RELATION OF GROUND-WATER FLOWPATHS AND TRAVEL TIME TO THE DISTRIBUTION OF RADIUM AND NITRATE IN CURRENT AND FORMER AGRICULTURAL AREAS OF THE KIRKWOOD-COHANSEY AQUIFER SYSTEM, NEW JERSEY COASTAL PLAIN

By Donald E. Rice and Zoltan Szabo

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
	Flow	
gallon per minute (gal/min)	0.06308	liter per second
	Hydraulic conductivity	
foot per day (ft/d)	0.3048	meter per day

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929-- a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Water-quality abbreviations:

mg/L - milligrams per liter
pCi/L - picocurie per liter

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ABSTRACT

Results of two-dimensional finite-difference simulations of ground-water flow along sections through the Kirkwood-Cohansey aquifer system in southwestern New Jersey were used to predict ground-water flowpaths and travel times beneath active or historical agricultural areas. Ground-water travel times increased with depth in the aquifer system, and travel times to the nested observation wells approximately matched the ranges of apparent ground-water ages determined by tritium age-dating. Simulation results showed that ground-water flowpaths extend downward and away from the ground-water divide, across the modeled sections, and then upward near the ground-water discharge boundary. Simulation results also show that ground water from agricultural areas travels along flowpaths that extend beneath adjacent forested land at depth.

The flowpaths and travel times predicted from simulation results were used to develop a conceptual model of the distribution of elevated concentrations of radium ($\geq$ 5 pCi/L) and nitrate (> 3 mg/L) within the aquifer as follows:

1. Because travel time increases with depth in the modeled aquifer sections, water containing elevated concentrations of radium and nitrate extends downward in the aquifer to a maximum depth of penetration limited by the time since intensive application of modern agricultural chemicals began (about 50 years ago). Therefore, this maximum depth of penetration is delimited by the 50-year line of equal travel time.

2. Water below the 50-year line of equal travel time predates the application of agricultural chemicals and is unlikely to contain elevated concentrations of radium and nitrate.

3. Water containing elevated concentrations of radium and nitrate originates in an agricultural area and can move along a flowpath that extends from the agricultural area to an area at depth in the aquifer that is overlain by nonagricultural land.

The conceptual model can be used to predict the aquifer areas that are likely to contain elevated concentrations of radium and nitrate. These aquifer areas are found beneath agricultural land where ground-water travel time is less than 50 years, and beneath nonagricultural land adjacent to agricultural land where ground water was recharged through agricultural land and has a travel time of less than 50 years. Concentrations of radium and nitrate in water samples from the nested observation wells and piezometers generally support the conceptual model.

INTRODUCTION

Radium in drinking water in concentrations greater than 5 pCi/L, the U.S. Environmental Protection Agency (USEPA) Maximum Contaminant Level (MCL), is known to increase cancer risks (Mays and others, 1985). According to the USEPA, the total risk posed by radionuclides in drinking-water supplies is greater than that posed by all other toxic chemicals (Cothern, 1987). During routine regulatory monitoring conducted by the New Jersey Department of Environmental Protection (NJDEP), levels of dissolved radium and gross-alpha particle activity greater than the USEPA MCL were detected in water from many public-supply systems. Water-quality data from 81 production wells sampled by the U.S. Geological Survey (USGS) (Kozinski and others, 1995) indicate a correlation between elevated concentrations of dissolved radium and areas of intensive agricultural land use where the outcrop of the Bridgeton Formation overlies the Kirkwood-Cohansey aquifer system. Because water withdrawn from the Kirkwood-Cohansey aquifer system, the principal unconfined aquifer of the southern Coastal Plain of New Jersey (fig. 1), is used for drinking-water supply, the presence of elevated levels of radium in the aquifer is of public concern.

In 1990, the USGS, in cooperation with the NJDEP, began a study to define the geochemical and hydrologic processes that control radium distribution in water in the Kirkwood-Cohansey aquifer system of the southern Coastal Plain of New Jersey. The hypothesis tested is that the quality of ground water in an agricultural area, especially with regard to concentrations of radium, varies with depth. If radium is mobilized in water whose chemical character has been changed by the leaching of agricultural chemicals, as concluded by Kozinski and others (1995), then radium is likely to be present in elevated concentrations at depths where the water quality has been most affected by the leaching of agricultural chemicals. Shallow, young ground water has been shown to be affected by recent leaching of modern agricultural chemicals (such as nitrate and organic pesticides) more than deep, old ground water (Szabo and others, 1994b). To test the hypothesis, variations in water quality, especially concentrations of dissolved radium and nitrate, and ground-water travel time with depth were characterized. The study results are discussed in two reports. The first (Szabo and others, 1997) discusses the geochemistry of the aquifer system and evaluates possible geochemical processes that result in the leaching of radium into solution. This report discusses the effects of the ground-water-flow system on the distribution of radium and nitrate in the aquifer system.

Purpose and Scope

This report presents the results of simulations of ground-water flow, including flowpaths and travel times, in three modeled sections used to determine the distribution of elevated[1] concentrations of radium and nitrate in the Kirkwood-Cohansey aquifer system. The installation of nested observation wells completed in the Kirkwood-Cohansey aquifer system at five sites is described, and the distributions of concentrations of radium and nitrate at the nested-well sites are defined. Travel times along flowpaths to the nested wells that were predicted from simulation results are compared to the range of possible apparent ages of the water determined from tritium age-dating

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[1] In this report, the presence of elevated concentrations of nitrate in ground water is assumed to be a result of the application of agricultural fertilizers. Nitrate concentrations are defined as "elevated" if they are > 3 mg/L, the maximum dissolved nitrate concentration in water from wells in the Kirkwood-Cohansey aquifer system in nonagricultural areas reported by Szabo and others (1997). Radium concentrations are defined as "elevated" if the sum of the concentrations of radium-226 and radium 228 is ≥ 5 pCi/L. This value is based on the maximum value of 4.8 pCi/L for concentrations of radium-226 and radium-228 reported by Szabo and others (1997) for water from wells in the Kirkwood-Cohansey in nonagricultural areas.

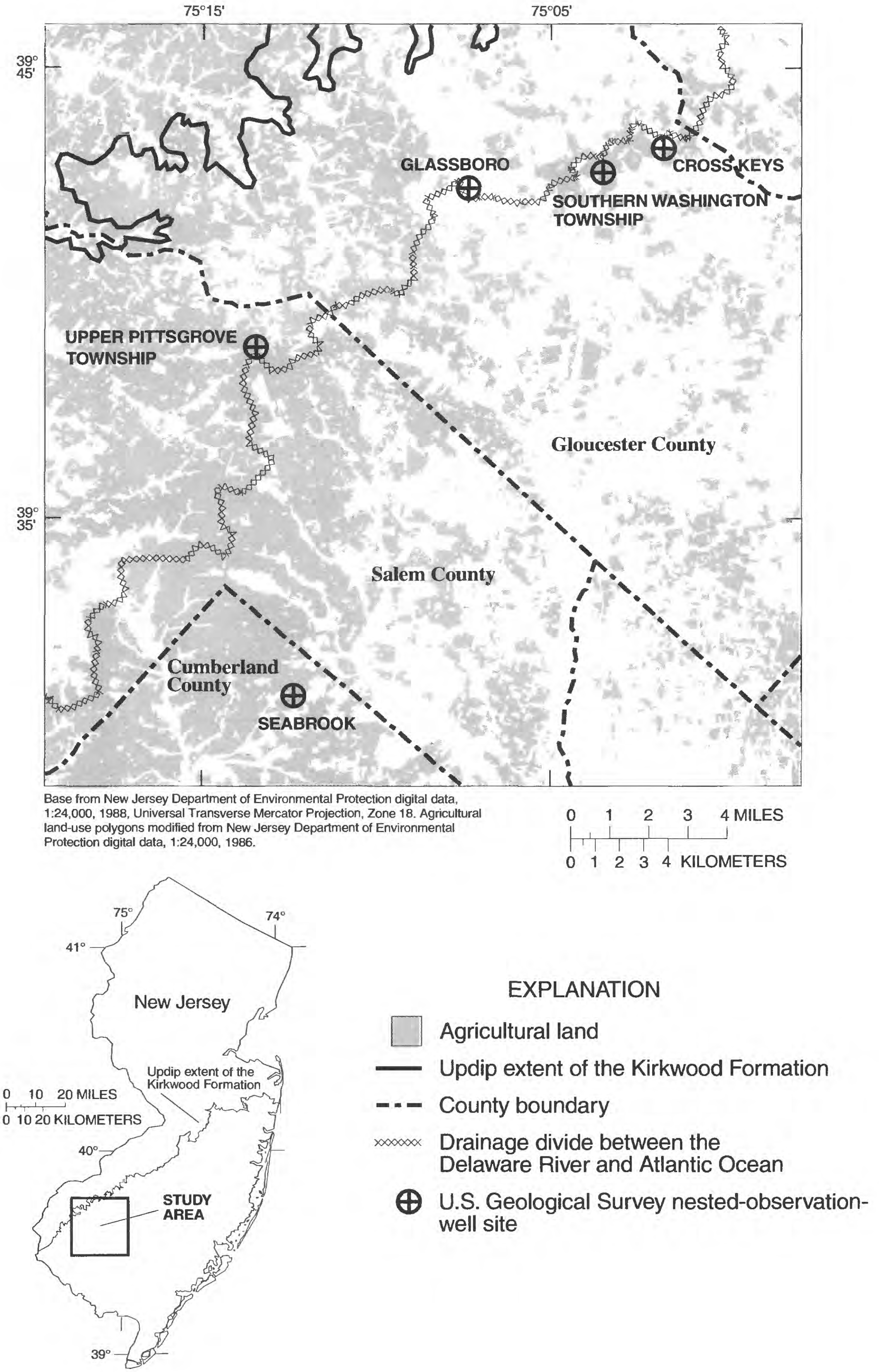


Figure 1. Extent of the Kirkwood-Cohansey aquifer system, area of agricultural land use, and locations of nested-observation-well sites.

techniques. A conceptual model that was developed from an examination of flowpaths, travel times, and water-quality data is used to predict the location of water containing elevated concentrations of radium and nitrate. The conceptual model is evaluated with respect to regional radium-concentration data from wells completed at various depths within the Kirkwood-Cohansey aquifer system, as reported by Kozinksi and others (1995) and Szabo and others (1997).

Acknowledgments

The authors thank Karl Muessig, Sonny Saroya, Barker Hamill, and Barbara Litt of the NJDEP for cooperating in the dissemination of information to the public. We thank Richard Westergaard of the Gloucester County Planning Department for assistance in the planning of drilling operations. The authors also thank the landowners (Washington Township Municipal Utilities Authority, Washington Township, Rowan College, Rutgers University, and William Coles) for allowing the installation of nested observation wells on their property.

DESCRIPTION OF STUDY AREA

The study area lies within the Coastal Plain Physiographic Province (fig. 1) and is characterized by low elevation and relief, both of which decrease from northwest to southeast. The area is predominantly agricultural and covers a large part of southwestern New Jersey in central and eastern Gloucester, eastern Salem, and northern Cumberland Counties. Five sites were selected for detailed study.

Geology and Soils

Uneroded remnants of the Bridgeton Formation that locally overlie the Cohansey Sand along ridgetops (fig. 2), mostly in the western and southwestern part of the New Jersey Coastal Plain (Johnson, 1950: Owens and Minard, 1979), form the surficial material at all five study sites (fig. 1). The Cohansey Sand underlies all the sites and is the thickest unit in the Kirkwood-Cohansey aquifer system. The Kirkwood Formation is a marine unit that forms the basal part of the aquifer system. The Kirkwood Formation crops out west of the study sites (fig. 1). Radium is present throughout these sediments, although concentrations vary slightly(Szabo and others, 1997).

Deposits of the Kirkwood Formation, early to middle Miocene in age, typically are micaceous, and calcareous shell material is abundant locally (Owens and Sohl, 1969, p. 252). The lithology of the Kirkwood Formation is composed of fine- to medium-grained quartz sand and silty sand in the subsurface at the five study sites. Clay beds are present only in the basal part of the Kirkwood Formation (Zapecza, 1989, p. B19).

The Cohansey Sand, middle Miocene in age, is a marginal marine deposit composed predominantly of light-colored, medium- to coarse-grained quartz sand with some gravel and silt. Thin interbedded clay layers are common locally. The Cohansey Sand contains only small amounts of potassium and sodium feldspars and virtually no other weatherable silicate minerals (Owens and Sohl, 1969). The Cohansey Sand contains secondary kaolinite, gibbsite, and silica (Owens and others, 1988; Owens and Sohl, 1969).

