COMPUTER-MODEL ANALYSIS OF THE USE OF DELAWARE RIVER WATER TO SUPPLEMENT WATER FROM THE POTOMAC-RARITAN-MAGOTHY AQUIFER SYSTEM IN SOUTHERN NEW JERSEY

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May 1980

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CONTENTS

TABLES

ILLUSTRATIONS

CONVERSION FACTORS

Inch-pound units	Multiply by	To obtain SI[1] units
feet (ft)	0.3048	meters (m)
cubic feet per second (ft^3/s)	0.02832	cubic meters per second (m^3/s)
miles (m)	1.609	kilometers (km)
square miles (mi^2)	2.590	square kilometers (km^2)

National Geodetic Vertical Datum of 1929 (NGVD of 1929). A datum plane derived from a general adjustment of the first order level nets of both the United States and Canada, formerly called "mean sea level." The datum was derived from the average sea level over a period of many years at 26 tide stations along the Atlantic, Gulf of Mexico, and Pacific Coasts.

[1] International System (metric) of units.

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ABSTRACT

A computer model of the Potomac-Raritan-Magothy aquifer system was used to simulate the effects of supplementing ground water with water from the Delaware River. Replacement of ground water pumpage with surface water in a 150-square-mile area near Camden, N.J., was simulated. Artificial recharge of surface water was also simulated in the same area. A series of nine simulations was made. The simulations include the period 1974 to 2000. Two projections for water use were used. Also, in some of the model simulations a line of injection wells was simulated to prevent movement of saline water into pumping centers.

The simulations indicate that heads will be as much as 100 feet higher in the year 2000 near the 150-square-mile area than that if only ground water would be used without supplement of surface water. In the model simulations, heads recover upon application of surface water, but start declining again within 2 years. The rate of head decline after surface-water application is slower than before the application.

INTRODUCTION

Pumpage from the Potomac-Raritan-Magothy aquifer system in southern New Jersey has increased significantly since 1900, nearly doubling during 1956-73. Pumping has caused head (water-level) declines over a large part of the aquifer system, and the possibility exists that the declines are causing water of poor quality to move toward pumping centers. Potential sources of water of poor quality include: saline water from the Delaware River estuary, contaminated water from certain reaches of the Delaware River, water from overlying aquifers, and saline water already within the aquifer. To reduce pumping stress on the aquifer system, the use of Delaware River water has been proposed. Water would be withdrawn from the river in the vicinity of Trenton, N.J., where its quality is considered good. Minimal treatment would, thus, be required. The river water could be used for public supply to supplement the ground water and to recharge the aquifer.

Purpose and Scope

This report presents the results of a study in which a computer model of the Potomac-Raritan-Magothy aquifer system was used to simulate the effect of using Delaware River water to supplement the aquifer water.

Results of model simulations are presented in head-contour maps, hydrographs, and flow-rate tables. Velocity of ground-water flow is also shown.

Previous Studies

Studies of coastal-plain geology and ground-water resources that include the Potomac-Raritan-Magothy aquifer system have been made in New Jersey, Pennsylvania, Delaware, and New York since about 1900. Most of the studies were restricted to a specific area, such as a county; collectively, the studies served as the basis for regional quantitative appraisals. County studies include those of Anderson and Appel (1969), Barksdale and others (1943), Hardt and Hilton (1969), Jablonski (1968), Sundstrom and Pickett (1971), Rosenau and others (1969), Rush (1968), Vecchioli and Palmer (1962), and Farlekas and others (1976). Regional appraisals include those of Parker and others (1964), Gill and Farlekas (1976), Barksdale and others (1958), and Luzier (1980).

The digital model was developed by Luzier (1980) for use in predicting head distribution resulting from extracting or injecting freshwater. The theory of the model, its calibration, and some water-level predictions are described in detail by Luzier (1980). Because the model is a simplified representation of the regional aquifer system, results of simulations are only approximations. Many local hydrologic details are not included.

Location and Extent of Study Area

The study area lies within the Coastal Plain physiographic province (Fenneman, 1938) and is almost entirely within New Jersey (fig. 1). It is a low lying, gently rolling plain that ranges in altitude from sea level to about 390 ft. The province is bordered on the west by the Fall Line, which separates the rolling hills of the Piedmont from the flat lowland of the Coastal Plain. The Fall Line lies along the west edge of the Potomac-Raritan-Magothy aquifer system, which extends slightly into eastern Pennsylvania. The study area is bordered on the north by Raritan Bay, on the south by Delaware Bay, and on the east by the Atlantic Ocean. A subarea of special study, referred to as area I (fig. 1), includes about 150 mi^2 and incorporates parts of Burlington, Camden, and Gloucester Counties. Although the model includes the Potomac-Raritan-Magothy aquifer system in the entire Coastal Plain of New Jersey, model accuracy decreases north of Burlington and Ocean Counties. Results of simulations are, therefore, not shown in this area.

GEOHYDROLOGY

The Potomac group, along with the Raritan and Magothy Formations, consists of a regionally extensive wedge-shaped aquifer system of interbedded sand, silt, and clay. The aquifer system underlies the entire Coastal Plain of New Jersey and parts of adjacent states and extends approximately 100 mi offshore to the continental slope. The aquifer system is exposed in a narrow outcrop belt along the Fall Line and the Delaware River. Between the outcrop near Camden and the coastline near Atlantic City, the top of the aquifer system dips to the southeast at about 40 ft/mi; whereas, the top of the bedrock dips to the southeast at about 90 ft/mi. At Atlantic City, the top and bottom of the wedge-shaped aquifer system lie at about 2,500 ft and 5,000 ft, respectively, below National Geodetic Vertical Datum of 1929. Sediments of approximately equivalent age (Early to Late Cretaceous) thicken seaward to more than 13,000 ft near the axis of the Baltimore Canyon trough about 60 mi off the New Jersey coast (Schlee and others, 1976, p. 927-940). Figure 2 is a cross section of the aquifer system.

The Potomac group, chiefly of Early Cretaceous age, is the oldest and thickest part of the aquifer system. This unit, in New Jersey, is a sequence of sand, silt, and silty clay. The Raritan Formation, of Late Cretaceous age, consists of sand and clay and overlies the Potomac group. The Magothy Formation, which consists chiefly of coarse beach sand and associated marine and lagoonal clay and silt, unconformably overlies the Raritan Formation and is of Late Cretaceous age. The Magothy Formation thins southward along coastal New Jersey. In contrast, the Raritan thins only slightly. The underlying Potomac group nearly triples in thickness southward. For a more detailed discussion of coastal-plain stratigraphy, the reader is referred to Perry and others

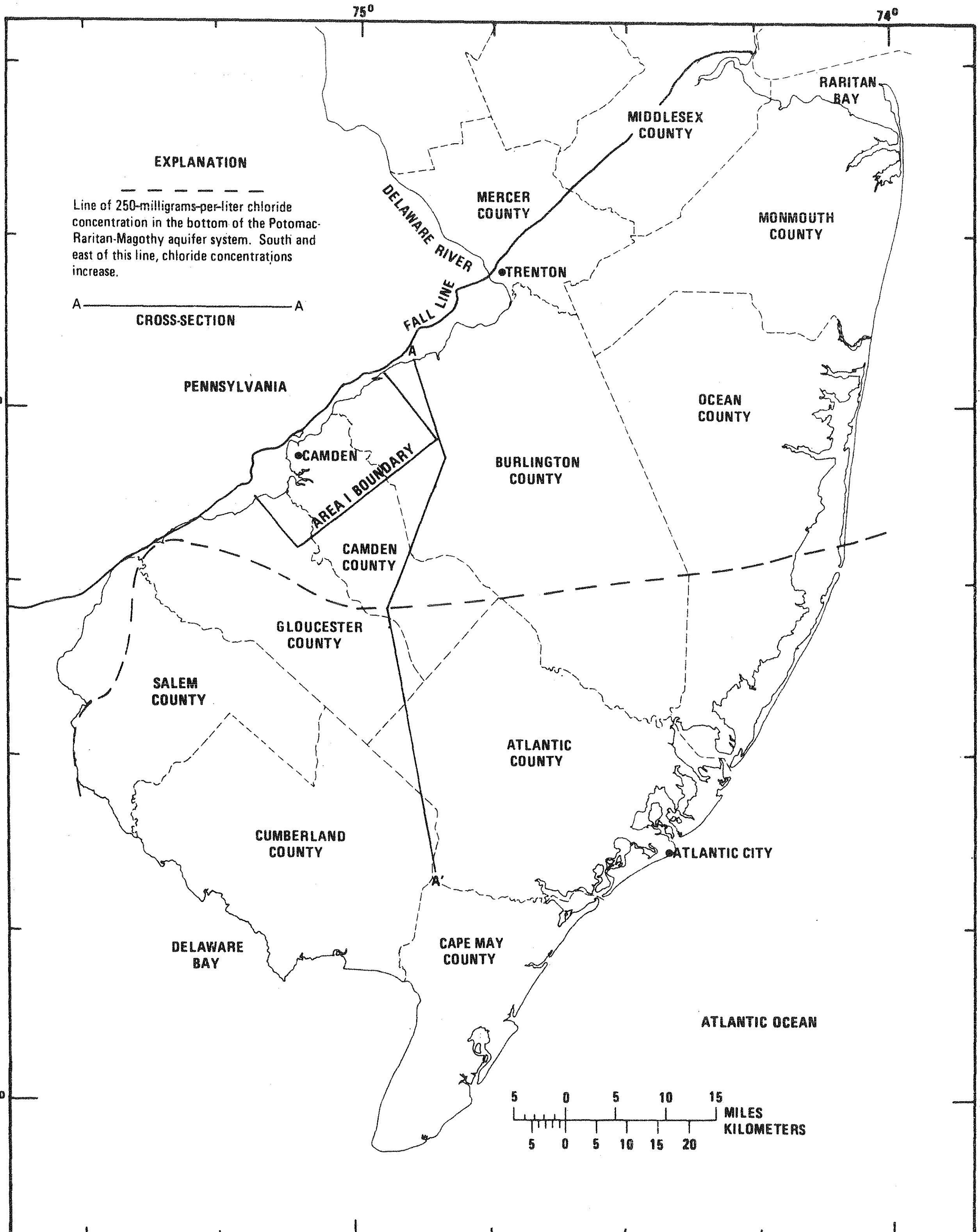

Figure 1.--Index map of southern New Jersey, showing line of 250-milligrams-per-liter chloride concentration, cross section A - A', and area 1.

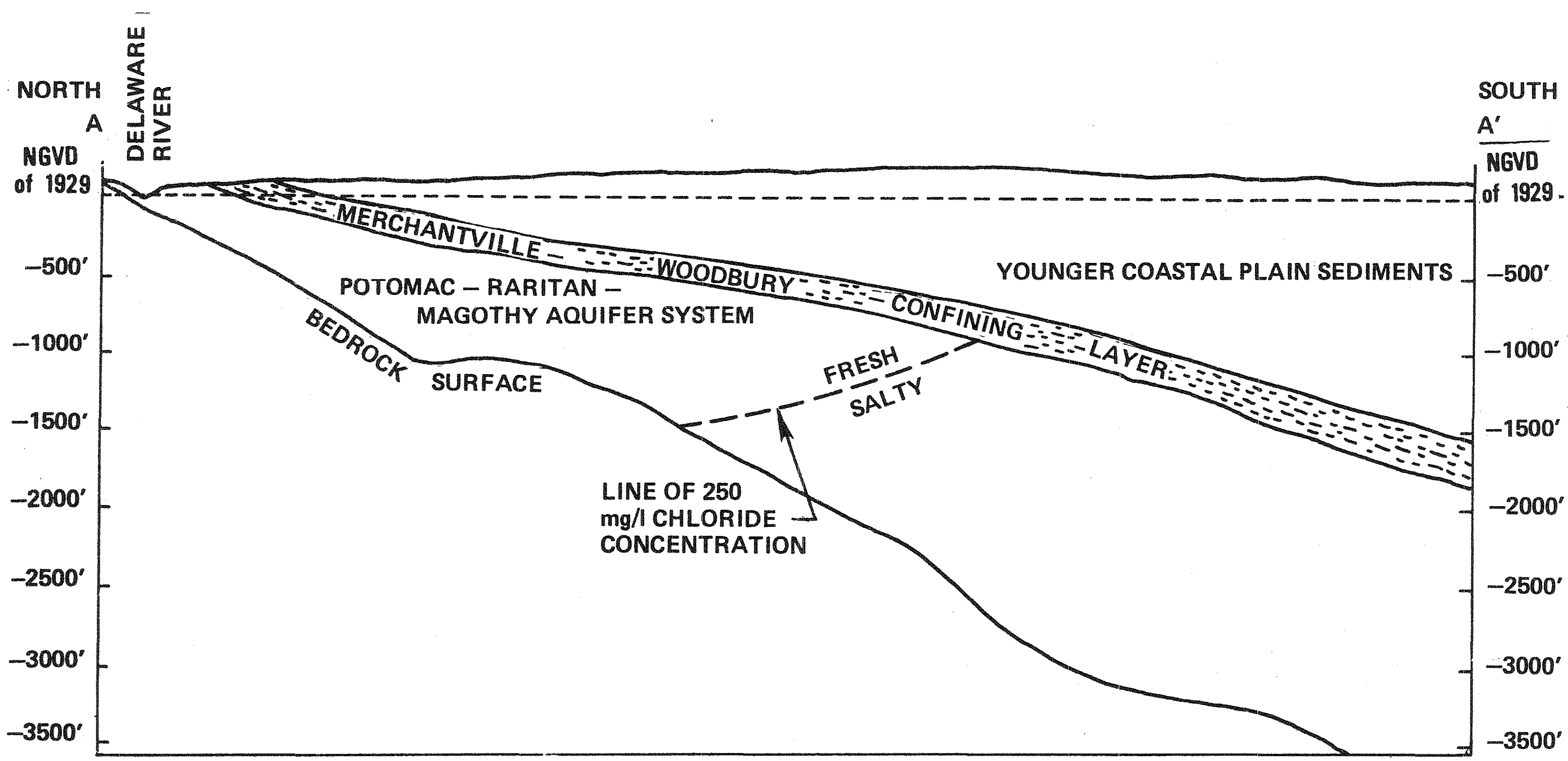

Figure 2.--Cross section of Potomac-Raritan-Magothy aquifer system (Modified from Luzier, 1980, fig. 4).

