to model the transient response of the aquifer system to changing pumpage from 1956 to 1981. This period was chosen for the following reasons: (1) sufficient pumpage and water-level data were available; (2) stressed steady-state conditions could be reasonably assumed for 1955, and (3) errors caused by the actual system not being in steady state would be negligible for the later pumping periods that have the most available water-level data. Transient-state calibrations were used to refine the estimates of transmissivity and leakance locally. Updated parameter values were then used as input to the steady-state simulation to assure compatibility between steady-state and transient-state simulations.

Two types of transient simulations were used for calibration. The model was used to simulate both heads and drawdowns (changes in head). Both types of simulations use the 1955 stressed steady-state simulation as the starting point. For simulations of head, the heads calculated by the 1955 stressed steady-state simulation are used as initial conditions and actual average pumpage for each pumping period is used. The calculated heads from these simulations were compared to observed water-level data. Drawdown simulations were made by calculating the change in heads from 1955. In this type of simulation, the 1955 heads are assumed to be in steady state, but actual water-level elevations are not known exactly. Therefore, areally constant heads are used as initial conditions for the drawdown simulation, and changes in head from the initial conditions are calculated. This type of simulation uses the average pumpage for each pumping period minus the pumpage at the time of the assumed steady-state condition (pumpage change). The calculated drawdowns (head change) from these simulations were compared to observed changes in water levels. Transient drawdown simulations allow model calibration using changes in water levels when absolute water-level altitudes are not known, unlike transient head simulations which require absolute water-level altitude data.

Several types of errors may cause simulated head changes to differ from observed head changes. The first type results from estimating observed heads, and therefore head changes, at the end of a pumping period using observed head data near, but not at, that time. This can be seen on the steady-state head maps where a range of heads are shown for years near 1955. This type of error will be referred to as type 1 errors. The second type, or type 2 error, results from estimating observed heads for a particular node from observed water levels from different wells. This type of error can be seen in hydrographs for wells Dc33-5 and Dc33-6 at Ommelanden Park (Martin and Denver, 1982, fig. 59). Although these wells are located at the same node and are in the same aquifer, water levels differ by almost 20 ft. A third type, or type 3 error, is the error associated with measuring water levels and calculating water-level elevations or changes in water levels. Water-level data collected since 1975 are the most reliable and are accurate to within 5 ft, which is within the criteria used for calibration. Water levels collected before 1975, however, can only be considered accurate to within 10 ft, primarily because measuring point elevations and method of measurement cannot be verified. The fourth type, or type 4 error, is the calibration error and the result of model inaccuracies. These inaccuracies are primarily caused by spatial and temporal discretization, choice of boundary conditions, and estimating aquifer and confining bed characteristics. Model acceptability is based on the size of the calibration error. However, analysis of the type 4 error is difficult if errors of types 1, 2, or 3 also exist. Calibration of the model at particular well fields will be discussed in terms of these four types of errors.

Steady-State Simulation

An unstressed steady-state simulation was made to reproduce the general conceptualized flow system described earlier. Unstressed steady-state conditions probably existed in the Potomac aquifers of New Castle County in the late 1800's before pumping began. The final results of this simulation are shown in the head maps for the three aquifers (figs. 14, 15, and 16). The calculated head maps compare reasonably well to the expected prepumping flow system. Heads are highest in the aquifer subcrop areas and are similar to those of the overlying constant head nodes. Head gradients within the aquifers are fairly steep in updip areas. Head gradients between aquifers are also steep, with over 20 ft of head difference in local updip areas. Flow near the subcrops is both along strike and downdip. In downdip areas the head gradient within the aquifers is much less steep as are gradients between aquifers. Flow in the downdip areas and under the Delaware Bay is upward from the lower aquifer to the upper aquifer and eventually to the unconfined aquifer.

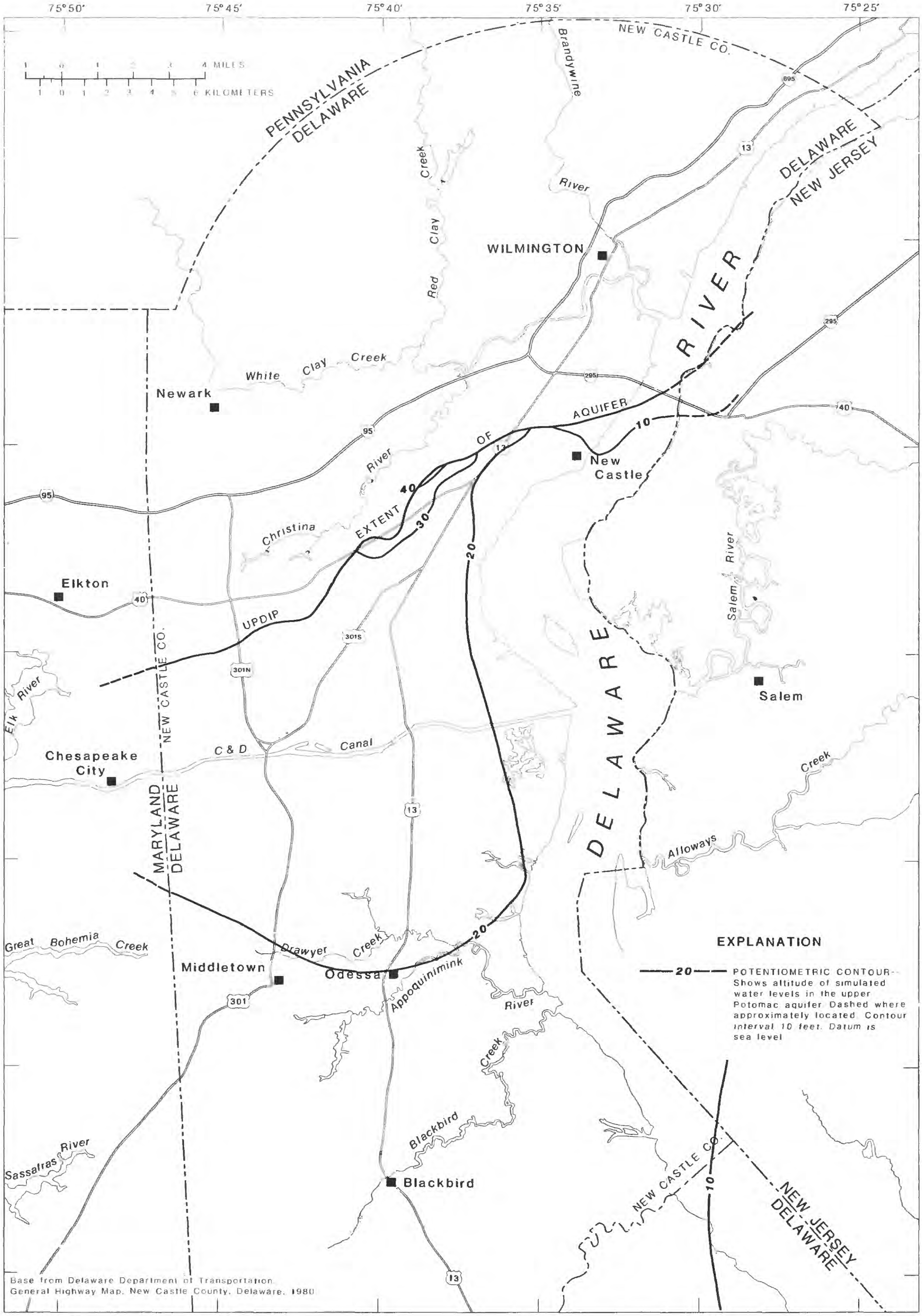


Figure 14.--Simulated prepumping potentiometric surface of the upper Potomac aquifer.

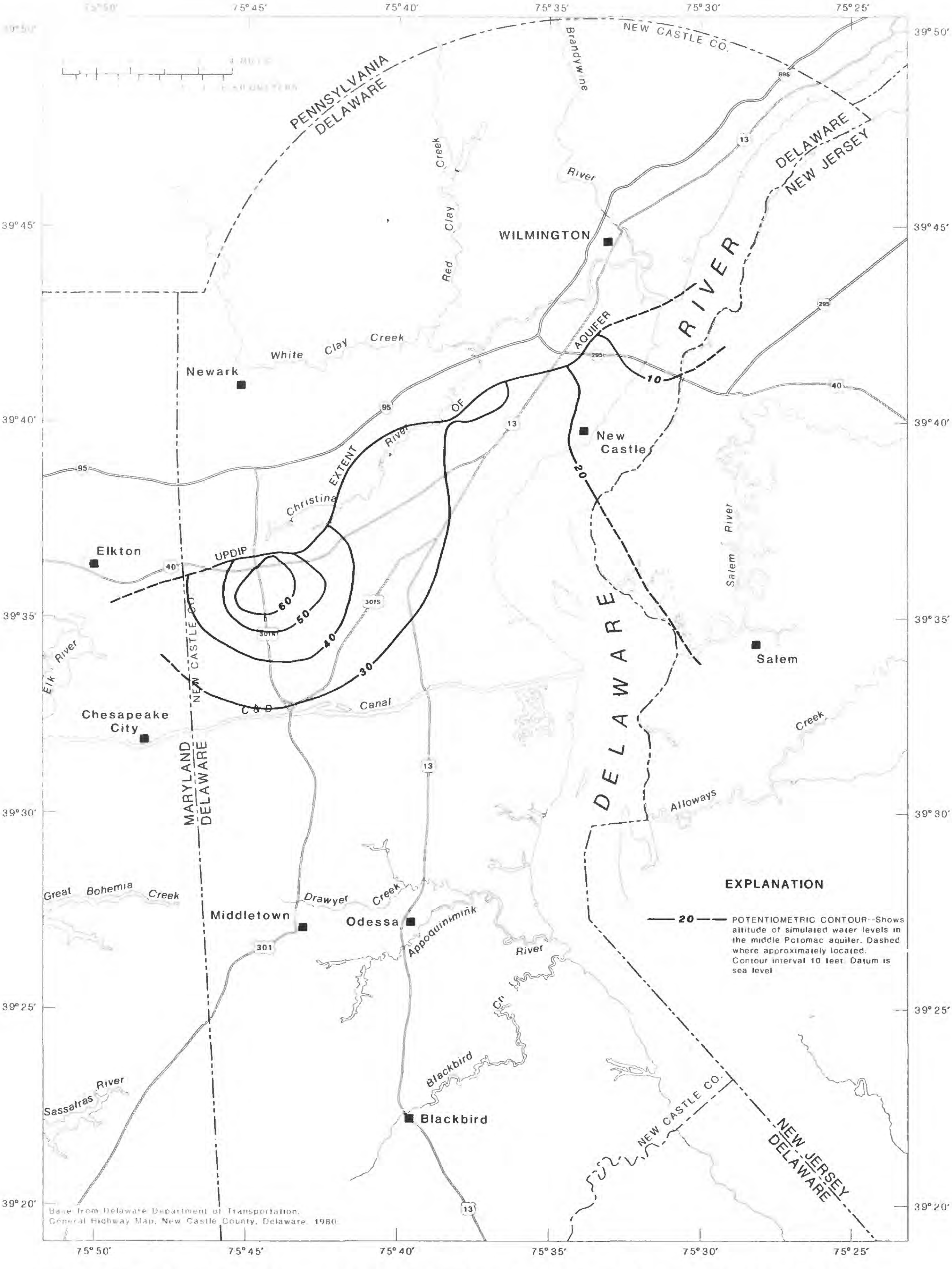


Figure 15.--Simulated prepumping potentiometric surface of the middle Potomac aquifer.

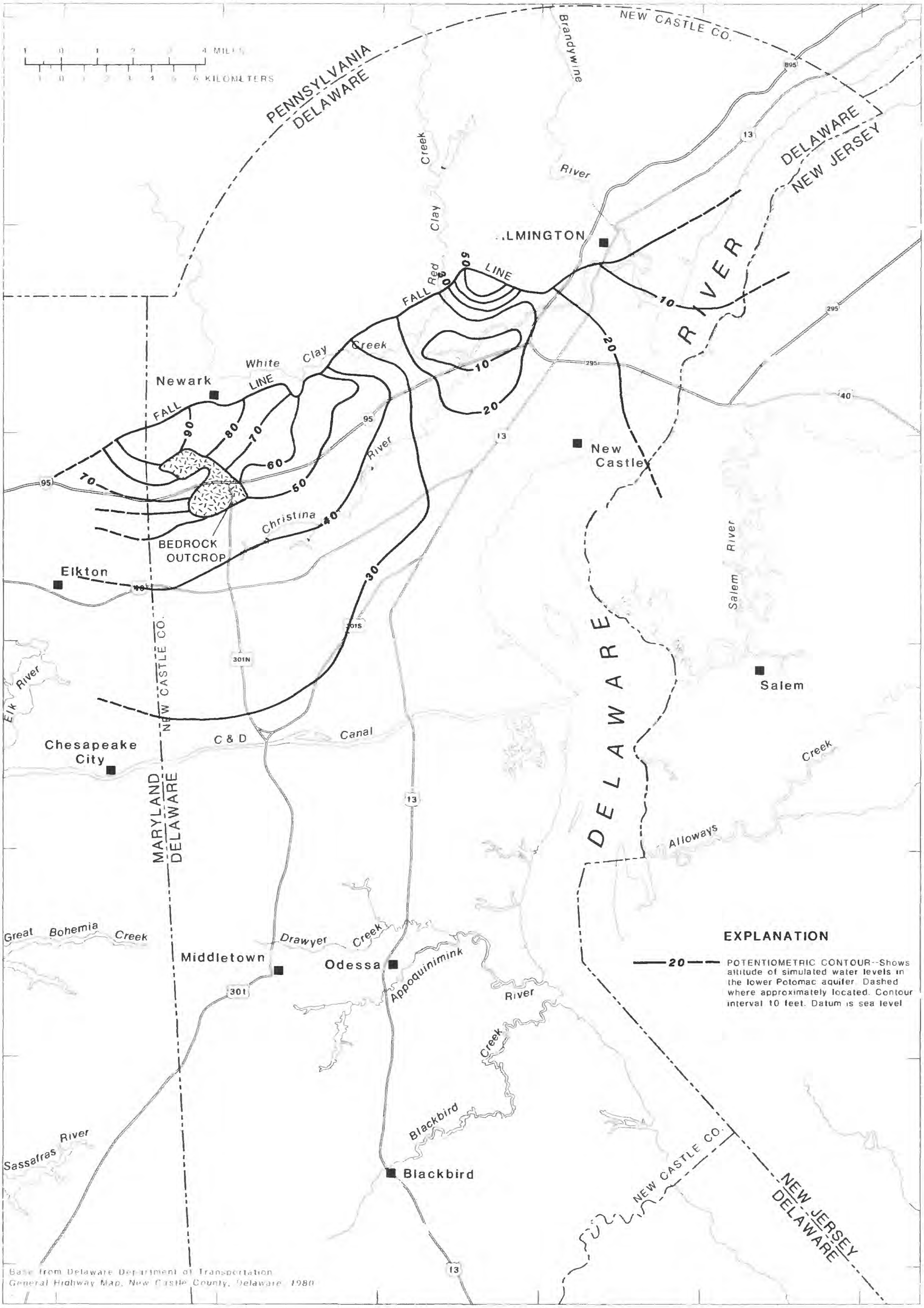


Figure 16.--Simulated prepumping potentiometric surface of the lower Potomac aquifer.

Figure 17 is a map showing flow from constant head nodes for prepumping conditions. This map compares reasonably well to the expected unstressed steady-state flow system. The largest surface-water bodies in the model area coincide with the discharge areas, shown by flow into the constant-head nodes. Recharge areas, shown by flow out of constant-head nodes, coincide with areas of higher topography. Also, the greatest flow rates to and from the water table are in and near the updip subcrop areas. Although the Delaware and Chesapeake Canal was not dug to its present depth of 35 ft until 1927, the low water-table heads representing the canal were left in the unstressed steady-state simulation for compatibility with the other simulations. Figure 15 shows that the canal under unstressed conditions is an area of high discharge.

A second steady-state simulation was made to reproduce slightly stressed equilibrium conditions. Pumpage in New Castle County was 4.8 Mgal/d in 1955 and is assumed to have been at approximately that rate long enough for the aquifer system to reach equilibrium. The final results of this simulation are shown in head maps for the three aquifers (figs. 18, 19, and 20). The calculated head maps compare reasonably well with the expected slightly stressed steady-state flow system. The general flow patterns within the aquifers are similar to the results of the unstressed steady-state simulation. However, small cones of depression are now apparent. Although the low gradients still exist in downdip areas, pumping from the lower aquifer has induced flow from the upper aquifers downward.

Few data exist for comparison with the calculated 1955 steady-state heads. These data were compiled by Martin and Denver (1982, table 4) and are shown in figures 18, 19, and 20. The calculated 1955 steady-state heads compare reasonably well with the observed data. An exact match between calculated and observed data was not expected because many early water-level observations did not occur in 1955, and estimated pumpage values and distributions for 1955 are less reliable than current data.

Transient Simulation

Transient drawdown simulations were used to refine aquifer transmissivity and confining bed leakance values in areas with observed head data. Drawdowns were simulated for January 1, 1956, to October 1, 1981. Fifteen pumping periods were used, varying from 10 years at the start of the simulation to 6 months at the end. These periods were chosen based on the availability of drawdown data. Average pumpage from the Potomac aquifers in New Castle County for each pumping period is shown in figure 12. The change in pumpage from 1955 steady-state withdrawals was used as model input in the drawdown simulations.

Transient calibration consisted of adjusting parameter values and comparing simulated well hydrographs to observed well hydrographs. Hydrograph comparisons were considered acceptable when the total difference between calculated and observed head

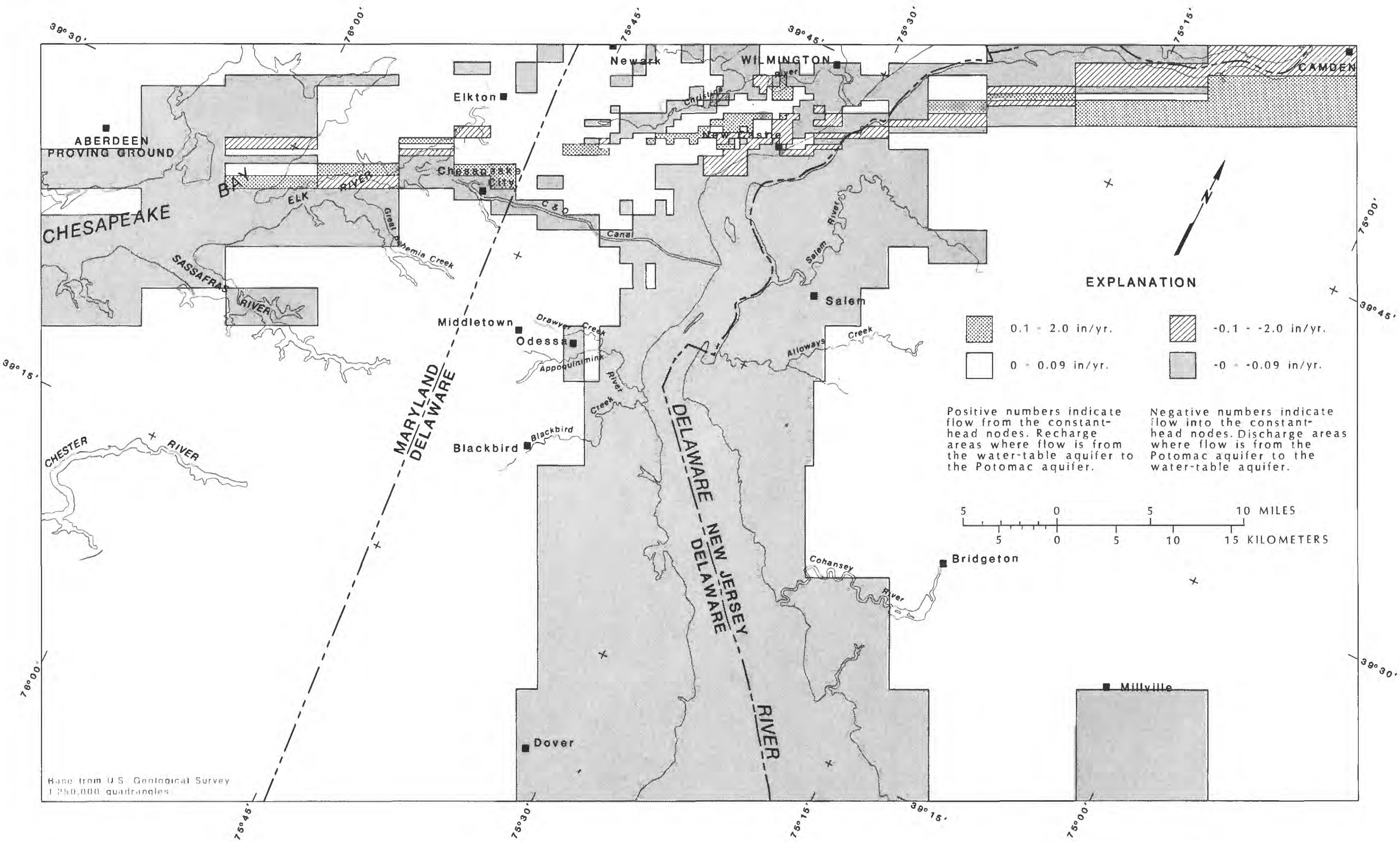


Figure 17.--Flow from constant-head nodes for prepumping conditions.

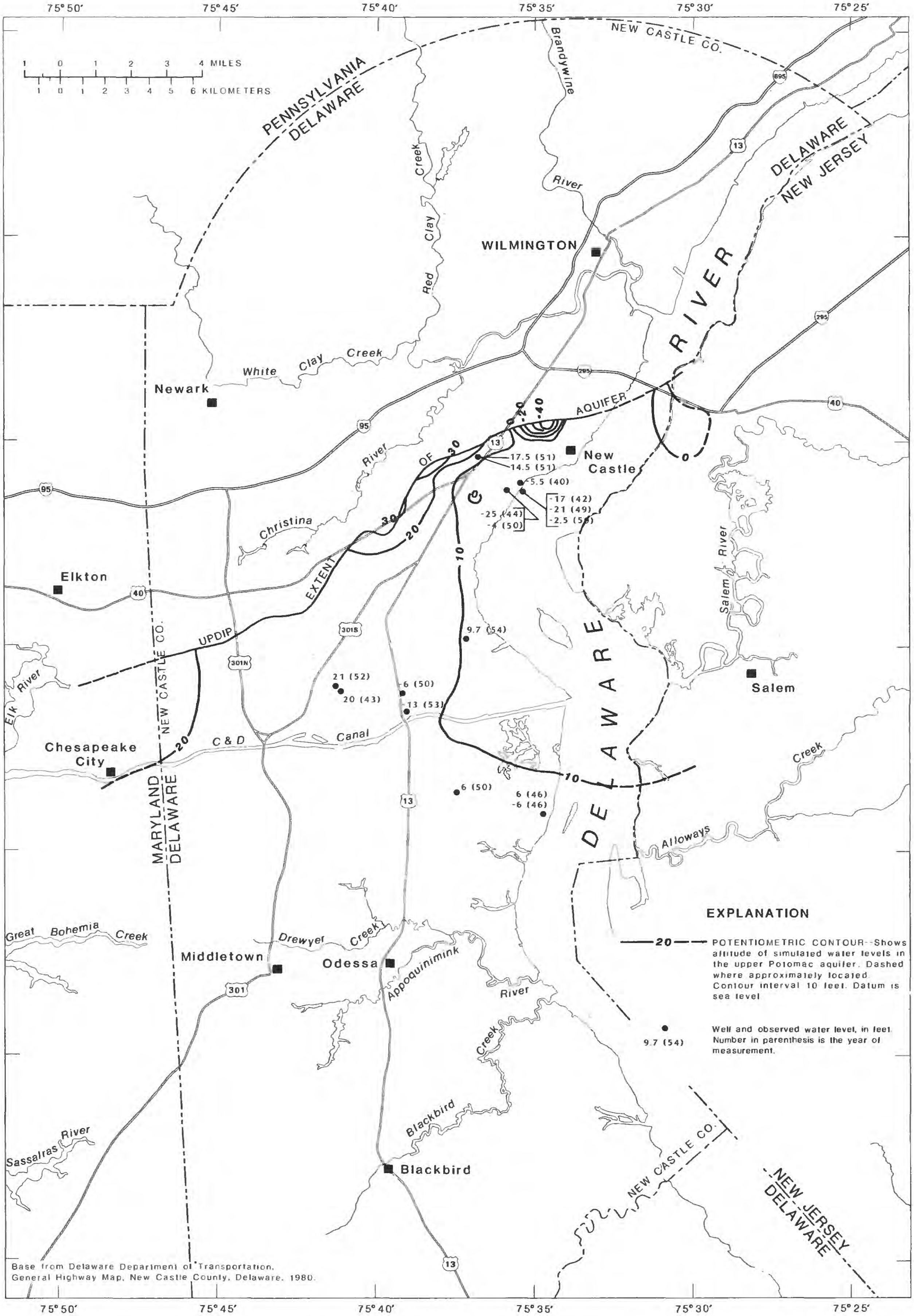


Figure 18.--Simulated 1955 steady-state potentiometric surface of the upper Potomac aquifer.