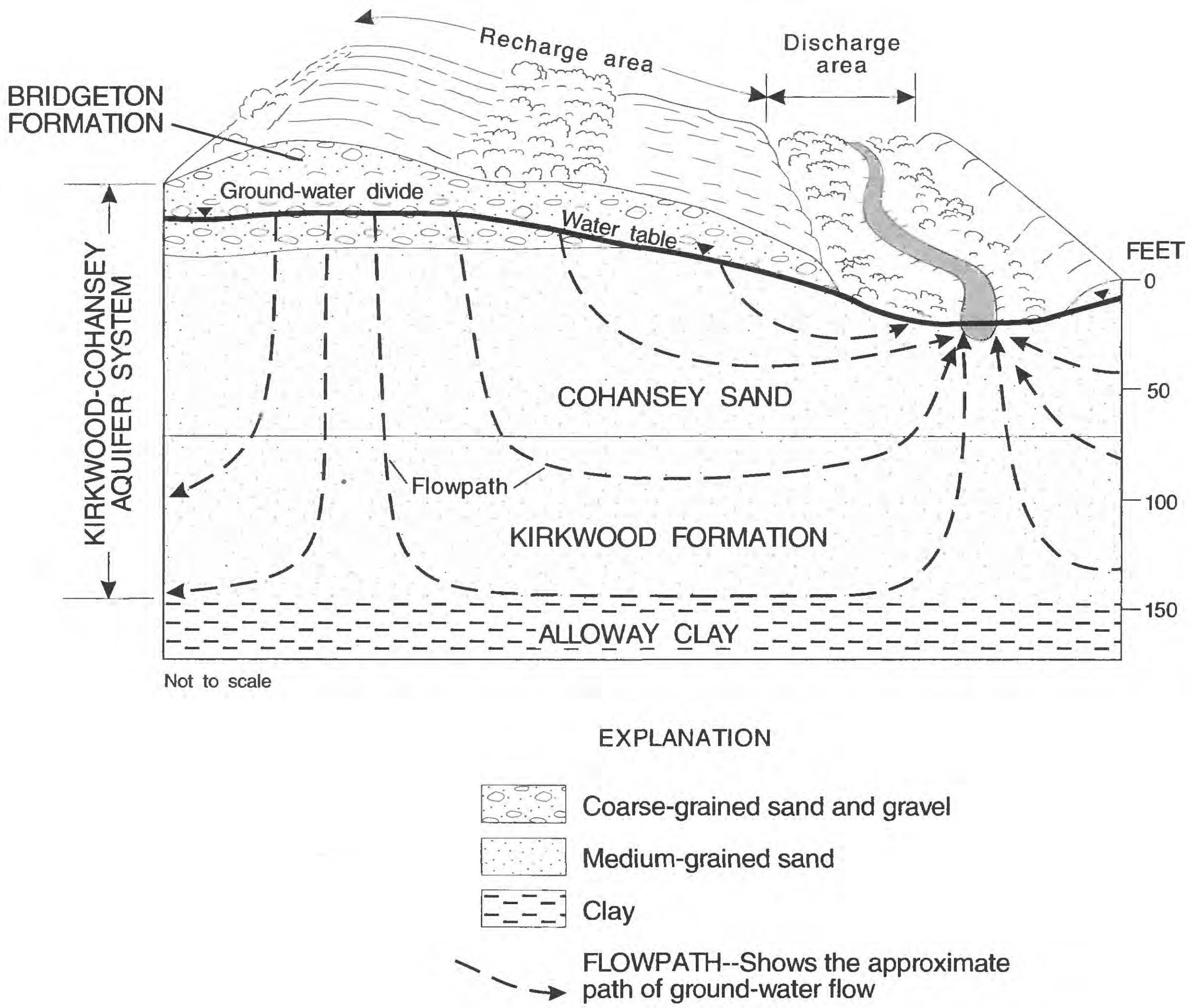


Figure 2. Generalized hydrogeologic section through the Kirkwood-Cohansey aquifer system and idealized ground-water flowpaths, southwestern New Jersey.

The Bridgeton Formation, late Miocene in age, crops out discontinuously throughout the study area, typically at topographic highs. Surficial deposits of the Bridgeton Formation generally are as much as 30 to 50 ft thick in parts of Camden, Gloucester, Salem, Cumberland, and Atlantic Counties (Owens and Minard, 1979, p. D14). The Bridgeton Formation is composed of feldspathic, quartz-rich sand and gravel eroded from bedrock highlands to the north. It is believed to have been deposited in river channels of the ancestral Hudson River that traversed the outcrop area of the Cohansey Sand (Owens and Minard, 1979, p. D 17; Martino, 1981, p. 1).

The soil types present in the study area are controlled primarily by the underlying geologic source material, age of soil, and degree of drainage. Most of the soils developed from the Bridgeton Formation are well-drained and are characterized by loamy, sandy, and gravelly texture (Johnson, 1978). These soils generally have medium to low natural fertility, have low pH (less than 4.5-5.0), and are susceptible to leaching of soil nutrients (Johnson, 1978). Soils developed from the Cohansey Sand generally are well-drained to excessively drained, are loamy and sandy, are relatively infertile, have low pH (less than 3.6-4.4), and are susceptible to leaching (Johnson, 1978). In low-lying, poorly drained areas, loamy, acidic, organic soils have developed from the Cohansey Sand.

Well-drained soils are necessary for commercial agriculture. The slightly less acidic, well-drained, moderately fertile soils that developed from the Bridgeton Formation generally are more suitable for agricultural development, such as commercial vegetable-crop production, than are low lying, poorly drained soils that developed from the Cohansey Sand. A large percentage of the study area underlain by the Bridgeton Formation is used for such commercial agriculture (Szabo and others, 1997). The soils that developed from the Cohansey Sand may be suitable only for specialized agriculture, such as acid-loving native fruit crops. Wetlands, such as those adjacent to streams in the vicinity of the five nested-well sites, are poorly drained and, because they are not suitable for agriculture, remain undeveloped (forested).

Because soils developed on the Bridgeton Formation are well-drained and naturally low in nutrients, they require the application of large amounts of fertilizers, pesticides, and herbicides for maximum crop yields. Most manufactured fertilizers contain nitrogen in the form of ammonia (Severson and Shacklette, 1988). Through the process of nitrification, bacteria in the soil convert (oxidize) ammonia to nitrate (Delwiche, 1970), a soluble nutrient that leaches readily to the ground water. Native fruit-crop production in low lying areas underlain by the Cohansey Sand requires only small amounts of soil additives; however, small amounts of dissolved agricultural chemicals have infiltrated to the ground water in these areas (Kozinski and others, 1995).

Hydrology

The Kirkwood-Cohansey aquifer system, the principal source of potable water in the study area, is an unconfined aquifer that underlies an area of about 3,000 mi^2 southeast of the updip limit of the outcrop of the Kirkwood Formation (Zapecza, 1989, p. B19). In the study area, the aquifer system is composed of hydraulically connected sediments of the Kirkwood Formation and Cohansey Sand, and the overlying deposits of the Bridgeton Formation. Clay beds in the basal part of the Kirkwood Formation form the regional confining unit (Zapecza, 1989, p. B20), which is the base of the aquifer (fig. 2). Local clay beds may cause perched water tables.

Ground water in the Kirkwood-Cohansey aquifer system flows from areas of high elevation to areas of low elevation, such as streams and swamps. In Gloucester County, the water table is more than 140 ft above sea level in areas of topographic highs that form the surface-water divide (Rooney, 1971; Farlekas and others, 1976; Lacombe and Rosman, 1995). The surface-water divide extends into Salem and Cumberland Counties in southwestern New Jersey (Rooney, 1971; Rosenau and others, 1969). This area was chosen as the focus of the study because the topographic highs probably coincide with the ground-water divide.

Recharge to the aquifer system is through direct infiltration of precipitation. Average annual precipitation over the study area ranges from 38 to 45 in. Estimated annual recharge to the Kirkwood-Cohansey aquifer system in Gloucester County is about 18 in. (Lacombe and Rosman, 1995). Rhodehamel (1973) estimates an annual recharge of 20 in., as does Martin (in press), but their estimates are for a larger area with fewer data points than that determined by Lacombe and Rosman (1995). The remainder of annual precipitation leaves the study area either as runoff (about 3 in.) or as evapotranspiration (about 24 in.) (Lacombe and Rosman, 1995).

Effects of Land Use on the Distribution of Radium and Nitrate

Water samples were collected from a regional sampling network of 42 wells screened in the Kirkwood-Cohansey aquifer system (Szabo and others, 1997). Results of analyses of the samples indicate that concentrations of dissolved radium-226 and radium-228 are significantly greater in agricultural areas than in nonagricultural areas. Concentrations of radium-226 and radium-228 ranged from 0.21 to 8.9 pCi/L and from <1.0 to 5.0 pCi/L, respectively, in samples from wells in agricultural areas, but concentrations ranged only from 0.18 to 2.4 pCi/L and from <1 to 2.4 pCi/L, respectively, in samples from wells in nonagricultural (residential or undeveloped) areas.The sum of radium-226 and radium-228 concentrations did not exceed the MCL of 5 pCi/L in any of the 13 ground-water samples collected from wells in predominantly nonagricultural areas; however, the MCL was exceeded in 11 of the 29 samples (38 percent) collected from wells in predominantly agricultural areas.

Concentrations of inorganic constituents such as nitrate, magnesium, calcium, barium, potassium, and chloride also were significantly higher in samples from wells in agricultural areas than in samples from wells in nonagricultural areas (Szabo and others, 1997). The greatest difference in concentrations in ground-water samples from agricultural and nonagricultural areas was noted for nitrate. The median concentration of nitrate for the 29 samples from wells in the predominantly agricultural areas was 8.2 mg/L, and the maximum concentration was 27 mg/L, whereas the median concentration of nitrate for the 13 samples from wells in predominantly nonagricultural areas was 0.3 mg/L, and the maximum concentration of only 3 mg/L was present in a sample collected in a residential area. All the water sampled was acidic (median pH 4.76).

METHODS OF INVESTIGATION

Nested observation wells were installed at ground-water divides in an agricultural area to determine vertical variations in hydraulic head and changes in concentrations of radium, nitrate, and tritium with depth. Possible flowpaths and travel times within unconfined ground-water-flow systems were determined with two-dimensional finite-difference flow models to evaluate possible advection paths of radium and nitrate, with the assumption that radium and nitrate are conservative.

Site Selection

Five sites were selected for installation of nested observation wells for vertical flowpath analysis and chemical sampling (fig. 1). Four of the sites are in southwestern New Jersey in agricultural parts of the Bridgeton Formation outcrop area. Agriculture is widespread in this area but is scattered on unconnected plots of land, and is concentrated on topographic highs with good drainage. The four sites were intentionally located at or near local surface-water divides, because these are assumed to represent ground-water divides, where vertical flow is maximized. This ensures that the samples collected from nested observation wells consist of water that moves along discrete flowpaths that originate near each other in the same agricultural area, facilitating determination of differences in general water quality and radium content with depth resulting from the recent leaching of modern agricultural chemicals to shallow ground water. The distribution of these constituents as a function of depth was used to evaluate the effect of ground-water flowpaths and travel time on radium and nitrate distribution.

The fifth site (Glassboro) was selected to be a nonagricultural control site. This site had no historical agricultural activity (in the last 50 years) but, like the other sites, it is located near a surface-water divide in the Bridgeton Formation outcrop area.

Observation-Well and Piezometer Installation

Nested observation wells were installed with a hollow-stem auger drill rig. Consistent procedures were followed with respect to depth of well placement and collection of soil and aquifer cores. All well installations followed NJDEP monitoring-well installation regulations (Michael Miller, N.J. Department of Environmental Protection, written commun., 1990). Deep wells were installed before shallow wells.

Either two, three, or four observation wells were installed at each site and were screened at various depths. Well-construction information for the nested observation wells is presented in table 1. The number of wells drilled at each site depended on the thickness of the aquifer at the site. All nested observation wells were 2 in. in diameter and had 5-ft screens.

The expected depth to the base of the Kirkwood-Cohansey aquifer system at each site was determined from the map of aquifer thickness prepared by Zapecza (1989). First, the deepest well at each site was drilled to about the full thickness of the aquifer. Split-spoon (2-ft-long) samples were collected after every 5 ft of drilling, or, if the lithology was uniform, after every 10 ft of drilling.