(1975) and Petters (1976). Brown, Miller, and Swain (1972) and Schlee and others (1976) contain a detailed discussion of the structural and stratigraphic framework.

The Potomac-Raritan-Magothy aquifer system is overlain by a confining layer consisting of the Merchantville Formation and the Woodbury Clay. The Woodbury Clay is the least permeable confining layer in the Coastal Plain of New Jersey (Barksdale and others, 1958, p. 136). These units effectively separate the Potomac-Raritan-Magothy aquifer system and overlying aquifers, such as the Englishtown Formation and the Wenonah Formation-Mount Laurel Sand.

The Potomac group and the Raritan and Magothy Formations seem to function as a hydrologic unit. Barksdale and others (1958, p. 91) believe that the major aquifers within this system are hydraulically connected. Long-term records of observation wells indicate that much of the aquifer system in New Jersey responds uniformly to pumping stress (Luzier, 1980). Most notably, potentiometric heads in most of the confined part of the aquifer system have been declining at 1.5 to 2.5 ft/yr in recent years (1966-76) (Luzier, 1980). The aquifer system is the most heavily pumped in New Jersey, yielding 224 ft^3/s in 1973 in Salem, Gloucester, Camden, and Burlington Counties. Individual wells yield more than 4.5 ft^3/s.

A large part of the Potomac-Raritan-Magothy aquifer system contains salty water, but the division between salty and fresh water is not distinct. Chloride concentration ranges from less than 10 mg/L to 27,000 mg/L (Luzier, 1980). Its concentration changes gradually laterally and with depth. A line of 250 mg/L chloride concentration (estimated) at the bottom of the aquifer system (Gill and Farlekas, 1976) is shown in figure 1. Chloride concentration increases downdip from this line. The line of 250 mg/L chloride concentration at the top of the aquifer system is farther downdip (fig. 2).

CONJUNCTIVE USE OF DELAWARE RIVER WATER AND GROUND WATER

The use of Delaware River water to supplement ground-water supplies is one method of slowing the rate of potentiometric head decline in the Potomac-Raritan-Magothy aquifer system due to pumping. The Delaware River Basin Commission (DRBC) developed the idea of using river water for supply at high flow and ground water at low flow. This management method is termed, in this report, conjunctive use of Delaware River water and ground water or, more simply, conjunctive use. This report contains the results of computer simulations of the conjunctive use.

Availability of Surface Water

Use of Delaware River water at high flows minimizes effects of river withdrawals on downstream locations. Seasonally, flow of the Delaware River varys widely. For example, in 1976, maximum daily flow at Trenton, N.J., was 99,600 ft^3/s, and minimum flow was 3,280 ft^3/s (U.S. Geological Survey, 1977). DRBC is considering enforcing a policy requiring a minimum flow of 3,000 ft^3/s at Trenton (DRBC 1975). This minimum flow was used for the purposes of this report. If, for example, 3,200 ft^3/s is flowing at Trenton, then 200 ft^3/s could be withdrawn for conjunctive use. The assumption is also made that water for conjunctive use would be withdrawn in the vicinity of Trenton.

Withdrawals of 200 and 600 ft^3/s were assumed to be the minimum and maximum for conjunctive use. Accordingly, Geological Survey records of streamflow for water years 1913-76 were analyzed to find when streamflow at Trenton was less than 3,200 and 3,600 ft^3/s. Daily flows were tabulated by months to find the average number of days per month that streamflow was less than 3,200 and 3,600 ft^3/s. If streamflow was less than a given rate for more than 3 days in a month, flow was considered inadequate for withdrawal during the whole month. Flow was less than 3,200 ft^3/s during more than 3 days each month from July through November. During the other 7 months, flow was more than 3600 ft^3/s during all but 3 or less days of each month. Thus, as much as 600 ft^3/s is considered available for conjunctive use 7 months a year.

To compare the long-term average with extreme low flow, the drought of 1962-66 was examined. Each year was analyzed separately to find the number of days in each month that flow was less than 3,200 ft^3/s. Three of the years, 1963-65, had flows less than 3,200 ft^3/s during more than 3 days during each of 6 months rather than the average of 5 months.

Selection of Area

Although no direct cost estimates were made, it would be most feasible to apply conjunctive use to areas near Trenton where water demand is large, as Trenton would be the point of withdrawal. The area in which conjunctive-use schemes were simulated is about 150 mi^2, which is indicated as area I in this report. (See fig. 1.) Forty percent of the total water withdrawn from the Potomac-Raritan-Magothy aquifer system in New Jersey is used in this area.

COMPUTER MODEL SIMULATIONS

A computer model of the Potomac-Raritan-Magothy aquifer system (Luzier, 1980) was used to simulate ground-water response to conjunctive use of water from the Delaware River and ground water. The model simulations are projections from 1974 through 1999. The computer simulations were divided into three groups. The simulations in each group share a common set of assumptions about aquifer conditions. The first simulation in each group shows response of the aquifer to the assumptions alone. The second and third simulations show response to conjunctive use. The effect of conjunctive use can be obtained by comparing simulations incorporating conjunctive use with the corresponding base simulation.

A summary of the model simulations and a brief description of conditions in each is given in table 1. "Replacement of pumpage" in this table and throughout this report indicates that water from the Delaware River is simulated to supply the projected water use in area I for 7 months of each year from 1984 through 1999. At all other times, the simulated supply for water use is ground water.

"Ninety percent recharge" indicates that artificial recharge was simulated in area I for 7 months of each year from 1984 through 1999 at 90 percent of the projected water-use rate for area I. Recharge was simulated at the locations of wells existing in 1973, and the recharge distribution was the same as the distribution of projected water use. None of the simulations consider recharge separately from replacement of pumpage because of the high cost of recharge. More detailed discussion of each group of simulations follows this section.

Figure 3 shows potentiometric heads at the beginning of all simulations (1974). These heads are the result of the model calibration simulation made by Luzier (1980). In this simulation, actual pumping rates from 1956-73 were used. The model computes a water budget showing flow to discharge areas and from recharge areas. Budget values for 1974 are shown below.

Table 1.—Summary of model simulations

Model simulation	Water-use rate	*Head barrier	Conjunctive-use scheme
		Group A	
A	3 percent growth.	No	None.
A0	3 percent growth.	No	Replacement of pumpage.
A90	3 percent growth.	No	Replacement of pumpage plus 90 percent recharge.
		Group B	
B	3 percent growth.	Yes	None.
B0	3 percent growth.	Yes	Replacement of pumpage.
B90	3 percent growth.	Yes	Replacement of pumpage. plus 90 percent recharge.
		Group C	
C	1 and 2 percent growth.	No	None.
C0	1 and 2 percent growth.	No	Replacement of pumpage.
C90	1 and 2 percent growth.	No	Replacement of pumpage plus 90 percent recharge.

* Artificial recharge to maintain a constant head 10 feet above NGVD of 1929, beginning in 1984.

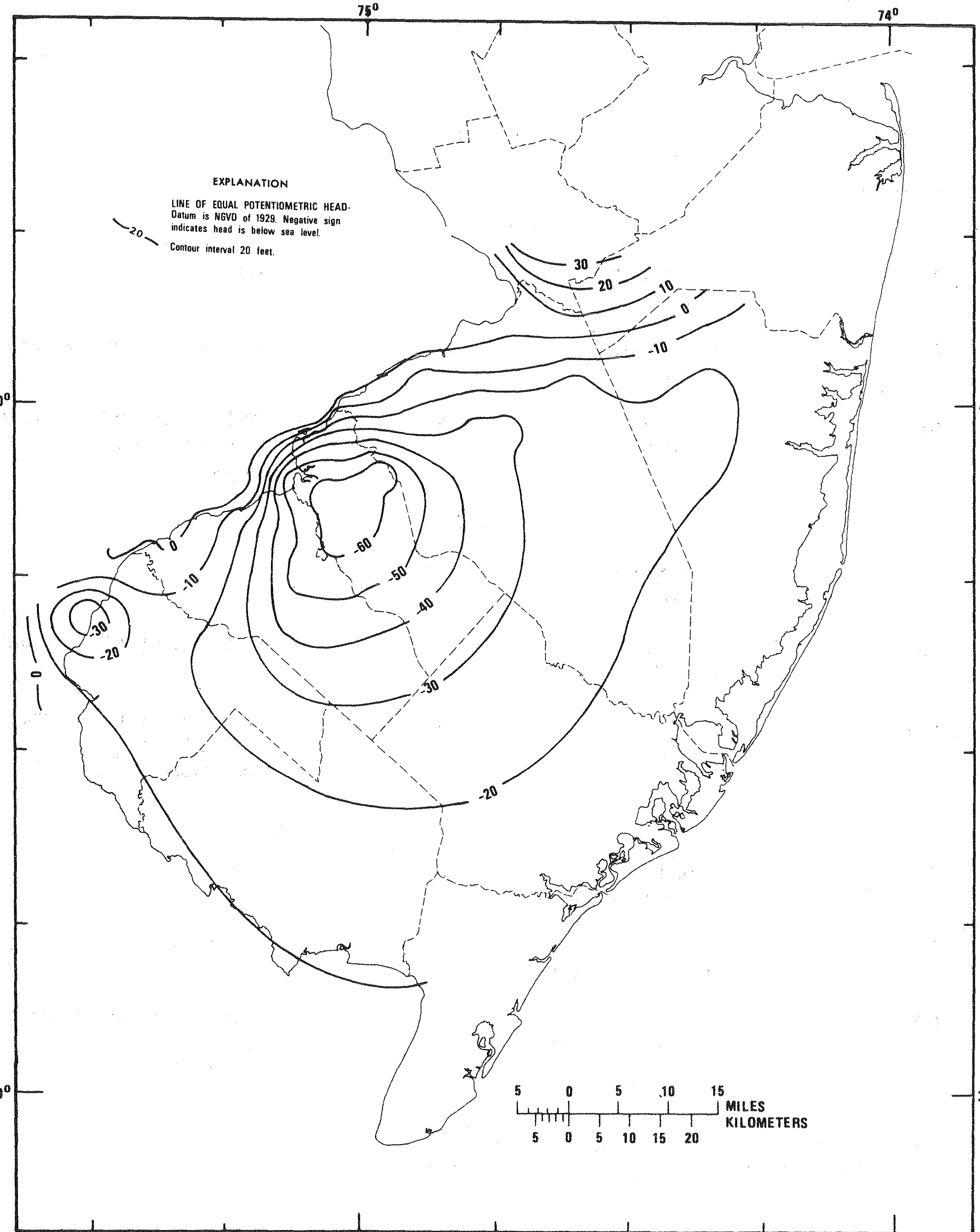

Figure 3.--Potentiometric heads at the start of the model simulations, 1974 (from Luzier, 1980).

Mass balance term	Cubic feet per second
Pumping- -	336
Net induced recharge from Delaware River - - (consists of net induced recharge from constant head boundary along and near Delaware River)	95
Leakage from overlying aquifers- - - - - - - -	99
Recharge from precipitation on outcrop area-	96
Release from aquifer storage - - - - - - - - -	7
Other sources - - - - - - - - - - - - - - - - - (consists of net induced recharge from constant head boundary other than along and near Delaware River. See Luzier [1980] for description and location of constant head boundary)	39

In devising the conjunctive-use schemes used in this report, proximity to the Delaware River at Trenton, demand for water, and availability of water in the Delaware River were considered. Other factors would have to be evaluated before management schemes could be implemented. For example, before water from the Delaware could be substituted for ground water or used for artificial recharge, the chemical quality and treatment of the water would have to be studied. Also, current research on artificial recharge of aquifers would need to be investigated.

Initial trial simulations used monthly values for pumping and artificial recharge, so that the monthly effects of conjunctive use could be simulated. Trial simulations were then made using average annual rates for pumping and artificial recharge. Although the annual method could not simulate the monthly effects of conjunctive use, both methods resulted in essentially the same average annual water levels. Therefore, all subsequent simulations used average annual rates. For example, if recharge at rate, Q, is specified for 7 months of the year, then recharge of (7/12)Q was applied for the entire year.

Group A Simulations

Annual water-use rates for group A simulations were projected through the use of a 3 percent annual growth, which according to Luzier (1980) is the highest expected growth rate. The yearly water-use rate was determined by multiplying the previous year's value by 1.03. The water-use rate for 1974 was determined by multiplying actual 1973 pumping rates by 1.03. Thus, spatial distribution of projected water use during 1974 to 2000 is assumed to be the same as in 1973. Outside of area I, the projected water-use rate is supplied by ground water. Inside area I, the sources which supply the water-use rate are varied in each simulation as listed below.

Simulation A: No conjunctive use--entire water use comes from pumpage

Simulation A0: replacement of pumpage by surface water for 7 months annually

Simulation A90: replacement of pumpage by surface water for 7 months annually plus recharge at 90 percent of the projected water-use rate

Results from group A simulations are shown by potentiometric head contour maps (figs. 4-6). The effects of conjunctive use in simulations A0 and A90 may be seen by comparing with simulation A. Comparing figures 4 and 5 indicates that heads in the center of the large cone of depression near area I are up to 60 ft higher in the year 2000 as a result of conjunctive use. The effects of recharge are shown in figure 6. The center of the cone of depression in simulations A0 and A90 is shifted to the south. The shift is a result of reduction of net ground-water withdrawal in area I; whereas, south of area I there is no reduction. Far from area I, the effects of conjunctive use are small (figs. 4 and 6). Heads in group A simulations at the end of 1999 are also shown in perspective (fig. 7).