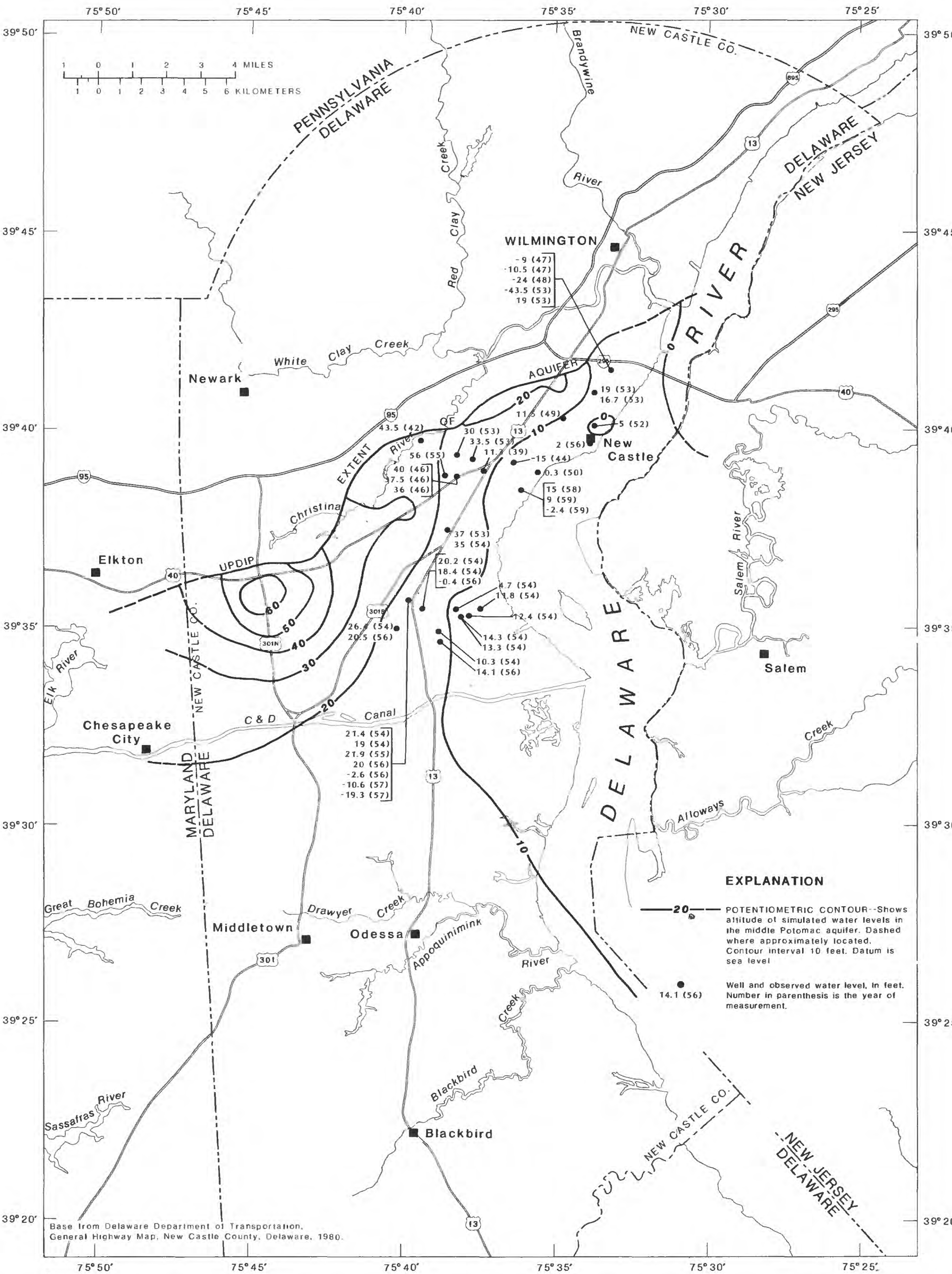


Figure 19.--Simulated 1955 steady-state potentiometric surface of the middle Potomac aquifer.

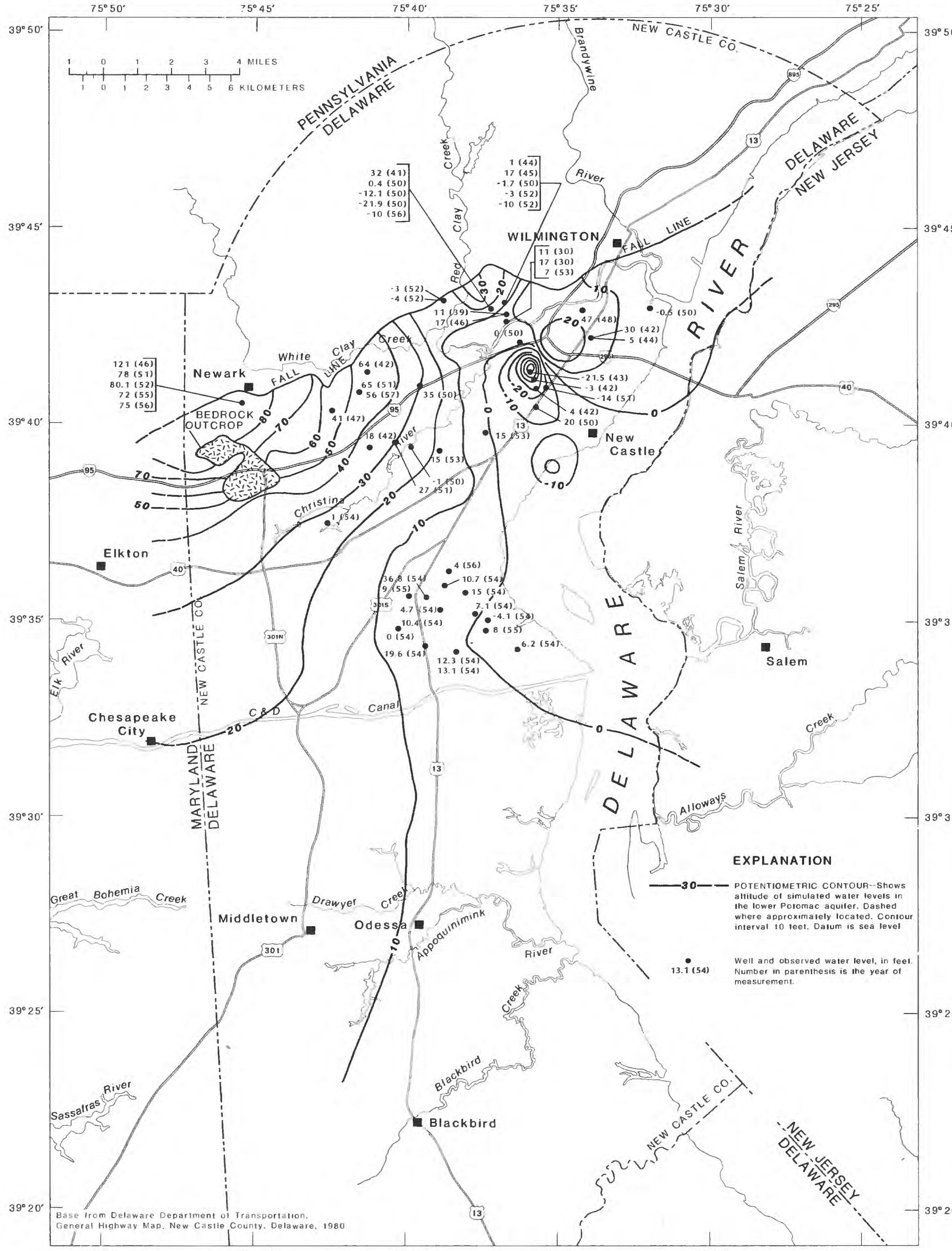


Figure 20.--Simulated 1955 steady-state potentiometric surface of the lower Potomac aquifer.

change was less than 1 ft/yr, but not more than 10 ft total difference over the period of observable data. Also, the differences between simulated and observed head changes for each pumping period were less than 10 ft. Differences between simulated and observed head changes for each observation well are shown in table 2. Observed changes in head, 1956-80, for each of the three aquifers are shown in figures 21, 22, and 23. Simulated and observed hydrographs for selected wells are shown in figures 24 to 35. Although the transient-state simulations were made for January 1956 to October 1981, model results are shown only to October 1980 (pumping period 13). October 1980 was used because significantly fewer observations were made in 1981. Discussion and illustration of areal differences in calibration is best shown for October 1980, when the most observed data were available. However, final calibration at several sites was based on data collected in 1981. Generally, the comparisons of calculated and observed drawdowns for pumping periods 14 and 15 were similar to periods 12 and 13. Table 2 shows the differences between the simulated and observed head changes for pumping periods 1 to 13. Model results are discussed and shown in illustrations only to October 1980.

Comparison of simulated and observed head changes for periods of 10 years or more are considered to be acceptable. Observed and simulated long-term hydrographs are shown for the Getty, Goodrich, and Union Carbide well fields (figs. 30, 31, 32, 34, and 35). Acceptable differences between simulated and observed head changes for each pumping period and for the period of observable data are shown (table 2) for these well fields and other well fields with long-term observed water levels including Amoco, Delaware State Hospital, Llangollen Estates, Midvale, Newark, New Castle, and Smalley's Dam.

The large total difference between simulated and observed head changes for Amoco Dc14-13 is partially attributed to error types 1 and 3. For Amoco Dc15-17, 18, 19, and 20, the large difference between simulated and observed head changes for pumping periods 3 and 5 is partially attributed to error types 2 and 3. Similarly, at Delaware State Hospital Dc41-11 and 18, the large total difference is attributed partly to error types 1, 2, and 3. Note that the large differences for pumping period 5 for Delaware State Hospital Dc41-11 and 18 and pumping period 2 for Amoco Dc14-13 are not considered excessive because they reflect head changes over more than one pumping period.

For Getty Dc51-4 and 9, Dc53-7, and Ec12-2 and 5 and Union Carbide Ec32-7, a larger difference between simulated and observed head changes are considered acceptable because of the large amount of drawdown at these wells.

For Glendale Dc31-13 and Fairwinds Dc23-16, the large differences between simulated and observed head changes were not considered acceptable. Also, for wells with no observed data before 1975, the differences between simulated and observed head changes, both total and for each pumping period, appear acceptable. How-

Table 2.--Comparison of simulated and observed head changes for each pumping period during transient calibration, 1956-80.

Well field: Locations shown on figure 1.
Well no: Delaware Geological Survey numbering system.
Aquifer: U: upper Potomac aquifer,
M: middle Potomac aquifer,
L: lower Potomac aquifer.

Node: row, column. Slash indicates well is on grid line between two rows or columns.
*: first observed head.
SS: steady-state simulation.
--: no observed head.

- Last pumping period = Pumping period 13, otherwise pumping period with last observed head.
- Head difference = [Observed head] - [Simulated head] for last pumping period.
- Total head change difference = [Observed head change] - [Simulated head change] for period between first and last observed heads.
- Head change difference per year = [Total head change difference] ÷ [number of years between first and last observed head].
- Head change difference for each pumping period = [Observed head change] - [Simulated head change] for each pumping period. If previous pumping period has no observed head, head change difference is sum of differences for all previous pumping periods after previous observed head.
- Negative head change difference indicates less simulated head change (rise or decline) than observed head change.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	Head change difference for pumping period (ft)													
						SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Airport Industrial Park																			
Dc 14-14	U	12,30	-5.1	-7.0	-1.2	--	--	--	--	*	-4.6	-2.9	--	-3.5	1.4	2.5	1.8	-0.3	-1.4
Dc 15-13	U	11,30	-1.2	-4.6	-1.2	--	--	--	--	*	-0.9	-2.4	-2.2	4.2	-3.3	--	--	--	--
Remarks: Calibration acceptable																			
Amoco																			
Dc 14-13	U	13,29	-8.0	12.7	1.8	--	*	--	12.7	--	--	--	--	--	--	--	--	--	--
Dc 15-17,18,19,20	U	14,30	-4.7	0.5	0.0	--	*	-3.8	11.7	5.7	-12.1	-5.4	-2.0	-2.3	3.3	2.7	3.0	-0.5	0.2
Dc 25-16	L	14,29/30	16.1	--	--	--	--	*	--	--	--	--	--	--	--	--	--	--	--
Remarks: Calibration acceptable for upper aquifer. Inadequate water-level data for calibration of lower aquifer.																			
Army Creek Landfill																			
Dc 14-45	U	13,29	-0.2	-1.4	0.2	--	--	--	--	*	0.9	-3.7	-4.7	0.2	2.0	1.3	3.3	-0.1	-0.6
Dc 23-19	U	13,26	-2.0	-14.1	-2.5	--	--	--	--	*	0.3	0.4	-6.1	-4.5	0.3	4.2	-.2	-2.6	-5.9
Dc 24-31	U	14,28	-0.9	-0.5	-0.1	--	--	--	--	*	1.6	-2.6	-5.7	-1.6	3.9	1.4	4.3	-0.2	-1.6
Dc 24-32	U	13,27	0.4	-3.9	-1.0	--	--	--	--	--	*	-0.6	-8.1	-1.1	2.7	1.1	5.0	-3.0	0.1
Dc 25-23	U	14,29	-0.8	-2.4	-0.6	--	--	--	--	--	-1.1	-3.3	-2.0	0.5	-0.9	1.3	4.3	-1.2	--
(49)	U	14,27	1.3	0.4	0.1	--	--	--	--	*	0.2	-0.1	-5.0	-0.9	1.7	0.7	4.5	1.0	-1.7
Remarks: Calibration acceptable.																			
Artisans Village																			
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Remarks: Calibration uncertain. No water-level data available. See Ommelanden Park and National Guard Armory.																			
Caravel Farms																			
Db 52-23,25	M	15,12	6.1	-8.9	-1.5	--	--	--	--	*	-2.9	1.0	-2.4	-2.3	-1.3	2.4	-1.5	0.5	-2.4
Remarks: Calibration acceptable.																			

Table 2.--Comparison of simulated and observed head changes for each pumping period during transient calibration 1956-80--Continued.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	Head change difference for pumping period (ft) SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Castle Hills																			
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Remarks: Calibration uncertain. No water-level data available. See Jefferson Farms.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Collins Park																			
Cd 42-16	L	9,39	9.4	-6.2	-2.5	--	--	--	--	--	--	--	--	*	1.0	-1.8	-1.8	0.4	-4.0

Remarks: Calibration acceptable for lower aquifer. No water-level data available for middle aquifer.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Crown Zellerbach																			
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Remarks: See Amoco.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Delaware State Hospital																			
CD 41-11,18	L	6/7,36	1.5	-12.5	-0.8	--	*	--	--	--	-14.0	-0.6	-0.4	2.9	0.8	-0.2	--	--	-1.0

Remarks: Calibration Acceptable.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Delmarva Power-Summit																			
Eb 44-9,45-10	U	23,12	-4.8	-4.0	-1.0	--	--	--	--	--	*	-2.8	-0.5	-2.6	0.1	-1.3	2.9	0.3	-0.1

Remarks: Calibration Acceptable.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	SS	1	2	3	4	5	6	7	8	9	10	11	12	13
duPont-Newport																			
Cc 34-14,15,19	L	3,33	-1.3	-3.0	-0.1	*	--	--	--	--	--	-0.8	-1.0	2.0	-2.1	-9.2	3.7	3.2	1.2

Remarks: Calibration Acceptable.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Fairwinds																			
Dc 22-12	M	12/13,23	8.4	4.7	1.2	--	--	--	--	--	*	1.0	-.3	-12.2	8.7	-3.6	9.0	2.8	-0.7
Dc 22-18	U	12,23	-7.5	-13.5	-2.3	--	--	--	--	*	-10.4	0.9	-4.9	-5.9	0.4	0.1	1.8	3.0	1.5
Dc 23-16	U	12,24	2.0	-18.9	-1.3	--	*	--	-24.2	14.5	-8.3	-0.8	-4.8	-2.4	0.0	-2.8	9.8	1.2	-1.0

Remarks: Calibration poor. Accuracy of pumpage data is questionable. Water levels in upper aquifer do not reflect pumpage trends. Middle aquifer observation well is multiply screened; lower screens are probably in sands connected to lower aquifer.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Getty																			
Dc 51-3,8																			
Dc 52-6,32	M	19,18	-6.0	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Dc 51-4,9	M	18,17	-2.6	-18.5	-0.7	*	-21.0	-8.0	1.3	10.3	-3.5	3.9	3.3	-9.8	-6.6	-6.0	5.2	-2.4	1.6
Dc 52-2,30,31	L	19,18	-8.8	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Dc 52-8	L	18,19	-35.1	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Dc 53-6	M	20,20	-3.8	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Dc 53-7	L	19,20	1.7	17.9	0.7	*	1.0	-9.5	-5.3	-19.0	37.2	-7.6	4.9	6.8	5.4	1.8	4.7	-0.5	7.8
Dc 53-23	L	20,21	3.8	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Dc 53-31[1]	M	20,21	-4.1	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Dc 53-31[2]	U	20,21	0.3	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Eb 15-2	M	19,16	-4.1	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--

Table 2.--Comparison of simulated and observed head changes for each pumping period during transient calibration, 1956-80--Continued.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	Head change difference for pumping period (ft) SS	1	2	3	4	5	6	7	8	9	10	11	12	13
Getty--Continued																			
Ec 11-2	L	20,16	13.7	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Ec 12-2,15	L	20,18	-5.3	10.1	0.4	*	-12.8	--	--	--	-14.1	13.9	-8.1	3.8	-0.3	17.2	-20.5	--	18.2
Ec 12-3	L	21,18	-10.4	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Ec 13-5	L	20/21,20	-4.6	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Ec 14-1	L	22,21/22	-8.7	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Remarks: Calibration good for lower and middle aquifers.																			
Glendale																			
Dc 31-13	M	13,19	-6.9	-13.0	-1.7	--	--	--	*	-13.6	4.8	-15.6	--	6.5	10.8	-8.0	6.2	5.2	-9.3
Dc 31-18	M	13,20	-28.8	-2.9	0.5	--	--	--	--	*	-22.1	-4.2	--	-0.5	-3.4	-18.6	43.7	10.2	-8.0
Dc 31-26,27	L	13,19	-2.8	14.8	2.5	--	--	--	--	*	9.6	-5.3	3.4	--	-2.5	4.9	10.7	1.0	-7.0
Remarks: Calibration poor for both aquifers. Hydrologic connection to lower aquifer and Fairwinds is uncertain.																			
Goodrich																			
Ea 33-1,2	L	18/19,8	1.2	1.6	0.1	--	*	-1.9	2.1	0.1	-0.3	-1.1	0.5	0.5	0.5	0.4	0.3	0.3	0.2
Remarks: Calibration good.																			
ICI																			
--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Remarks: Calibration uncertain. No water-level data available.																			
Jefferson Farms																			
Cd 51-13	M	10,36	8.6	-4.4	-0.8	--	--	--	--	*	-15.6	-1.5	-3.3	4.5	2.8	-0.9	9.4	-0.2	0.4
Remarks: Calibration acceptable. However, simulated water levels slightly below top of aquifer may indicate unconfined conditions.																			
Langollen Estates																			
Dc 24-40	U	14,26	-3.0	4.8	0.6	--	--	--	*	5.2	-5.9	3.2	-7.7	1.0	6.7	-0.7	3.1	0.4	-0.5
Remarks: Calibration good.																			
Lums Pond																			
Eb 23-22B	U	20,12	-6.9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	*
Eb 23-22C	M	20,12	18.2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	*
Eb 23-22D	L	20,12	23.1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	*
Remarks: None																			
Midvale																			
Dc 13-10	U	10,27	-1.7	-1.5	-0.4	--	--	--	--	--	*	-1.5	-2.1	-0.5	0.2	1.5	1.3	0.9	-1.3
Dc 14-54	U	11,28	.1	1.1	0.1	--	--	*	7.0	-6.8	2.5	-2.8	-2.7	1.5	1.1	1.7	-0.9	0.0	0.5
Remarks: Calibration good.																			

Table 2.--Comparison of simulated and observed head changes for each pumping period during transient calibration, 1956-80--Continued.

Well field and well no.	Aquifer	Node	Head difference (ft)	Total head change difference (ft)	Head change difference per year (ft/yr)	Head change difference for pumping period (ft) SS	1	2	3	4	5	6	7	8	9	10	11	12	13
National Guard Rifle Range																			
Dc 34-5	L	16,25	.9	4.8	1.2	--	--	--	--	--	*	-0.7	-2.7	-5.0	6.1	-3.5	5.3	6.0	-0.7
Dc 34-6	U	16,25	-2.3	-2.3	-0.6	--	--	--	--	--	*	-5.6	-1.9	-2.6	4.9	1.5	2.0	3.2	-3.8
Remarks: Calibration acceptable.																			
Newark																			
Ca 55-2,8	L	2,14	-11.5	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Db 12-39,40	L	4,15	5.7	-10.4	2.6	--	--	*	--	-10.4	--	--	--	--	--	--	--	--	--
Db 22-40,41,46,48,49	L	5,15	-2.6	12.8	2.2	--	--	*	--	--	12.8	--	--	--	--	--	--	--	--
Db 12-27	L	8,14	1.9	-3.9	0.9	--	--	--	*	--	--	-3.9	--	--	--	--	--	--	--
Remarks: Calibration acceptable, but no recent water-level data available.																			
New Castle																			
Cc 55-10, Cd 51-8	U	11,32	-5.0	-7.2	-0.9	--	--	*	--	--	--	--	--	--	-7.2	--	--	--	--
Cd 52-14,26	M	13,36	5.7	-16.4	-1.2	--	*	--	--	--	-23.0	3.2	5.1	-3.7	0.9	2.6	--	-1.5	--
Dd 12-3	M	14,35	-15.7	0.7	0.4	--	--	--	--	--	*	0.7	--	--	--	--	--	--	--
Dc 15-16	U	11,31	-7.9	-2.4	-1.2	--	--	--	--	--	*	-2.2	-2.7	0.8	1.7	--	--	--	--
Remarks: Calibration acceptable.																			
Newport																			
Cc 34-12	L	3,33	21	--	--	*	--	--	--	--	--	--	--	--	--	--	--	--	--
Remarks: See duPont-Newport.																			
Ommelanden Park																			
Cc 33-5,6	U	16,24	-4.9	-4.4	-1.1	--	--	--	--	--	*	-2.7	--	-7.5	-0.8	0.5	7.5	2.6	-4.0
Remarks: Calibration acceptable. See also National Guard Rifle Range.																			
Smalley's Dam																			
Db 15-5	L	8,20	-3.4	9.2	0.6	--	*	--	--	--	4.7	0.2	--	-3.5	1.0	1.6	3.4	3.0	-1.2
Remarks: Calibration acceptable.																			
Union Carbide																			
Ec 32-3,4	U	23,17	5.9	-5.8	-0.4	--	*	-2.0	3.0	0.4	-2.0	-0.9	-3.6	-2.6	1.3	-4.6	2.3	2.5	0.3
Ec 32-7	L	23,17	-6.6	-12.2	-0.8	--	*	-22.2	0.3	12.3	-10.5	15.6	-16.5	0.3	1.2	4.4	-2.3	6.8	-1.6
Remarks: Calibration good.																			

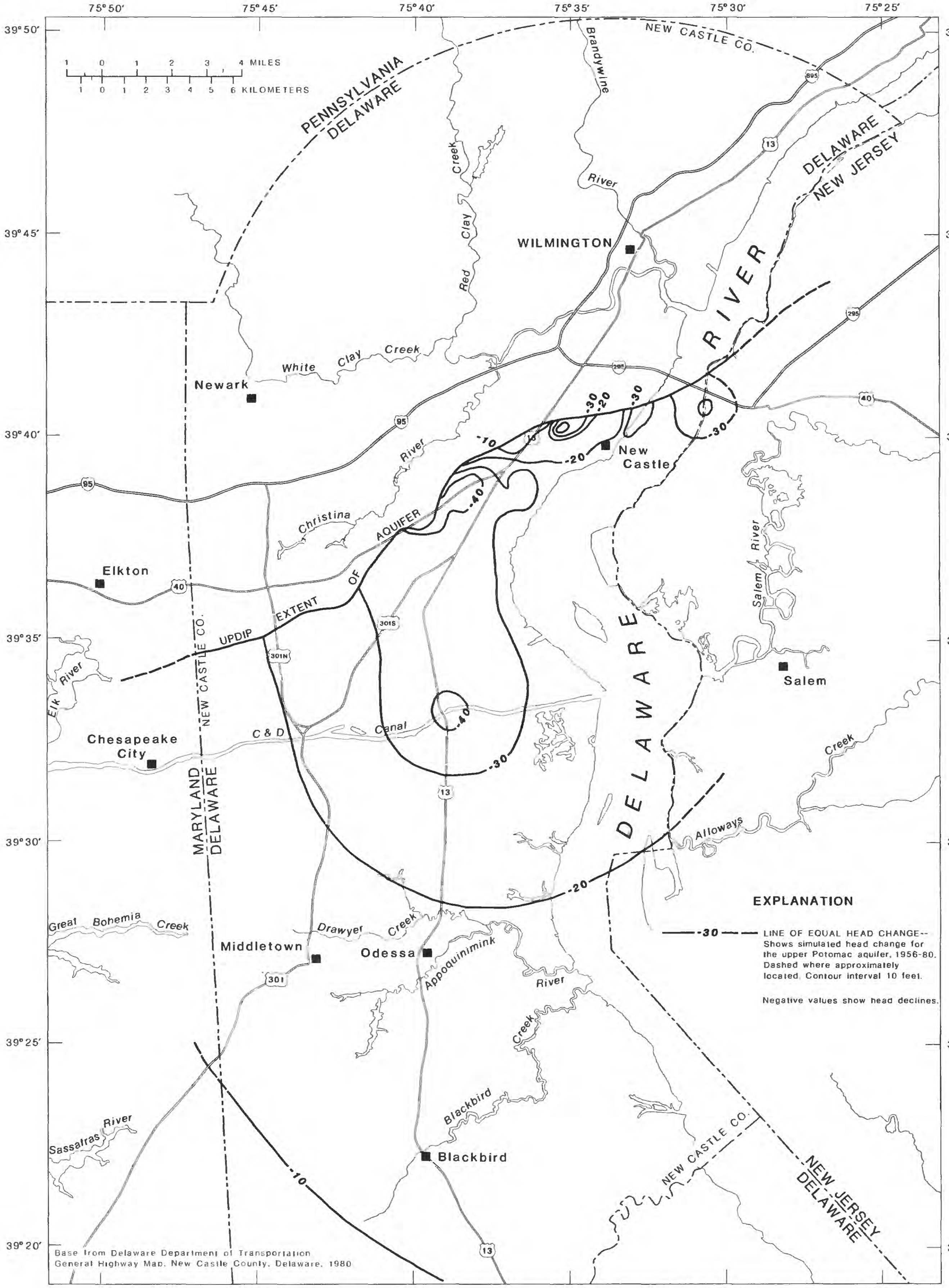


Figure 21.--Simulated changes in head for the upper Potomac aquifer, 1956-80.