Drilling was stopped when drill cuttings and split-spoon samples contained dark-gray to black clay typical of the Alloway Clay confining unit, which underlies the Kirkwood-Cohansey aquifer system. Drilling was stopped before the Alloway Clay confining unit was reached only at the Seabrook site because the expected depth to the base of the aquifer (greater than 150 ft (Zapecza, 1989)) was greater than the depth the drill rig was capable of reaching. When drilling for the deepest well was completed at each site, a gamma-ray log was run in the hole through the augers and was used to determine the optimum depth for the screen. After the log was completed, the well was installed. To ensure a good connection with the aquifer, the well screen was placed above any fine-grained material (assumed low-conductance zones) shown on the geophysical logs.

Table 1. Selected well-record information for nested observation wells and piezometers, Kirkwood-Cohansey aquifer system, southwestern New Jersey

(--, data unavailable; TWP, Township)

U.S. Geological Survey well number	Township	New Jersey permit number	Latitude	Longitude	Date of construction	Elevation of land surface (feet)	Depth of well or piezometer (feet)	Top of screened interval (feet)	Bottom of screened interval (feet)
				Seabrook site					
[1]11-0696	UPPER DEERFIELD TWP	--	393047	0751249	11-19-91	102	13	11	13
[1]11-0700	UPPER DEERFIELD TWP	--	393047	0751249	11-21-91	102	53	51	53
11-0692	UPPER DEERFIELD TWP	34-03742	393104	0751222	09-28-90	120	38	33	38
11-0693	UPPER DEERFIELD TWP	34-03743	393104	0751222	09-27-90	120	78	73	78
11-0694	UPPER DEERFIELD TWP	34-03744	393104	0751222	09-26-90	120	115	105	110
				Upper Pittsgrove Township site					
33-0680	UPPER PITTSGROVE TWP	30-06586	393849	0751328	05-16-90	144	32	27	32
33-0681	UPPER PITTSGROVE TWP	30-06587	393849	0751328	05-15-90	145	45	40	45
				Glassboro site					
15-1054	GLASSBORO BORO	31-33949	394221	0750722	06-05-90	154	36	31	36
15-1055	GLASSBORO BORO	31-33950	394221	0750722	06-07-90	154	66	61	66
15-1056	GLASSBORO BORO	31-33951	394221	0750722	06-06-90	154	84	79	84
				Southern Washington Township site					
15-1057	WASHINGTON TWP	31-33946	394242	0750330	05-18-90	156	27	22	27
15-1063	WASHINGTON TWP	31-34116	394242	0750330	06-08-90	156	40	35	40
15-1058	WASHINGTON TWP	31-33947	394242	0750330	05-22-90	156	75	70	75
15-1059	WASHINGTON TWP	31-33948	394242	0750330	05-17-90	156	100	95	100
				Cross Keys site					
15-1051	WASHINGTON TWP	31-33952	394314	0750145	05-25-90	152	27	22	27
15-1052	WASHINGTON TWP	31-33953	394314	0750145	05-24-90	152	65	60	65
15-1053	WASHINGTON TWP	31-33954	394314	0750145	05-23-90	152	97	92	97

[1] Drivepoint piezometer

Medium-depth wells were drilled next. Split-spoon samples were collected at 10-ft intervals and at depths where the gamma-ray log from the deepest well indicated changes in lithology. Screens were placed about midway between the deeper well screens and the water table, and at a depth where the gamma-ray log indicated no fine-grained sediments were present.

The shallow wells were installed last. During drilling, Central Mine Equipment (CME)[2] continuous split-tube samples were collected from land surface to the water table. Screens were placed 10 to 15 ft below the water table.

Two exceptions were made to these procedures. First, only two wells were installed at the Upper Pittsgrove Township site, because the Kirkwood-Cohansey aquifer system is thin (the base of the aquifer is about 55 ft below land surface) there. Installation procedures for these wells corresponded to those for the shallow and deep wells in the procedure described above; however, the depth of the "deep" well at this site corresponds more closely with the depth of the medium-depth wells at the other four sites. The split-spoon samples typically collected during drilling of the medium-depth well were collected at this site during drilling of the shallow well.

An additional (fourth) well was installed at the southern Washington Township site. Drill cuttings, split-spoon samples, and the gamma-ray log from the deep hole at this site revealed the presence of a 20-ft-thick silt layer at the approximate depth of the proposed screened interval of the medium-depth well. To investigate the hydrologic effect of this silt layer on flow in the aquifer, well screens were set immediately above and below it. At this site, then, the medium-depth well was replaced with two wells, referred to as the "medium-shallow" and "medium-deep" wells. Split-spoon samples were collected only during the drilling of the medium-deep well.

A temporary drive-point piezometer was installed about 2,400 ft from the Seabrook nested observation wells. The location was believed to be downgradient from the nested observation wells and upgradient from the area of ground-water discharge, a stream about 1,000 ft to the east. The piezometer was used to measure a water level and collect water samples. The piezometer screen was constructed from a 2-ft length of steel AW drill rod. A number of 0.5-in.-diameter holes were drilled in rows around the drill rod. A stainless-steel screen made of 100-mesh wire cloth on an expanded steel support was inserted inside the drill rod as a filter to prevent sediment from entering the sampler. A hardened-steel drive point was screwed on the bottom of the screen to facilitate driving the device into the subsurface. Five-ft sections of AW drill rod were added to the drive-point screen and driven into the subsurface with a 240-pound drive hammer. The water level was measured when the piezometer was 13 ft below land surface. Water samples were collected at this depth and after the piezometer had been driven to 53 ft below land surface.

Well-Numbering System

Information on the location, construction, and elevation of the observation wells discussed in this report is stored in the Ground-Water Site Inventory data base maintained by the USGS. This information is stored under a 6-digit unique well number assigned by the USGS. This well number consists of a 2-digit county code followed by a 4-digit sequence number. County codes used in this report are 11 (Cumberland), 15 (Gloucester), and 33 (Salem). For example, well 11-696 is the 696th well inventoried in Cumberland County.

[2] Use of brand or trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

Determination of Sediment Characteristics

Sediment subsamples collected from the cores were analyzed to characterize lithology, texture, and mineralogy. The mineralogy, color, texture, degree of sorting, and grain size of each subsample were determined in the field by visual inspection. Descriptions were compared to lithology interpreted from gamma-ray logs. Subsamples also were examined in the laboratory with a binocular microscope to determine the amount of silt or clay in the sediment matrix.

Measurement of Water Levels

A measuring point was established at the top of the casing of each well and piezometer. The measuring-point elevations were leveled in with an accuracy of 0.0005 ft. Water levels were measured in each well with a weighted steel tape, and measurements were repeated at each well until two identical values were obtained. Water-level measurements were accurate within 0.005 feet. Water levels in each well were measured approximately bimonthly from March 1991 through September 1992. The altitude of the water level in each well was calculated by subtracting the measured water level from the elevation of the measuring point. Water-level data collected at all five sites during 1991-92 can be found in Bauersfeld and others (1992; 1993).

Calculation of Vertical Head Differences

Vertical head differences between the nested observation wells at each site were calculated from same-day determinations of nested-well water-level altitudes. The mean of the vertical head differences at each site was calculated from vertical head differences obtained from the bimonthly water-level measurements.

Calculation of Horizontal Head Difference

An additional water-level measurement was made in the drive-point piezometer. The piezometer screen was driven just below the water table, about 11 ft below land surface. A measuring point on the AW rod was leveled in with an accuracy of 0.01 ft. The water level in the piezometer was measured with an electric tape accurate to 0.01 ft. The water level in the shallow nested well was measured immediately after the water level was measured in the piezometer. The horizontal difference between the head in the Seabrook shallow nested observation well and the head in the piezometer was calculated. The combined errors in leveling and water-level measurement resulted in a horizontal head difference accurate to 0.03 ft. The horizontal head difference is representative of water-table conditions only at the time the water levels were measured (November 20, 1991).

Simulation of Flow and Determination of Flowpaths and Travel Time

A finite-difference ground-water flow model (McDonald and Harbaugh, 1988) was used to simulate flow within selected sections of the Kirkwood-Cohansey aquifer system under steady-state (unstressed) conditions. Simulated heads and intercell flows were input to a post-processing particle-tracking program (Pollock, 1989) to calculate ground-water flowpaths and travel time. Porosity was an additional input to the particle-tracking program. An aquifer porosity of 0.35 was used, and a silt porosity of 0.45 was input when a silt layer was present in a section; these are reasonable estimates of porosity for aquifers of the New Jersey Coastal Plain.

Collection and Analysis of Ground-Water Samples

All water samples were collected from the nested observation wells with a portable variable-pumping-rate Grundfos submersible pump. A pumping rate of about 6 gal/min was generally maintained. The pump was set 10 ft below the static water level during well purging and sample collection. During pumping, the dissolved-oxygen concentration, pH, specific conductance, and temperature of the water were measured at 5-min intervals.

Samples were collected after a minimum of three casing volumes of water had been removed from the well and when the pH, temperature, and specific conductance did not vary by more than 5 percent in three consecutive sets of measurements made at 5-min intervals, according to methods described by Wood (1976). This procedure ensured the collection of fresh water from the aquifer rather than standing water from within the well casing (Claassen, 1982).

Ground-water samples were filtered through a 0.45-micron filter in the field. Samples that were analyzed for radionuclides were acidified in the field immediately after collection to a pH of less than 2 with laboratory-grade nitric acid. Samples analyzed for nutrients were preserved in the field with mercuric chloride and chilled.

Concentrations of radium-226 were determined by radon-222 de-emanation (Krieger and Whitaker, 1980). Concentrations of radium-228 were determined by beta counting of ingrown actinium-228 progeny (Krieger and Whittaker, 1980). Nutrient concentrations were measured by ion chromatography (Fishman and Friedman, 1985).

Estimation of Ground-Water Travel Time from Tritium Concentrations

The range of possible apparent ground-water ages was determined from concentrations of tritium in ground water, as described by Hendry (1988) and Bradbury (1991). Concentrations of tritium were determined by beta counting with the liquid-scintillation technique after gaseous enrichment of the samples in Ostlund-type glass cells with slight modifications to the technique of Ostlund and Dorsey (1977).

SITE CHARACTERISTICS

Sediment

Lithologic descriptions of core samples from all five sites are included in Szabo and others (1997, app. 2B) and were compared to the gamma-ray logs collected immediately after the deep wells were drilled (fig. 3); sediment lithology interpreted from the gamma-ray logs corresponds to the lithology determined from core samples (gamma-ray emissions increase as grain size decreases). In general, the sediment composing the Kirkwood-Cohansey aquifer system is fine- to medium-grained quartz sand. Grain size is generally homogenous, especially within the Cohansey Sand, but can grade into medium- to coarse-grained sand or silty sand to silt. Silty sand to silt strata approximately 10 ft thick or more are noted in the Cohansey Sand at three of the five sites investigated (fig 3): from 50 to 70 ft at southern Washington Township, from 48 to 58 ft at Glassboro, and from 78 to 88 ft at Seabrook. In general, the sediment appears to be slightly coarser grained and more homogenous at the Seabrook, Upper Pittsgrove Township, and Cross Keys sites than at the Glassboro and southern Washington Township sites.