Figures 4-6 show average ground-water speed contours as well as potentiometric head contours. The speed contours were constructed from velocity values, which were calculated by Darcy's Law. Velocity cannot be contoured because velocity indicates both direction and magnitude of flow; therefore, only the magnitude of velocity (speed) was contoured. Direction of flow may be determined by the direction of the potentiometric gradient. Direction of flow is toward decreasing heads and perpendicular to head contours. It was assumed when calculating the velocities that the aquifer contains only fresh water and that effective porosity is 25 percent. Also, it was assumed that one-third of the aquifer thickness consists of sand and that water moves only through the sand. Luzier (1980) found that 20 to 50 percent of aquifer thickness is sand. Because of these assumptions and the regional approximations used in making the model, the speed contours are generalized and are regional in nature. The speed contours may be used to estimate the rate of movement of contaminants in the aquifer if it is assumed that contaminants move with (at the same speed as) the water without consideration

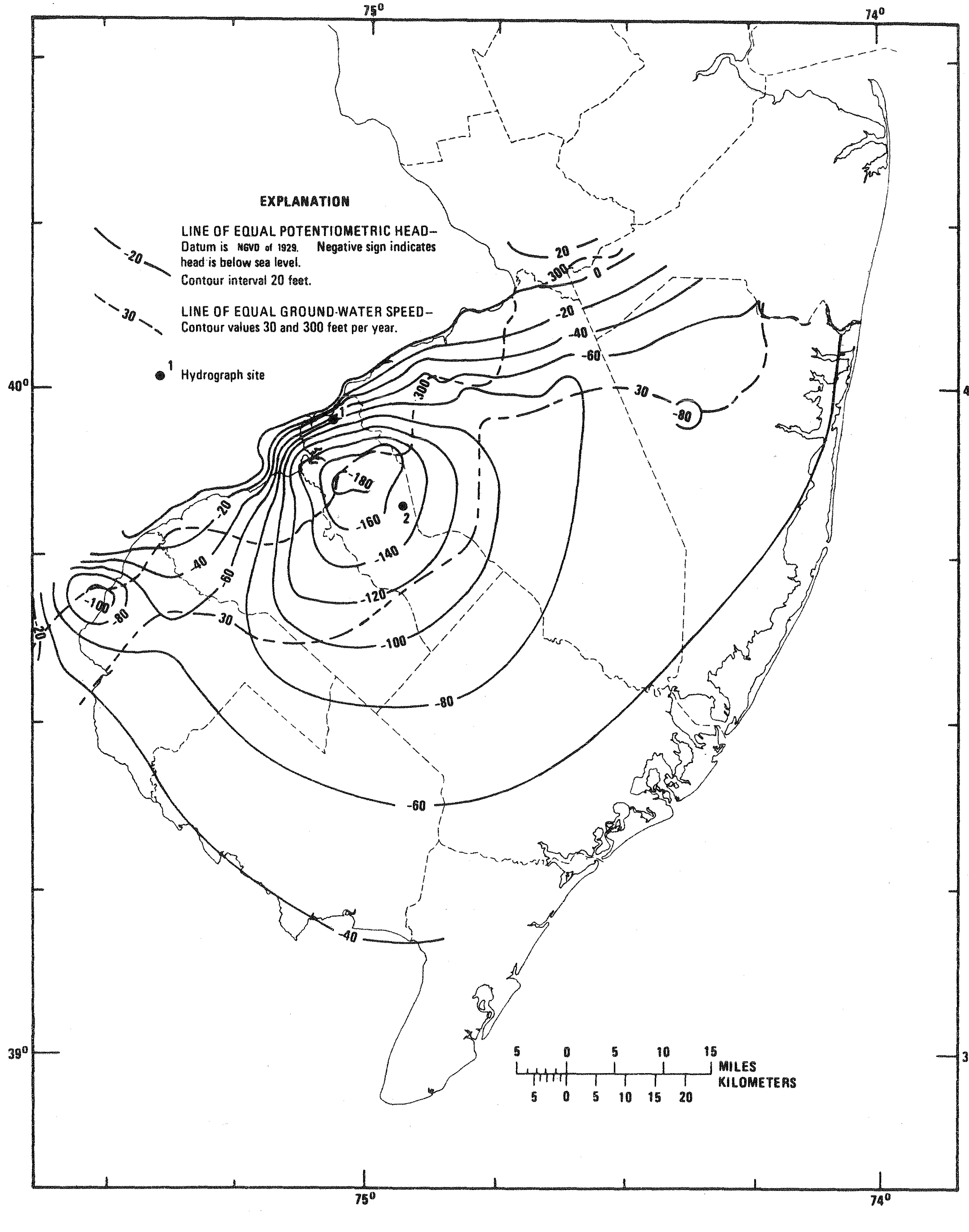

Figure 4.--Heads at the end of 1999 for simulation A without conjunctive-use scheme.

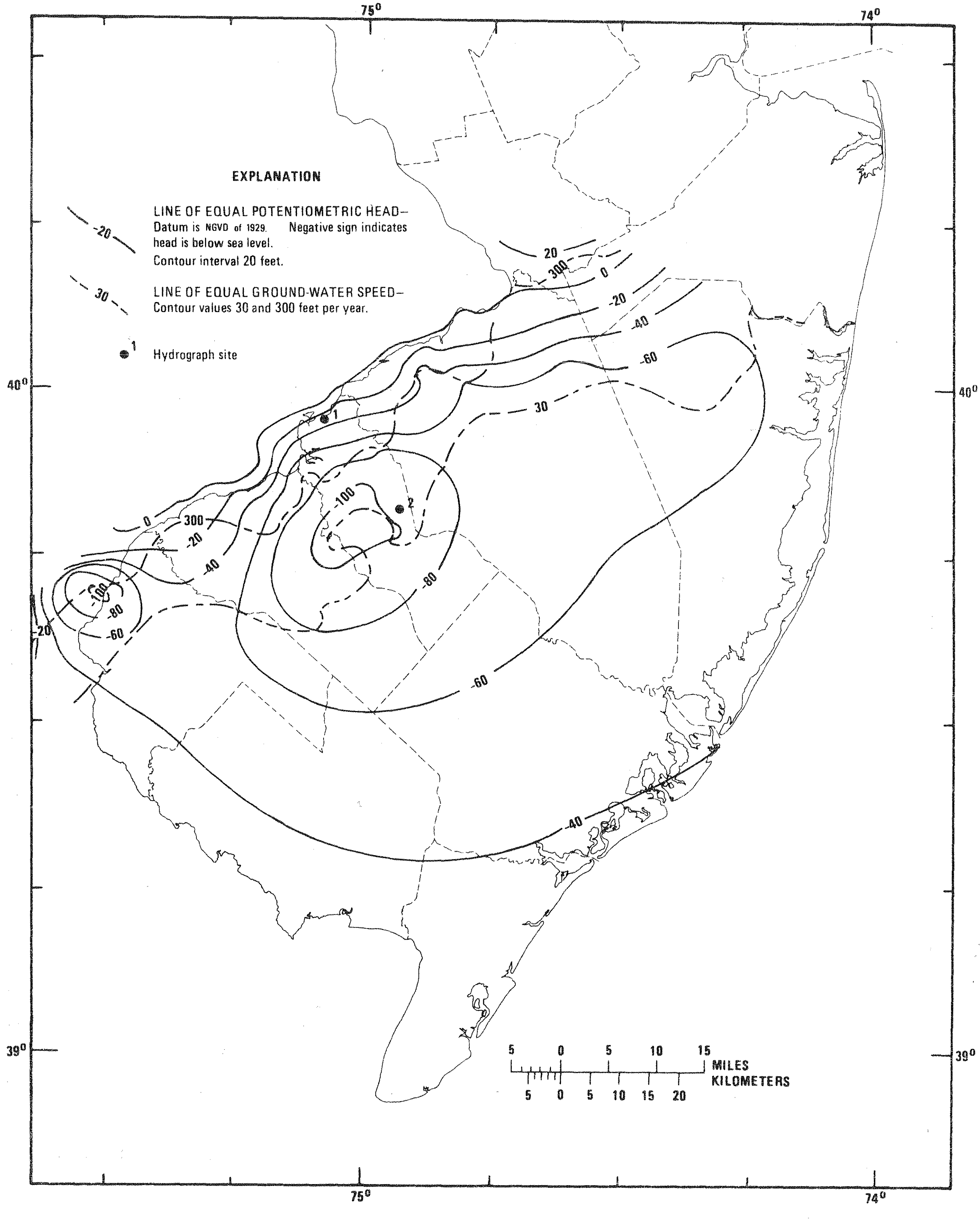

Figure 5.--Heads at the end of 1999 for simulation A0 with conjunctive-use scheme.

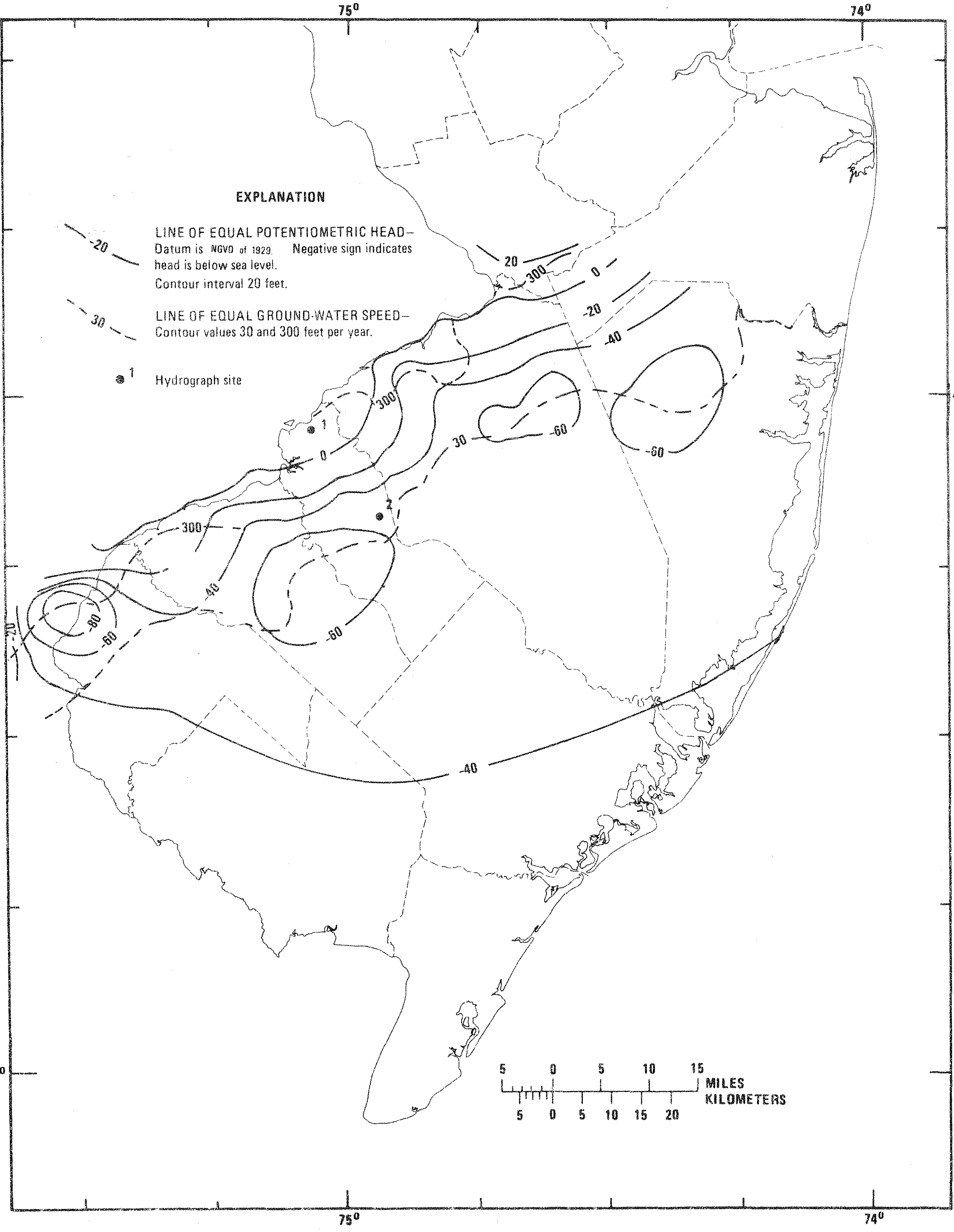

Figure 6.--Heads at the end of 1999 for simulation A90 with conjunctive-use scheme plus 90 percent recharge.