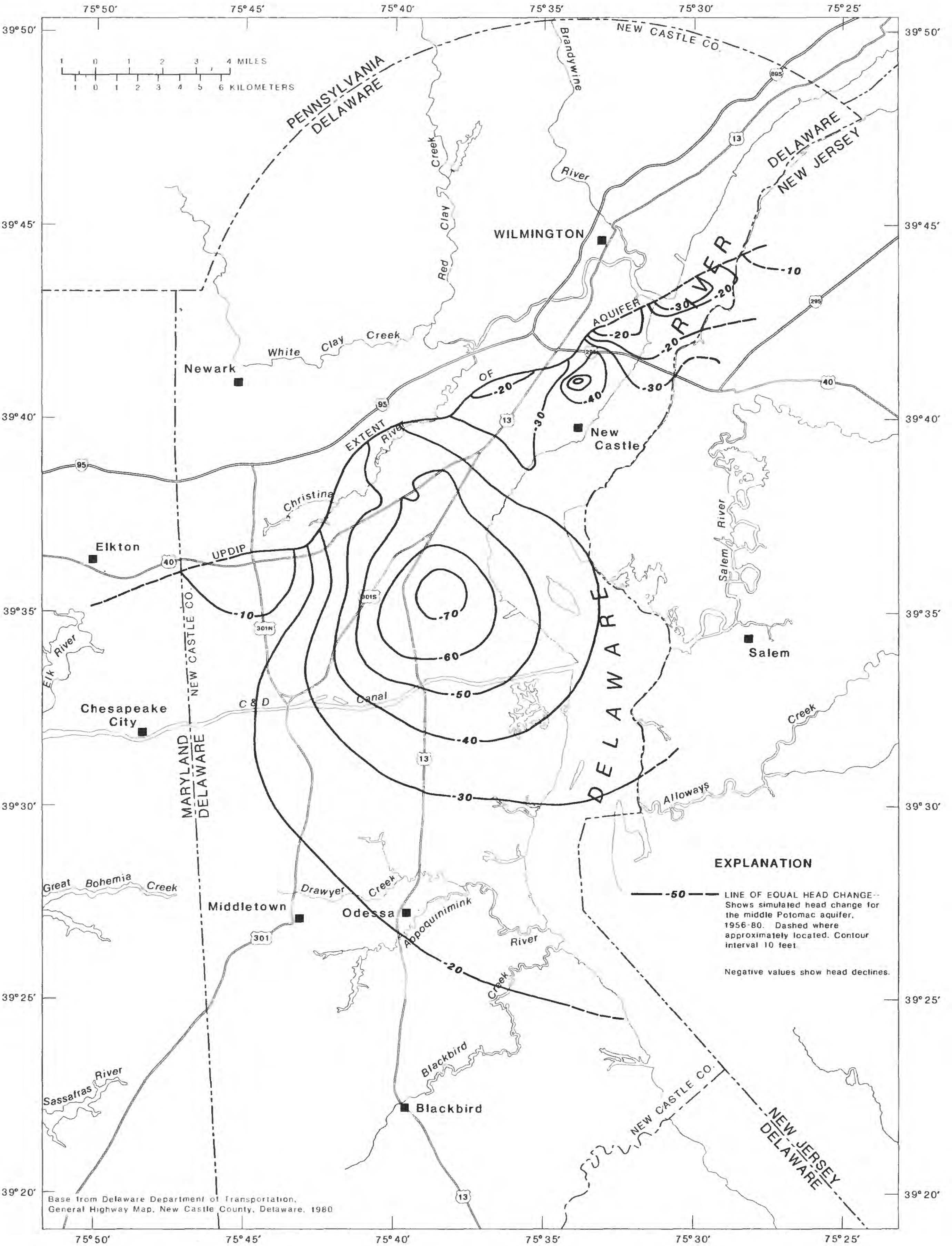


Figure 22.--Simulated changes in head for the middle Potomac aquifer, 1956-80.

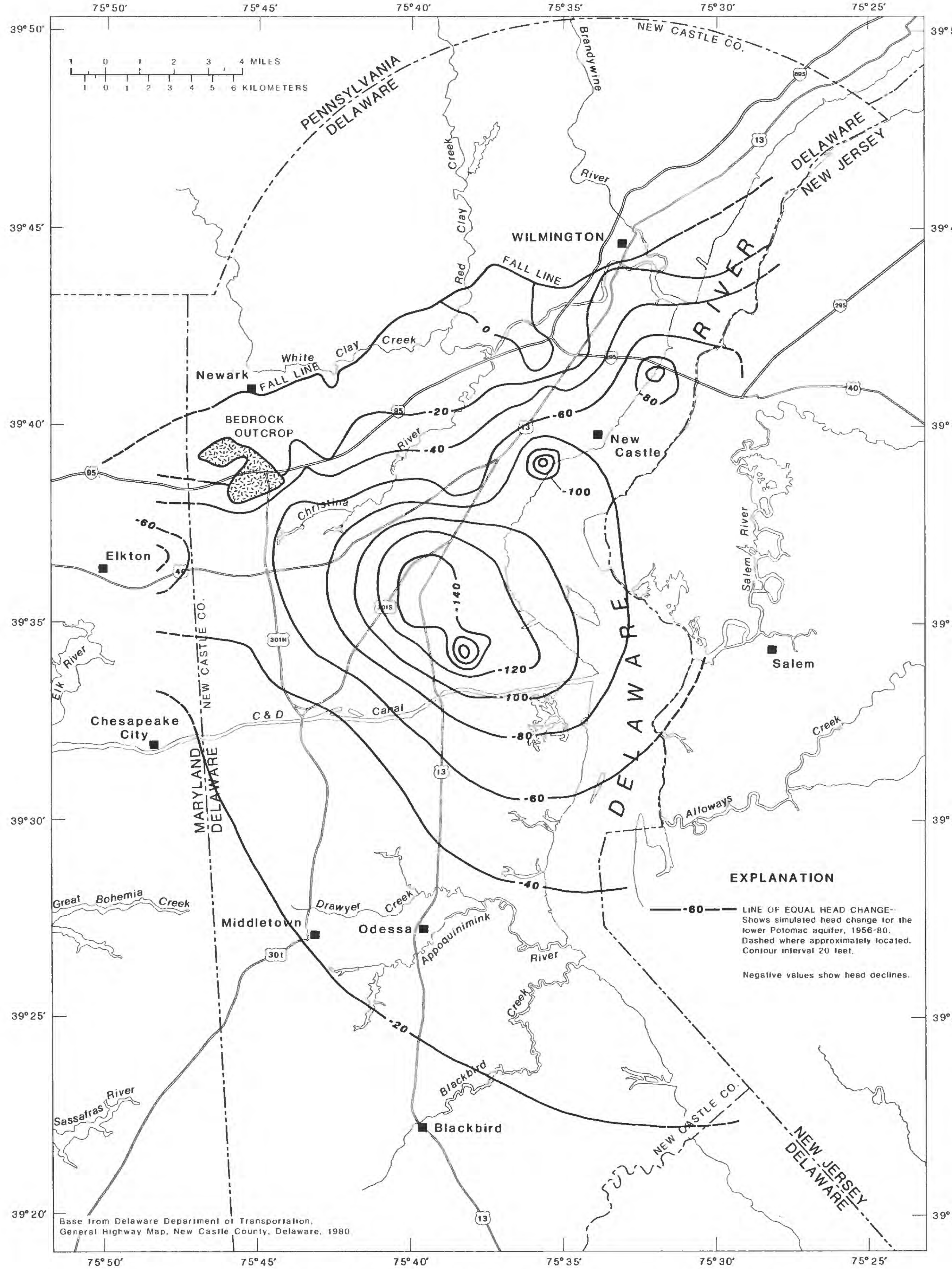


Figure 23.--Simulated changes in head for the lower Potomac aquifer, 1956-80.

EXPLANATION

——— Observed head ◎ First simulated head shown • Simulated head at end of pumping period

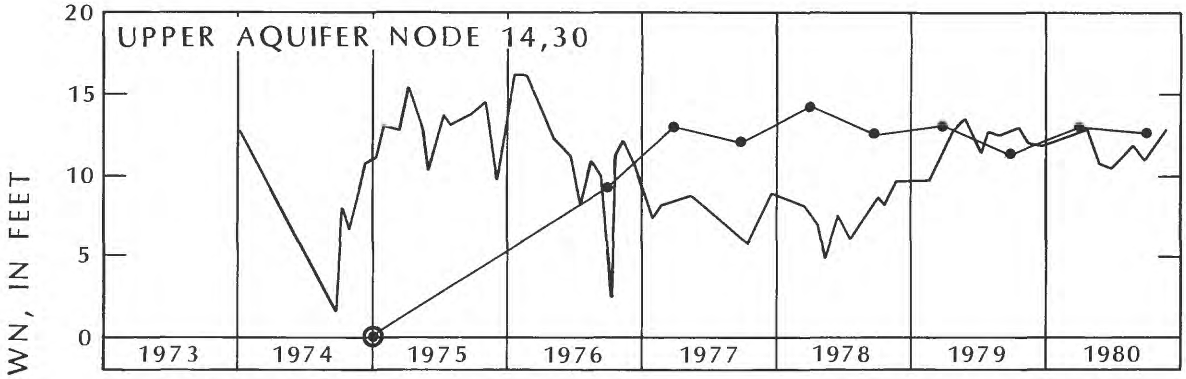


Figure 24.--Simulated and observed changes in head for the upper Potomac aquifer at Amoco well Dc15-20.

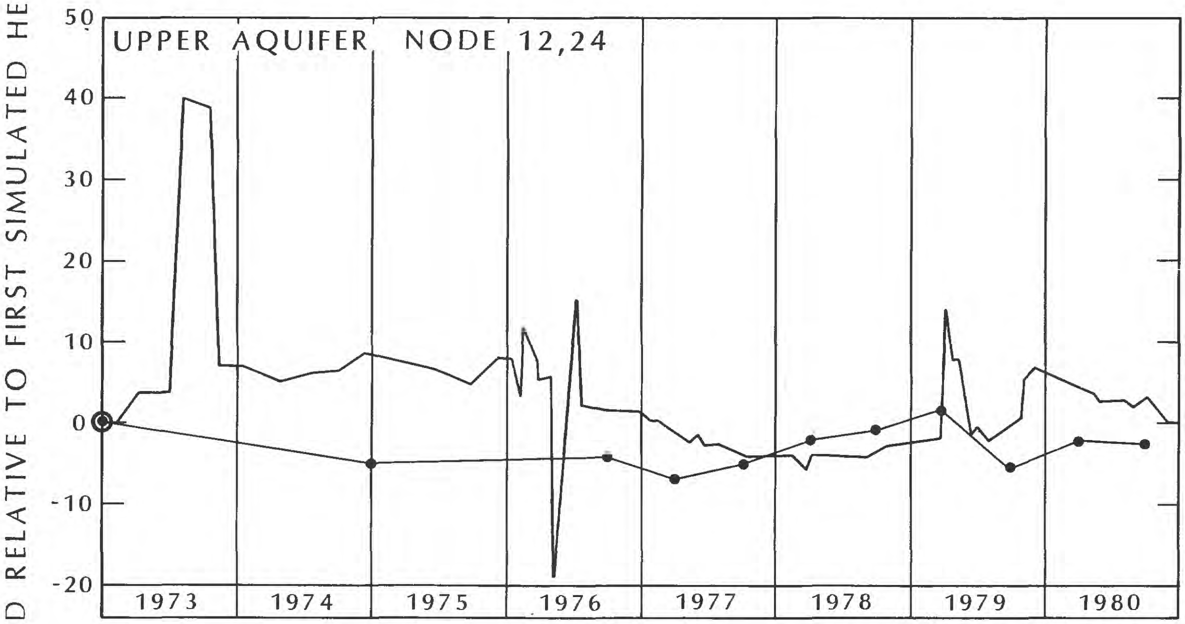


FIGURE 25.--Simulated and observed changes in head for the upper Potomac aquifer at Fairwinds well Dc23-16.

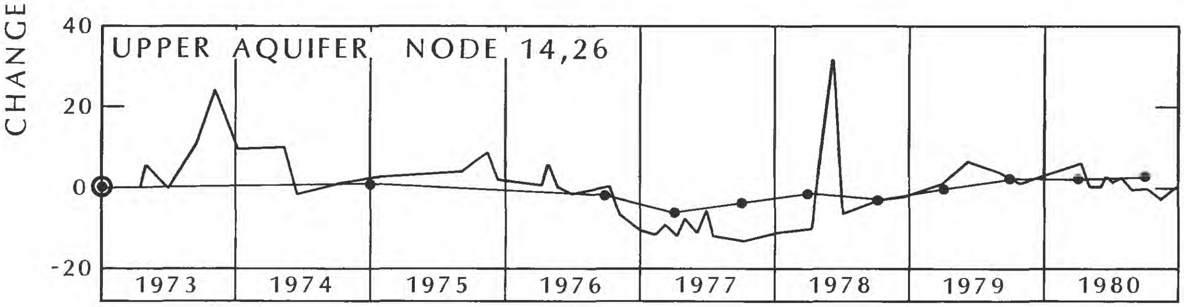


Figure 26.--Simulated and observed changes in head for the upper Potomac aquifer at Llangollen Estates well Dc24-40.

EXPLANATION

——— Observed head ◎ First simulated head shown • Simulated head at end of pumping period

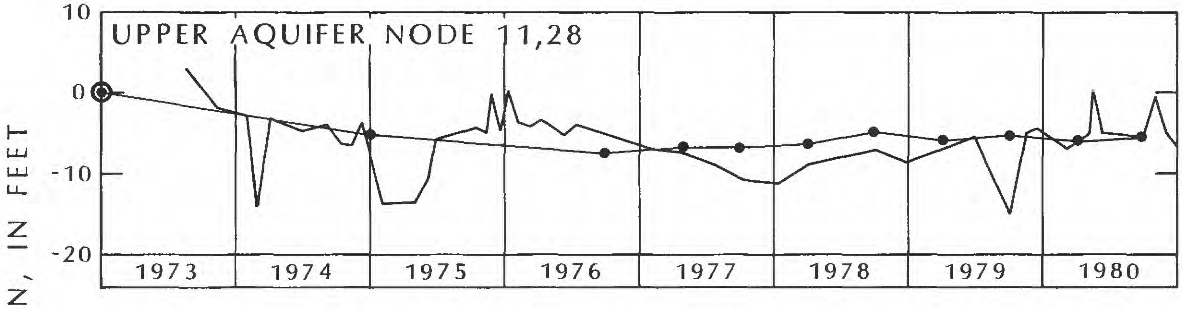


Figure 27.--Simulated and observed changes in head for the upper Potomac aquifer at Midvale well Dc14-54.

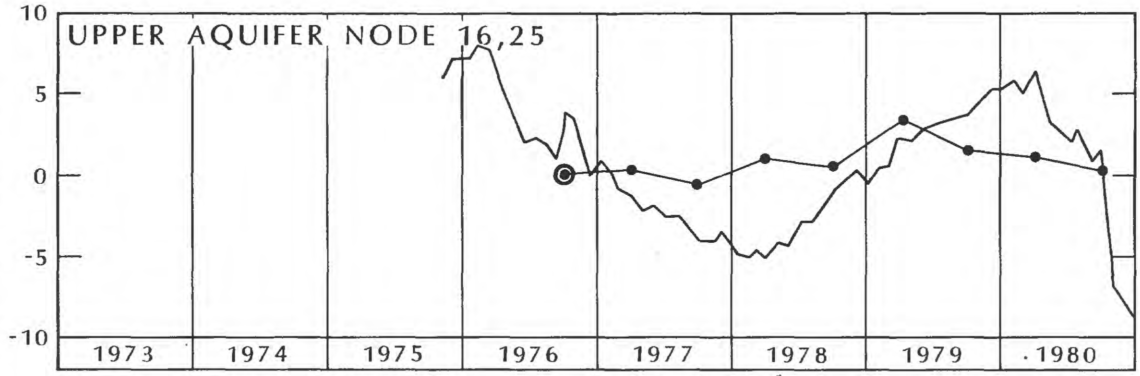


Figure 28.--Simulated and observed changes in head for the upper Potomac aquifer at National Guard Rifle Range well Dc34-6.

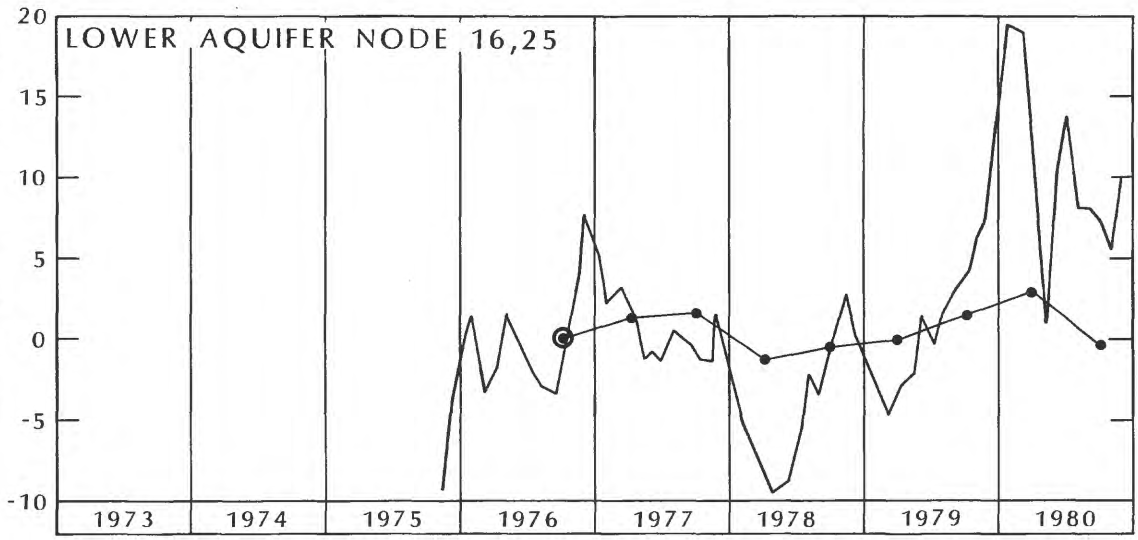


Figure 29.--Simulated and observed changes in head for the lower Potomac aquifer at National Guard Rifle Range well Dc34-5.

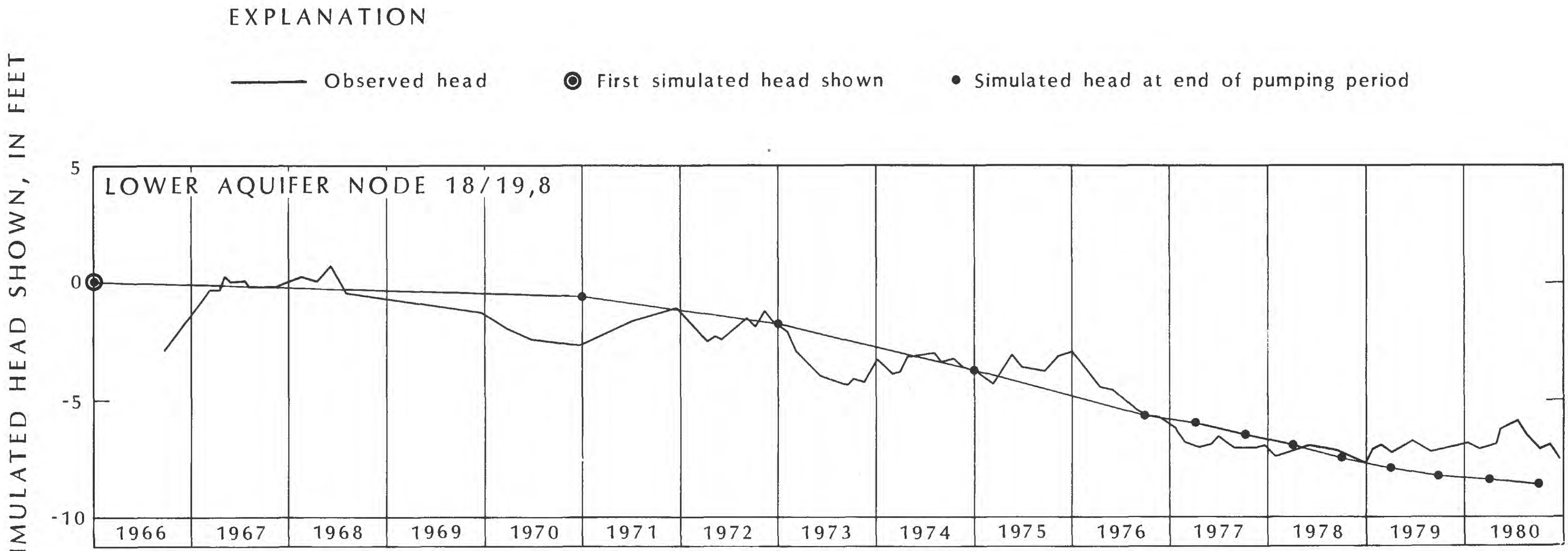


Figure 30.--Simulated and observed changes in head for the lower Potomac aquifer at Goodrich well Ea33-1.

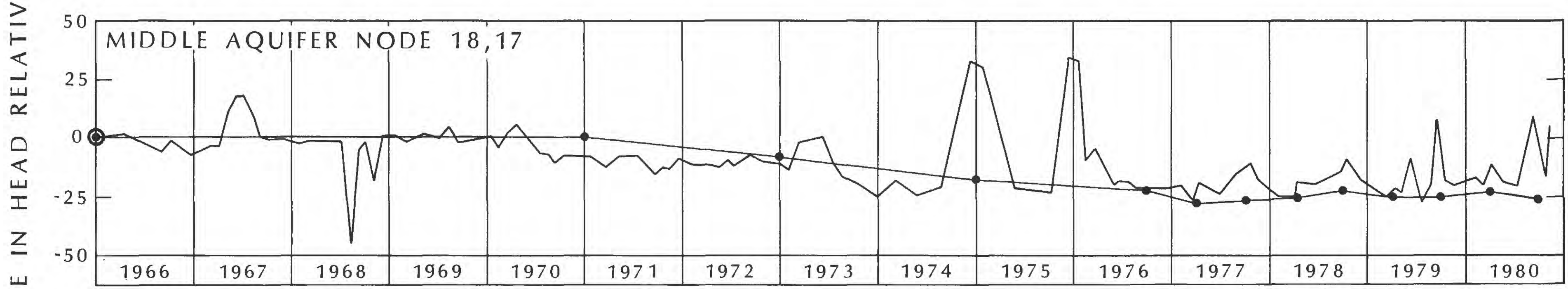


Figure 31.--Simulated and observed changes in head for the middle Potomac aquifer at Getty well Dc51-9.

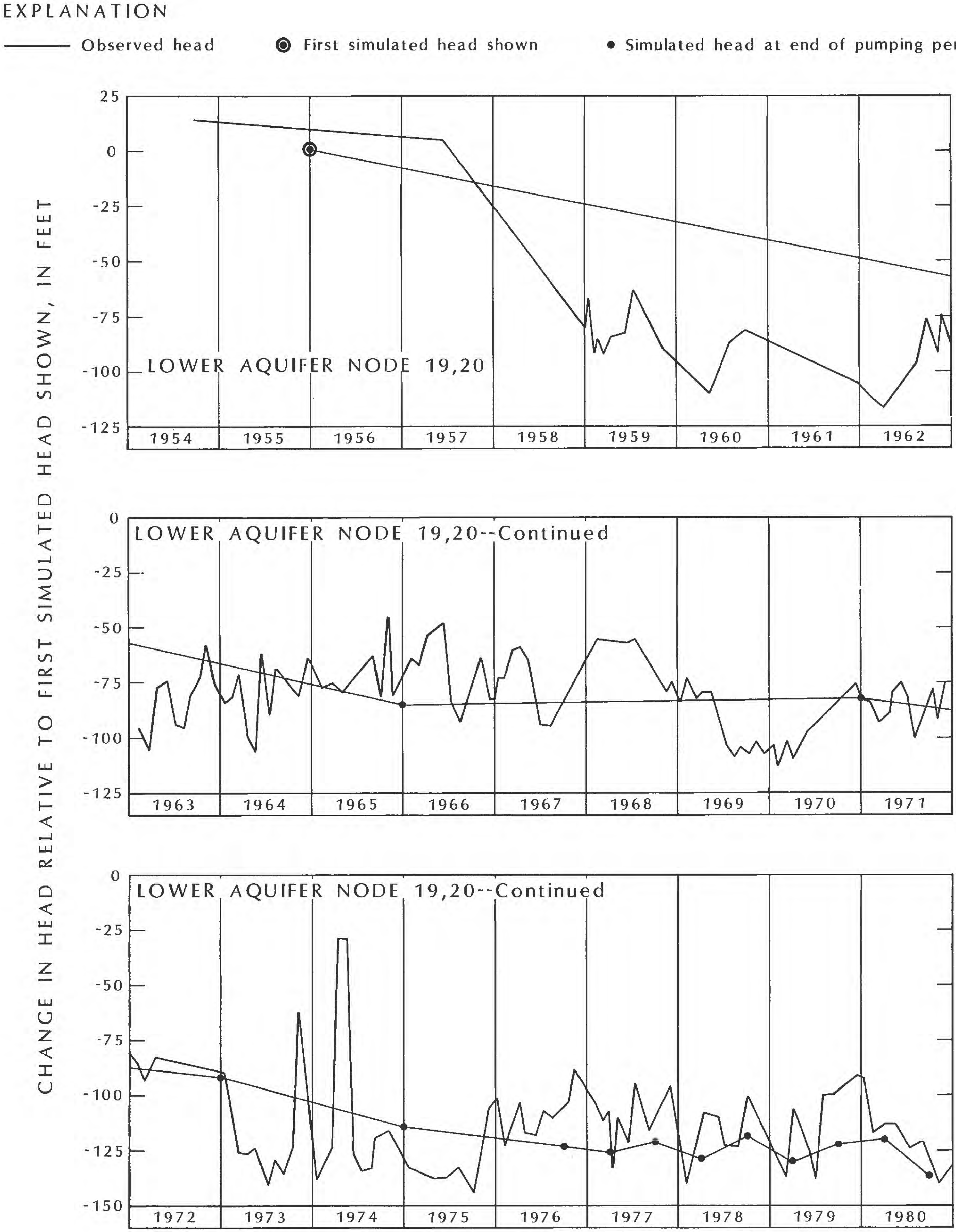


Figure 32.--Simulated and observed changes in head for the lower Potomac aquifer at Getty well Dc53-7.