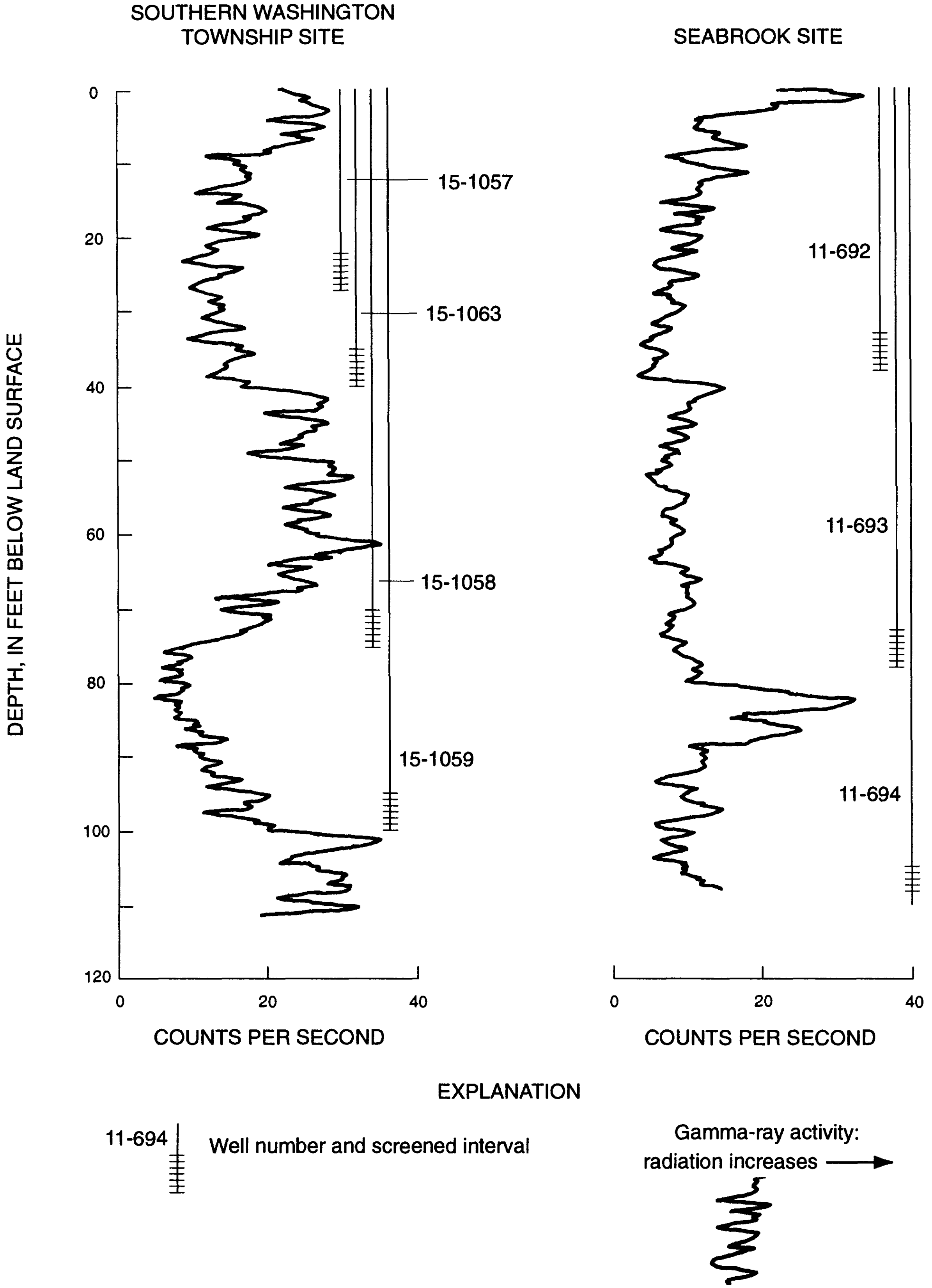


Figure 3. Gamma logs of the Kirkwood-Cohansey aquifer system at five nested-observation-well sites in southwestern New Jersey.

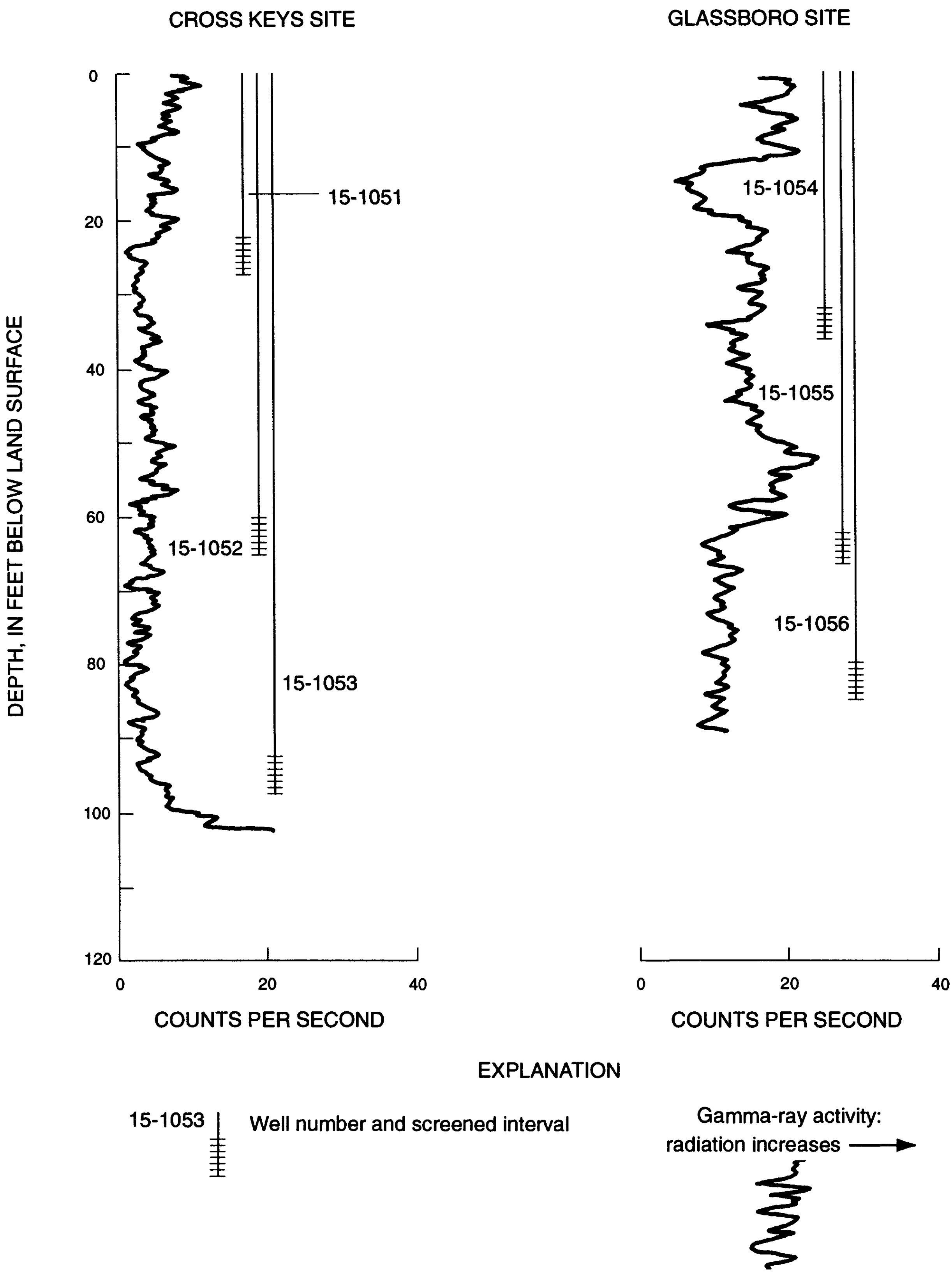


Figure 3. Gamma logs of the Kirkwood-Cohansey aquifer system at five nested-observation-well sites in southwestern New Jersey--Continued.

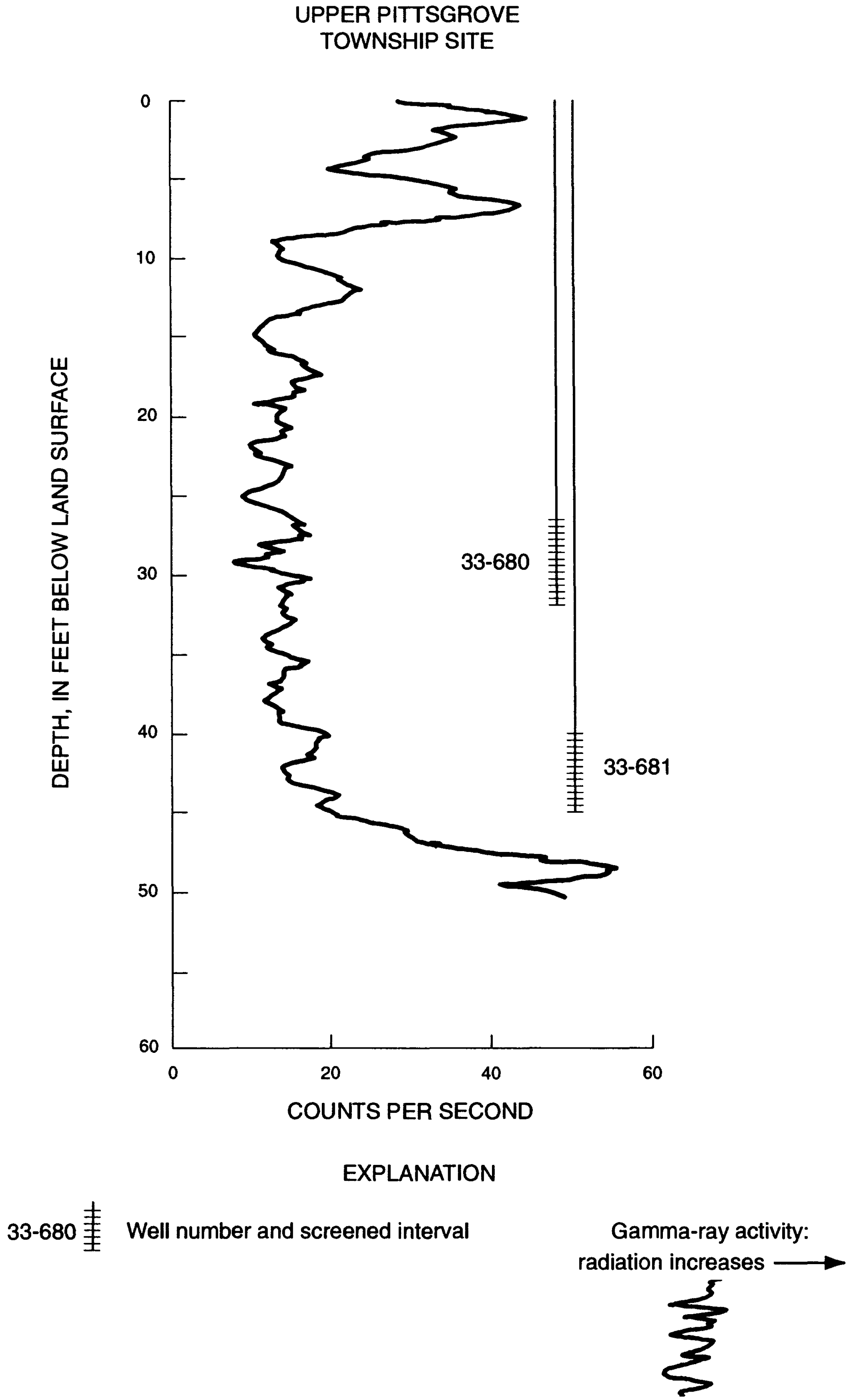


Figure 3. Gamma logs of the Kirkwood-Cohansey aquifer system at five nested-observation-well sites in southwestern New Jersey--Continued.

Trends in grain size were noted near land surface and near the base of the aquifer. Grain size tends to be greatest at shallow depths (medium to coarse sand is common, with occasional gravel), most likely because of the presence of the Bridgeton Formation, which caps the Cohansey Sand. Grain size decreases at the base of the Cohansey Sand (fine- to very fine-grained sand to silty sand) near the gradational contact with the Alloway Clay Member of the underlying Kirkwood Formation. In general, however, sediment mineralogy and texture varied little among the sites (fig. 3) and with depth; therefore, the hydraulic properties of the aquifer are expected to be fairly uniform.

Geohydrologic characteristics of the Kirkwood-Cohansey aquifer system at the Seabrook site are shown in figure 4. A 10-ft-thick silt layer is shown in the section; the altitude of the top of the silt layer is 28 ft. The silt layer was indicated by the geophysical log of the deep well (fig. 3), and was confirmed by core samples collected from the deep well (fig. 4). The silt layer is assumed to be areally extensive because it is noted in the drillers' logs submitted with well records for wells drilled in the area and it was reported by Remson (1954). A saturated thickness of 150 ft at the ground-water divide was interpreted from thickness maps of the Kirkwood-Cohansey aquifer system (Zapecza, 1989).

The geophysical logs and split-spoon core samples from the deepest nested observation well at the southern Washington Township site revealed a 20-ft-thick silt layer 50 to 70 ft below land surface (fig. 3). The geophysical logs and split-spoon cores from the deepest nested observation well at the Cross Keys site indicated that no silt layer is present in the aquifer at the site.

Ground Water

The unsaturated zone is thickest near the ground-water divide (resulting in well-drained soils suitable for agriculture) and is thinnest in the ground-water discharge area (resulting in poorly drained soils not suitable for agriculture). Typically, agricultural land in the study area extends from a ground-water divide toward an area near a stream or swamp; head differences cause ground water to flow from the former to the latter. This was the case at the four sites located in agricultural areas: Seabrook, southern Washington Township, Cross Keys, and Upper Pittsgrove Township. The altitude of the water table and the vertical head differences determined from water levels measured at the nested-observation-well sites are listed in table 2.

Water Levels

Potentiometric-surface maps for the areas around the nested observation wells near Seabrook (fig. 5) and southern Washington Township and Cross Keys (fig. 6) were prepared from field-measured ground-water levels and stream elevations. These maps were used to determine the orientation and length of the three modeled sections by interpreting the horizontal flow direction from the ground-water divide through the nested observation wells to the ground-water-discharge area. Once the location of the Seabrook section had been established, a temporary piezometer was installed approximately halfway between the nested wells and Parsonage Run.The location of the ground-water divide interpreted from the potentiometric contours in figure 6 coincides with that reported by Lacombe and Rosman (1995). Ground water in the Cross Keys section discharges to a swamp (fig. 6).