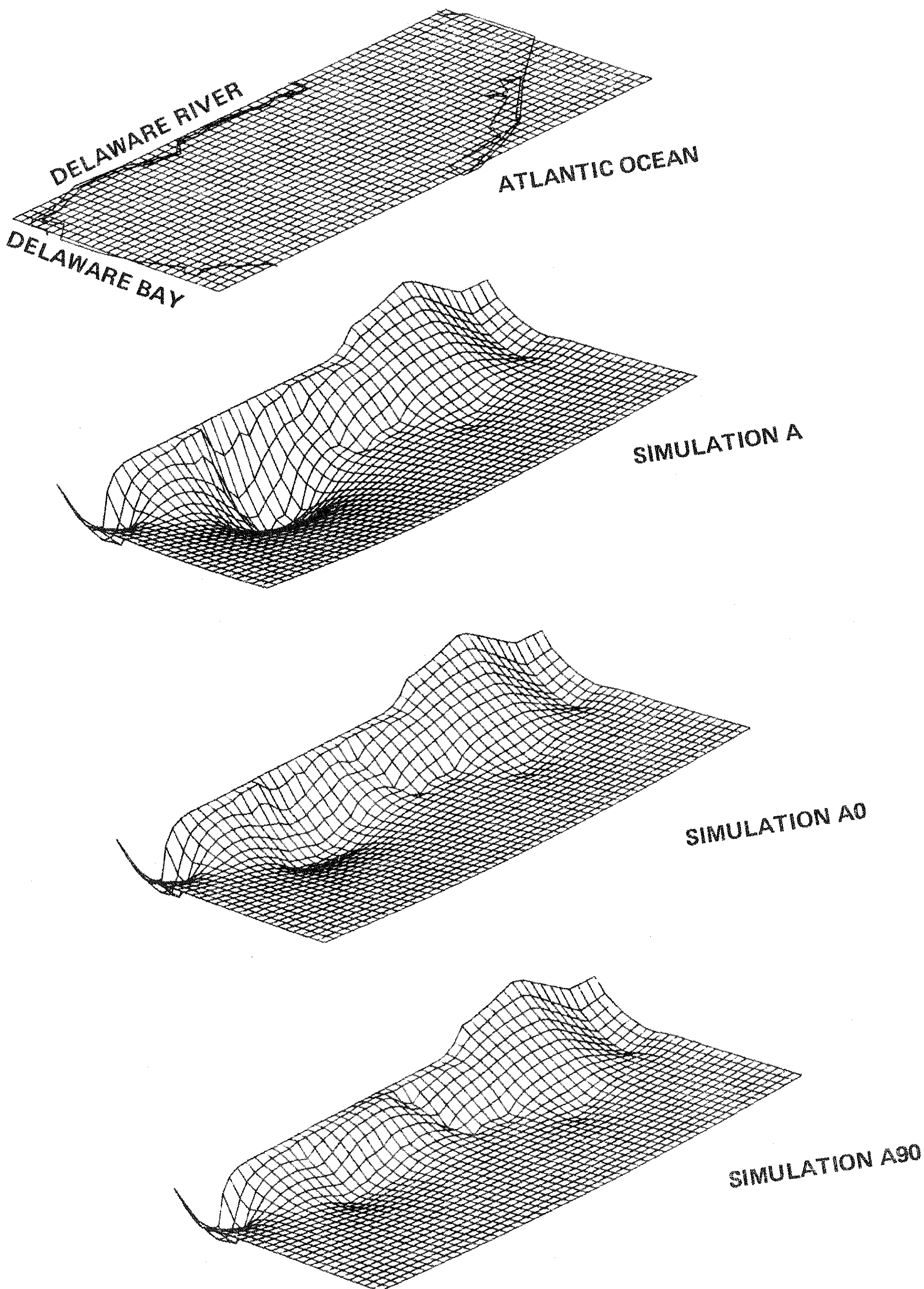

Figure 7.--Perspective view of potentiometric heads for simulations A, A0, and A90 at the end of 1999.

of dispersion. The speed contours also show the effects of conjunctive use. For example, figures 4 and 5 show that simulation A0 (fig. 5) has little effect on speed contours, except in the vicinity of area I, where both the 30 ft/yr and 300 ft/yr contours are moved a few miles west.

Results of group A simulations are also presented in hydrographs at selected sites. The site locations are shown in figures 4, 5, and 6, and the hydrographs are shown in figures 8 and 9. The hydrographs show an increase in head as a result of conjunctive use starting in 1984.

Flows for group A simulations at the end of 1999 are given in table 2. One of the primary reasons for considering conjunctive use is the concern over the amount of recharge induced into the Potomac-Raritan-Magothy aquifer system from the Delaware River. Table 2 shows the effectiveness of conjunctive use in decreasing inflow from the Delaware. For example, in simulation A0, an average withdrawal of 168 ft^3/s from the river near Trenton for conjunctive use will reduce net induced recharge by 127 ft^3/s, as compared with simulation A. Reduction of net induced recharge from the river is about 75 percent of the surface-water withdrawal for simulations A0 and A90.

To evaluate the cost of implementing the conjunctive-use schemes, one must know the projected water-use rate, the withdrawal rate from the river, the pumping rate, and the artificial recharge rate within area I. These rates may be calculated from the 1973 pumping rate in area I, which is 133 ft^3/s.

For example, consider group A simulations in 1984, the first year of conjunctive use. If water-use rate, U, is the 1973 rate compounded at 3 percent annually for 11 years, then:

$$U = 133 \times 1.03^{11} = 184 \ ft^3/s$$

Consider simulation A90 for 1984, in particular. The pumping rate is 0 for 7 months of the year and U for 5 months. This is an average rate of 5/12(U) or 77 ft^3/s. The recharge rate is 90 percent of U or 166 ft^3/s for 7 months and 0 for 5 months, an average yearly rate of 97 ft^3/s. The withdrawal rate from the river is the pumpage replacement rate plus the artificial recharge rate. This is 0 for 5 months and U + 90 percent of U or 350 ft^3/s for 7 months. These calculations may be made at any time in groups A, B, and C simulations.

Group B Simulations

For group B simulations, annual water use was projected, as for group A, by applying a 3 percent annual growth in pumping to wells existing in 1973. A head barrier makes group B simulations different from group A.

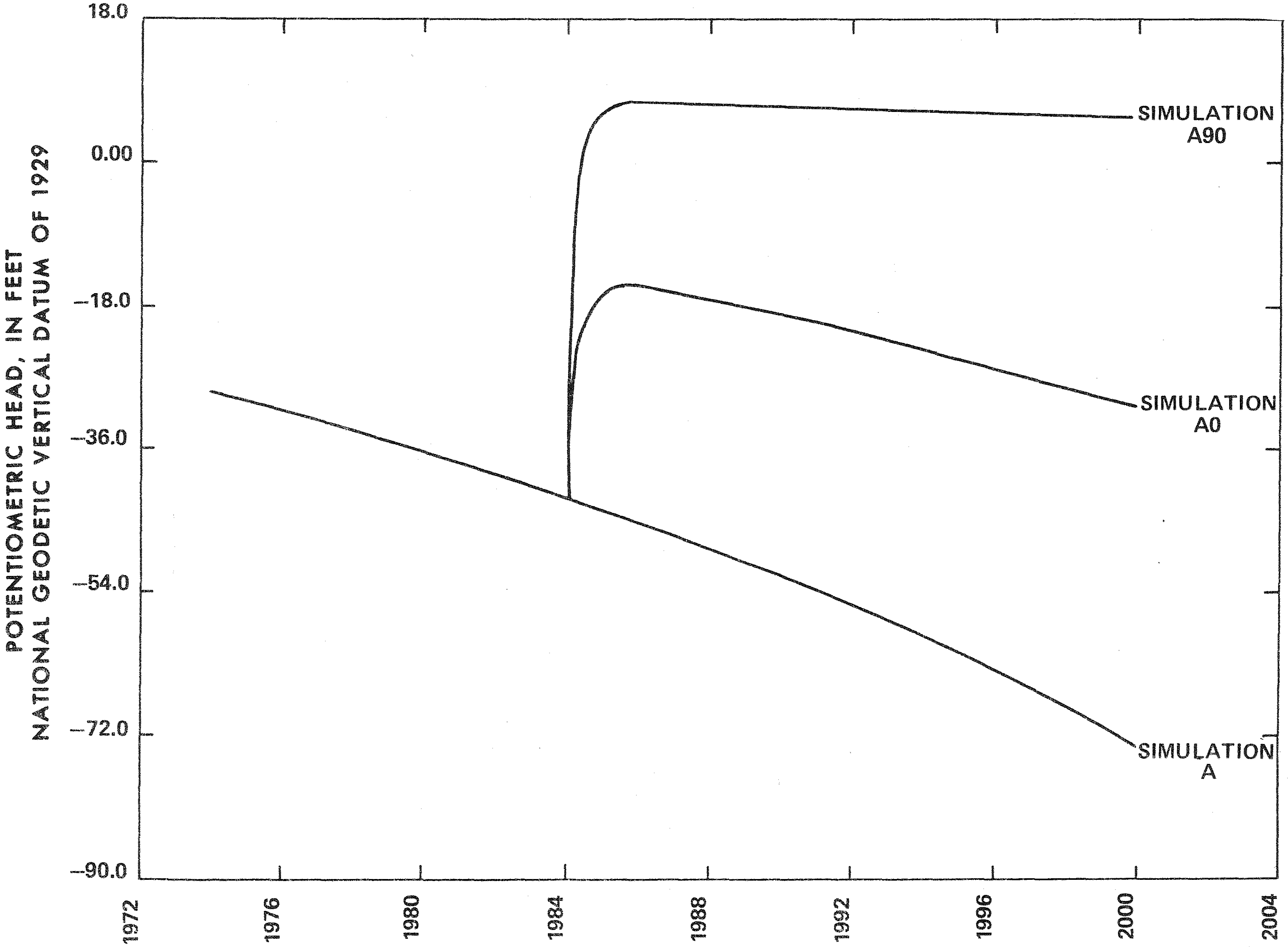

Figure 8.--Hydrographs for group A simulations at site 1.

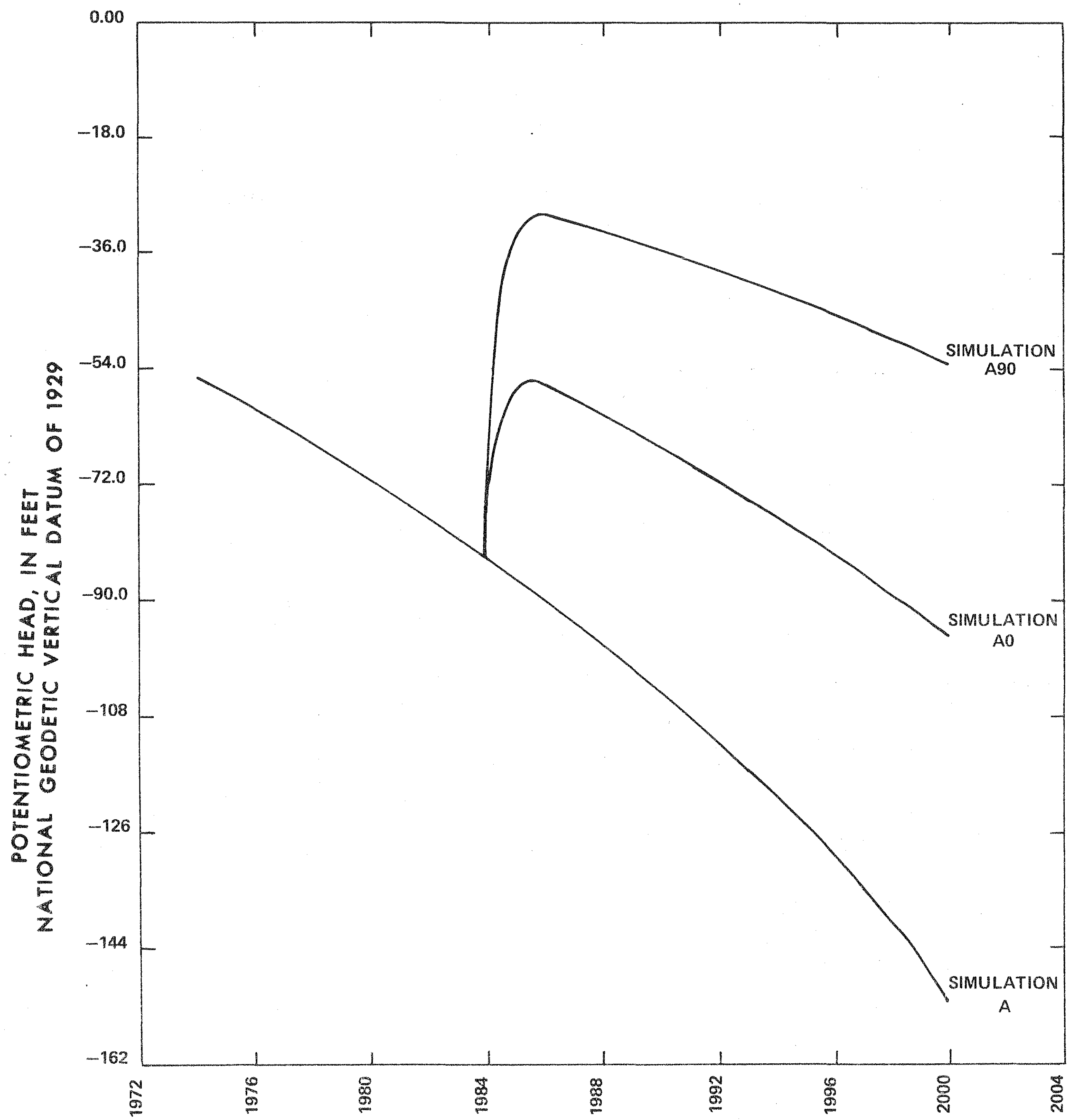

Figure 9.--Hydrographs for group A simulations at site 2.

Table 2.--Model flow rates at end of 1999 for group A simulations
(cubic feet per second)

Model simulation	Pumping	Artificial recharge	Withdrawal from Delaware River[1]	Net induced recharge from Delaware River[2]	Leakage from overlying aquifers	Recharge from precipitation on outcrop area	Release from aquifer storage	Other sources[3]
A	725	--	--	300	169	96	13	149
A0	557	--	168	173	134	96	10	145
A90	557	152	320	64	95	96	8	142

[1] Withdrawal from the Delaware River is not a part of the model, but it is a result of the assumptions used in the simulations.

[2] Consists of net induced recharge from constant head boundary along and near Delaware River.

[3] Consists of net induced recharge from constant head boundary other than along and near Delaware River. See Luzier (1980) for description and location of constant head boundary.

The head barrier consists of 19 simulated wells with heads maintained at 10 ft above National Geodetic Vertical Datum of 1929 beginning in 1984. These simulated wells (fig. 10) are along the saltwater-freshwater transition zone (Luzier, 1980). This barrier was considered by Luzier (1980) as a means of preventing further northwestward movement of salt water. It is assumed for the simulations that the 10 ft head is maintained by injection of fresh water supplied from a source external to the Potomac-Raritan-Magothy aquifer system. Identification of a source need not be specified for modeling purposes. Besides preventing the movement of salt water, the barrier provides recharge to the Potomac-Raritan-Magothy aquifer. Specific group B simulations are listed below.