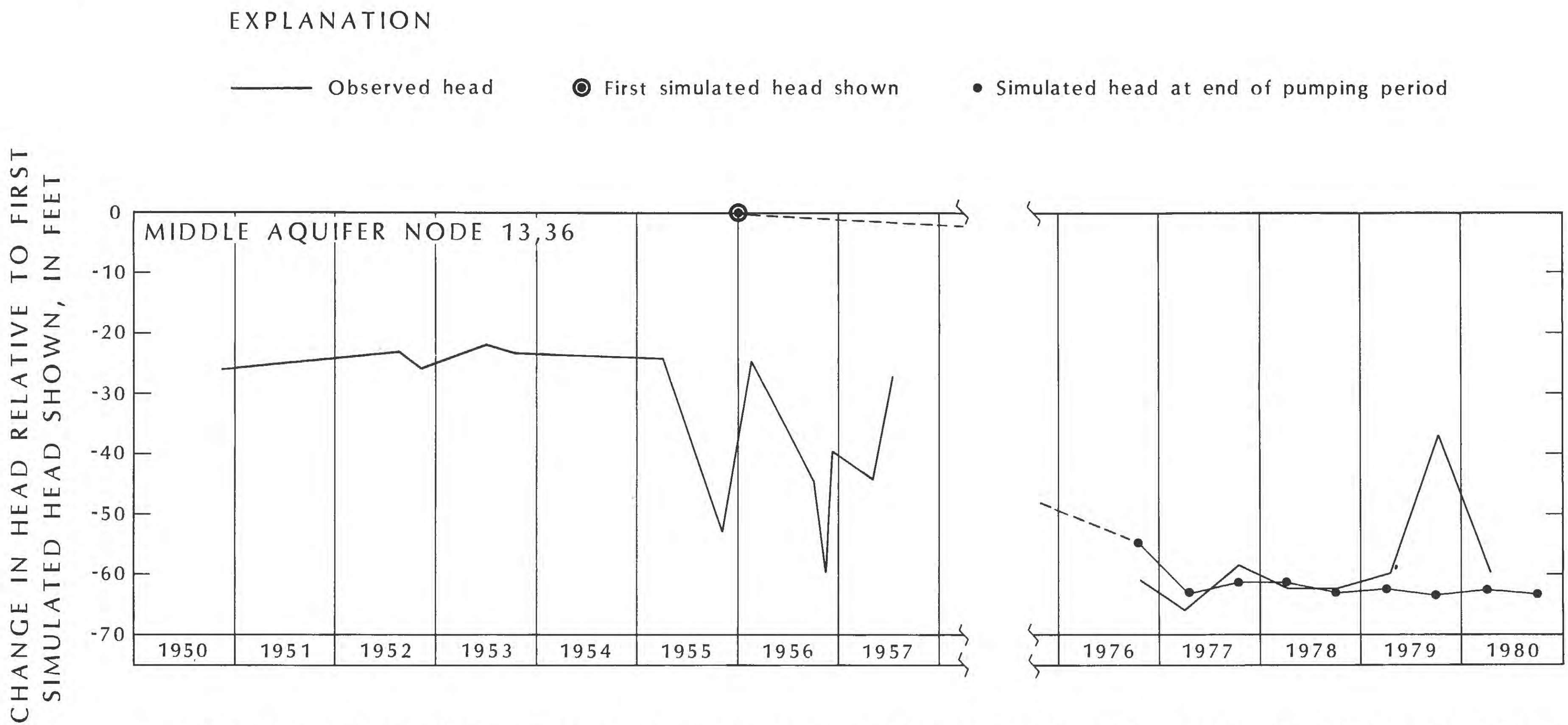


Figure 33.--Simulated and observed changes in head for the middle Potomac aquifer at New Castle wells Cd52-14 and Cd52-26.

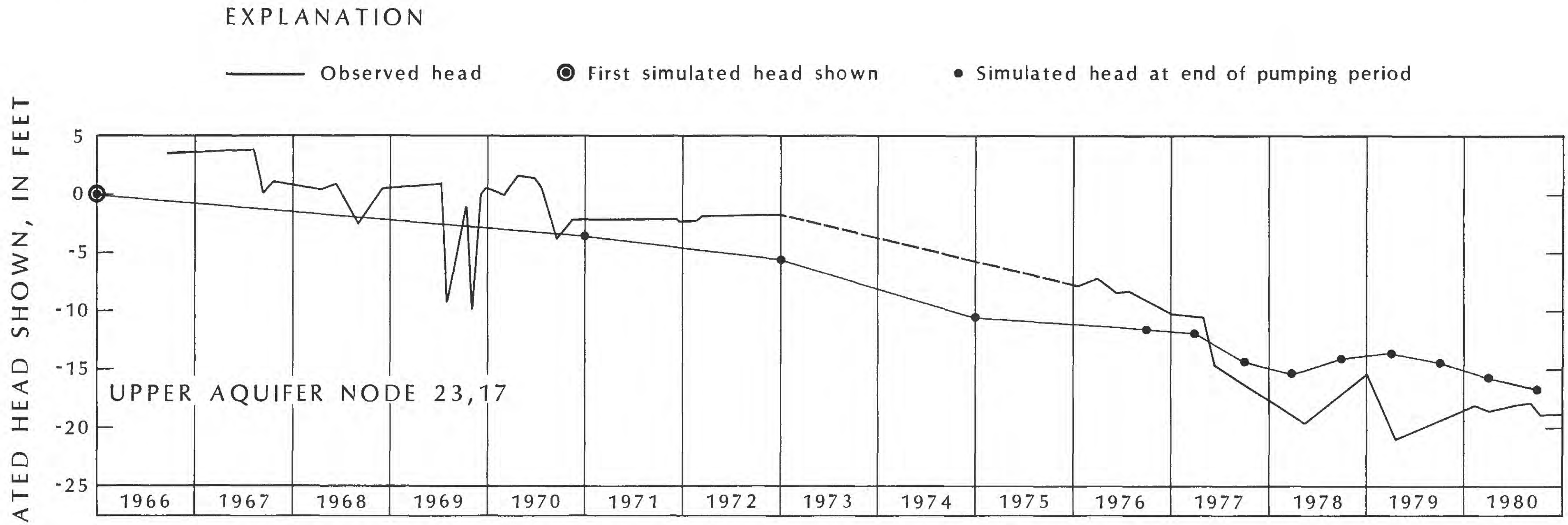


Figure 34.--Simulated and observed changes in head for the upper Potomac aquifer at Union Carbide well Ec32-3.

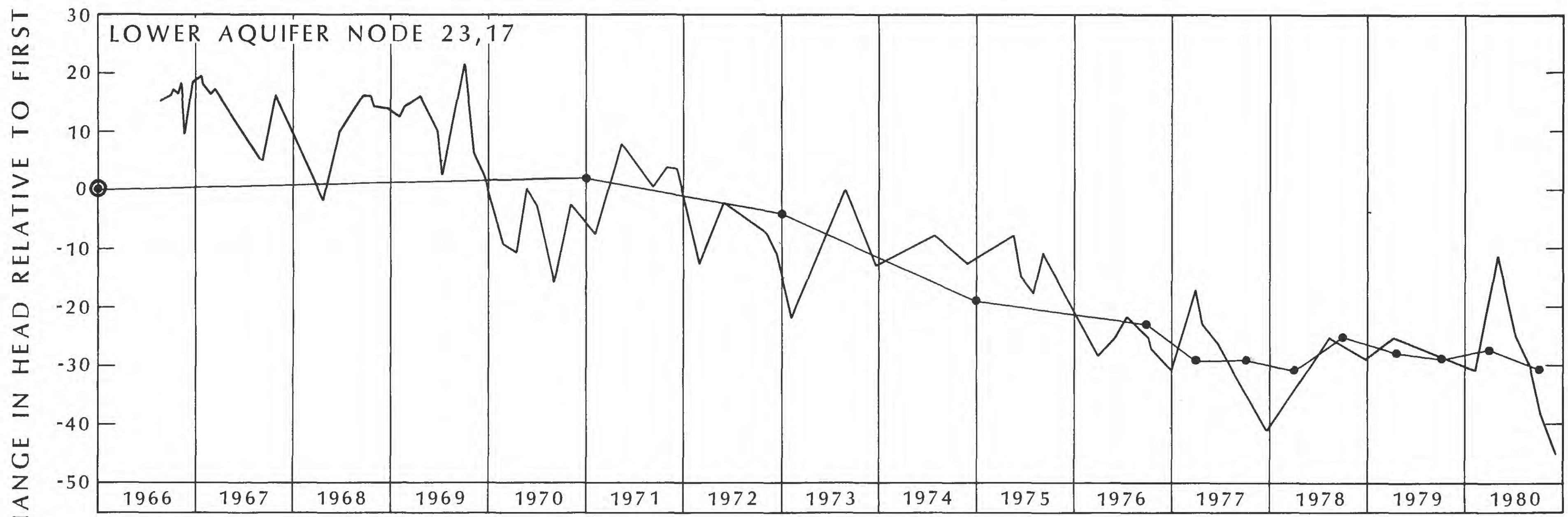


Figure 35.--Simulated and observed changes in head for the lower Potomac aquifer at Union Carbide well Ec32-7.

ever, hydrographs for many of these wells do not show similar trends. This can be seen in figures 24, 25, 28, and 29. In general, the decline of water levels in 1976 and 1977 and the subsequent rise in water levels in 1978 and 1979 which were not reproduced by the model is most apparent in updip wells in eastern New Castle County. Although several explanations for both the low water levels and the lack of reproducibility were considered, the most reasonable explanation is that recorded water levels reflect variations in actual pumpage and that reported pumpage data used in the model are inaccurate.

Although monthly pumpage figures had been compiled and used to calculate the average pumpage per pumping period, pumpage figures before 1978 do not appear to be accurate on a monthly basis for individual wells. Consequently, average pumpage values used for the 6-month pumping periods are probably inaccurate. However, when averaged over 1- or 2-year periods, pumpage values should be reasonable. Because the transient drawdown simulation could not reproduce water-level trends for 6-month periods, a transient head simulation was made to determine calibration acceptability. The model was considered to be calibrated if the October 1980 simulated heads were within 5 or 10 ft of observed heads, depending on the location of the well. Maps of the October 1980 (pumping period 13) simulated heads are shown in figures 36, 37, and 38. Observed heads are also shown in these figures, and differences between simulated and observed heads are shown in table 2.

In general, relatively good comparison is seen between simulated and observed heads. However, in the Fairwinds, Glendale, and Lums Pond well fields, differences between simulated and observed heads were considered too large. The difference between simulated and observed heads at Lums Pond could not be explained. Although the downward direction of flow between the aquifers was simulated, the simulated gradient between aquifers was too low. It should be noted, however, that the Goodrich and Getty well fields to the west and east of Lums Pond are considered to be well calibrated. The well field at Glendale is not considered to be calibrated in the upper and middle aquifers. The lack of calibration in this area is probably the result of inaccurate reproduction of the local geology. Simulating the occurrence of local sand bodies and their hydraulic connection appears to be critical for calibration. In particular, the middle aquifer at Fairwinds appears to be connected to the lower aquifer at Glendale.

Simulated drawdowns at the saltwater-interface boundary are about 10 ft in the upper aquifer and 15 ft to 20 ft in the middle and lower aquifers. The drawdown for the upper aquifer is acceptable; however, the drawdown for the middle and lower aquifers is considered somewhat high. Drawdowns may be greater than anticipated in this area because of incorrect estimates of aquifer and confining bed properties or inaccuracies in simulating the interface boundary. Estimated interface velocities, calculated

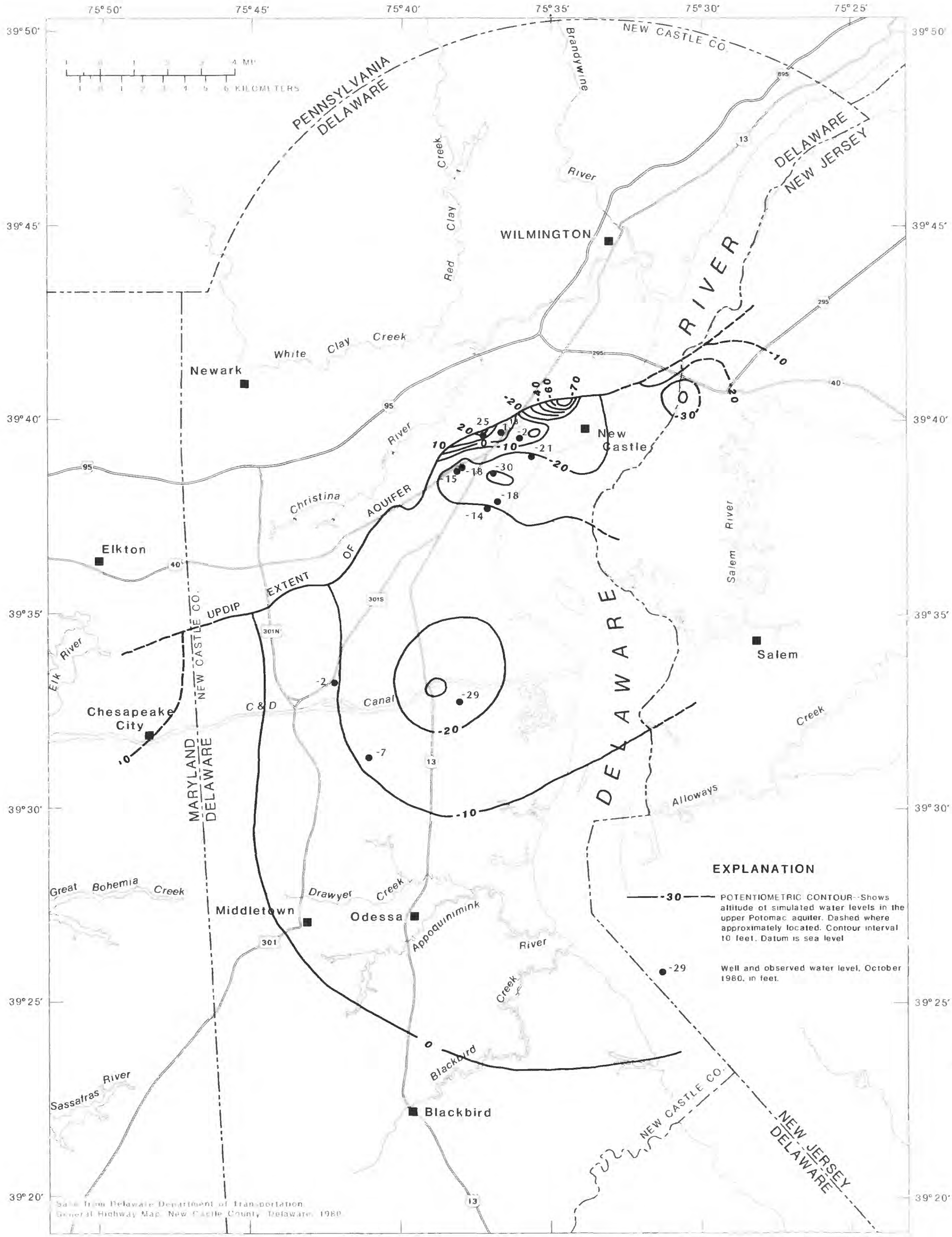


Figure 36.--Simulated and observed heads for the upper Potomac aquifer, October 1980.

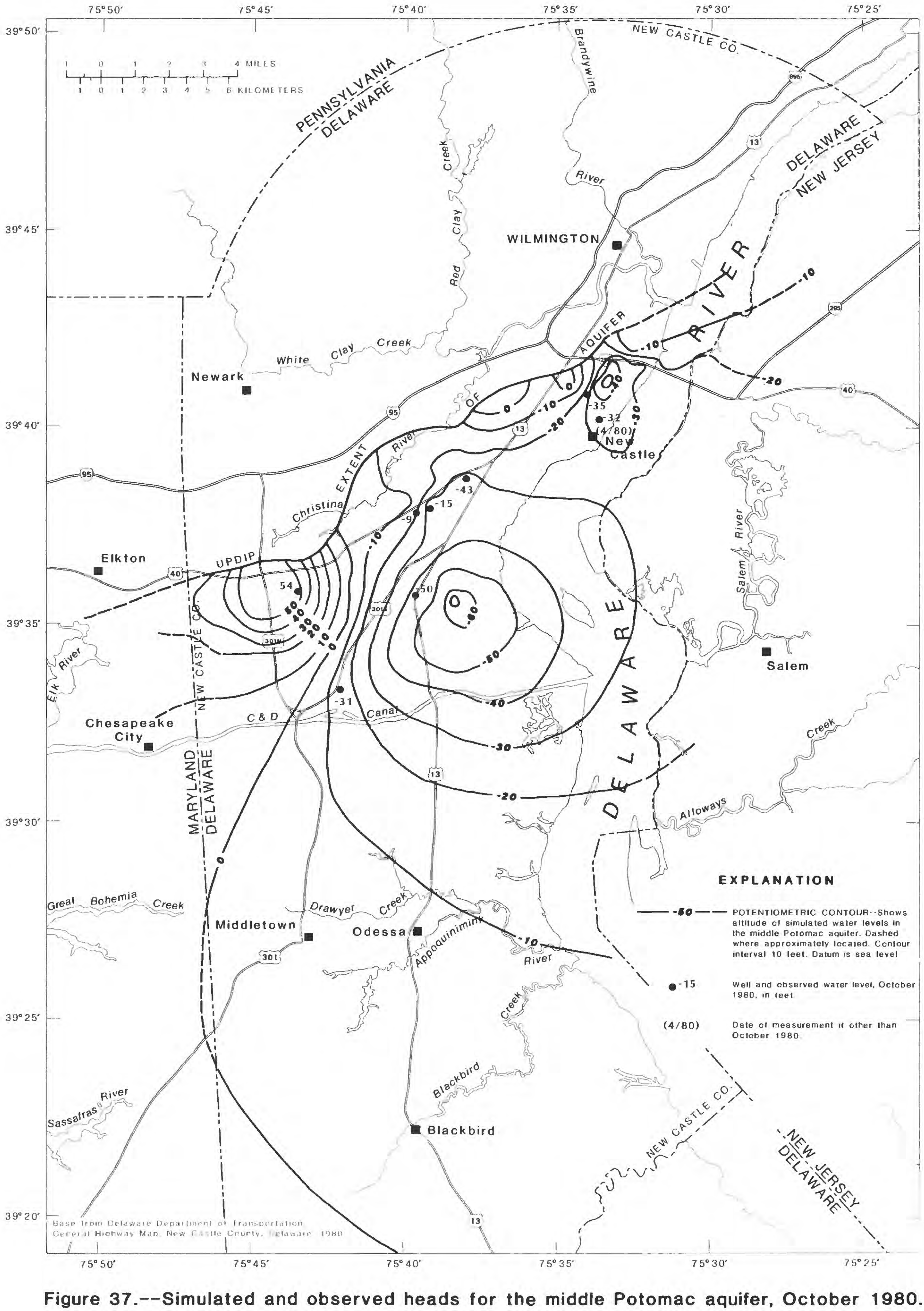


Figure 37.--Simulated and observed heads for the middle Potomac aquifer, October 1980.

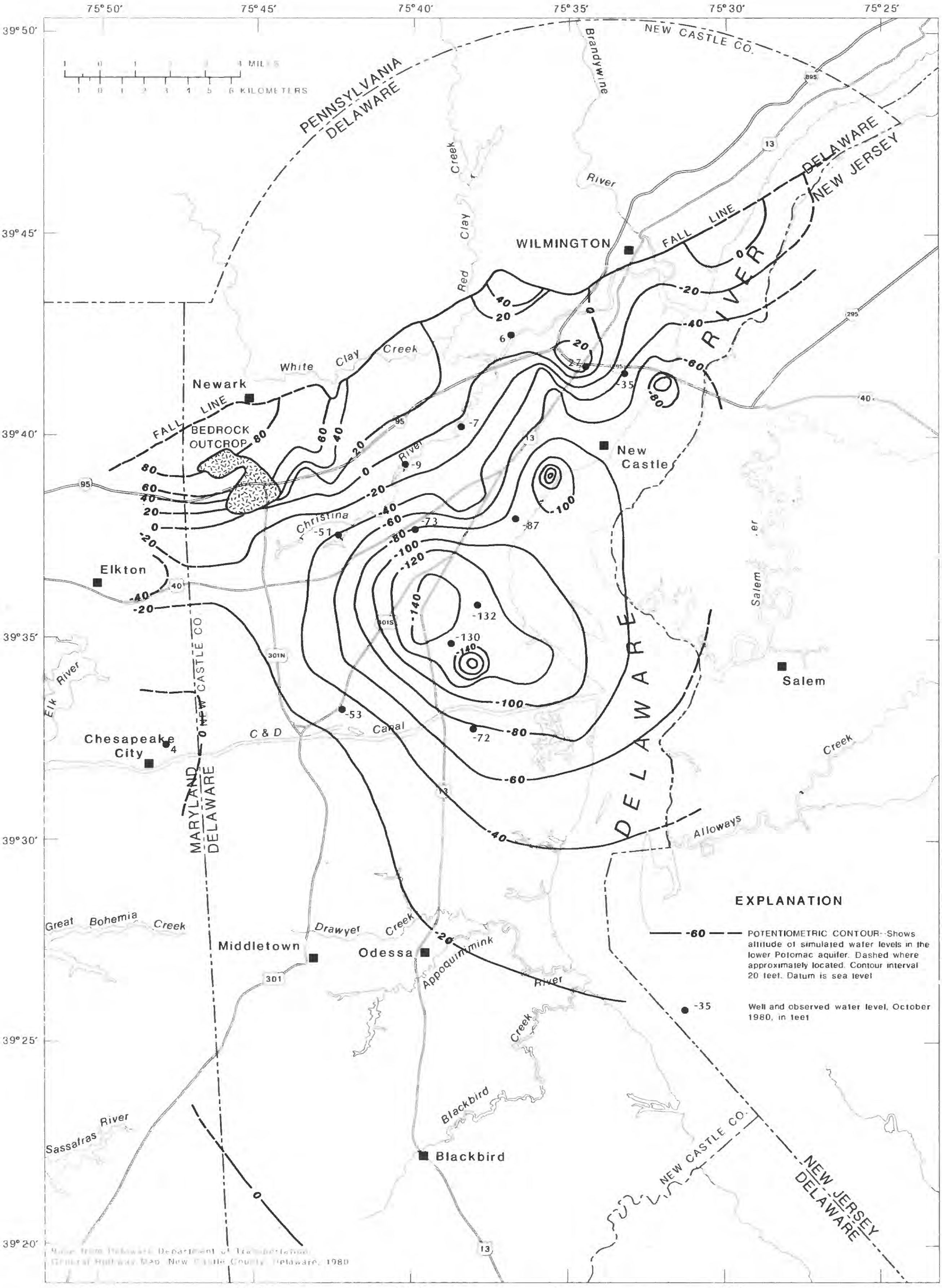


Figure 38.--Simulated and observed heads for the lower Potomac aquifer, October 1980.

using simulated heads in the two rows adjacent to the interface are less than 5 ft/yr. The interface boundary is not considered to seriously affect model results because even though drawdowns for the upper two aquifers were high, they were not excessive, and because velocities were low near the interface.

Comparison of pumpage changes and simulated heads at a node indicates that the modeled hydrologic system responds quickly to changes in stress. Changes in simulated water levels for the 6-month pumping periods at the end of the simulation correspond closely to nearby pumpage changes for each period. The modeled system appears to approach steady-state conditions rapidly. However, because of continually changing stress conditions, the system cannot be described as being in steady state.

Simulation Results

The final transmissivity values used in the calibrated model are shown in figures 39, 40, and 41. The transmissivity of all three aquifers increases downdip, primarily as a result of increasing thickness. In general, transmissivities are lowest in the lower aquifer and highest in the upper aquifer. The maximum transmissivity of the lower aquifer is between 1,000 ft^2/d and 1,500 ft^2/d. Maximum transmissivity of the middle aquifer is between 3,000 ft^2/d and 3,500 ft^2/d. Maximum transmissivity of the upper aquifer is between 5,000 ft^2/d and 6,000 ft^2/d.

Large changes of transmissivity over small distance may indicate not only variations in aquifer hydraulic properties, but also variations in aquifer geometry (extent and thickness). Although nodal size was made fairly small to allow separate nodes for closely spaced well fields, geophysical logs were not always available to define the hydraulic relationship between individual sands or between the confined aquifers and overlying water-table aquifer.

Figures 42, 43, and 44 show leakances for each of the three confining beds. Values for the three layers are similar and range between 1×10^{-8}/d to 1×10^{-2}/d. The highest values and greatest range of values are in the areas near the subcrop. The lowest leakance values are downdip and in western Delaware. The smallest amount of lateral variability in leakance is seen in the confining bed overlying the upper aquifer.