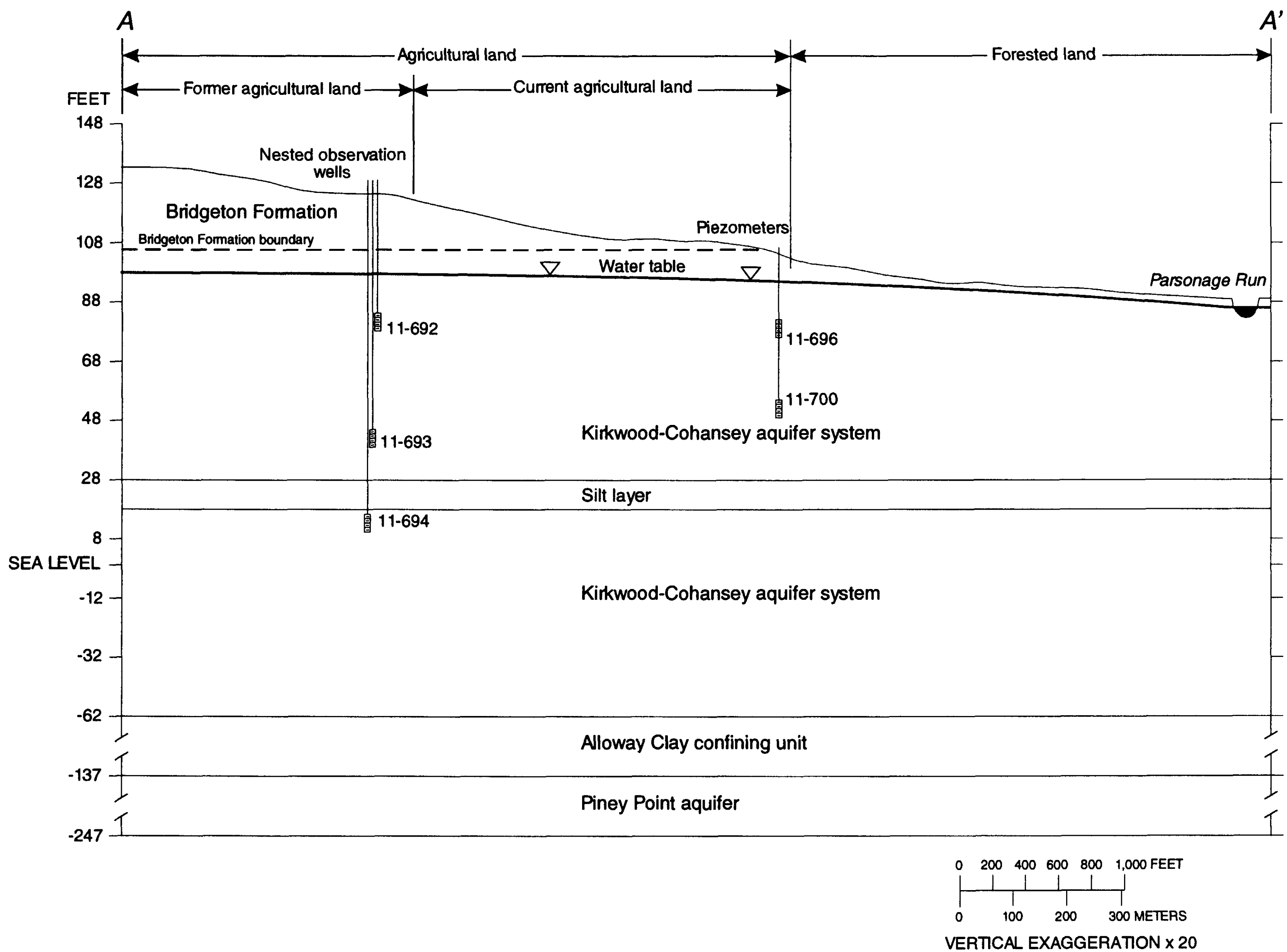


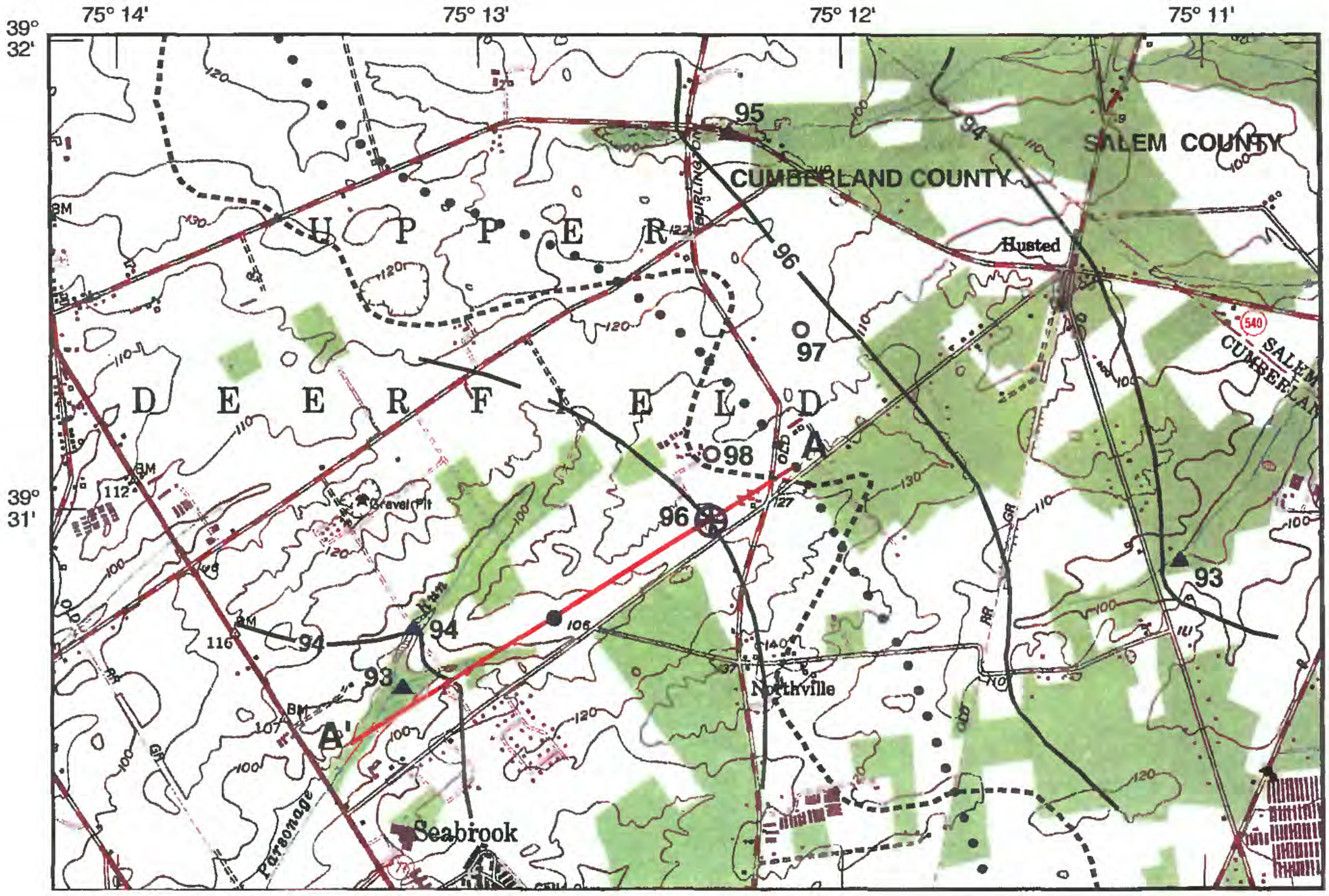
Figure 4. Generalized hydrostratigraphic section *A-A'*, showing land use and nested observation wells near Seabrook, Cumberland County, New Jersey. (Location of section shown in fig. 5)

Table 2. Range of heads and vertical and horizontal head differences at three nested-observation-well sites, Kirkwood-Cohansey aquifer system, southwestern New Jersey, 1991-92

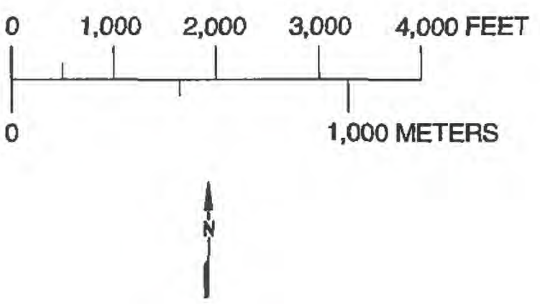
(--, consistent value not obtained; n.a., not applicable)

Site	Range of heads (feet above sea level)	Vertical difference in head, shallow and medium-depth wells (feet)	Vertical difference in head, medium-depth and deep wells (feet)	Horizontal difference in head, shallow well and piezometer (feet)
Seabrook	92.8-97.1	[1]0.014± 0.009	[1]0.078± 0.013	1.99
Southern Washington Township	137.8-140.4	--	--	n.a.
Cross Keys	137.1-140.7	[2]0.026	[3]0.008± 0.005	n.a.

[1]Mean and standard deviation.
[2]All differences identical.
[3]Median and interquartile range.



Base from U.S. Geological Survey digital
raster graphic 1:24,000 Elmer quadrangle



EXPLANATION

—94— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 2 feet. Datum is sea level

------ SURFACE-WATER DIVIDE

• • • • ESTIMATED GROUND-WATER DIVIDE

LOCATION OF MODELED SECTION

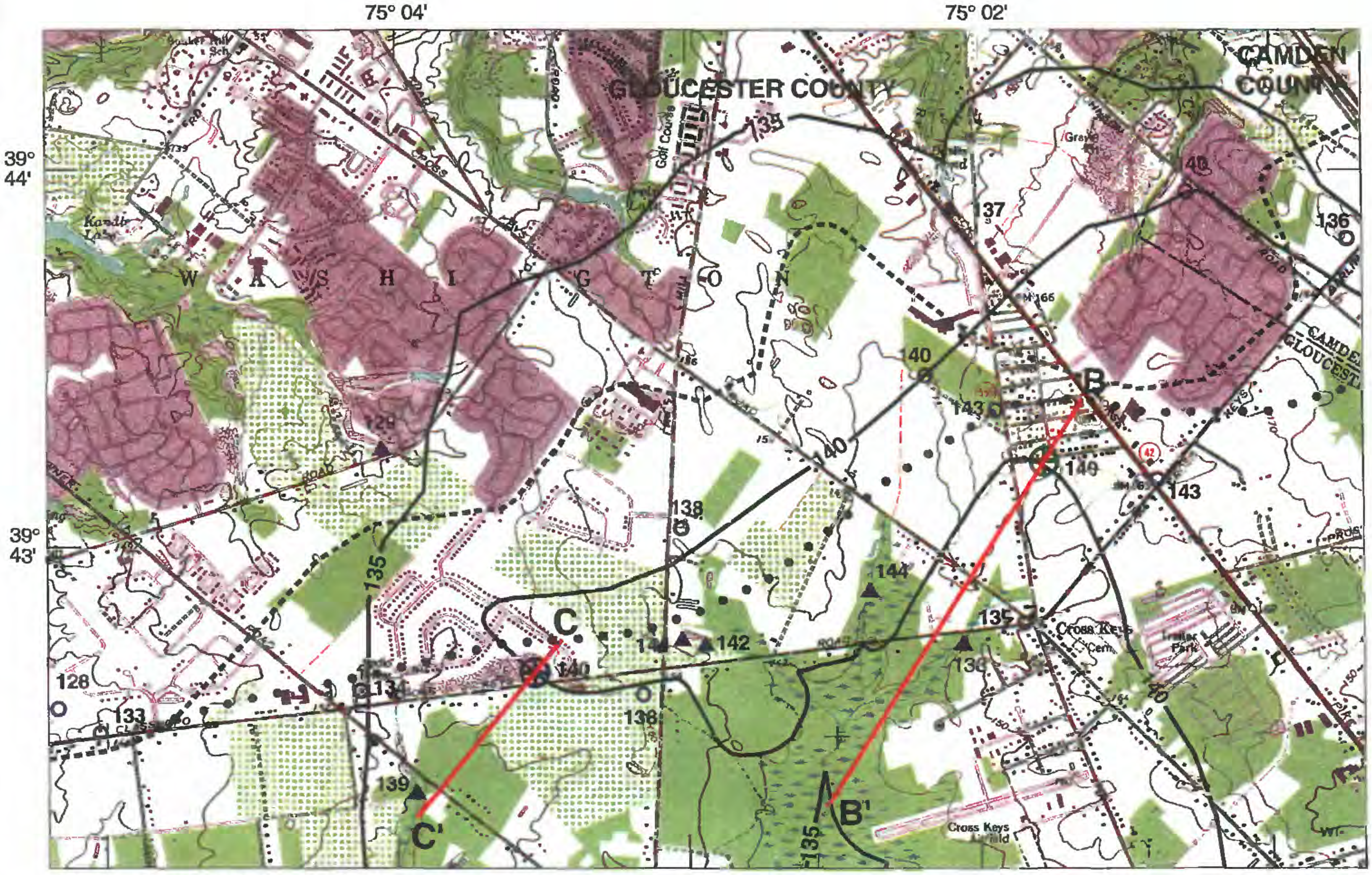
96⊕ Location of Seabrook nested-observation-well site. Number is altitude of water level, in feet. Datum is sea level

● Location of piezometer

o 97 Well with measured water level. Number is altitude of water level, in feet. Datum is sea level

▲94 Stream-elevation measurement site. Number is elevation of water level, in feet. Datum is sea level

Figure 5. Potentiometric surface of the unconfined Kirkwood-Cohansey aquifer system near Seabrook, Cumberland County, New Jersey, July 29, 1991.