Simulation B: no conjunctive use--entire water use comes from pumpage

Simulation B0: replacement of pumpage by surface water for 7 months annually

Simulation B90: replacement of pumpage by surface water for 7 months annually plus recharge at 90 percent of the projected water-use rate

Potentiometric contour maps from group B simulations are shown in figures 10-12. Comparison of simulation B0 with simulation B at the end of 1999 (figs. 10 and 11) shows that the conjunctive-use scheme without recharge results in heads that are about 60 ft higher at the center of the cone of depression near area I. Figure 13 shows perspective views of heads in group B simulations at the end of 1999. The ridge caused by the barrier wells is prominent in these views.

The effect of the head barrier is also apparent in the group B simulation hydrographs (figs. 14-16). See figures 10-12 for hydrograph locations. In the hydrographs, simulation B, which has no conjunctive use, shows a rise in head beginning in 1984. This rise is a result of the head barrier. The effect of the barrier is greatest close to the barrier. The hydrograph at site 3 which is close to the barrier, shows a large effect from the barrier (simulation B) and only a slight additional effect from conjunctive use (simulations B0 and B90). (See fig. 16.)

Flows for group B simulations are shown in table 3. Inflow from the head barrier is included in this table. As more surface water is used for conjunctive-use and recharge schemes, less inflow from the barrier wells is required to maintain heads at 10 ft.

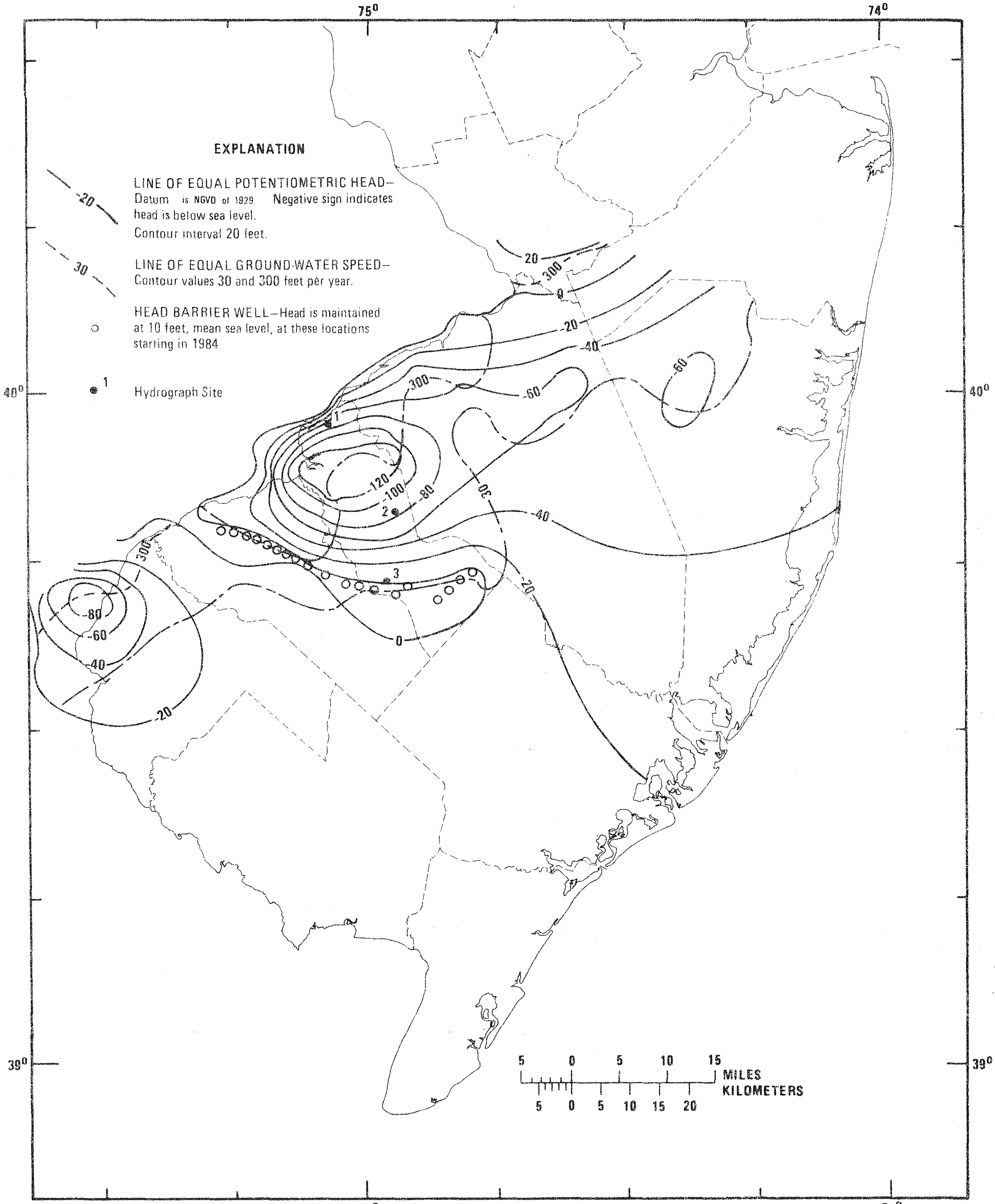

Figure 10.--Heads at the end of 1999 for simulation B without conjunctive-use scheme.

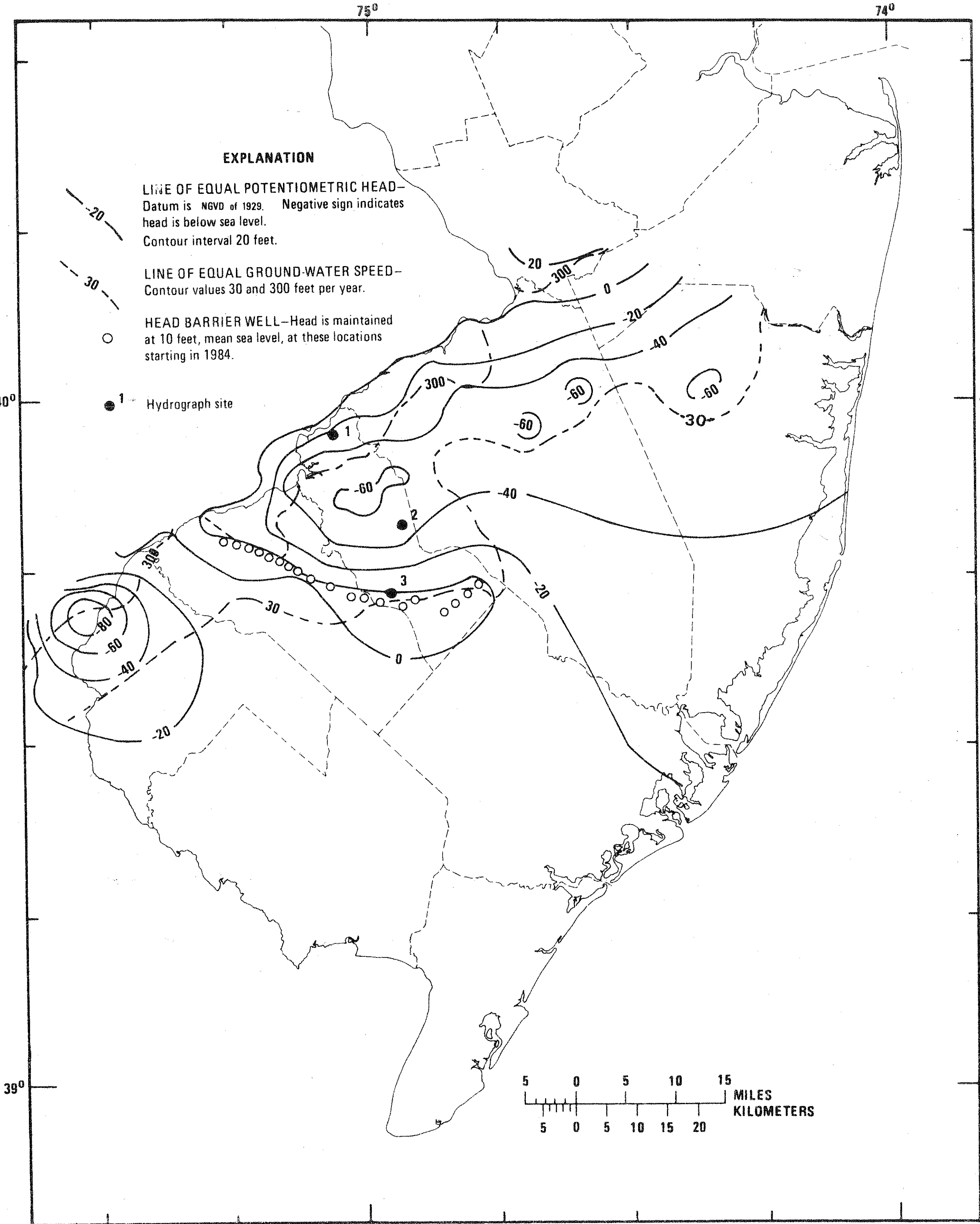

Figure 11.--Heads at the end of 1999 for simulation B0 with conjunctive-use scheme.

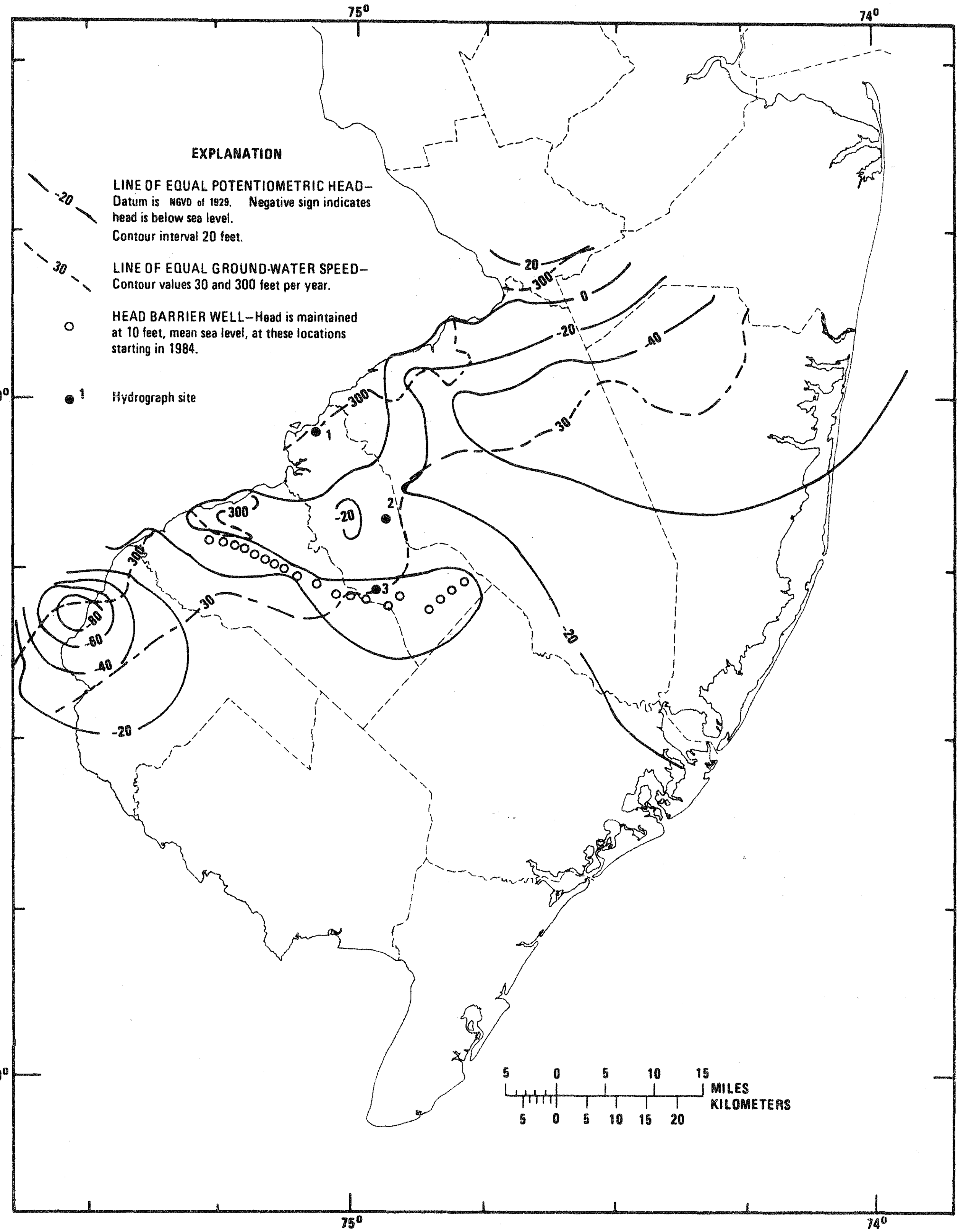

Figure 12.--Heads at the end of 1999 for simulation B90 with conjunctive-use scheme plus 90 percent recharge.