Sensitivity Analysis

The model was tested for sensitivity to aquifer transmissivity and confining bed leakance. In general, areal estimates of transmissivity, from aquifer test analysis or through modeling, are expected to be in error by less than 50 percent. Estimated leakance values are expected to be within 1 to $1^1/_2$ orders of magnitude of actual values. In modeling, the accuracy of the final estimates of transmissivity and leakance will depend on the data available, grid spacing, and boundary conditions. Four sensi-

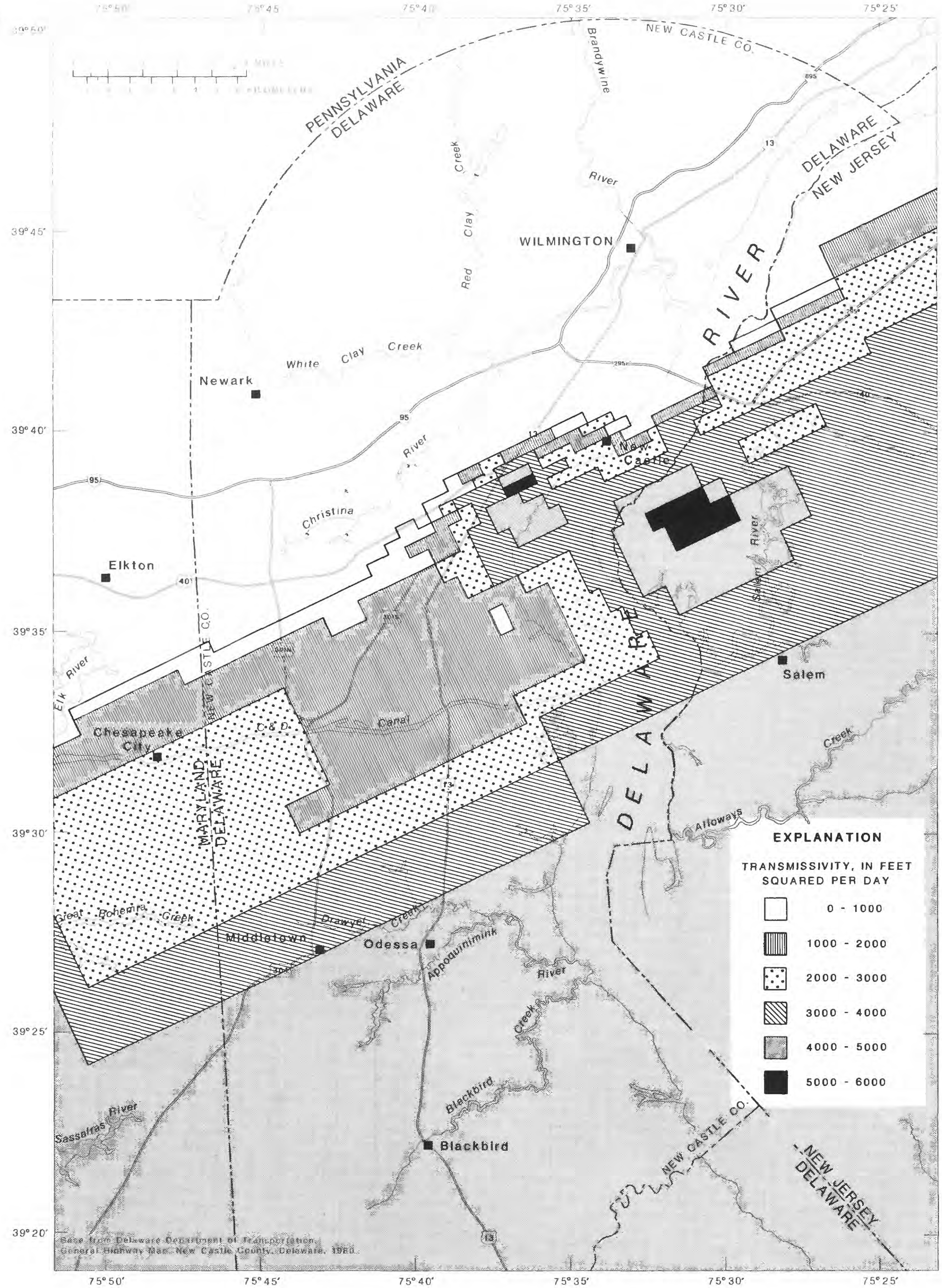


Figure 39.--Transmissivity of the upper Potomac aquifer.

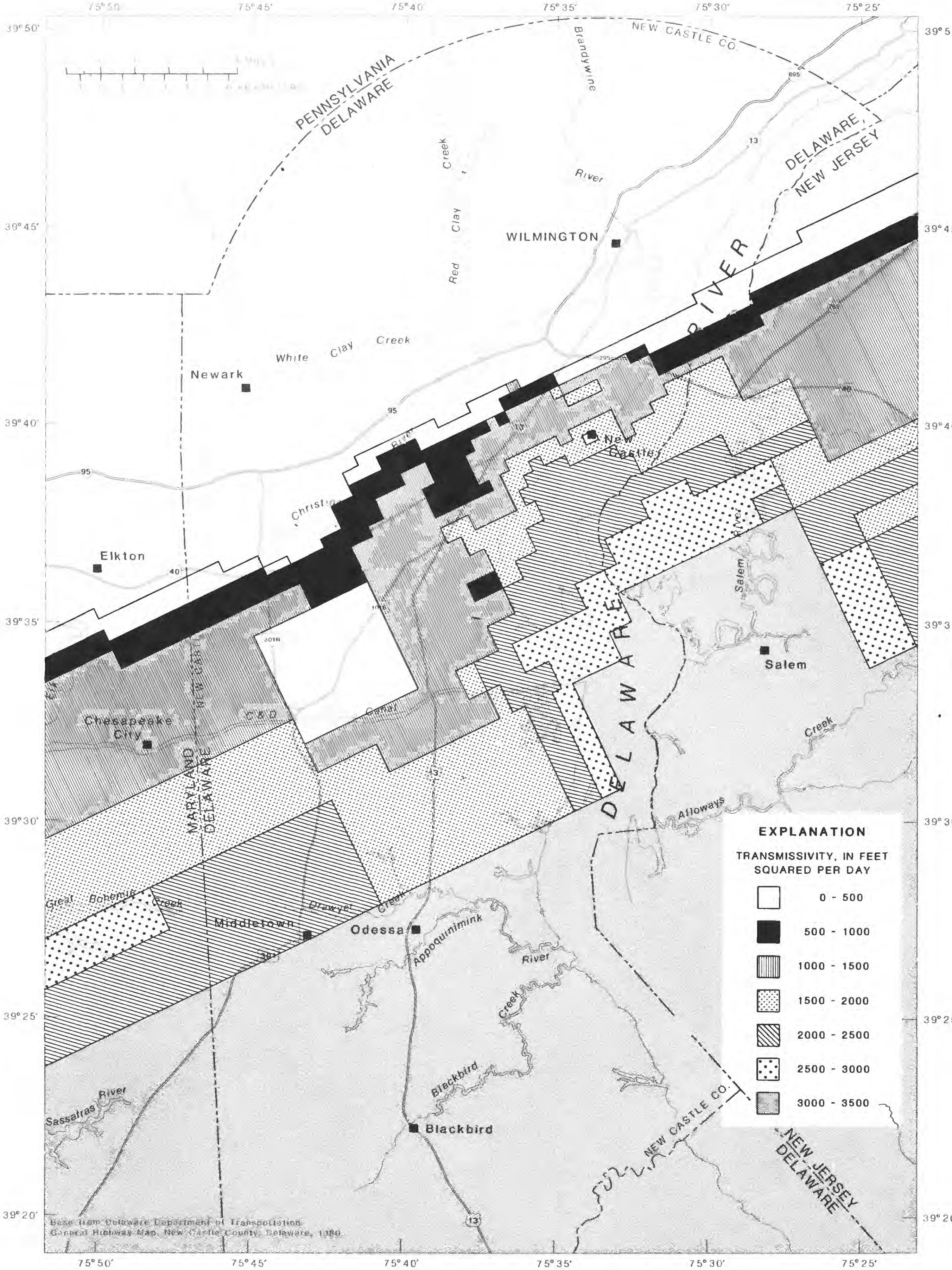


Figure 40.--Transmissivity of the middle Potomac aquifer.

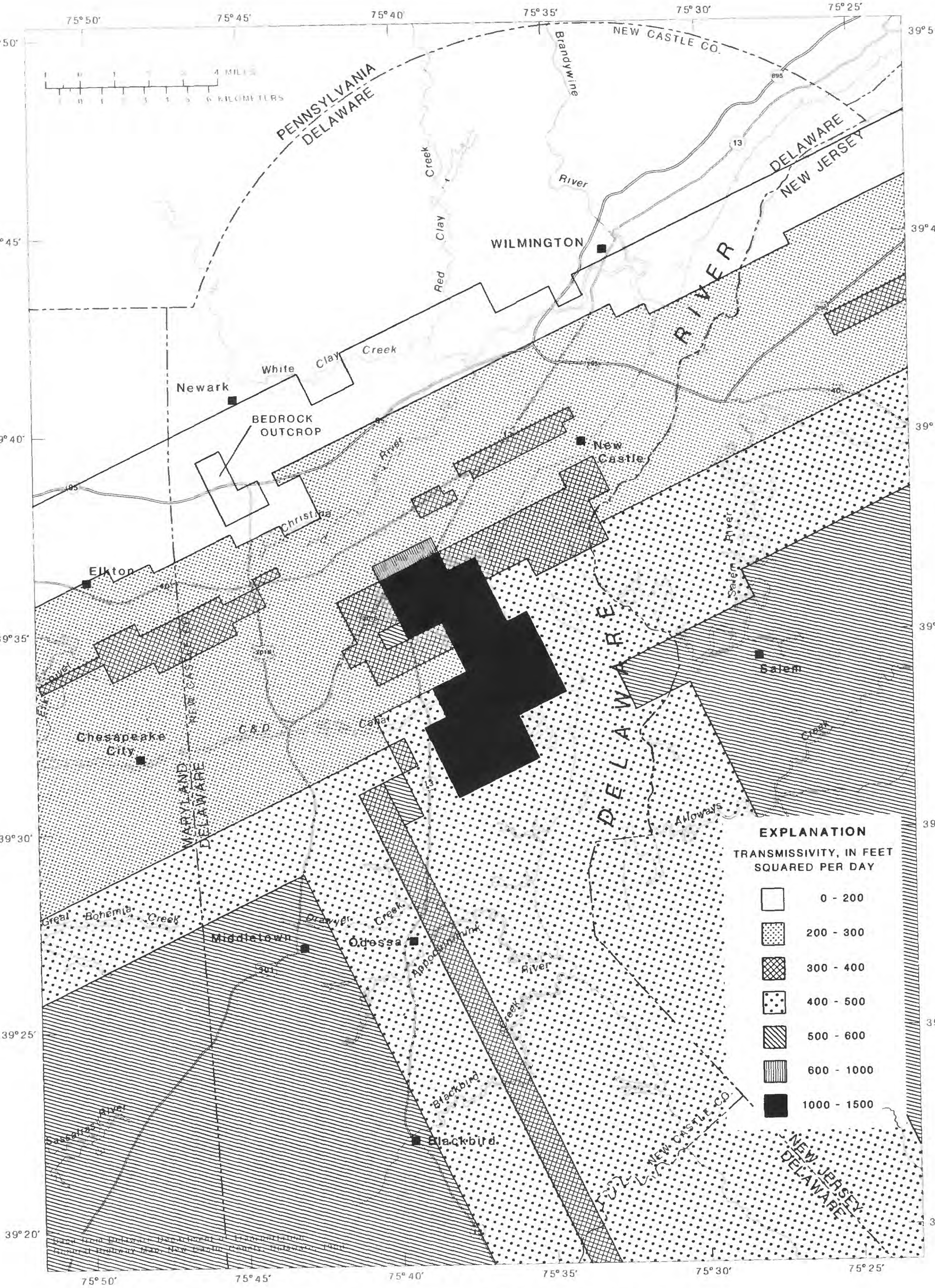


Figure 41.--Transmissivity of the lower Potomac aquifer.

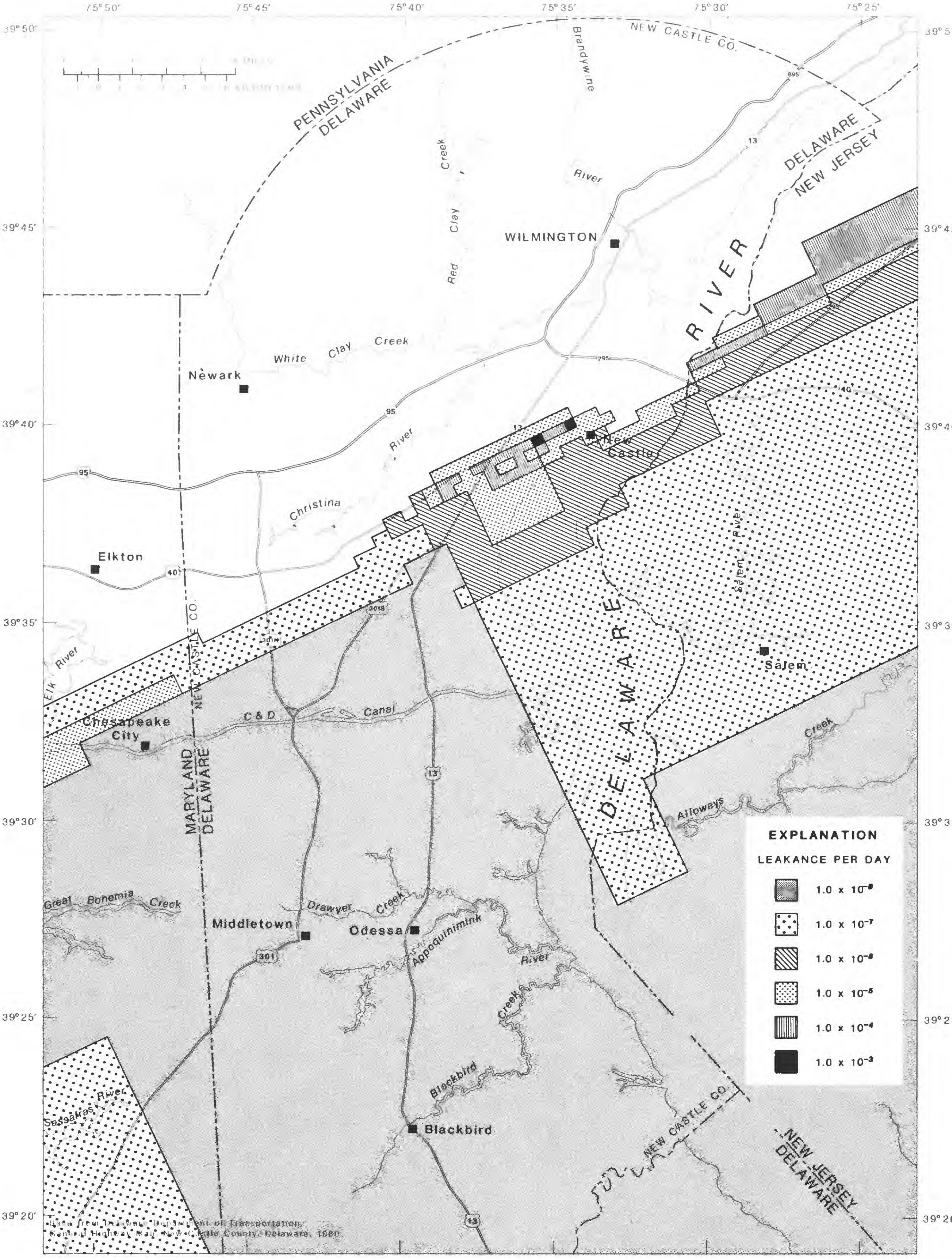


Figure 42.--Leakance of the confining bed and other formations overlying the upper Potomac aquifer.

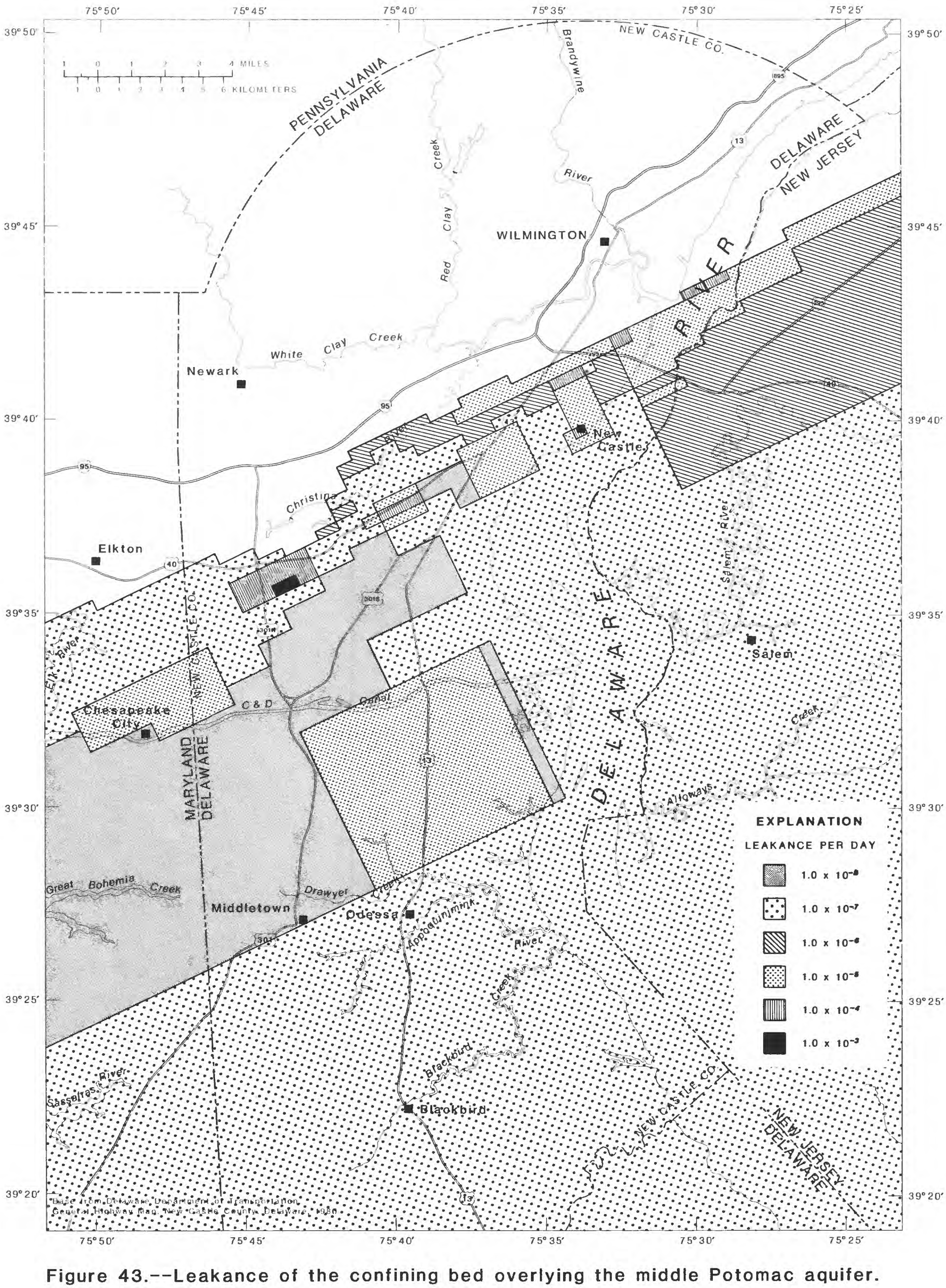


Figure 43.--Leakance of the confining bed overlying the middle Potomac aquifer.

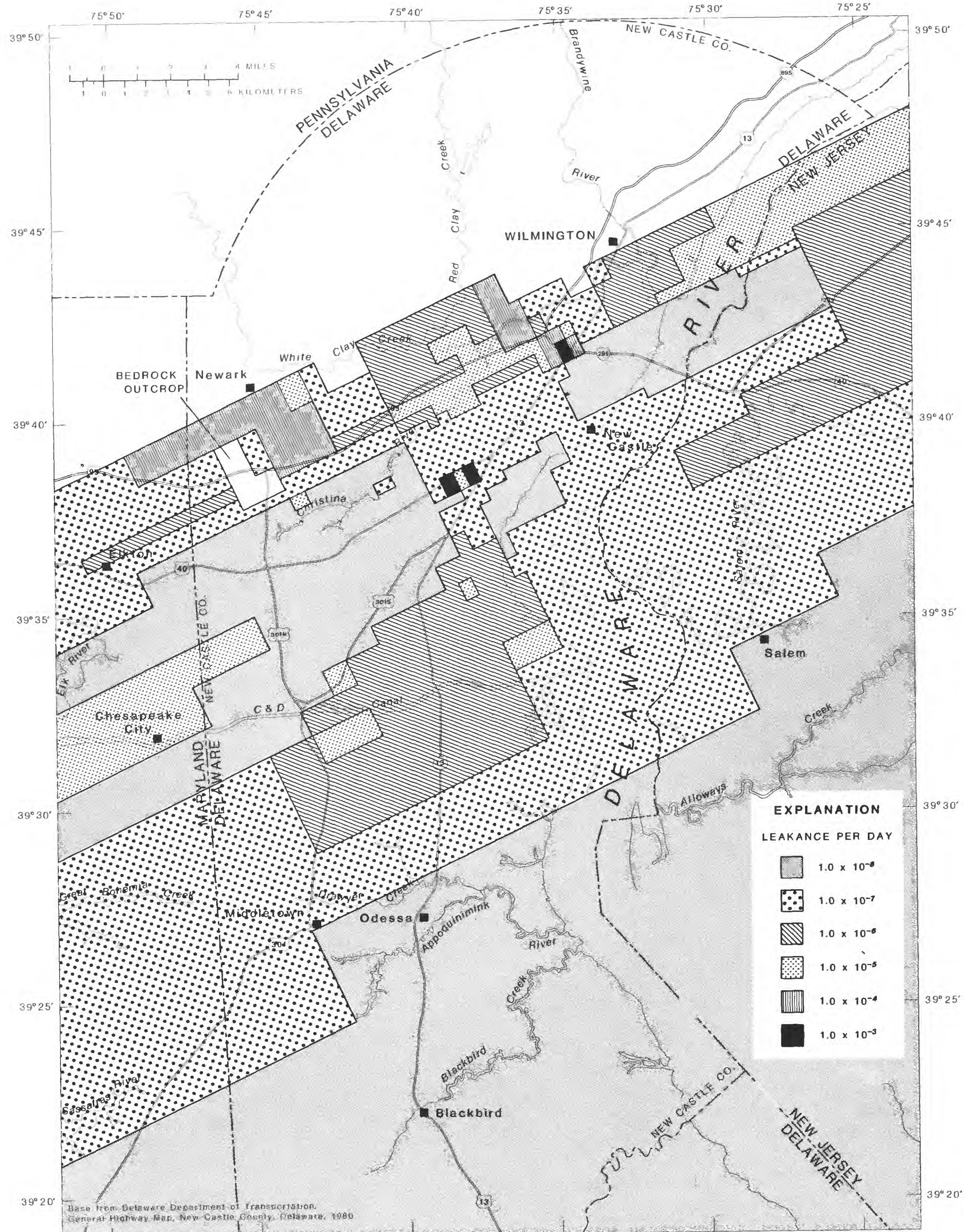


Figure 44.--Leakance of the confining bed overlying the lower Potomac aquifer.

tivity simulations were made by increasing or decreasing either transmissivity or leakance values by 50 percent for all of the aquifers or confining beds over the entire model area. The results of these simulations are summarized in hydrographs for four wells in figures 45-48. The four wells include two updip wells at the same node--one well in the upper aquifer and one in the lower aquifer, and two downdip wells at the same node--one in the upper aquifer and one in the lower aquifer. The updip and downdip nodes correspond to the National Guard Rifle Range and Union Carbide well fields, respectively.

This method of sensitivity analysis is only a general approach to defining the acceptability of transmissivity and leakance values. Estimated values of transmissivity are not expected to be in error by the same percentage throughout the model area, but by varying degrees locally. However, several observations can be made. The greatest changes in model results are seen in the updip and downdip wells in the lower aquifer. For all the wells, decreasing transmissivity and leakance has a greater effect on model results than increasing these parameters. Changing transmissivity had a greater effect than changing leakance on the updip well in the lower aquifer and the downdip well in the upper aquifer. Changing leakance had a greater effect than changing transmissivity in the updip well in the upper aquifer and in the downdip well in the lower aquifer. In general, changing transmissivity or leakance for all of the aquifers or confining beds over the entire model area has a significant effect on model results.

Model Application

Five simulations were made to evaluate the effects of five different future pumpage scenarios. Information on expected and proposed future ground-water withdrawals was provided by the Delaware Department of Natural Resources and Environmental Control. These transient drawdown simulations are continuations of the calibrated transient drawdown simulation. Results for these simulations are shown as head changes from October 1980 to October 2005. Five 5-year pumping periods were used. Because the modeled system approaches steady-state conditions quickly, most of the change in heads for each simulation occurs in the first pumping period. Head changes of less than 15 ft for October 1980 to October 2005 will not be discussed.

Using the model to evaluate effects of future pumping must be done cautiously. Although the differences between simulated and observed head changes are generally within acceptable limits during calibration, these differences are expected to increase with time beyond the end of the calibration simulation. That is, the farther beyond October 1980 that a transient simulation is used, the less reliable the results.

The first simulation is based on an assumption of no change in pumpage rates for the next 25 years, except at Amoco and

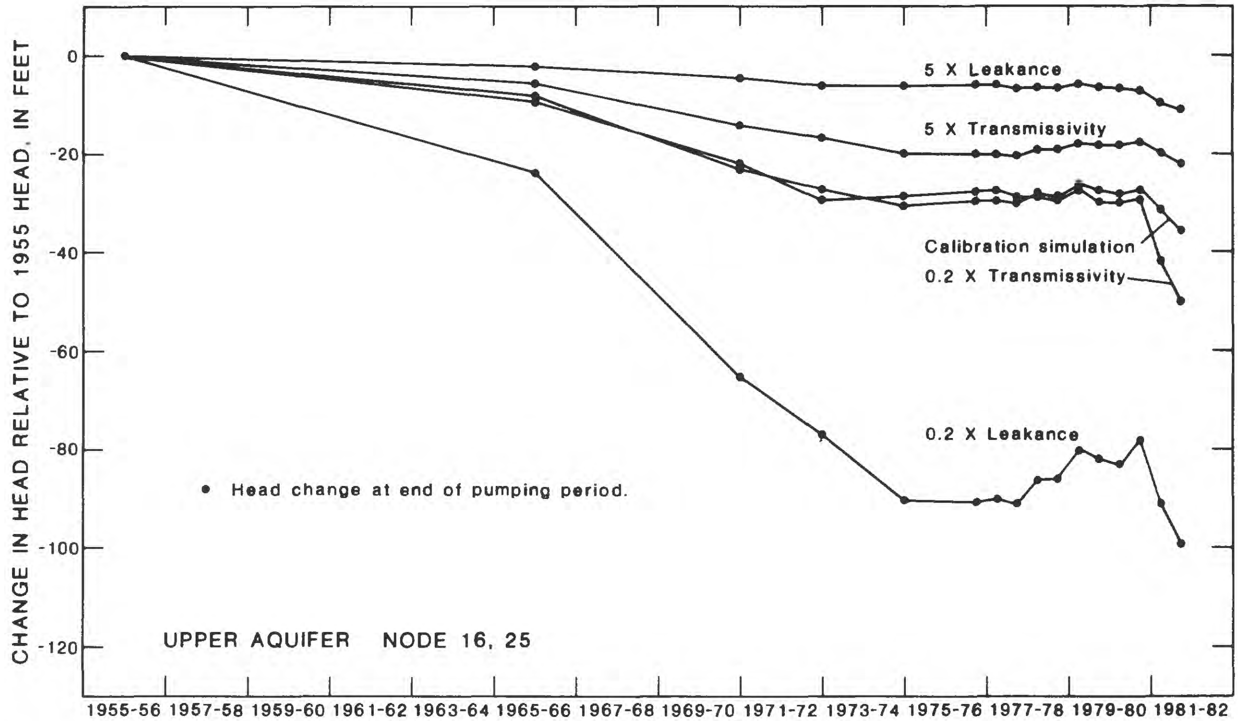


Figure 45.--Simulated hydrographs for National Guard Rifle Range well Dc34-6 from sensitivity analysis.