Base from U.S. Geological Survey digital
raster graphic 1:24,000 Pitman East quadrangle

0 1,000 2,000 3,000 4,000 FEET

0 1,000 METERS

N

EXPLANATION

—— 135 —— POTENTIOMETRIC CONTOUR--Shows altitude at which water level would have stood in tightly cased wells. Contour interval 5 feet. Datum is sea level

- - - - - - SURFACE-WATER DIVIDE

• • • • ESTIMATED GROUND-WATER DIVIDE

—— LOCATION OF MODELED SECTIONS

⊕ 140 Location of Southern Washington Township nested-observation-well site. Number is altitude of water level, in feet. Datum is sea level

⊕ 140 Location of Cross Keys nested-observation-well site. Number is altitude of water level, in feet. Datum is sea level

138 ○ Well with measured water level. Number is altitude of water level, in feet. Datum is sea level

129 ▲ Stream elevation measurement site. Number is elevation of water level, in feet. Datum is sea level

Figure 6. Potentimetric surface of the unconfined Kirkwood-Cohansey aquifer system near Washington Township, Gloucester County, New Jersey, July 30, 1991.

Water levels were measured and water-table maps were constructed for the remaining two sites (Glassboro and Upper Pittsgrove Township). Because stream gradients adjacent to the nested-observation-well sites are steep, additional information was needed to define the potentiometric-surface contours in these two areas, especially near the streams. Because no additional data were available, the potentiometric-surface contours and flow lines could not be determined; therefore, modeling efforts for these two sites were ended.

Head Differences

The mean of the field-determined vertical head differences between the shallow and medium-depth wells at the Seabrook site was 0.014 ft, with a standard deviation of 0.009 ft; the mean of the vertical head differences between the medium-depth and deep wells was 0.078 ft, with a standard deviation of 0.013 ft (table 2). At the Cross Keys site, all the vertical head differences between the water levels in the shallow and medium-depth wells were 0.026 ft. The vertical head differences between the water levels in the medium-depth and deep wells at the Cross Keys site were not normally distributed; therefore, both the median value of 0.008 ft and the interquartile range of 0.005 ft are reported in table 2. The calculated vertical head differences at the southern Washington Township site exhibited no consistent pattern; the standard deviation from the mean was so high that there was no confidence that the mean was representative of typical hydrologic conditions. Therefore, the mean vertical head differences at this site were unusable.

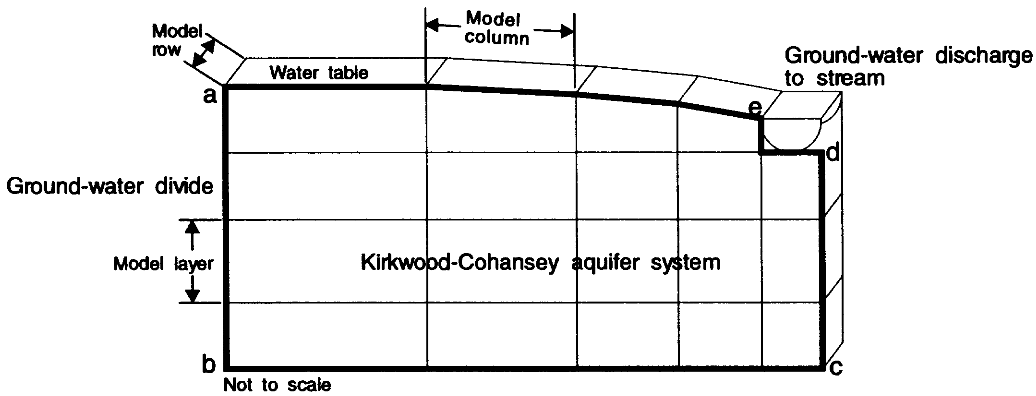
A horizontal head difference also was determined at the Seabrook site. The horizontal head difference of 1.99 ft (table 2) was calculated from the water levels measured in the shallow well and a piezometer located about halfway between the nested wells and Parsonage Run (fig. 5), a distance of about 2,000 ft. Only one head measurement was obtained from the piezometer because the piezometer was a temporary installation; therefore, this field-measured head is not an approximation of average hydrologic conditions, but only of unstressed conditions.

SIMULATION OF GROUND-WATER FLOW

Two-dimensional ground-water flow models of aquifer sections at three sites were constructed to simulate flow within the Kirkwood-Cohansey aquifer system. The locations of the modeled sections were selected because they were representative of the hydrologic conditions and agricultural-land-use characteristics of the study area. The simulated heads in the modeled sections were used in flowpath analysis to determine the origin of flowpaths and the travel time of ground water at any position along them.

Description of Model

The modeled sections were represented with a single 50-ft-wide horizontal row extending from the ground-water divide, through a set of nested observation wells, to the ground-water discharge area at a stream or swamp (fig. 7). The section length was represented by multiple columns of increasing length. The column at the ground-water-discharge area was 15 ft long, and the length of each successive column toward the ground-water divide (right to left in fig. 7) was 1.08 times that of the previous column. Anisotropy within the modeled sections was represented with multiple layers. Model layers were 10 ft thick, with the exception of the top layer, which was of variable thickness because it contains the water table. This discretization scheme provided the greatest detail in the area of ground-water discharge, where flowpaths were expected to converge.



SEGMENT	BOUNDARY CONDITION
ab	no flow
bc	constant head
cd	no flow
de	constant head
ae	specified flux

Figure 7. Schematic section showing boundary conditions for the models of the unconfined Kirkwood-Cohansey aquifer system, Gloucester and Cumberland Counties, New Jersey.

Vertically, the modeled sections extended from the water table through the Kirkwood-Cohansey aquifer system, with leakance to the underlying aquifer. The vertical leakance between the bottom layer and the layer immediately above it was used to simulate flow from the base of the Kirkwood-Cohansey aquifer system through the Alloway Clay confining unit to the underlying aquifer. Flow through the confining unit is assumed to be vertical and is controlled by the leakance. The vertical leakance of the Alloway Clay is equal to its vertical hydraulic conductivity, 5.2×10^{-5} ft/d (Nemickas and Carswell, 1976, p. 4), divided by its thickness.

Average unstressed hydrologic conditions were simulated with the model. The field-determined heads and vertical head differences in the nested observation wells used in model calibration were considered to approximate heads under these conditions.

Boundary Conditions

The boundary conditions assigned to the modeled sections are shown in figure 7. No-flow boundaries are the ground-water divide, represented by vertical line ab, and vertical line cd directly beneath the ground-water-discharge area. The ground-water-discharge area to the streambed or swamp, represented by segment DE, and the aquifer underlying the Kirkwood-Cohansey aquifer system, represented by line bc, are constant-head boundaries. Recharge was assumed to enter the section uniformly across the water table and was applied at a uniform annual rate of 18 in. to all modeled sections. Therefore, the water table, represented by line ae, is a specified-flux boundary.

Calibration

Heads and vertical head differences determined from measured water levels in the nested wells were used as targets in model calibration. Additionally, the horizontal head difference determined from the water levels in the shallow nested well and piezometer in the Seabrook section was used in model calibration. The model was calibrated by adjusting vertical and horizontal hydraulic conductivities in all model layers, including silt layers, if present. The conductivities were uniform throughout the model layers representing the unconfined aquifer, with the exception of the silt layer, where lower conductance values were expected. Conductivities were adjusted until one or more of the following criteria were met:

1. Model-predicted heads were within 1 ft of the range of values for field-measured heads.

2. Vertical head differences calculated from heads predicted for the layers and column that correspond to the locations of the screened intervals of the nested observation wells matched the vertical head difference values for the nested observation wells reported in table 2 to within 0.001 ft. (The vertical head differences used in model calibration were between the shallow and medium-depth, and the medium-depth and deep, nested observation wells.)

3. The horizontal head difference calculated from the simulated heads for the layers and columns that correspond to the screened interval of the shallow nested observation well and the piezometer matched the horizontal head difference calculated from a single measurement of the water level in the shallow nested observation well and in the piezometer to within 0.01 ft.

The Seabrook model met all three calibration criteria. Model-predicted head differences were matched precisely to measured head differences (table 2) during model calibration. The vertical head differences calculated from simulated heads matched, to within one standard deviation, the mean of the vertical head differences calculated from measured heads, and the horizontal head difference calculated from simulated heads matched, to within the measurement error, the horizontal head difference calculated from measured heads.

The Cross Keys model met only the first two calibration criteria and the southern Washington Township model met only the first criterion. Lack of measured horizontal head differences in the Cross Keys and southern Washington Township sections and lack of accurate measured vertical head differences for the southern Washington Township nested observation wells (table 2) limited the use of the established calibration criteria that were successfully met at the Seabrook site. Therefore, the southern Washington Township and Cross Keys models were less rigorously calibrated than the Seabrook model, and the southern Washington Township model was the least rigorously calibrated of the three. The small changes in horizontal and vertical conductivities that could result from a more tightly constrained and more accurately calibrated model would not be significant enough, however, to substantially affect the ground-water travel times or flowpath locations within the Cross Keys and southern Washington Township sections because calculation of travel time generally is not sensitive to conductivity values.

Simulated Ground-Water Flowpaths and Travel Times

Seabrook Site

The potentiometric-surface map (fig. 5) was used to determine the location of the ground-water divide (a no-flow boundary) near the Seabrook site and the approximate location of the area of ground-water discharge to Parsonage Run (a constant-head boundary). At this site, the distance from the ground-water divide to the discharge area along section A-A' is 6,793 ft (figs. 4 and 5). This length resulted in a model grid with 47 columns. The model has 16 layers, representing a saturated thickness of about 150 ft for the Kirkwood-Cohansey aquifer system. Layer 16 represents the Piney Point aquifer, which underlies the Kirkwood-Cohansey aquifer system in this area. A leakance of 6.0×10^{-7} (ft/d)/ft was calculated for the simulated Alloway Clay confining unit between layers 15 and 16. The leakance value is equal to the vertical hydraulic conductivity of 5.2×10^{-5} ft/d for the Alloway Clay (Nemickas and Carswell, p. 4, 1976) divided by 85 ft, the thickness of the confining unit in this area (Zapecza, 1989). The constant-head value for the Piney Point aquifer is 25 ft (Rosman and others, 1995). Layer 8 represents the silt layer. Ground-water discharge from the section to Parsonage Run is represented by row 1, column 1, layer 1, with a constant-head value equal to 89 ft (fig. 4). The initial estimate of horizontal hydraulic conductivity input to the model was 150 ft/d. This value was calculated from results of two separate aquifer tests conducted in 1959 and 1966 near Seabrook (Rhodehamel, p. 55, 1973).

The calibrated horizontal conductivity of the aquifer material is 103.3 ft/d. The calibrated vertical conductivity of the aquifer material is 8.9 ft/d. The silt layer has a horizontal conductivity of 3.2 ft/d and a vertical conductivity of 0.28 ft/d.

Selected ground-water flowpaths and lines of equal travel time predicted from simulation results, and the locations of the screened intervals of the nested observation wells in the modeled section are shown in figure 8. Ground-water flowpaths are represented as stream lines in figure 8.