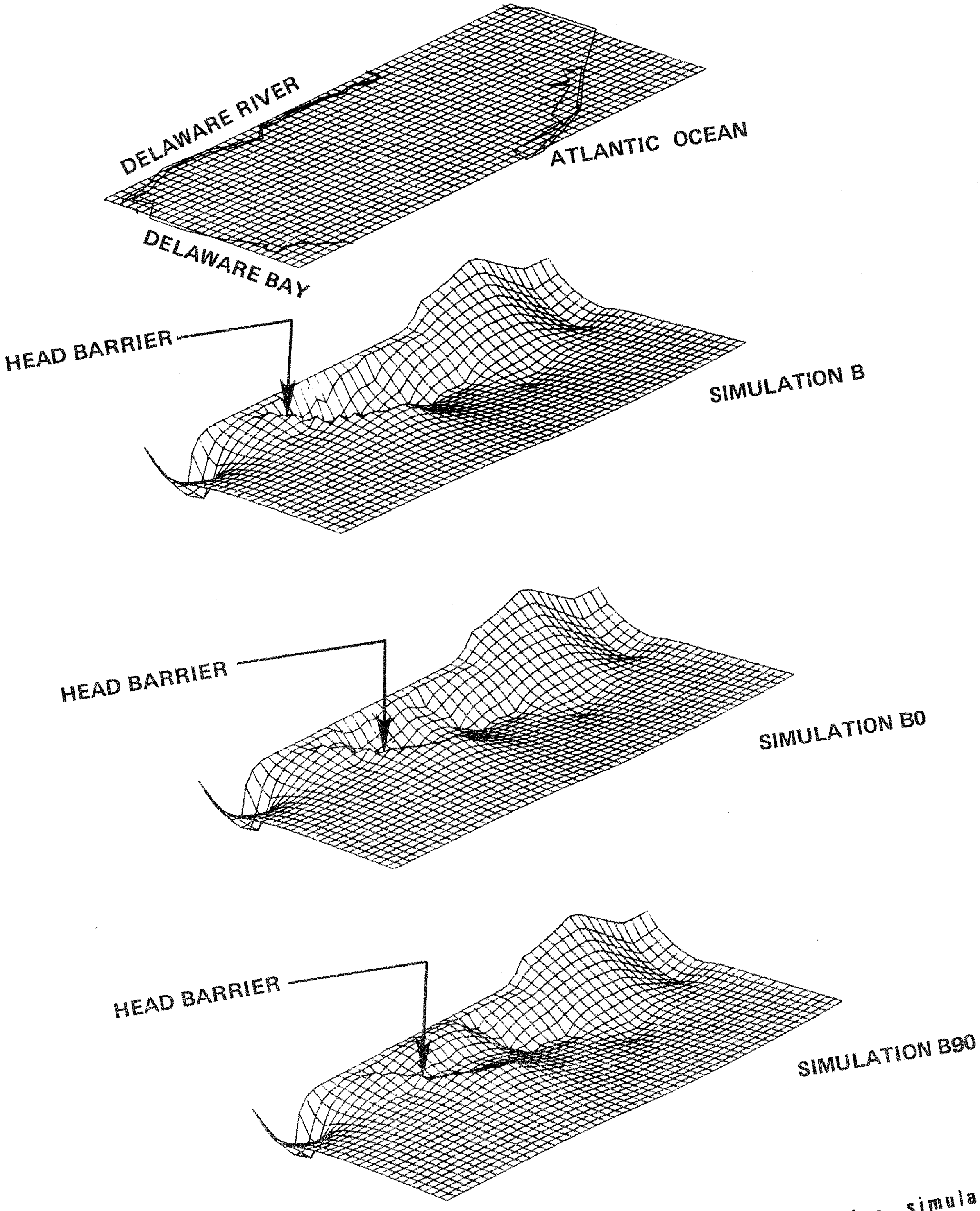

Figure 13.--Perspective view of potentiometric heads for simulations B, B0, B90 at the end of 1999.

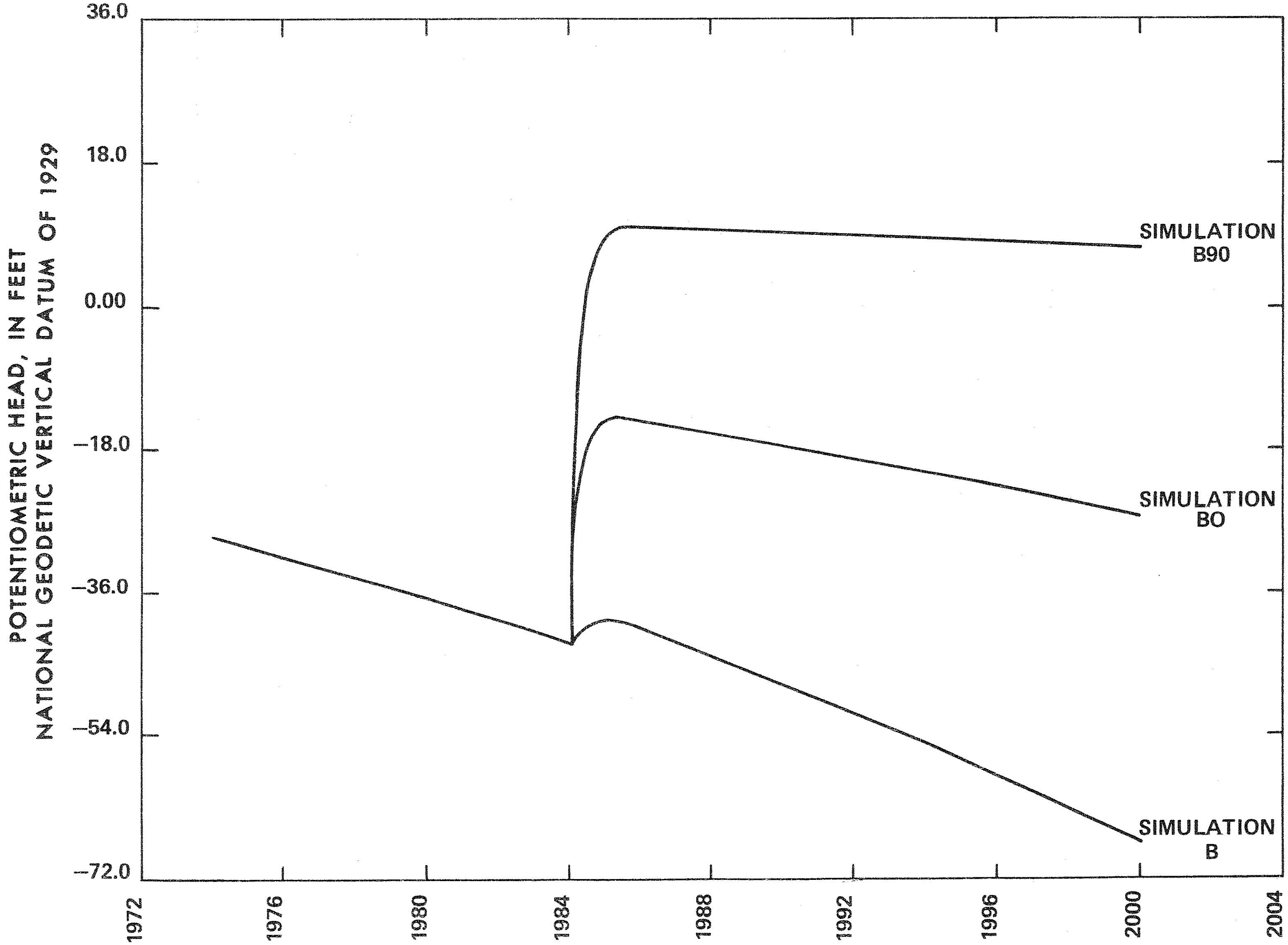

Figure 14.--Hydrographs for group B simulations at site 1.

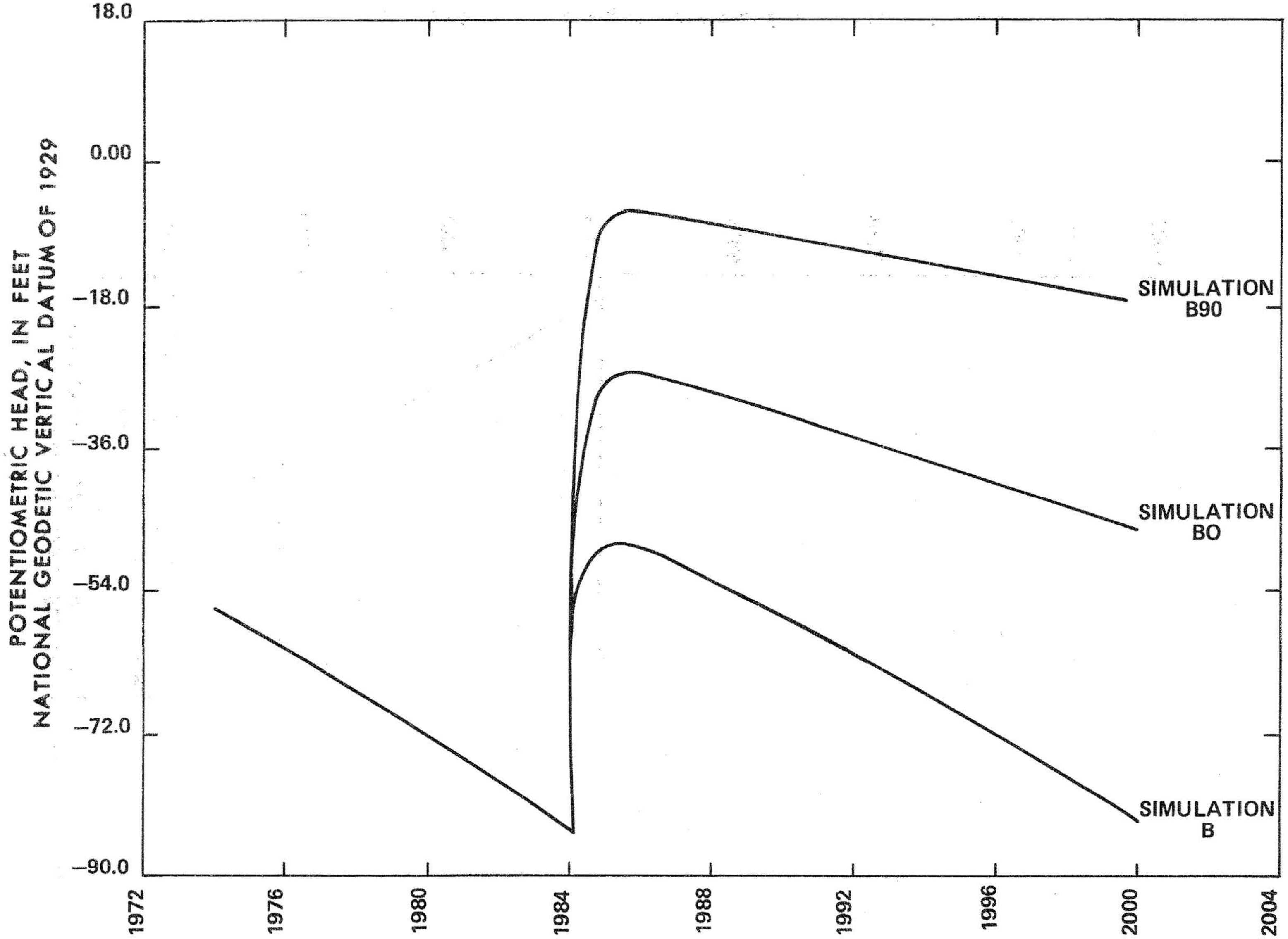

Figure 15.--Hydrographs for group B simulations at site 2.

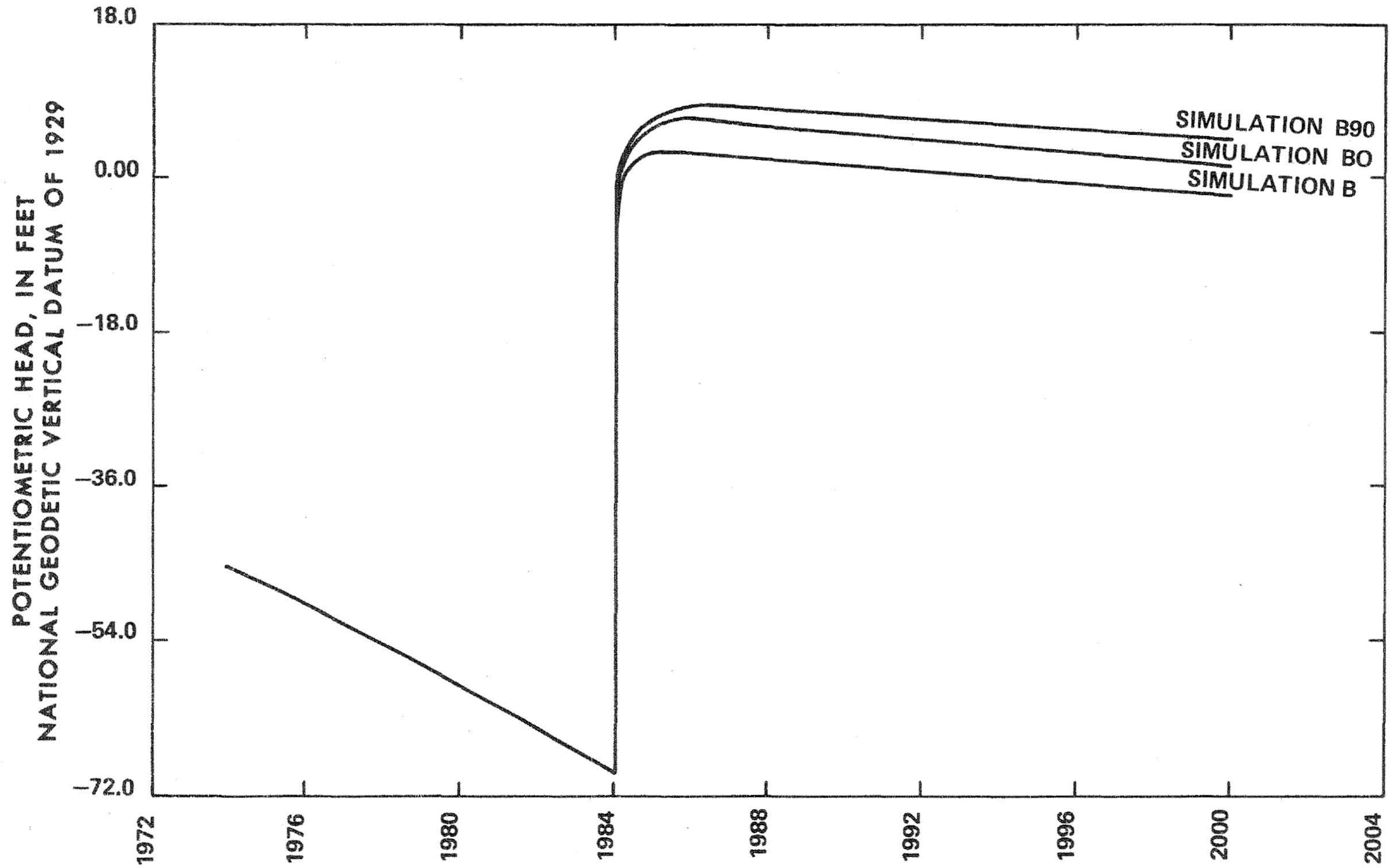

Figure 16.--Hydrographs for group B simulations at site 3.