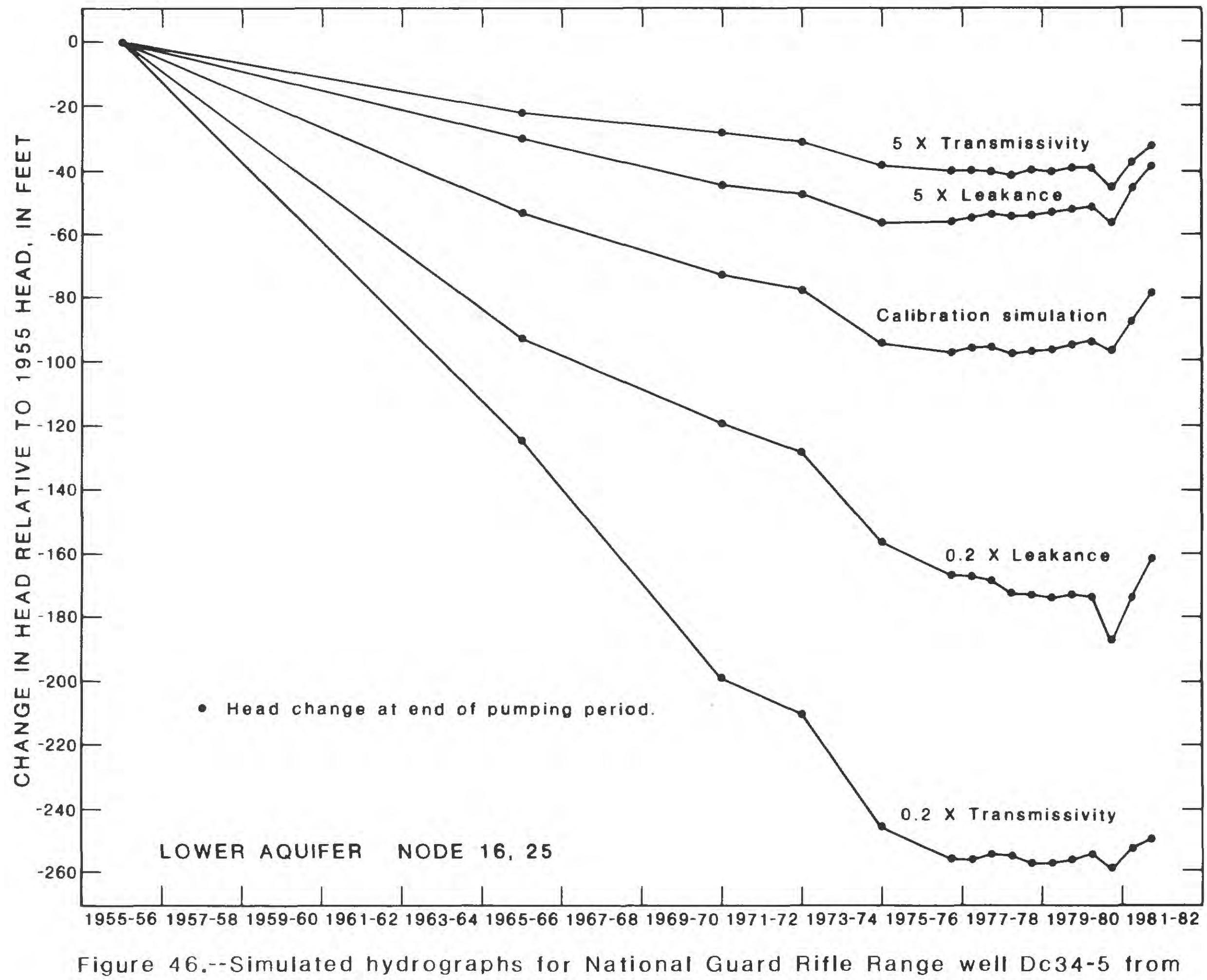


Figure 46.--Simulated hydrographs for National Guard Rifle Range well Dc34-5 from sensitivity analysis.

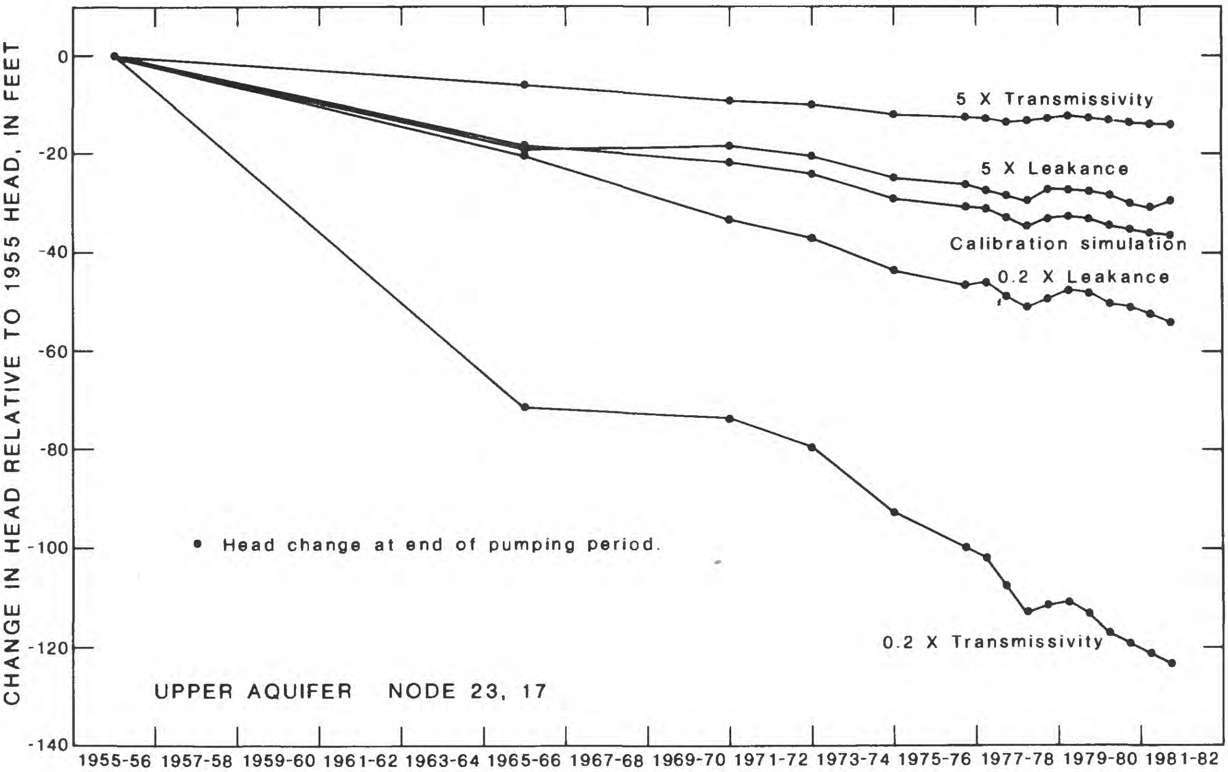


Figure 47.--Simulated hydrographs for Union Carbide well Ec32-3 from sensitivity analysis.

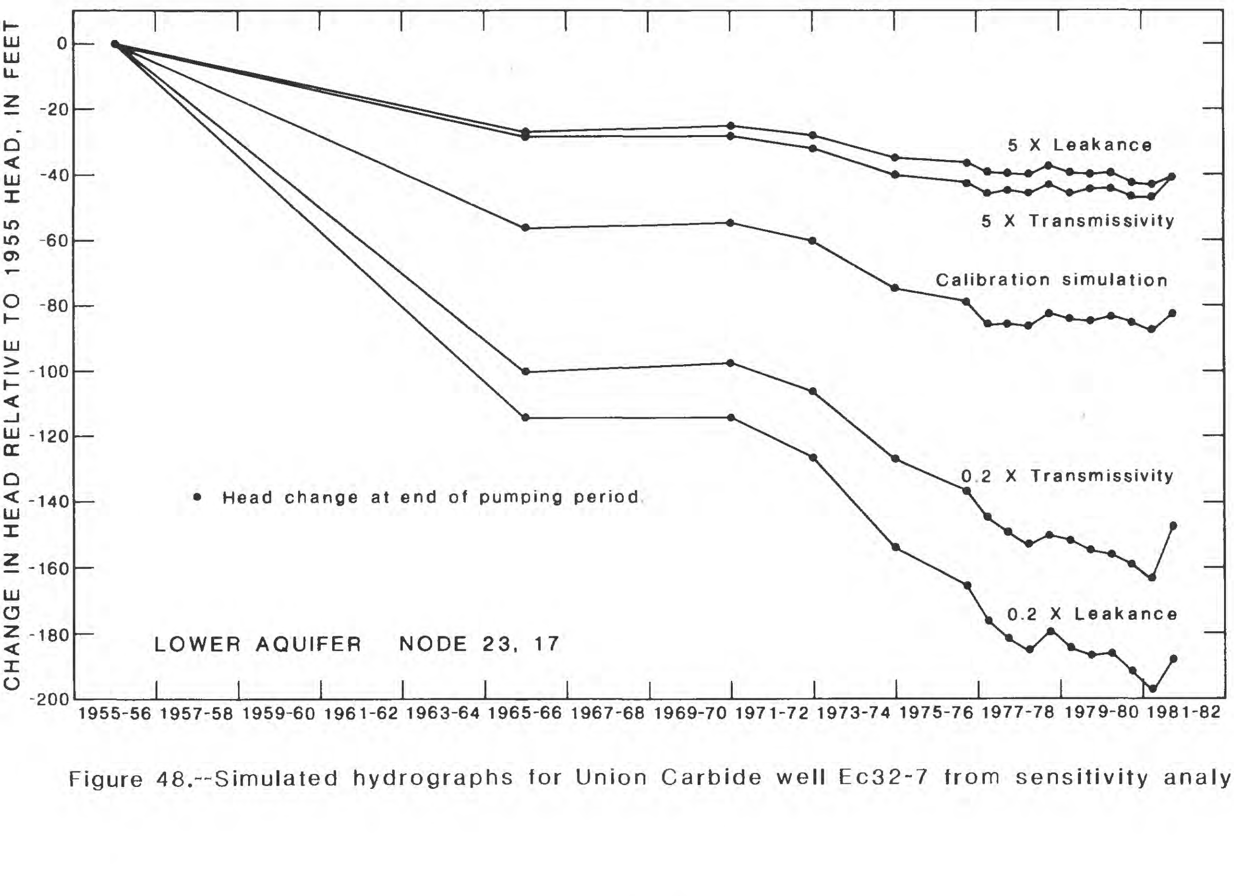


Figure 48.--Simulated hydrographs for Union Carbide well Ec32-7 from sensitivity analysis.

Artisans Village. This simulation is used as a basis of comparison for the other simulations. An average pumpage for 1979-81 at each node is used as an estimate of current pumpage. For wells in the Amoco well field, a minimal amount of pumpage is used because of the 0.8 Mgal/d reduction in pumpage in October 1980, which is expected to be permanent. For the new well field at Artisans Village, the 1981 pumpage rate is used. Pumpage for each 5-year pumping period is the same and is shown for each well field in table 3.

The results of this simulation are shown in figures 49 and 50. Heads in the upper aquifer at Artisans Village declined 15 ft. Head declines elsewhere for the upper aquifer are less than 5 ft and are not shown in figure 49. The reduction of pumpage at Amoco resulted in a local 120-ft recovery of water levels in the lower aquifer (fig. 50). In western Delaware and south of the Chesapeake and Delaware Canal, water levels declined in the lower aquifer. However, these declines are generally less than 10 ft and are not shown in figure 50. Head changes were less than 10 ft in the middle aquifer and are not shown. However, heads in the middle aquifer declined in western Delaware and south of the canal, but rose in northeastern New Castle County.

A second simulation was made to compare the amount of water-level recovery at Amoco from the first simulation to predicted changes in water levels if the reduction in pumpage had not occurred. The second simulation is identical to the first except that pumpage at the Amoco well field is assumed to be the same as the pumpage prior to the October 1980 reduction. Pumpage for each 5-year pumping period is the same and is shown in table 3. Drawdowns for portions of the upper and lower aquifers are shown in figures 51 and 52.

Comparison of figures 49 and 50 with figures 51 and 52 shows the amount of water-level recovery at Amoco. Simulated heads in the year 2005 for the upper and middle aquifers are similar to those of the first simulation, although drawdowns at Artisans Village are over 20 ft in the second simulation as shown in figure 51. Results for the middle aquifer and the western and southern portions of the upper aquifer are not shown because head changes were less than 10 ft. Drawdowns in the lower aquifer for the second simulations are shown in figure 52. The results are similar to the first simulation except there is no head change at Amoco. Head change in parts of the study area not shown in figure 52 have less than 10 ft head change.

The second simulation indicates that continued pumping at the average 1979-81 rate would produce little additional drawdown by the year 2005. Generally, drawdowns are less than 15 ft. However, there are local drawdowns of 25 ft caused by the new well field at Artisans Village (where pumpage began in November 1980) and pumpage at Getty.

Table 3.--Pumpage and simulated available drawdowns for simulations assuming no change in pumpage.

Well field	Aquifer (U, upper M, middle L, lower)	Representative node (row, column)	Simulated available drawdown October 1980 (feet)	First simulation		Second simulation	
				Pumpage (Mgal/yr)	Available drawdown October 2005 (feet)	Pumpage (Mgal/yr)	Available drawdown October 2005 (feet)
Airport Industrial Park	U	11,30	23	0	23	0	22
Amoco	U	14,30	29	2	37	177	27
	L	14,30	UC	4	UC	165	UC
Army Creek Landfill	U	13,29	30	429	32	429	29
Artisans Village	U	16,23	21	380	7	380	6
Brennan Farms	L	18,10	UC[1]	0	UC	0	UC
Caravel Farms	M	15,12	85	87	85	87	85
Castle Hills	M	10,37	UC	375	UC	375	UC
Collins Park	M	9,39	UC	118	UC	118	UC
	L	9,39	127	0	136	0	128
Crown Zellerbach	U	15,30	32	160	35	160	30
	M	15,30	UC	0	UC	0	UC
	L	15,30	UC	0	UC	0	UC
Delaware City	L	22,23	UC	80	UC	80	UC
Delmarva Power and Light-Summit	U	23,12	238	0	234	0	233
duPont-Newport	L	3,33	0	19	13	19	-2
Eastern States	L	11,10	UC	0	UC	0	UC
Fairwinds	U	12,23	UC	554	UC	554	UC
Getty	U	20,21	UC	149	UC	149	UC
	M	18,17	173	71	173	71	172
	L	19,20	297	1,115	312	1,115	306
Glendale	M	13,19	UC	396	UC	396	UC
ICI	L	11,41	UC	130	UC	130	UC
Jefferson Farms	M	10,36	-9	243	-4	243	-4
Llangollen Estates	U	14,26	2	694	-1	694	-3
Middletown	U	25,9	UC	0	UC	0	UC
Midvale	U	11,28	16	158	15	158	15
Newark	L	5,15	8	413	13	413	13
New Castle	U	11,32	-10	210	-4	210	-5
	M	13,36	81	0	82	0	81
Newport	L	3,33	0	19	13	19	-2
Union Carbide	L	23,17	491	0	492	0	492
Wilmington Airport	L	7,33	UC	66	UC	66	UC
Wilmington Manor Gardens	L	11,33	UC	227	UC	227	UC

Negative available drawdowns indicate water levels below the top of the aquifer.
Drawdowns are at representative node.

[1] UC indicates uncertain or unacceptable calibration at indicated well field; therefore, available drawdown is not shown.

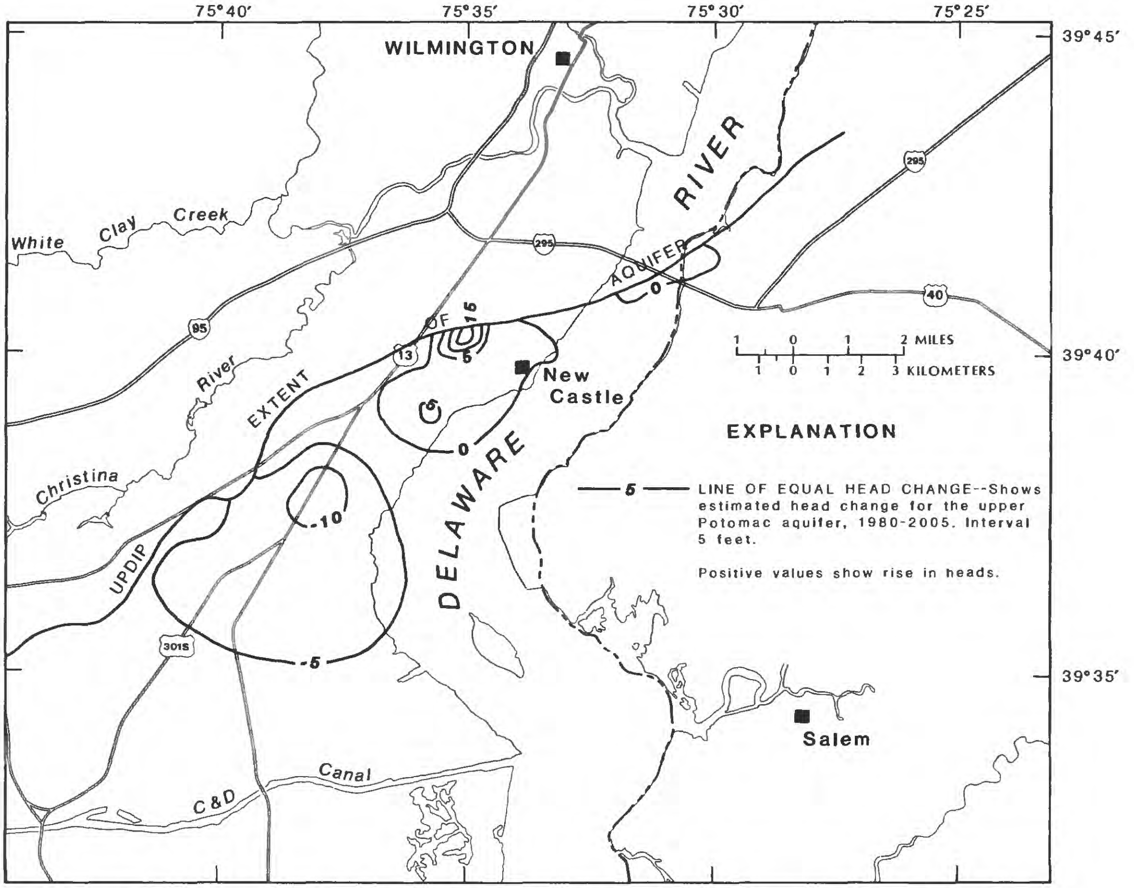


Figure 49.--Estimated changes in head, 1980-2005, for the upper Potomac aquifer, first simulation. (Assumes 1979-81 average pumpage except for a reduction at Amoco and an increase at Artisans Village.)

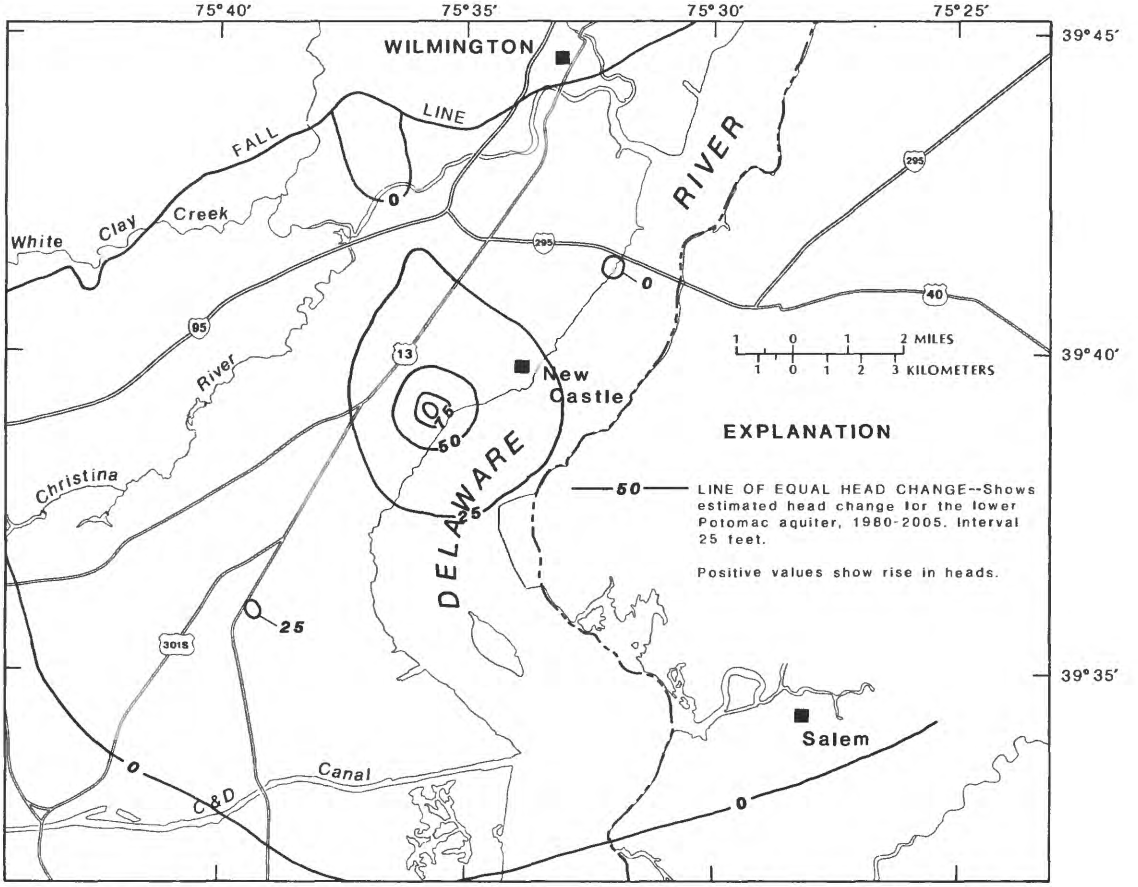


Figure 50.--Estimated changes in head, 1980-2005, for the lower Potomac aquifer, first simulation. (Assumes 1979-81 average pumpage except for a reduction at Amoco and an increase et Artisans Village.)

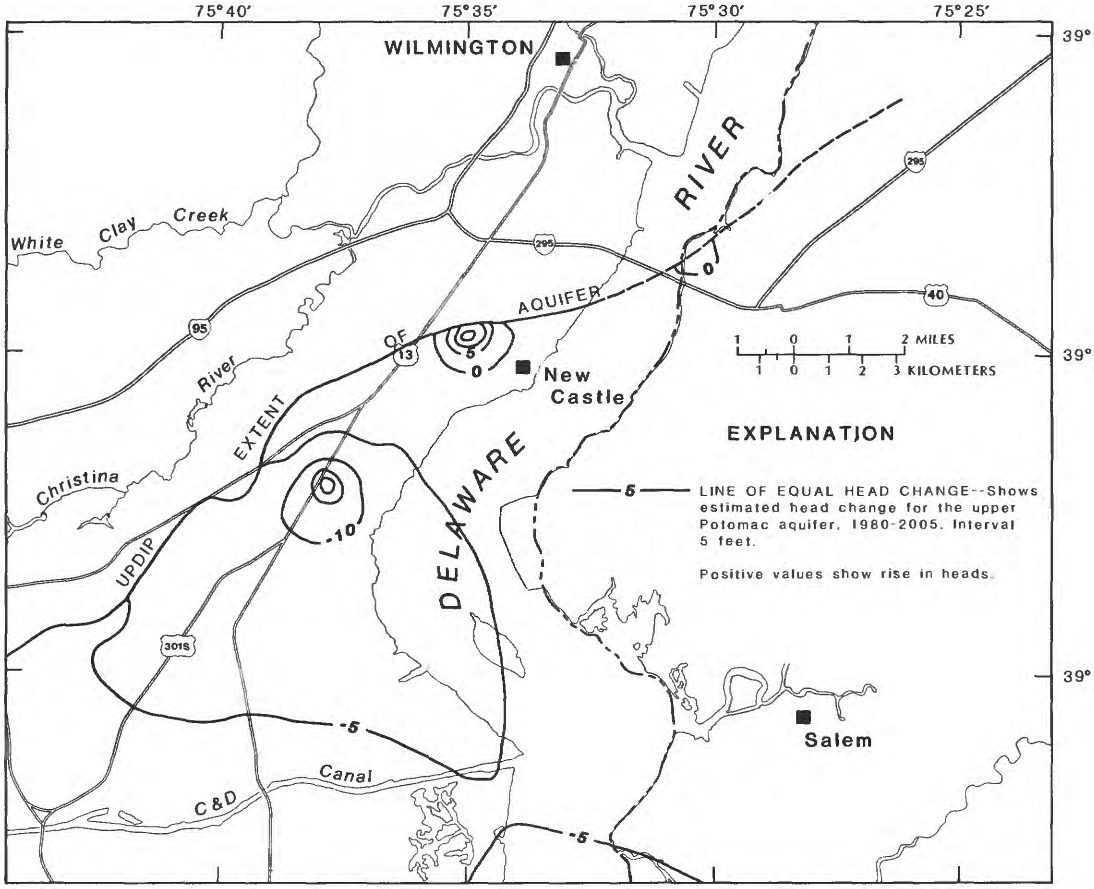


Figure 51.--Estimated changes in head, 1980-2005, for the upper Potomac aquifer, second simulation. (Assumes 1979-81 average pumpage except for an increase at Artisans Village.)