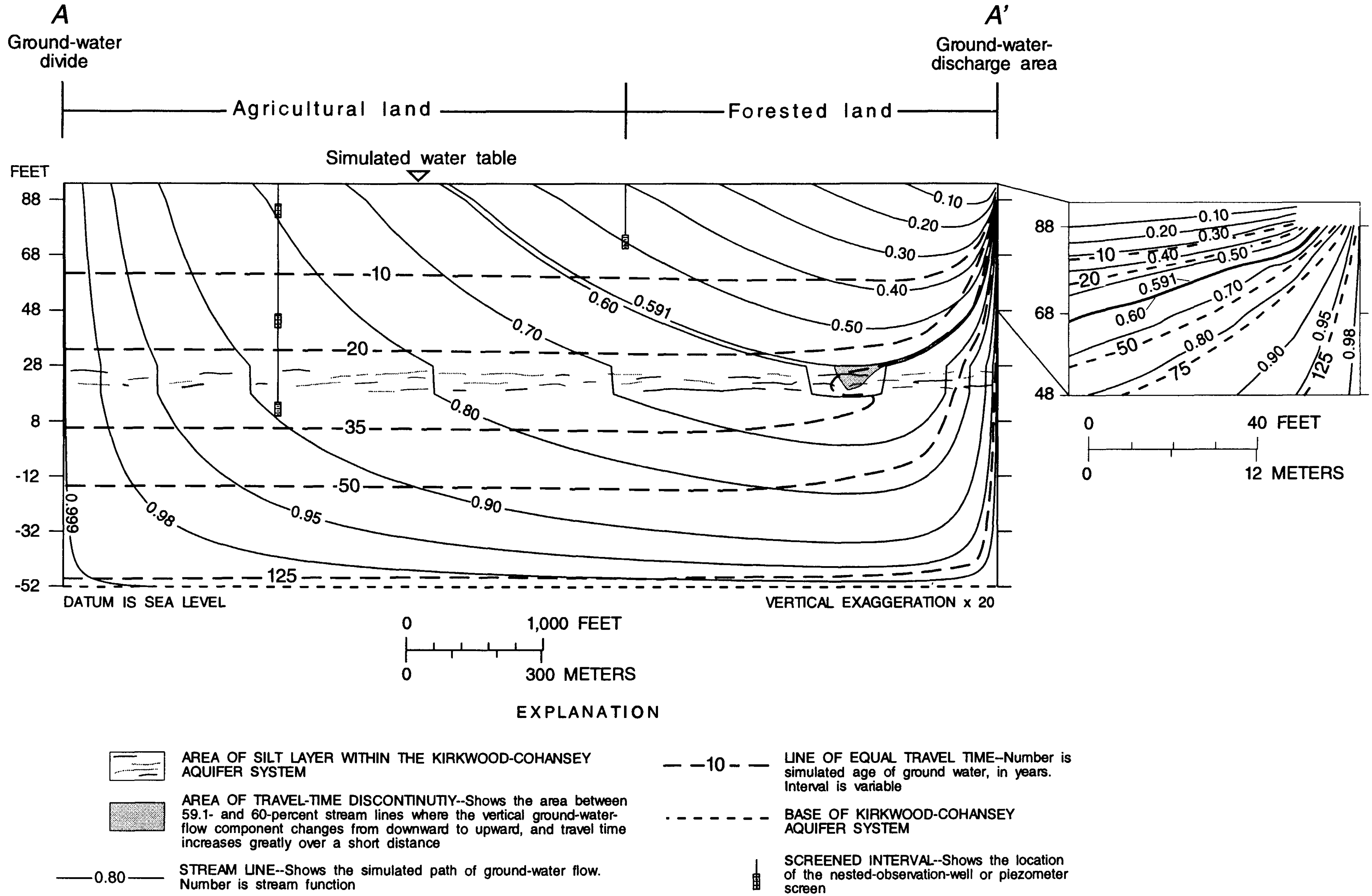


Figure 8. Schematic section through the Seabrook nested-observation-well site with simulated lines of equal travel time and stream lines, Kirkwood-Cohansey aquifer system, Cumberland County, New Jersey. (Location of section shown in fig. 5)

A stream line is a flowpath that has an assigned value, the stream function. The stream function indicates the decimal fraction of the total flow through the system, ranging from 0 at the discharge area to 1.0 for the limiting flowpath originating at the ground-water divide (Buxton and Modica, 1992, p. 858); the stream functions are cumulative (from right to left in figure 8). The stream lines show that ground water flows downward and away from the ground-water divide toward the discharge area. Near the no-flow boundary beneath the discharge area, ground water flows upward.

Simulation results show that flowpaths extend from beneath agricultural land across the aquifer section toward the discharge area; the aquifer near the discharge area is overlain by forested land. Ground-water flowpaths that originate beneath agricultural land are found at depth beneath the forested land (fig. 8). The 0.40 stream line in figure 8, for example, originates at the boundary between agricultural and forested land; therefore, 60 percent of ground-water flow in the section enters the aquifer through agricultural land. The 40 percent of flow that does not enter the aquifer through agricultural land is not affected by modern agricultural chemicals, and travels along the shortest flowpaths (has the fastest travel times) through the aquifer to the discharge area.

Examination of the distribution of travel times within the modeled section shows that, in general, ground-water travel time increases with depth in the aquifer section (fig. 8). Ground-water travel times to the nested-observation-well screens illustrate this pattern. The travel time is estimated from figure 8 to be 4 years to the shallow well (top of screen, 5 ft below the water table), 16 years to the medium-depth well (top of screen, about 48 ft below the water table), and 32 years to the deep well (top of screen, about 80 ft below the water table). Travel time increases little with horizontal distance traveled along a flowpath, because the horizontal velocities of ground water are much greater than the vertical velocities.

The maximum ground-water travel time within the section is approximately 200 years. This travel time is achieved by ground water that recharges the underlying Piney Point aquifer. Recharge to the Piney Point aquifer originates at the ground-water divide and extends near the 0.98 stream line; therefore, recharge to the Piney Point aquifer in the simulated section is derived from less than 2 percent of the water in the Kirkwood-Cohansey aquifer system.

Results of the flowpath analysis showed an area of travel-time discontinuity, where travel time does not increase with depth, in the area of the stream line that penetrates but does not cross completely through the silt layer (fig. 8). In this area, the vertical component of ground-water flow changes from downward to upward, and the vertical and horizontal head differences are extremely low; hence, ground-water velocity also is very low, and travel time increases greatly over a short distance. In the area of travel-time discontinuity, older water overlies younger water; below the travel-time discontinuity, age again increases with depth. The shape of the area of travel-time discontinuity would likely be more complex in the real aquifer system than in the model because of the complex three-dimensional geometry of the aquifer system and the transient stresses (such as recharge) that were not simulated by this model. A low-permeability silt layer between two highly conductive aquifer layers probably would produce an area of travel-time discontinuity as predicted by the model; however, no data were collected to demonstrate the existence of this phenomenon.

Buxton and Modica (1992), in their examination of the aquifers on Long Island, New York, describe extreme travel-time discontinuities related to stream lines that penetrate but do not completely cross major confining units. Sharp changes in the chemical composition of water in the vicinity of the simulated travel-time discontinuities were found, indicating that the travel-time discontinuities probably exist.

In general, the travel time of ground water in the aquifer section increases with depth; therefore, the greater the depth obtained by a flowpath, the greater the travel time required for water to reach the discharge area along that flowpath. The horizontal spacing between the lines of equal travel time far from the Parsonage Run discharge area (fig. 8) indicates a nonlinear increase in travel time with depth; the rate at which the travel time increases is greater with increasing depth in the aquifer section.

Southern Washington Township and Cross Keys Sites

The conceptual framework for the model of the Seabrook section was applied to two other geologically and hydrologically similar sections through the Kirkwood-Cohansey aquifer system (B-B' and C-C', fig. 6) to examine the effects of aquifer thickness, section length, and differences in aquifer conductivity on ground-water flowpaths and travel time. Boundary conditions were kept constant but the model grid was adjusted to reflect the dimensions of the sections and lower conductivity values were used in layers representing areas of low permeability. These changes made recalibration of the model necessary.

The two additional modeled sections extend through the nested observation wells at the Cross Keys and the southern Washington Township sites. As at Seabrook, nested observation wells at these sites are located near the ground-water divide. Agricultural land-use patterns at the Cross Keys and southern Washington Township sites are similar to those at the Seabrook site, with agricultural land extending from the ground-water divide toward but not to the ground-water-discharge area.

The Cross Keys and southern Washington Township sections are 7,955 ft and 4,255 ft long, respectively (figs. 6 and 9). The thickness of the section was estimated from the driller's and geophysical logs (fig. 3) for the deepest nested observation well at each site. The Cross Keys section is 90 ft thick at the ground-water divide and the southern Washington Township section is 95 ft thick. These dimensions resulted in a model grid of 1 row, 49 columns, and 10 layers for the Cross Keys section and 1 row, 41 columns, and 11 layers for the southern Washington Township section.

The length of the constant-head boundary of the Cross Keys section was adjusted to 88 ft (columns 1-5 of layer 1) to simulate the swamp that is the discharge area; a head of 135 ft was interpreted for the discharge area from the USGS Pitman East 7 1/2-minute topographic quadrangle. The length of the constant-head discharge boundary of the southern Washington Township section is 15 ft, the same as that of the Seabrook section; a head of 140 ft was interpreted for the discharge area from the USGS Pitman East 7 1/2 minute topographic quadrangle.

The leakance through the Alloway Clay in these sections is equal to the vertical hydraulic conductivity for the Alloway Clay of 5.2×10^{-5} ft/d (from the Seabrook model) divided by the thickness of the Alloway Clay beneath the sites (250 ft at the Cross Keys site and 225 ft at the southern Washington Township site). The resultant leakances were 2.1×10^{-7} (ft/d)/ft for the Cross Keys section and 2.3×10^{-7} (ft/d)/ft for the southern Washington Township section; a rounded leakance value of 2×10^{-7} (ft/d)ft was input to both modeled sections. The annual recharge of 18 in., the aquifer porosity of 0.35, and the silt porosity of 0.45 were assumed to be constant for all models.

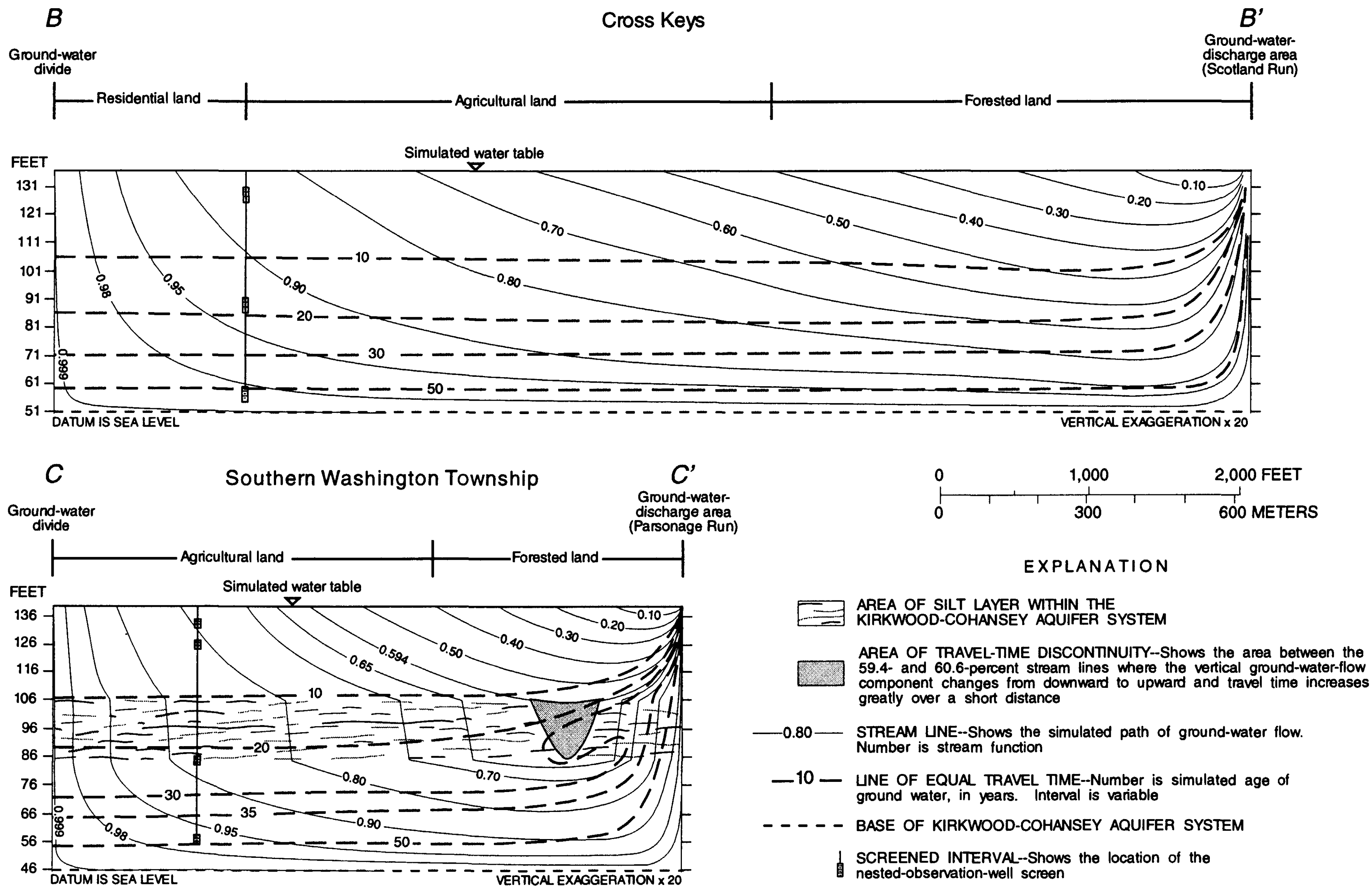


Figure 9. Schematic sections through the Cross Keys (*B-B'*) and southern Washington Township (*C-C'*) nested-observation-well sites with simulated lines of equal travel time and simulated stream lines, Kirkwood-Cohansey aquifer system, Gloucester County, New Jersey. (Location of sections shown in fig. 6)

Two model layers (layers 5 and 6) represented the thick silt layer (fig. 3) at the southern Washington Township site. Flow through the silt layer was simulated by reducing vertical and horizontal hydraulic conductivities within these layers to values lower than those for the vertical and horizontal conductivities of the aquifer material.