Table 3.--Model flow rates at end of 1999 for group B simulations
(cubic feet per second)

Model simulation	Pumping	Artificial recharge	Withdrawal from Delaware River[1]	Net induced recharge from Delaware River[2]	Leakage from overlying aquifers	Recharge from precipitation on outcrop area	Inflow from head barrier	Release from aquifer storage	Other sources[3]
B	725	--	--	248	147	96	93	7	138
B0	557	--	168	134	115	96	73	6	136
B90	557	152	320	35	79	96	56	6	135

[1] Withdrawal from the Delaware River is not a part of the model, but it is a result of the assumptions used in the simulations.

[2] Consists of net induced recharge from constant head boundary along and near Delaware River.

[3] Consists of net induced recharge from constant head boundary other than along and near Delaware River. See Luzier (1980) for description and location of constant head boundary.

Group C Simulations

For group C simulations, projected water-use outside of area I is calculated through the use of a 2 percent annual water-use growth for wells existing in 1973. In area I, however, 1 percent annual growth is applied. The 2 percent and 1 percent values were generalized from estimates of water use for Camden, Burlington, and Gloucester Counties up to year 2030 provided by the U.S. Army Corps of Engineers (written commun., 1978).

Group C simulations are listed below. There is no head barrier.

Simulation C: no conjunctive use--entire water use comes from pumpage

Simulation CO: replacement of pumpage by surface water for 7 months annually

Simulation C90: replacement of pumpage by surface water for 7 months annually plus recharge at 90 percent of the projected water-use rate

Results from group C simulations are shown in potentiometric contour maps (figs. 17-19) and in hydrographs (figs. 20-21). Conjunctive use without recharge results in a head difference of more than 30 ft. between simulations C and CO at the end of 1999, (figs. 17 and 19). The flows for group C simulations are shown in table 4. Again, conjunctive use is effective in reducing the stress on the Potomac-Raritan-Magothy aquifer system.

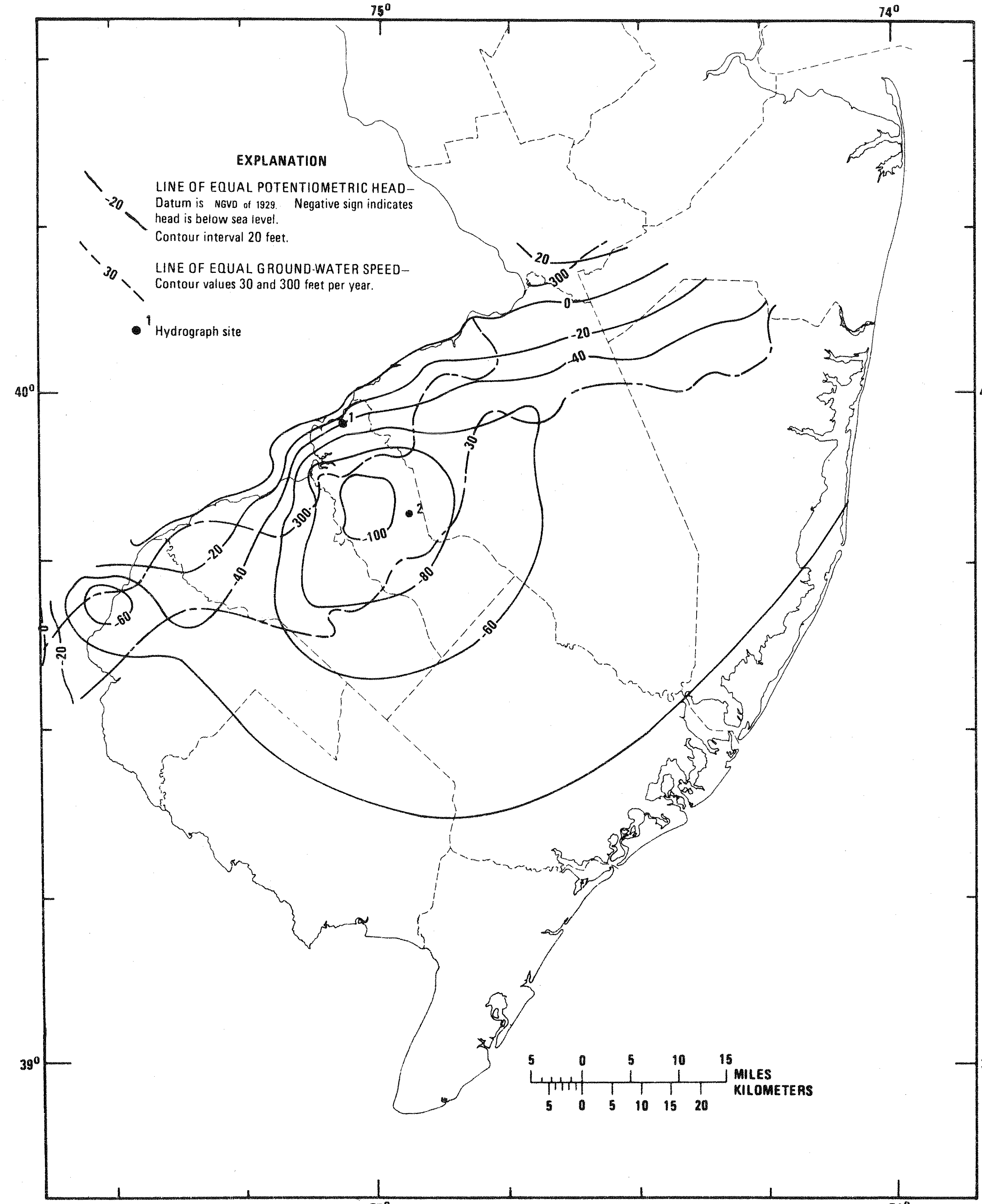

Figure 17.--Heads at the end of 1999 for simulation C without conjunctive-use scheme.

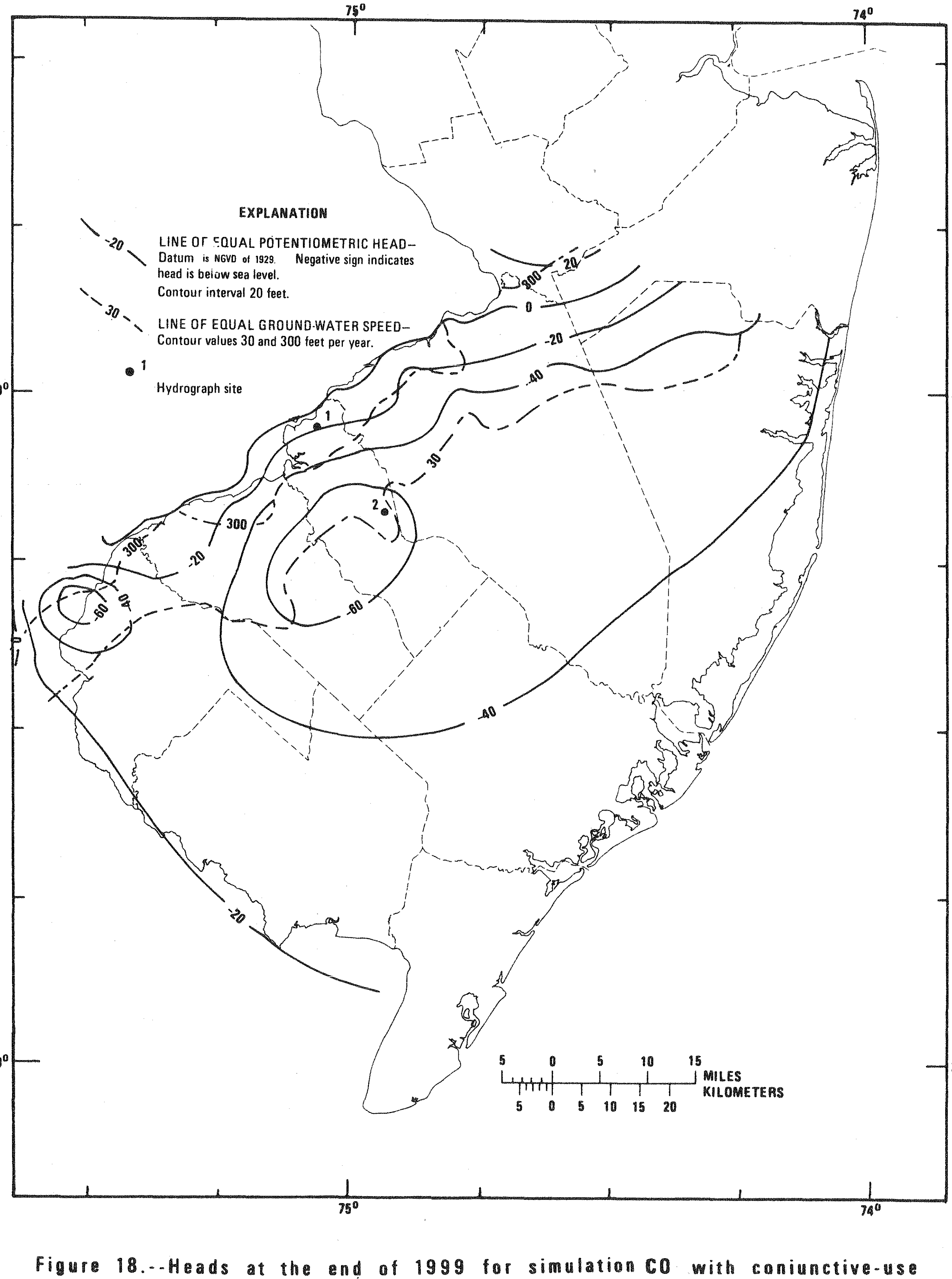

Figure 18.--Heads at the end of 1999 for simulation CO with conjunctive-use scheme.

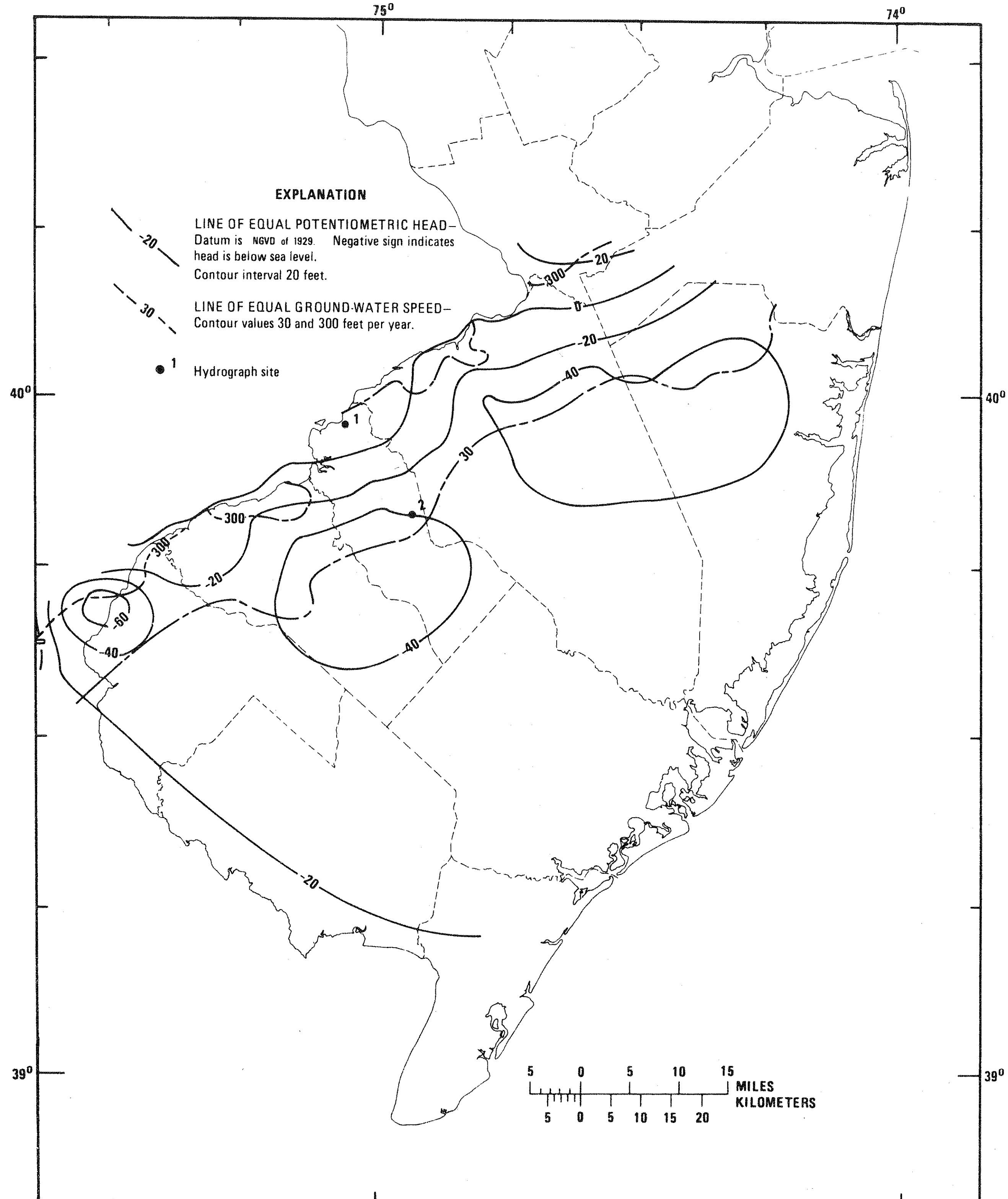

Figure 19.--Heads at the end of 1999 for simulation C90 with conjunctive-use scheme plus 90 percent recharge.