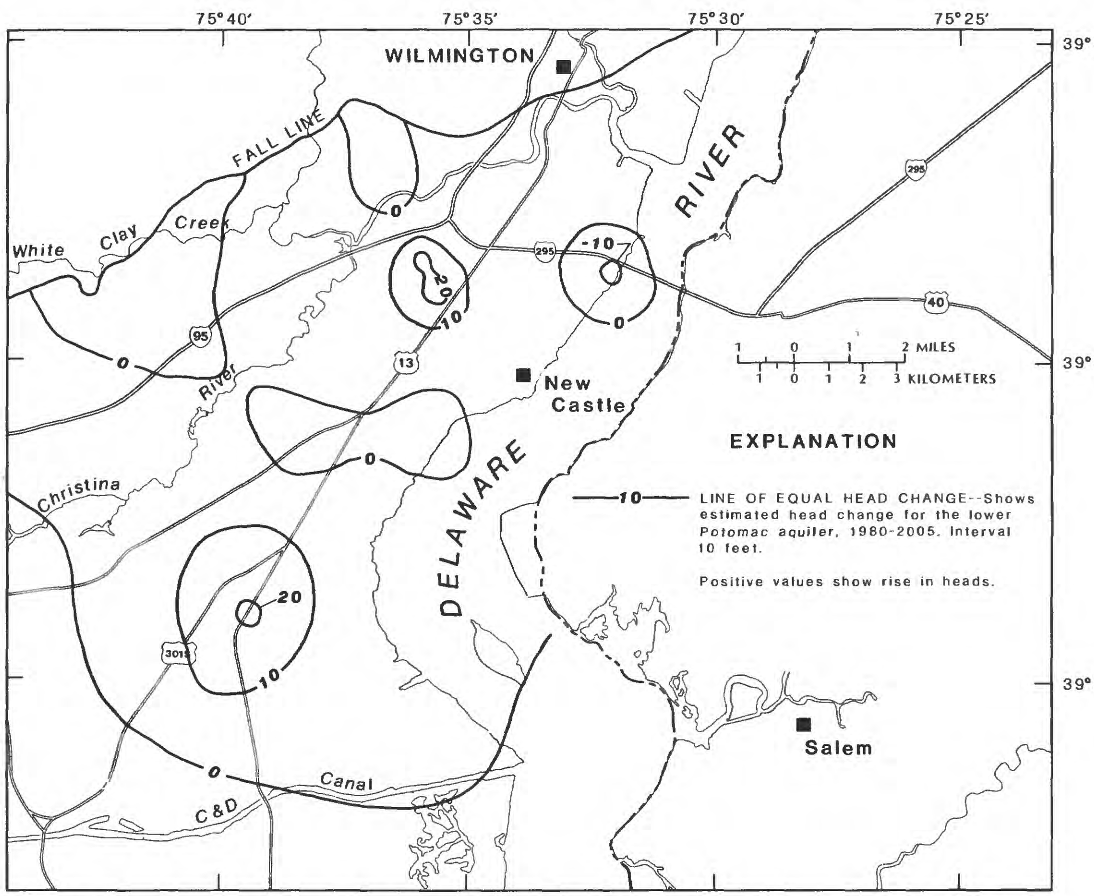


Figure 52.--Estimated changes in head, 1980-2005, for the lower Potomac aquifer, second simulation. (Assumes 1979-81 average pumpage except for an increase at Artisans Village.)

A third simulation to evaluate the effects of possible future pumping is based on redistribution of current pumping. Initial pumpage for this simulation is the same as the first simulation. Beginning in October 1985, pumpage is decreased in wells near the Delaware River at Collins Park, Llangollen Estates, and Getty. This pumpage is replaced by pumpage at the existing well field at Caravel Farms and new production wells at Delmarva Power-Summit, Union Carbide, Eastern States, and Brennan Farms (table 4).

The results of this simulation indicate that heads at Eastern States will be drawn down significantly below the top of the lower aquifer. The model program used does not accurately simulate aquifers that change from confined conditions to unconfined conditions during the simulation. In such cases, transmissivity decreases with head declines, and storage increases several orders of magnitude when the system changes from confined to unconfined. This change of conditions occurred before the end of the first pumping period. Therefore, the results of this simulation are inaccurate. However, several generalizations can be made. Both Eastern States and Brennan Farms are in areas which had limited geophysical or hydrologic data available at the time of calibration. Therefore, the model is not rigorously calibrated in these areas. Accurate simulation of flow in these areas may require adjustment of the current transmissivity and leakance values in the model as new data become available. However, calibration of the model in these areas could not be based on long-term head changes, as water-level data are not available.

If the simulated drawdown at Eastern States in the lower aquifer were possible, drawdowns in western Delaware in the middle aquifer would be less than 30 ft. Similarly, drawdowns in western Delaware in the upper aquifer would be less than 20 ft. Also, if these drawdowns in western Delaware were correct, the decrease in pumpage near the Delaware River would cause rises in heads of more than 120 ft in the lower aquifer at Amoco and Llangollen Estates, but less than 20 ft in the upper and middle aquifers in this area.

A fourth simulation is based on expected demands for the next 25 years. The same pumpage as the first simulation is used, except increased pumpage was assumed for the existing well fields at the city of New Castle, Caravel Farms, Newport, Getty, and Middletown. Although additional withdrawals are expected for new well fields at Brennan Farms and Eastern States near the Delaware-Maryland State line, no increase in pumpage in this area is assumed for this simulation. This assumption avoids the simulation of heads below the top of the aquifer, as resulted in the third simulation. Pumpage changes for each well field and pumping period are shown in table 4. Drawdowns for parts of the upper and lower aquifers are shown in figures 53 and 54.

Results of the fourth simulation are generally similar to results of the first simulation. Drawdowns for the upper aquifer (fig. 53) are similar to those of the first simulation, except

Table 4.--Pumpage changes and simulated available drawdowns for simulations assuming pumpage redistribution, increased pumpage, and pumpage reduction.

Well field	Aquifer (U, upper M, middle L, lower)	Third Simulation: Pumpage change from first simulation (Mgal/yr) Pumping period 1	2	3	4	5	Available drawdown[1]	Fourth Simulation: Pumpage change from first simulation (Mgal/yr) Pumping period 1	2	3	4	5	Available drawdown October 2005 (feet)	Fifth Simulation: Pumpage change from first simulation (Mgal/yr) Pumping period 1	2	3	4	5	Available drawdown October 2005 (feet)
Airport Industrial Park	U	-	-	-	-	-	-	-	-	-	-	-	-20	-	-	-	-	-	28
Amoco	U	-	-	-	-	-	-	-	-	-	-	-	32	-	-	-	-	-	44
	L	-	-	-	-	-	-	-	-	-	-	-	UC	-	-	-	-	-	UC
Army Creek Landfill	U	-	-	-	-	-	-	-	-	-	-	-	28	-	-	-	-	-	40
Artisans Village	U	-	-	-	-	-	-	-	-	-	-	-	5	-	-125	-251	-251	-251	30
Brennan Farms	L	-	263	263	263	263	-	-	-	-	-	-	UC[2]	-	-	-	-	-	UC
Caravel Farms	M	-	130	130	130	130	-	-	105	105	105	105	83	-	-29	-57	-57	-57	87
Castle Hills	M	-	-	-	-	-	-	-	-	-	-	-	UC	-	-124	-248	-248	-248	UC
Collins Park	M	-	-106	-106	-106	-106	-	-	-	-	-	-	UC	-	-39	-78	-78	-78	UC
	L	-	-	-	-	-	-	-	-	-	-	-	134	-	-	-	-	-	144
Crown Zellerbach	U	-	-	-	-	-	-	-	-	-	-	-	31	-	-	-	-	-	44
	M	-	-	-	-	-	-	-	-	-	-	-	UC	-	-	-	-	-	UC
	L	-	-	-	-	-	-	-	-	-	-	-	UC	-	-	-	-	-	UC
Delaware City	L	-	-	105	105	105	-	-	-	-	-	-	UC	-	-	-	-	-	UC
Delmarva Power and Light-Summit	U	-	210	210	210	210	-	-	-	-	-	-	228	-	-	-	-	-	245
DuPont-Newport	L	-	-	-	-	-	-	-	-	-	-	-	-18	-	-	-	-	-	-2
Eastern States	L	-	420	420	420	420	-	-	-	-	-	-	UC	-	-	-	-	-	UC
Fairwinds	U	-	-	-	-	-	-	-	-	-	-	-	UC	-	-183	-366	-366	-366	UC
Getty	U	-	-	-	-	-	-	-	-	-	-	-	UC	-	-	-15	-30	-45	UC
	M	-	-	-	-	-	-	-	-	-	-	-	162	-	-	-7	-14	-21	205
	L	-	-420	-420	-420	-420	-	-	263	263	263	263	270	-	-	-111	-222	-333	371
Glendale	M	-	-	-	-	-	-	-	-	-	-	-	UC	-	-131	-261	-261	-261	UC
ICI	L	-	-	-	-	-	-	-	-	-	-	-	UC	-	-	-	-	-	UC
Jefferson Farms	M	-	-	-	-	-	-	-	-	-	-	-	-5	-	-80	-160	-160	-160	29
Llangollen Estates	U	-	-694	-694	-694	-694	-	-	-	-	-	-	-3	-	-229	-458	-458	-458	22
Middletown	U	-	-	-	-	-	-	-	-	-	105	105	UC	-	-	-	-	-	UC
Midvale	U	-	-	-	-	-	-	-	-	-	-	-	12	-	-52	-104	-104	-104	24
Newark	L	-	-	-	-	-	-	-	-	-	-	-	13	-	-	-	-	-	15
New Castle	U	-	-	-	-	-	-	-	210	263	263	263	-25	-	-	-	-	-	4
	M	-	-	-	-	-	-	-	-	-	-	-	79	-	-	-	-	-	100
Newport	L	-	-	-	-	-	-	-	53	53	53	53	-18	-	-	-	-	-	-2
Union Carbide	L	-	210	210	210	210	-	-	-	-	-	-	474	-	-	-	-	-	531
Wilmington Airport	L	-	-	-	-	-	-	-	-	-	-	-	UC	-	-22	-44	-44	-44	UC
Wilmington Manor Gardens	L	-	-	-	-	-	-	-	-	-	-	-	UC	-	-75	-150	-150	-150	UC

Available drawdowns are for nodes listed in table 3. Negative drawdowns indicate water levels below the top of the aquifer. Pumpage for each well field is for aquifer shown.

[1] Third simulation results are unreliable because of extreme drawdown below the top of the aquifers in western Delaware.
[2] UC indicates uncertain or unacceptable calibration at indicated well field; therefore, available drawdown is not shown.

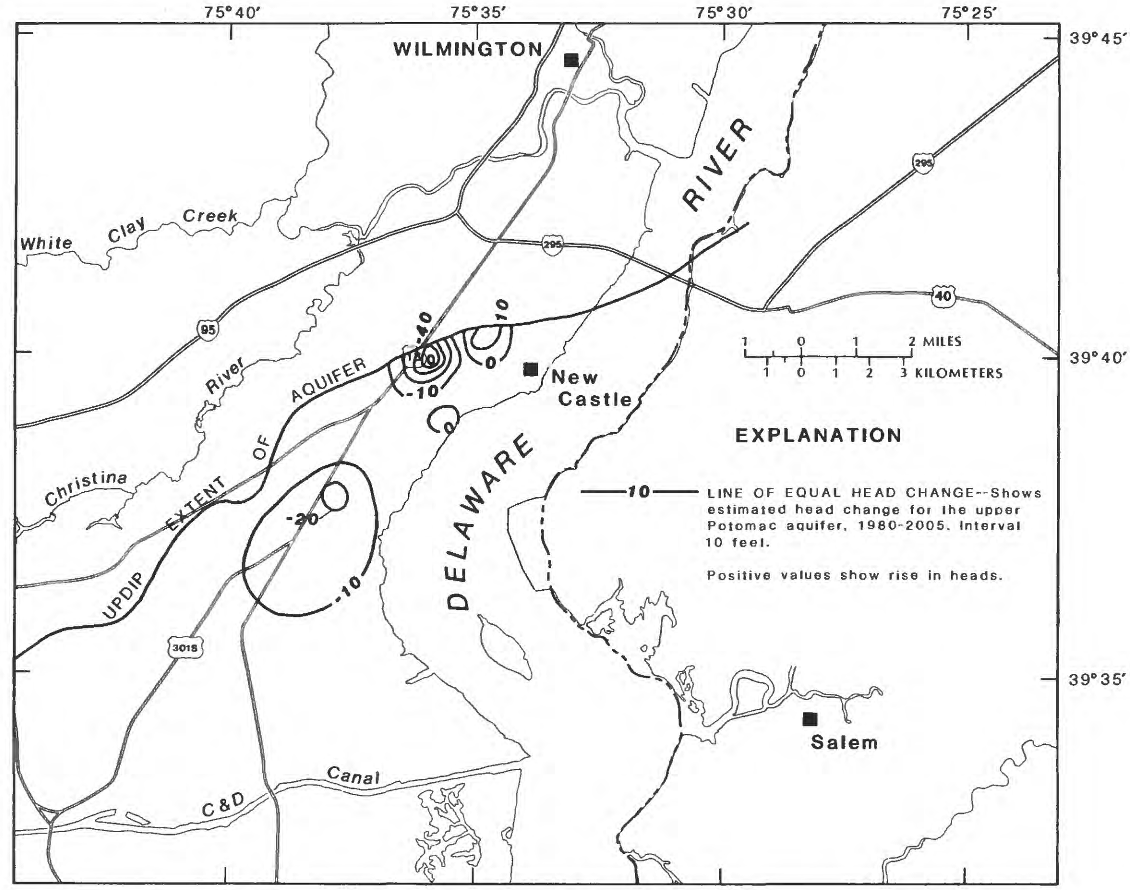


Figure 53.--Estimated changes in head, 1980-2005, for the upper Potomac aquifer, fourth simulation. (Assumes an increase in pumpage from that of the first simulation.)

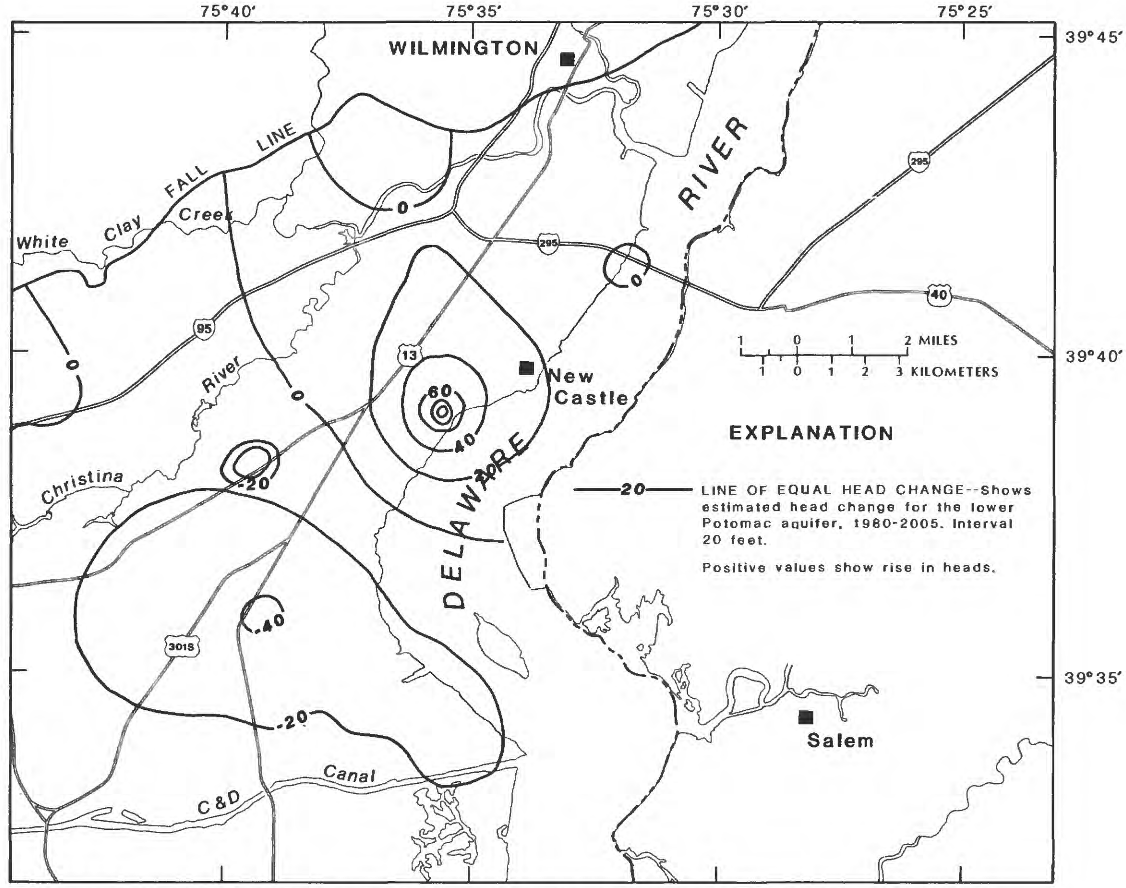


Figure 54.--Estimated changes in head, 1980-2005, for the lower Potomac aquifer, fourth simulation. (Assumes an increase in pumpage from that of the first simulation.)

that drawdown at the New Castle field is about 50 ft and at Artisans Village is more than 20 ft. Other parts of the study area not shown in figure 53 have less than 15 ft of head change. Generally, the expected increases in pumpage have little effect on the middle aquifer. The middle aquifer has less than 15 ft of head change and is not shown. However, there is more than 10 ft of head decline in the middle aquifer in the southern portion of the study area. The lower aquifer has a 100-ft head rise at Amoco as in the first simulation, but more than 40 ft of drawdown at Getty. Head declines beneath the Delaware River are less than 10 ft in the upper and middle aquifers. In the lower aquifer, heads beneath the Delaware River increase almost 60 ft adjacent to Amoco and decline more than 20 ft adjacent to Getty, but head change is less than 10 ft in the subcrop area.

The fifth simulation is based on an assumed substitution of substantial amounts of ground water. The substitution supply is assumed to be a surface or ground water that is outside the model area and is not hydraulically interactive with the Potomac aquifers. Pumpage for 1981-85 is the same as the first simulation. Reductions of 33 and 66 percent in private water company production is assumed for October 1985 and October 1990, respectively. Ten, twenty, and thirty percent reductions in production at Getty are assumed for October of 1990, 1995, and 2000, respectively. As in the first simulation, pumpage at Amoco is minimal. Pumpage is shown for each well field and pumping period in table 4.

The results of this simulation are shown in figures 55, 56, and 57. Recovery of water levels would be greatest in the lower aquifer. Heads rose more than 125 ft at Amoco and between 75 and 100 ft at Getty. Greatest recovery of heads in the upper aquifer would be more than 50 ft at New Castle. Head recovery in the middle aquifer would be 40 ft at Getty and Jefferson Farms. Head rise beneath the Delaware River is less than 15 ft in the upper aquifer. In the middle aquifer, head rise beneath the Delaware River is greatest adjacent to Getty where it is more than 20 ft. In the lower aquifer, heads rise beneath the Delaware River more than 50 ft adjacent to Getty and 100 ft adjacent to Amoco.

STREAM BASE FLOW

Low flows were measured at 21 sites within the study area from September 1978 to July 1980. These measurements which are shown in Martin and Denver (1982, table 6), are assumed to have been made during periods when streamflow is primarily ground-water discharge (base flow). Seven of these sites and one additional site had base-flow data prior to 1978. These data were used primarily to determine if streams overlying aquifer subcrop areas have different base-flow characteristics than streams not overlying aquifer subcrop areas.

Base-flow measurements for 20 sites are shown in figure 58. Site locations are shown in figure 59. Data for two sites are not

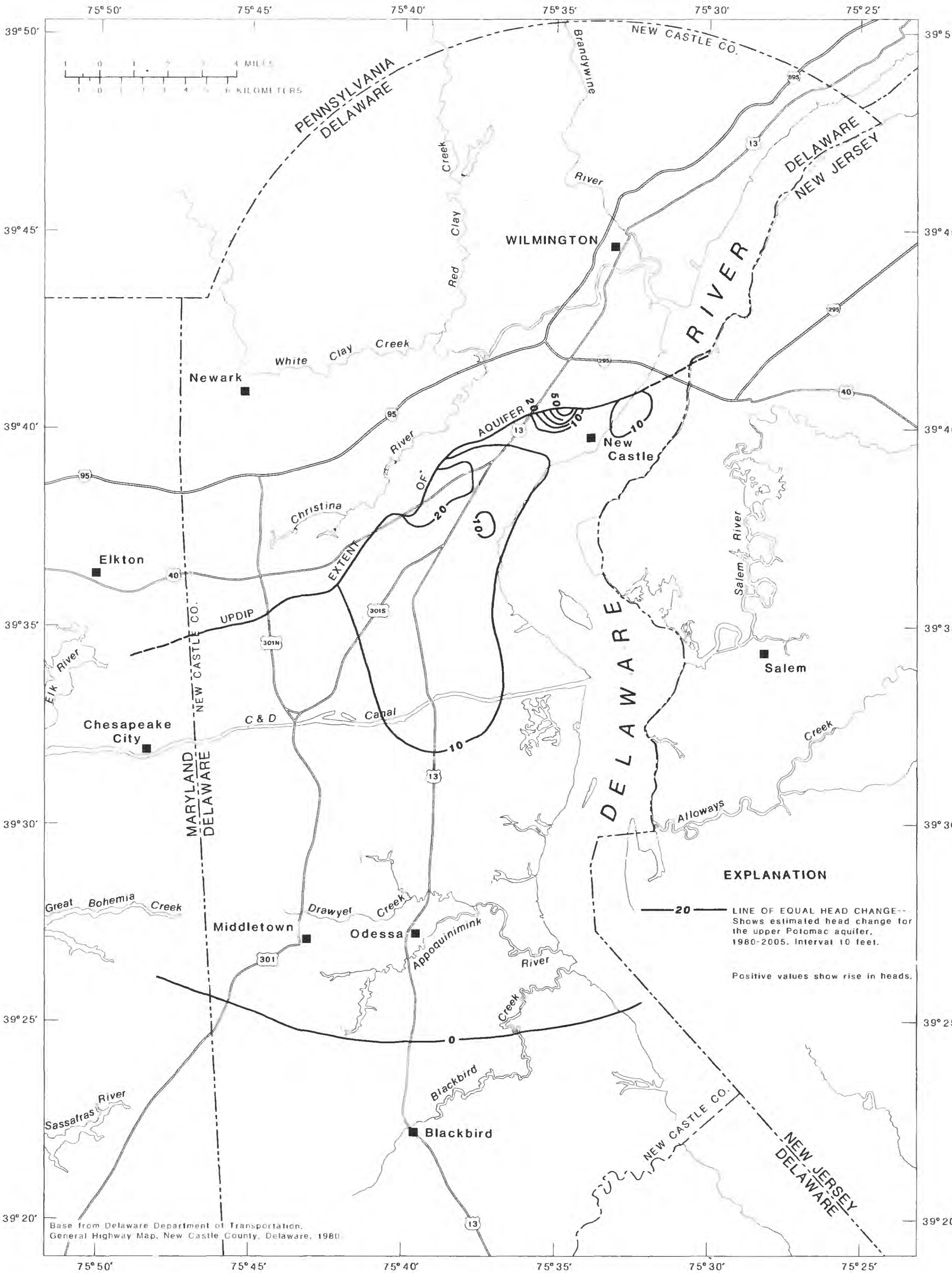


Figure 55.--Estimated changes in head, 1980-2005, for the upper Potomac aquifer, fifth simulation. (Assumes a reduction in pumpage from that of the first simulation.)

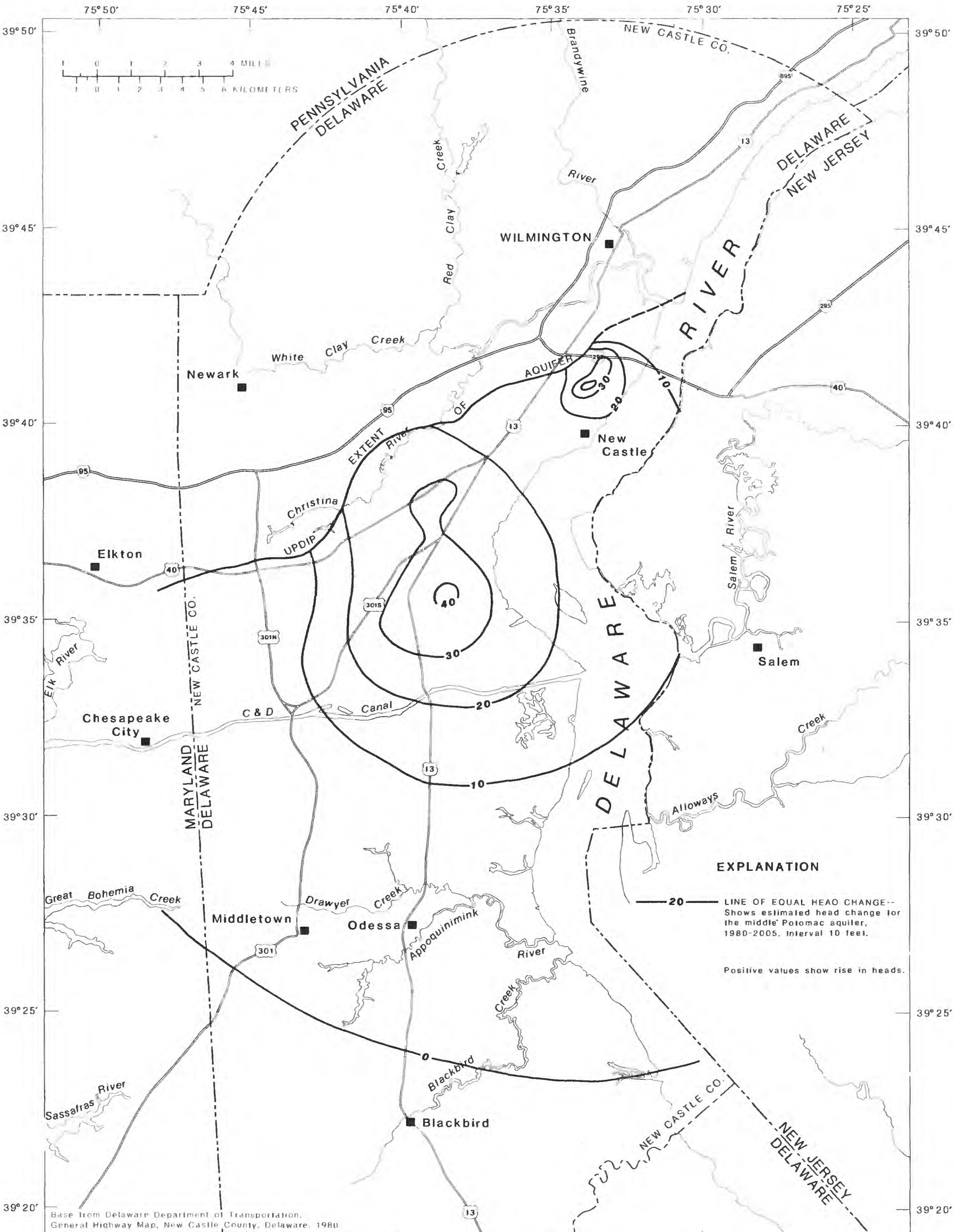


Figure 56.--Estimated changes in head, 1980-2005, for the middle Potomac aquifer, fifth simulation. (Assumes a reduction in pumpage from that of the first simulation.)