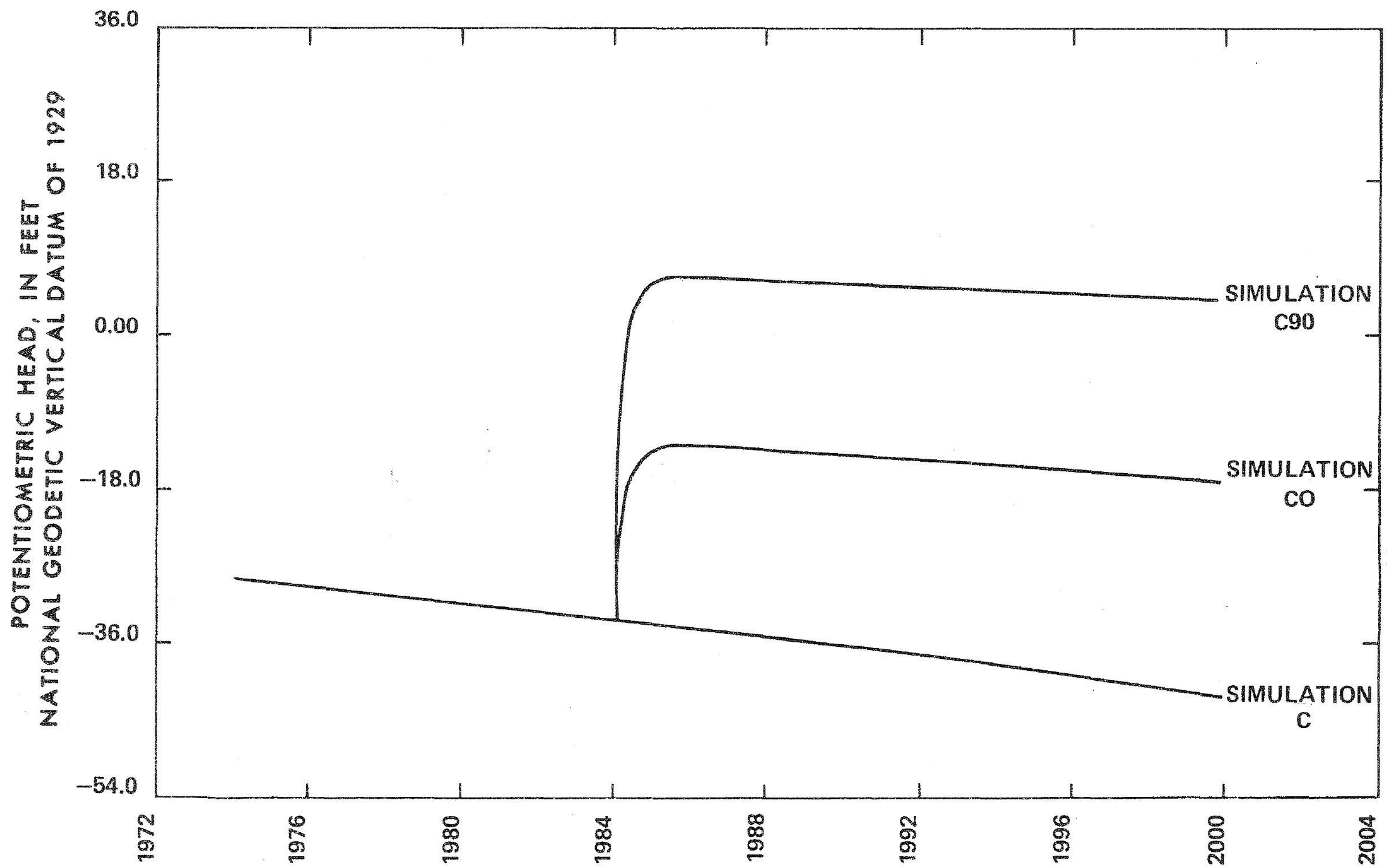

Figure 20.--Hydrographs for group C simulations at site 1.

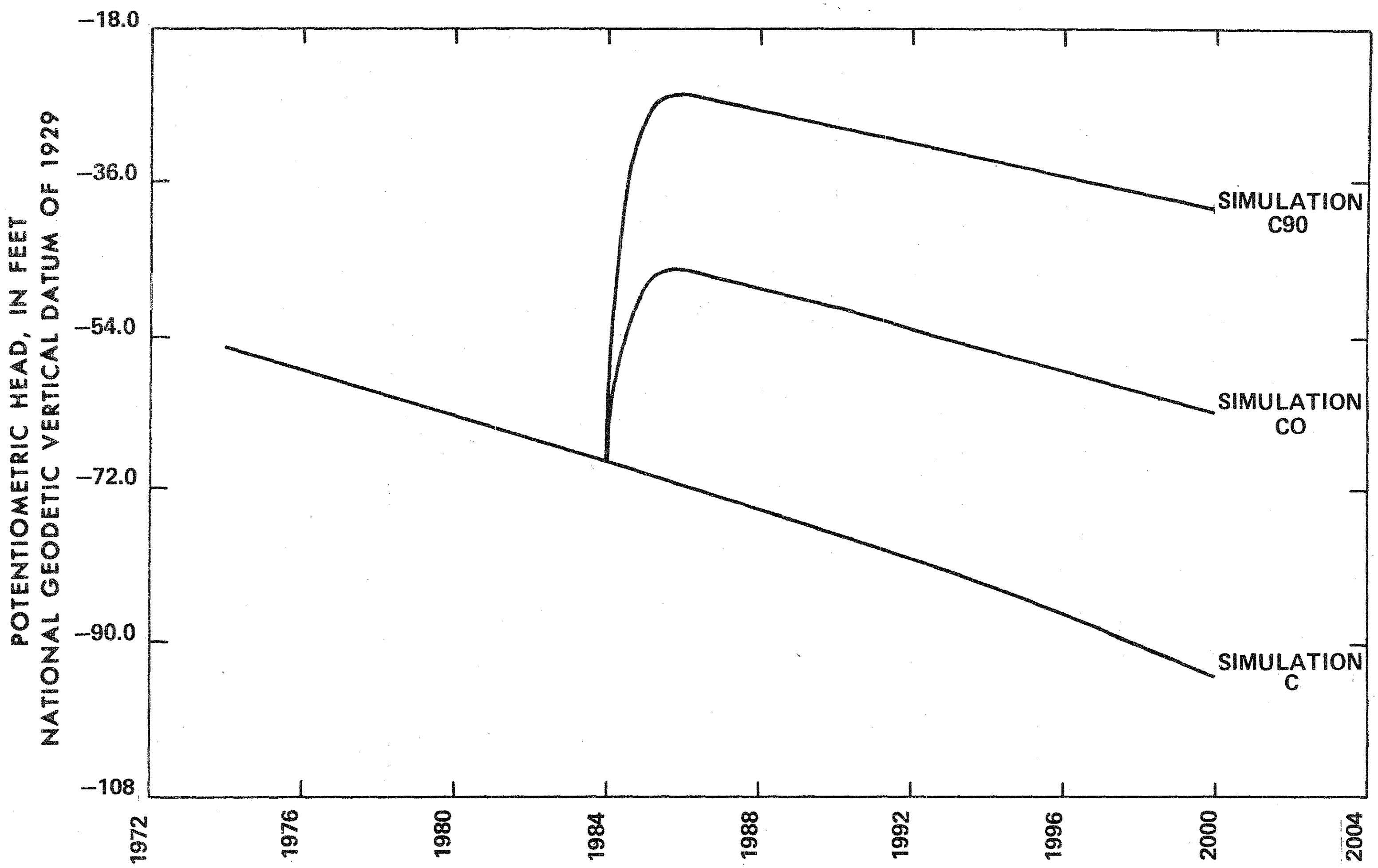

Figure 21.--Hydrographs for group C simulations at site 2.

Table 4.--Model flow rates at end of 1999 for group C simulations (cubic feet per second)

Model simulation	Pumping	Artificial recharge	Withdrawal from Delaware River[1]	Net induced recharge from Delaware River[2]	Leakage from overlying aquifers	Recharge from precipitation on outcrop area	Release from aquifer storage	Other sources[3]
C	512	--	--	176	131	96	6	104
CO	411	--	101	102	107	96	5	101
C90	411	91	192	38	83	96	5	99

[1] Withdrawal from the Delaware River is not a part of the model, but it is a result of the assumptions used in the simulations.

[2] Consists of net induced recharge from constant head boundary along and near Delaware River.

[3] Consists of net induced recharge from constant head boundary other than along and near Delaware River. See Luzier (1980) for description and location of constant head boundary.

DISCUSSION OF RESULTS

Effect of the Head Barrier

The effect of the simulated head barrier may be seen by comparing the results of group B simulations with those of group A. At and near the barrier, group B heads (figs. 10-12) are higher than group A (figs. 4-6), and the cone of depression near area I is much smaller and shallower in group B. The higher heads in group B are the result of water injected into the aquifer at the barrier (table 3). This additional water causes less water to infiltrate from the river in group B simulations than in group A (tables 2 and 3).

The head barrier is included to prevent the northward movement of saline water toward pumping centers. By comparing the direction of head gradient, which is the direction of ground-water flow, for groups A and B, one can see the effect of the barrier. In group A, the direction of flow near the barrier is generally from the south toward the center of the cone of depression. In group B, however, the direction of flow is different on each side of the barrier. North of the barrier, simulated flow is toward the center of the cone of depression. This flow consists of fresh water from the barrier wells. South of the barrier, direction of flow is reversed. Thus, saline water on the south does not pass the barrier.

The effectiveness of the head barrier is dependent upon maintaining a continuous line of head at 10 feet or more. Although 19 wells were used to simulate the head barrier, it would probably be desirable to use more wells in a real situation. The 10 foot heads maintained in the simulated wells are average values. Heads at each injection site would be much higher than this average value. The greater the spacing is between wells, the higher the heads must be at each well in order to prevent heads between wells from dropping below 10 feet.

Effect of Water-Use Growth Rate

The effect of water-use growth rates may be seen by comparing group A simulations with group C. In 1999, the total projected water use in the Potomac-Raritan-Magothy aquifer is 725 ft^3/s for group A simulations and 512 ft^3/s for group C. This large difference results in higher heads in group C simulations. The head near the center of the cone of depression is 160 ft below sea level for simulation A (fig. 4) and 100 ft below sea level for simulation C (fig. 17). This head difference, caused by the different growth percentages, suggests that a firm estimate of water use is required before conjunctive use can be evaluated. No attempt has been made in this study to evaluate the validity of the two growth schemes used.

Steady State Conditions

The hydrographs (figs. 8-9, 14-16, and 20-21) show sharp increase in head after application of conjunctive use in 1984. It takes 2 years or less for the heads to reach their maximum level before starting the downward trend again. The rapid response is a reflection of the low storage coefficient of the aquifer system. If changes in stresses (pumping and artificial recharge) stopped at any time during the model simulations, heads would approach steady-state conditions within 2 years. Steady-state levels would be between the heads existing at the time that changes in stresses stopped and the heads that would have occurred 2 years later, assuming that changes in stresses did not stop. In the simulations, heads decrease slowly in response to the annual water-use increase except during 1984-85 in the conjunctive-use simulations. If changes in stresses stopped during slow head change, the steady state levels would be approximately the same as the water levels when the stresses became constant.

Stopping Head Declines

Heads continue to decrease in the simulations after 2 years of conjunctive use because of the continued growth of pumping. Pumping outside of area I is growing at the assumed growth rate since no conjunctive use is applied. Inside area I, during the first year of conjunctive use, pumping decreases to 5/12 of the water-use rate. But in subsequent years, pumping increases again inside of area I because the pumping during the 5 months of no conjunctive use is increasing at the assumed growth rate. Although growth in pumping rate is smaller than without conjunctive use, there is still growth.

There are two methods of stopping head declines. One would be to hold the pumping rate constant with no artificial recharge, and the other would be to balance pumpage with artificial recharge. If a constant pumping rate were maintained, then heads would approach steady state rapidly. Any increase in demand for water would have to be from a source outside the Potomac-Raritan-Magothy aquifer system.

Although it would be possible to stop head declines by balancing pumpage and artificial recharge, the model simulations show that it would be difficult to stop declines everywhere by recharging in area I. This is because recharge is most effective at the location of recharge, and the effect decreases rapidly away from the recharge site. A comparison of simulations A (fig. 4) and A90 (fig. 6) shows that the effect of conjunctive use in simulation A90 is greater in area I than far from area I. The most effective method of artificial recharge, then, would be to inject water at every pumping location; however, this would be economically impractical. The recharge schemes simulated in this study were applied within area I, a small but highly pumped area. Examination of the hydrographs for simulation A90 at sites 1 and 2 (figs. 8 and 9) shows that pumpage and recharge are close to being at equilibrium (no head decline or rise) at site 1, but not at site 2. Theoretically, enough water could be recharged in area I alone to offset or even reverse declines in all areas. However, the amount of recharge required would result in a tremendous buildup of water levels within area I, causing much of the recharge to discharge into the Delaware River. The amount of recharge needed would be much greater than the total Potomac-Raritan-Magothy aquifer system pumpage. It would be impractical to attempt to recharge this quantity of water.

SUMMARY AND CONCLUSIONS

Model results show that conjunctive use of Delaware River water and ground water could be an effective method of slowing decline of the potentiometric head in the Potomac-Raritan-Magothy aquifer system. In the simulations, heads rise when conjunctive-use is first applied, but decline again within 2 years. Continued growth of water use causes the resumption of declines. Declines after conjunctive use begins are slower. Depending on the amount of water used and the conjunctive-use scheme applied, heads at year 2000 could be at or above present levels over a large area of the aquifer.

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