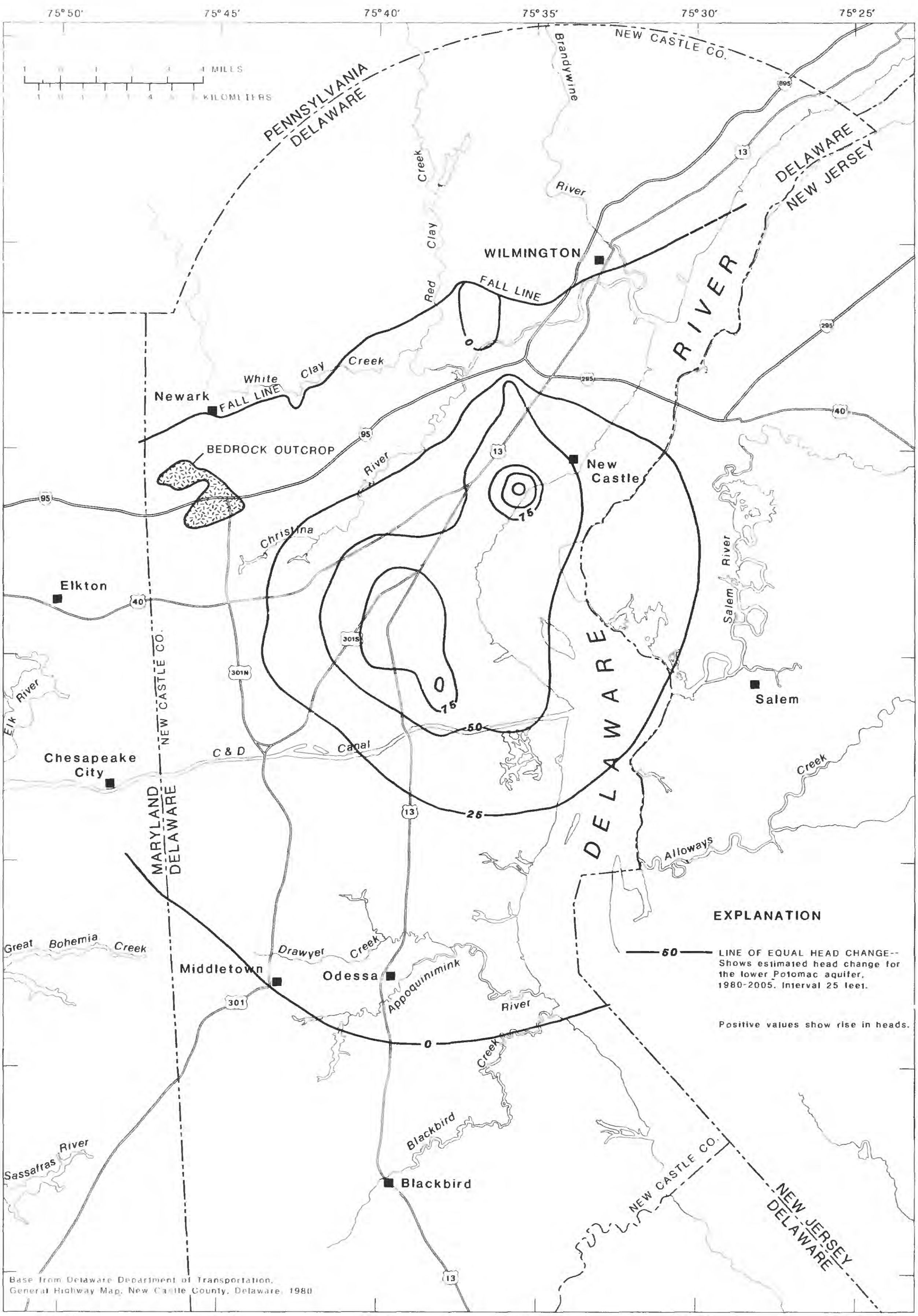
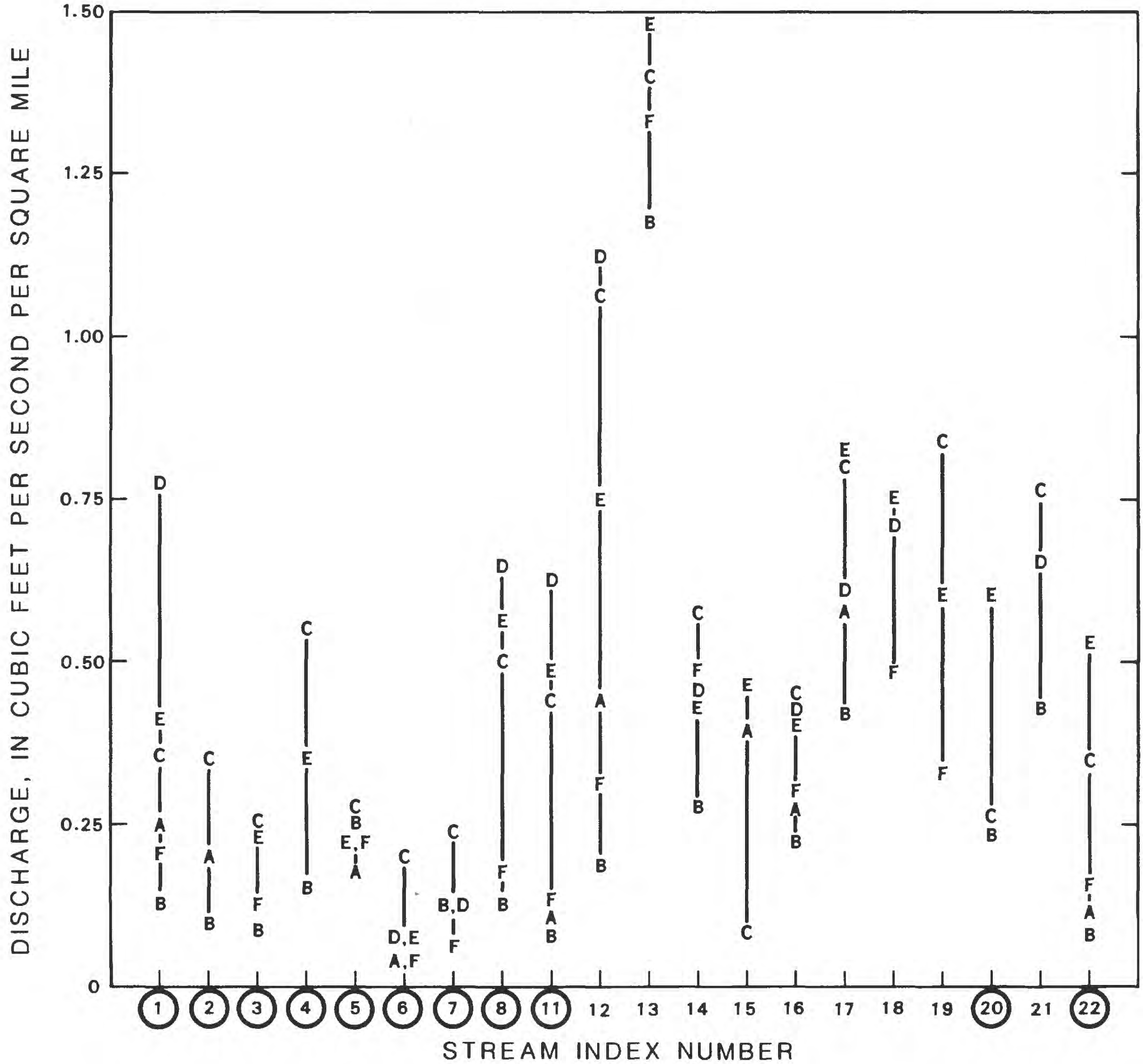


Figure 57.--Estimated changes in head, 1980-2005, for the lower Potomac aquifer, fifth simulation. (Assumes a reduction in pumpage from that of the first simulation.)



EXPLANATION

(5) Stream overlying subcrop area

12 Stream not overlying subcrop area

Discharge measurement taken:

A	September	1978
B	October	1978
C	May	1979
D	November	1980
E	February	1980
F	July	1980

INDEX NUMBER	DISCHARGE MEASUREMENT SITE
1	Belltown Run near Glasgow
2	Muddy Run at Glasgow
3	Muddy Run near Coochs Bridge
4	Christina River near Bear
5	White Clay Creek Tributary near Ogletown
6	Army Creek at State Road
7	Army Creek Tributary at State Road
8	Red Lion Creek near Red Lion
11	Dragon Creek at Kirkwood
12	Dragon Creek Tributary at Kirkwood
13	Joy Run near Summit Bridge
14	Scott Run near Boyds Corner
15	Wiggins Millpond Outlet at Townsend
16	Drawyer Creek near Mount Pleasant
17	Drawyer Creek Tributary near Armstrong
18	Drawyer Creek Tributary near Odessa
19	Blackbird Creek at Blackbird
20	Perch Creek near Elkton
21	Back Creek near Mount Pleasant
22	Long Creek near Chesapeake City

Figure 58.--Base-flow measurements for streams in the study area.

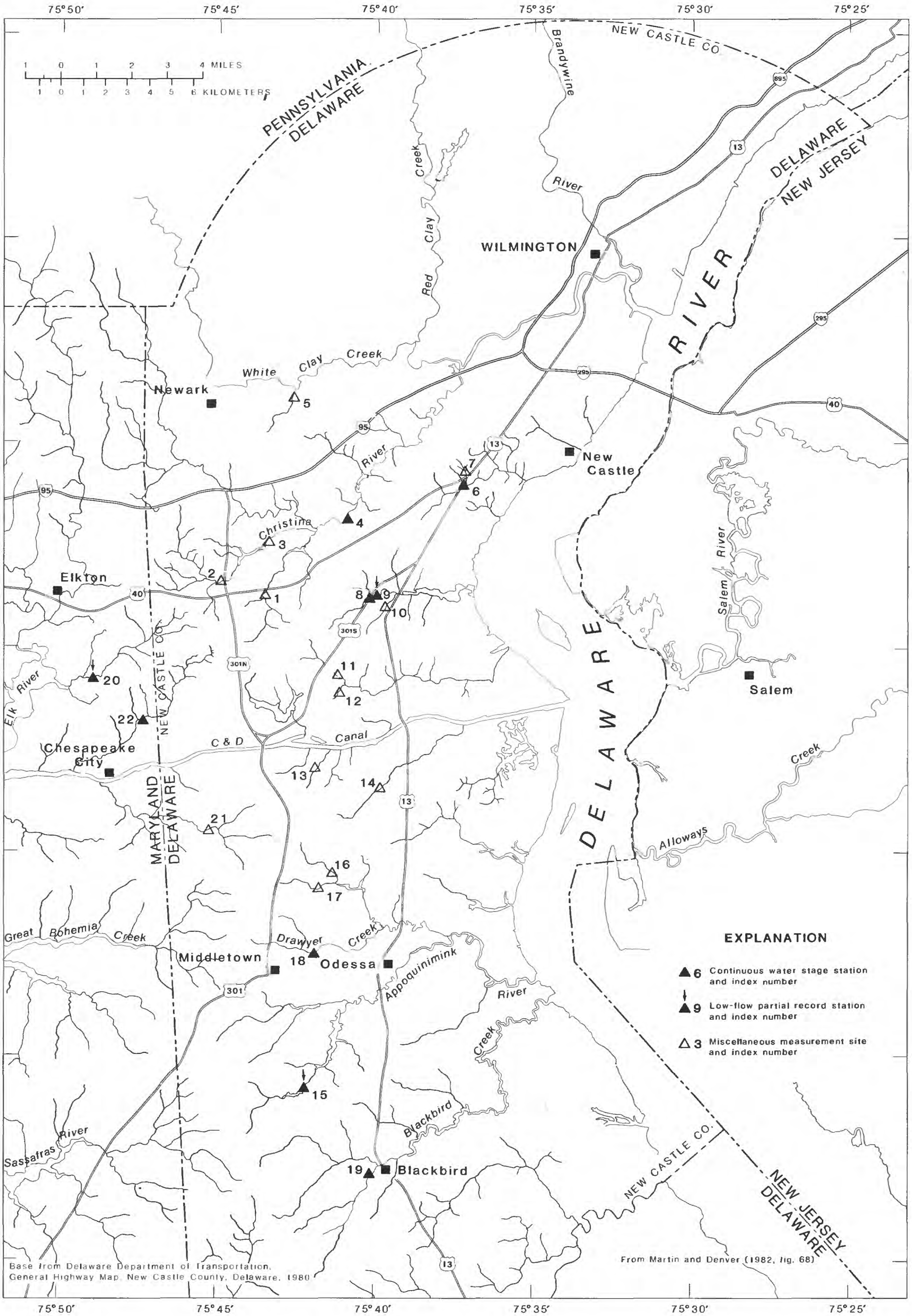


Figure 59.--Location of base-flow measuring sites.

shown in figure 58 because they were not measured at the same time as the other sites. Each line represents the range of base flow for a particular stream. The letters indicate measurements at a particular date. Stream index numbers within a circle indicate streams that overlie parts of a Potomac aquifer subcrop. All of the measurements are between 0.04 and 1.5 $(ft^3/s)/mi^2$ (0.03 and 0.97 $(Mgal/d)/mi^2$) and the majority of measurements (64 percent) are between 0.15 and 0.77 $(ft^3/s)/mi^2$ (0.1 and 0.5 $(Mgal/d)/mi^2$).

The discharge per square mile for streams overlying subcrop areas is slightly less than those for streams not overlying the subcrop areas. All but one measurements less than 0.15 $(ft^3/s)/mi^2$ (0.1 $(Mgal/d)/mi^2$) are from streams overlying subcrop areas. All measurements greater than 0.77 $(ft^3/s)/mi^2$ (0.5 $(Mgal/d)/mi^2$) are for streams south of the Potomac subcrop areas. Generally, base flow for streams overlying the subcrop areas is about 0.3 $(ft^3/s)/mi^2$ (0.2 $(Mgal/d)/mi^2$) less than base flow for streams not overlying the subcrop areas. This value was calculated based on the mean base flow for each group of streams for a particular date. This value represents a difference in base flow over several years (1978 to 1980). However, the amount of this difference will vary from wet to dry years and from season to season.

The relationship between surface and ground water is complex and the difference in base flows for streams overlying subcrop areas and streams not overlying subcrop areas may be the result of several factors. Four important factors are natural recharge to confined aquifers, pumpage, interpreting ground-water drainage areas, and data limitations.

The Potomac aquifers receive recharge in their subcrop areas. Some of this water enters a confined flow system that discharges outside the drainage basin being measured. The unstressed steady-state simulation (fig. 17) indicates that, regionally, larger streams and rivers are discharge areas. These discharge areas include the Delaware River and its estuaries, the Chesapeake and Delaware Canal, and larger streams such as the Christina River. The prepumping simulation also shows that the greatest recharge from the water-table aquifer to the underlying confined aquifers occurs in the aquifer subcrop areas, where confining beds are thin and discontinuous. With head gradients toward the confined aquifers in most of the subcrop areas, leakage to the confined aquifers will result in lower base flow during unstressed (prepumping) conditions.

The local distribution of leakage to the confined aquifer cannot be accurately determined from the model. The model results show leakage to and from the water table in relation to the regional geohydrologic framework of the model. These results are reasonable values of regional leakage (fig. 17). Recharge or discharge for a particular basin, however, cannot be determined because the model was not calibrated to individual basin base flows. Also, a smaller grid spacing may be needed for the model to accurately reproduce local flow systems.

The calculated 0.3 $(ft^3/s)/mi^2$ difference in base flow for streams overlying and those not overlying the Potomac subcrop areas is partly the result of the natural leakage to the confined aquifers that would occur under unstressed conditions. However, the base-flow measurements were not made during unstressed conditions and pumping near the subcrop areas is also likely to affect stream base flow.

Pumping from the Potomac aquifers has caused a reduction in base flow by increasing recharge to, or decreasing discharge from, the confined aquifers underlying the water-table aquifer. Water-level declines in the confined aquifers, caused by pumping, will cause more water to enter the aquifers where confined water levels are below the water table (increased recharge) and will cause less water to leave the aquifers where confined water levels are above the water table (decreased discharge). Base flow is expected to decrease in response to nearby pumpage in basins within the subcrop areas. However, quantifying the effects of pumpage on base flow for a particular basin is very complex because changes in leakage from or to other confined aquifers and changes in the water-table altitude may also occur. Data are not available for comparison of the base-flow difference based on 1978-80 data with prepumping conditions, so effects of pumping on base flow cannot be quantified. Long-term base-flow data for four streams, two near the subcrop areas and two in downdip areas, are available. However, there is no pumpage in or near these basins, and the data do not show any observable decline in base flow.

Some of the variation in base flow per square mile of drainage basin is caused by differences between local ground-water divides and surface-drainage divides. These divides are generally similar, but in the geologic setting of the study area they can differ significantly. Therefore, the area contributing ground water to base flow at a station may be greater or less than the surface drainage area. This may explain the relatively high or relatively low discharge per square mile for several stations.

Data limitations may also affect the analysis of base flow. Although low-flow measurements are accurate indications of low flow at the time of measurement, error associated with each measurement limits the generalization of base flow for large areas or at other times. The use of continuous discharge hydrographs may provide a better estimate of base flow than low-flow measurements because mean annual base flow is more accurate for comparing base-flow characteristics between streams.

Hydrographs of daily discharge for six streams for water years 1979 and 1980 are shown in Martin and Denver (1982). An attempt was made to compute base flow for these streams using a method described by Riggs (1963). Generally, long recessions in streamflow had not occurred often enough to provide sufficient data points for rigorous definition of the base-flow recession curves by this method. Preliminary recessions curves and base-flow separations, however, indicate that the mean annual base flow is 55 to 70 percent of total stream flow.

Analysis of the relationship between surface water and ground water is incomplete. Although the regional relationship between stream base flow and pumpage can be assumed for large areas, quantifying this relationship for particular stream basins from model results is not possible. More data are needed to provide base-flow characteristics, streambed characteristics, and the thickness and extent of confining beds in the subcrop areas. Simu-lation of the ground-water flow system can be improved by incorporating this information into the model.

DISCUSSION

Although the flow model satisfactorily simulates historic water levels at most well fields, the need for several future studies of ground-water flow in the Potomac aquifers is indicated.

Better determination of aquifer recharge areas is important to water-resources management in the Potomac aquifers. The flow from constant-head nodes for the unstressed steady-state simulation indicates that leakage from the water table to the underlying aquifers is greatest in the aquifer subcrop areas. To protect the quantity and quality of this recharge, better determination of aquifer recharge areas by analysis of shallow geophysical logs and recharge rates by more detailed flow modeling is needed.

Figure 17 shows recharge and discharge areas for unstressed steady-state conditions, but these are only defined regionally and are not an accurate representation of flow into the aquifers for any particular stream basin. To more accurately represent recharge and discharge areas within the study area, modification of the present flow model is needed to simulate head changes in the water-table. A finer grid spacing may also be needed. Both water levels and the underlying confining-bed geometry would have to be defined more accurately. Such a revised model could be calibrated using both water levels and base flow. However, data on streambed leakance characteristics, and an estimate of base flow in tidal streams, which are difficult to measure, are needed if base flow were used.

In several areas, head simulation could be improved if the model program could simulate heads in a confined system that changed to an unconfined system. Aquifer test analysis at Fairwinds indicate such conditions exist, and model simulations with increased pumpage in western Delaware and eastern Maryland indicate these conditions may exist in the future. However, better definition of the water-table aquifer, the underlying Potomac aquifers, and any intervening confining beds is also needed for better head simulation in these areas.

Another important and largely unknown factor affecting water resources of the Potomac aquifers is the potential for brackish-water infiltration from the Delaware River and its estuaries. Vertical head differences for October 1980 between the Potomac aquifers and the overlying brackish waters of the Delaware Bay were 0-20 ft for the upper aquifer, 0-50 ft for the middle aquifer, and 0-120 ft for the lower aquifer. The largest vertical head differences beneath the bay and its estuaries occur near the major pumping centers at Getty, Llangollen Estates, Amoco, and ICI.

Sundstrom and others (1967, p. 66-79) give a general discussion of the potential for saltwater infiltration into the Potomac aquifers. However, little quantitative evaluation of the thickness and hydraulic conductivity of the confining units under the Delaware Bay and its estuaries has been done. Jordan and Groot (1962, p. 6) described the river channel sediments at the Delaware River Memorial Bridge as sufficiently fine grained to act as a barrier against leakage into the Potomac aquifers in the subcrop areas. They also state that the lateral extent of the channel sediments is not known. Because head gradients are toward the underlying Potomac aquifers, the hydraulic conductivity and thickness of the confining beds beneath the bay determine the potential of brackish-water intrusion, particularly near the subcrop areas. The previous discussion on surface-water discharge notes the necessity of determining streambed hydraulic characteristics and the extent of aquifer subcrop areas for determining aquifer recharge areas and quantifying flow into the aquifers. This previous discussion is particularly applicable to evaluating the potential of brackish-water intrusion. Also, detailed areal and temporal chloride concentrations, pumpage, and precise head data are needed to quantify the movement of chloride through these sediments.

SUMMARY AND CONCLUSIONS

Flow in three aquifers and intervening confining units of the Potomac Formation of Cretaceous age in New Castle County, Delaware, was simulated using a multilayered finite-difference model. The geometry and extent of the aquifers were based on interpretation of geophysical data. The water-table aquifer was simulated as a constant-head boundary and the bottom and lateral boundaries were no-flow boundaries. The model simulated the response of water levels in the Potomac aquifers to pumpage. Water-level and pumpage data were taken from a hydrologic data report of the Potomac Formation in New Castle County, Delaware, by Martin and Denver (1982). The major assumptions made during the modeling process include:

(1) a layered aquifer system,
(2) the location and extent of the aquifer subcrops, and
(3) the selection of boundary conditions.

The model was calibrated by comparing simulated and observed heads and head changes. Transmissivity and leakance values were changed from their initial estimates during calibration. Stressed and unstressed steady-state flow systems were simulated reasonably well. The limited number of observed water levels available for 1955 compare to simulated water levels generally within 10 ft. Long-term drawdowns were simulated within 10 ft of observed data for each pumping period, and within 10 ft for the period of observation for most wells. However, 6-month drawdown trends were not acceptably reproduced, probably because of inaccurate monthly pumpage records. October 1980 heads were simulated to within 10 ft for most wells. However, the Glendale, Fairwinds, and Lums Pond well fields are not accurately calibrated because configuration of the aquifers at Glendale and Fairwinds is not adequately represented in the model.

Results of the calibration procedure show transmissivity values are lowest in the lower aquifer and highest in the upper aquifer. The maximum transmissivity of the lower aquifer is between 1,000 ft^2/d and 1,500 ft^2/d. Maximum transmissivity of the middle aquifer is between 3,000 ft^2/d and 3,500 ft^2/d. Maximum transmissivity of the upper aquifer is between 5,000 ft^2/d and 6,000 ft^2/d. Values of vertical leakance for the three confining beds are similar and range between $1 \times 10^{-8}/d$ to $1 \times 10^{-2}/d$. The highest values and greatest range of values are in the areas near the subcrop. The lowest leakance values are downdip and in western Delaware. The smallest amount of lateral variability in leakance is seen in the confining bed overlying the upper aquifer. A storage coefficient of 5.6×10^{-4} was used in each of the aquifers. A specific storage value of $6 \times 10^{-6}/ft$ was used for each confining bed. The model was not sensitive to aquifer storage coefficients and they were not changed during calibration.

The calibrated model was used to evaluate changes in water levels resulting from five scenarios of future pumpage. The first simulation was based on the assumption of no change in pumping rates for the next 25 years. A head recovery of 120 ft in the lower aquifer at Amoco resulted from the reduction of pumping that occurred in October 1980. The second simulation was similar to the first simulation except Amoco pumpage was assumed not to decrease in October 1980. Head changes for 1980 to 2005 for this simulation were generally less than 25 ft for the three aquifers. The second simulation indicated that pumping at the average 1979-81 rate would produce little additional drawdown in the year 2005. Except for approximately 25 ft of drawdown at Artisans Village and Getty, drawdowns in all three aquifers for the 25-year period were less than 15 ft.

The third simulation was based on a proposed redistribution of pumpage. This simulation resulted in drawdowns below the top of the lower aquifer at Eastern States in western Delaware. The results of this simulation are not reliable because the model program does not simulate unconfined conditions in the Potomac aquifers. The fourth simulation was based on expected increases in pumpage in eastern Delaware. Pumpage in the lower aquifer resulted in 40 ft of drawdown in the lower aquifer from 1980 to 2005. This pumpage also caused drawdowns of about 5 ft in the upper and middle aquifers. The fifth simulation was based on an assumed substitution of ground-water supplies. If private water company production were reduced by 66 percent and production at Getty by 30 percent, head recovery would be greatest in the lowest aquifer. Water levels would rise more than 125 ft at Amoco and between 75 and 100 ft at Getty.

Base-flow discharge measurements indicate that, in general, streams overlying aquifer subcrop areas have lower base flow per square mile of drainage area than streams not overlying aquifer subcrop areas. This difference in base flow is probably the result of natural recharge to the underlying confined aquifers and discharges outside the drainage basin being measured, base flow diverted to pumping wells, and differences between ground-water divides and surface drainage areas. Analysis of continuous discharge hydrographs may provide better understanding of stream-aquifer relationships if longer periods of record are obtained.

Simulation of the ground-water flow system could be improved by incorporating stream base-flow information. However, more information would be needed on streambed hydraulic characteristics and the extent and thickness of confining beds in the aquifer subcrop areas.

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