Comparison of Flowpaths and Travel times Among the Three Modeled Sections

Although the differences in the dimensions and stratigraphy among the models resulted in minor differences in the positions of flowpaths and depths of lines of equal travel time, consistent patterns of flowpaths and travel times were produced (figs. 8 and 9). The ground-water flowpaths originating in agricultural areas extend, at depth, beneath the downgradient nonagricultural land adjacent to the ground-water-discharge area in all sections. Furthermore, travel time increases with depth in all sections (except in the area of the travel-time discontinuity, where present). The similarity between the position of the ground-water flowpaths and lines of equal travel time in the modeled sections in southwestern New Jersey indicate that the model can be used to predict the general distribution of flowpaths and travel times in other areas where hydrogeologic conditions are similar.

Model Limitations

Errors in the measurement of field heads, the use of the means of the vertical head differences, and the limited number of control points with which simulated results could be compared limit the accuracy of model calibration. A further limitation of the model is the nonuniqueness of its solution. The position of the lines of equal travel time is unique only to a porosity of 0.35 and a model calibrated with an annual recharge of 18 in. The calculation of travel time is sensitive to changes in porosity and recharge rate. The uncertainty regarding the exact recharge rate for the modeled section creates the possibility of obtaining other nonunique calibrated model solutions for alternative recharge rates. For example, if the actual recharge rate is greater than the value input to the model, and the actual vertical and horizontal conductivities are greater than the calibrated value by a percentage equal to the percent change in recharge rate, the head distribution and flowpaths would remain identical to those of the model calibrated with an annual recharge of 18 in., but the position of the lines of equal travel time would change. Such alternative model solutions, however, still produce the pattern of increasing travel time with depth in the aquifer section.

Comparison of Simulated Travel Times to Apparent Ages Estimated from Tritium Concentrations

The travel times determined by flowpath analysis were compared to approximate ranges of apparent ages of ground water based on the concentration of tritium. The concentration of tritium varied greatly with depth. Concentrations were highest in samples collected during spring 1991 from the medium-depth wells (table 3). In wells 11-693 (depth, 78 ft) and 15-1058 (depth, 75 ft), concentrations of tritium were about 130 and 160 pCi/L, respectively. Samples of water from the medium-depth wells at the other three sites contained tritium concentrations ranging from 50 to 56 pCi/L, which were generally higher than those in the shallowest wells and significantly higher than those in the deep wells. In samples from the shallow wells, concentrations of tritium ranged from 37 to 55 pCi/L. Concentrations of tritium in samples from three of the four deep wells were less than or equal to 3 pCi/L; the concentration in the shallowest of the four wells (well 15-1056, depth 84 ft) was 53 pCi/L. The tritium concentrations were used to determine the apparent ages of

Table 3. Concentrations of nitrate, the sum of radium-226 and radium-228, and tritium in, and apparent ground-water ages and travel times at, nested observation wells, Kirkwood-Cohansey aquifer system, southwestern New Jersey

(mg/L, milligrams per liter; pCi/L, picocuries per liter; <, less than; <<, much less than; ≤, less than or equal to; >, greater than; --, no data; n.a., not applicable; concentration data from samples collected in spring 1991)

Nested-observation-well site	U.S. Geological Survey well number	Depth (feet)	Nitrogen, NO2 + NO3, dissolved (mg/L as N)	Sum of radium-226 plus radium-228 (pCi/L)	Tritium (pCi/L)	Tritium apparent age (years)	Flowpath-analysis travel time (years)
Seabrook	11- 696	13	1.90	3.0	--	--	<3
Seabrook	11- 700	53	14.0	30.3	--	--	<10
Seabrook	11- 692	38	6.70	3.59	47 ± 3	<<27	3-4.5
Seabrook	11- 693	78	23.0	18.6	130 ± 4	≤27	15-17.5
Seabrook	11- 694	115	5.10	<1.76	3 ± 1	>32-<50	31-33.5
Southern Washington Township	15-1057	27	4.00	7.6	47 ± 3	<<27	1.5-3.2
Southern Washington Township	15-1063	40	1.70	6.1	47 ± 3	<<27	5.5-7.0
Southern Washington Township	15-1058	75	8.70	2.9	160 ± 11	≤27	23-25
Southern Washington Township	15-1059	100	.140	<1.09	<1	>32	39-46
Cross Keys	15-1051	27	3.80	3.1	37 ± 3	<<27	3-4
Cross Keys	15-1052	65	7.20	8.1	56 ± 4	<<27	16-20
Cross Keys	15-1053	97	3.50	<1.76	1	>32-<50	47-65
Glassboro	15-1054	36	4.20	<1.85	55 ± 4	<<27	n.a.
Glassboro	15-1055	66	2.70	<4.3	50 ± 3	<<27	n.a.
Glassboro	15-1056	84	.62	<1.08	53 ± 4	<<27	n.a.
Upper Pittsgrove Township	33- 680	32	5.20	<1.07	41 ± 3	<<27	n.a.
Upper Pittsgrove Township	33- 681	45	10.0	<1.97	50 ± 4	<<27	n.a.

ground-water samples shown in table 3 by using the methods of Hendry (1988) and Bradbury (1991). Apparent ages of water samples from the nested observation wells generally confirm the pattern of increasing travel time with depth in the simulated sections.

The recharge-rate and porosity estimates used are reasonable and the travel times to the screens of the nested observation wells are within the range of apparent tritium ages for water from the nested observation wells (table 3). Additional age dating of ground water with chlorofluorocarbons and tritium/helium-3 resulted in a match with model-predicted travel times to within a few years (Szabo and others, 1996).

RELATION OF GROUND-WATER FLOWPATHS AND TRAVEL TIME TO THE DISTRIBUTION OF RADIUM AND NITRATE

Results of analyses of samples from the 15 nested observation wells at the five sites and the two piezometers near the Seabrook site show a moderate-to-high correspondence between concentrations of radium and nitrate (Szabo and others, 1997). Concentrations of radium-226 plus radium-228 and concentrations of nitrate were substantially higher in the shallow and medium-depth wells and piezometers than in the deep wells. At the three modeled sites, the sum of the radium-226 and radium-228 concentrations exceeded 5 pCi/L (the USEPA MCL) in samples of water from either the shallow or medium-depth wells and piezometers (wells 11-693, 11-700, 15-1052, 15-1057, and 15-1063), but were low in water from the deep wells. Similarly, at the Seabrook and Upper Pittsgrove Township sites, the nitrate concentration exceeded 10 mg/L (the USEPA MCL) in samples of water from either the shallow or medium-depth wells and piezometers (table 3), but the nitrate concentrations in water from the deep wells at all the sites were generally low. The maximum concentrations of dissolved radium and nitrate generally were found in water between the water table and a depth of about 80 ft below land surface.

Szabo and others (1997) and Kozinski and others (1995) found that concentrations of radium and nitrate in water from the Kirkwood-Cohansey aquifer system were strongly correlated. Elevated concentrations of these dissolved constituents were greatest in areas of agricultural land use; concentrations were lowest in forested areas (Szabo and others, 1997). These results demonstrate that the presence of nitrate in ground water is an indicator of the presence of agricultural chemicals in the ground-water-flow system.

The strong relation between concentrations of both radium and nitrate and depth indicates that the correlation between these constituents in withdrawal wells on a regional scale (Szabo and others, 1997; Kozinski and others, 1995) is not coincidental or the result of mixing of water of varying quality at the well screen. Further, this relation indicates that an increase in mobility of radium in shallow ground water whose composition has been substantially modified by the presence of nitrate and other agricultural chemicals is a probable reason for the correlation on a regional scale. Therefore, to understand the distribution of dissolved radium through the aquifer, it is necessary to evaluate the dispersal of nitrate derived from agricultural sources within the aquifer. The distribution of nitrate in the aquifer system can then be used to identify aquifer areas where elevated radium concentrations are likely be found. Conservative transport of nitrate is a reasonable assumption for areas of similar hydrologic and geochemical conditions in the Kirkwood-Cohansey aquifer system, because the general absence of dissolved nitrogen gas in excess of that expected in precipitation in equilibrium with the atmosphere indicates that nitrate reduction is minimal at the nested-well sites (Vowinkel and Szabo, 1996).

Flowpaths and Travel Time

The distribution of nitrate within the aquifer is controlled largely by three factors: (1) the spatial distribution of agricultural land use, (2) the transport of water that entered the aquifer system through an agricultural recharge area, and (3) the age distribution of water in the aquifer. Water that contains nitrate must have entered the aquifer through a recharge area with agricultural land use. Also, water that contains elevated concentrations of nitrate must postdate its intensive application. The intensive agricultural application of nitrate probably began about 1940 (Brown, 1970, p. 101).

Simulated flowpaths can be used to determine whether water at a given position within the aquifer has been recharged through agricultural land. Furthermore, travel time can be calculated at any position on a flowpath, delineating where the ground-water age predates the intensive application of nitrate. The probable extent of radium and nitrate within the modeled sections was delineated by defining the limits of the part of the aquifer where ground-water flowpaths originated in agricultural-recharge areas and by the 50-year line of equal travel time (fig. 10). Two assumptions were made in defining this extent: (1) nitrate leaching from fertilizer application is transported conservatively along the flowpaths and (2) radium is dissolved from the aquifer matrix with the passing of the front of nitrate-laden acidic water (Szabo and others, 1997). It is not necessary to assume conservative transport of radium, however; the delineated area in the aquifer is the probable extent of elevated concentrations of dissolved radium.

Conceptual Model of the Distribution of Radium and Nitrate

The three sites selected for simulation were assumed to be representative of the hydrologic, land-use, and geochemical conditions within much of the Kirkwood-Cohansey aquifer system in southwestern and south-central New Jersey. Fertilizers were assumed to be a continuous source of nitrate to the ground-water-flow system in agricultural areas (fields are fertilized every year). Also, as previously stated, nitrate was assumed to be conservatively transported along the flowpaths. Given these assumptions, the simulation results can be used to delineate two boundaries of a simple conceptual model that define the distribution of water that contains elevated concentrations of radium and nitrate in the Kirkwood-Cohansey aquifer system. These boundaries are illustrated in figure 10.

Water that contains elevated concentrations of nitrate must have entered the aquifer system through an agricultural recharge area. One boundary, therefore, is the flowpath that originates at the boundary between agricultural and nonagricultural land. This bounding flowpath corresponds to the 0.40 stream line at the Seabrook site (fig. 10); it extends at depth below forested (nonagricultural) land and discharges to the stream. At the Cross Keys and southern Washington Township sites, this bounding flowpath also originates at the point that approximately corresponds to the origin of 0.40 stream line (fig. 9), indicating that the distribution of land use at these three sites is similar and, therefore, is assumed to be representative of the overall distribution of land use in the study area. Figure 10 implies, therefore, that a potential maximum of 60 percent of the water in the aquifer in the study area was recharged through agricultural land and may contain elevated concentrations of radium and nitrate.

Because ground water that contains nitrate derived from modern agricultural chemicals must be old enough to postdate its intensive application, the 50-year line of equal travel time is the other approximate boundary of the distribution of modern agricultural chemicals in the aquifer.

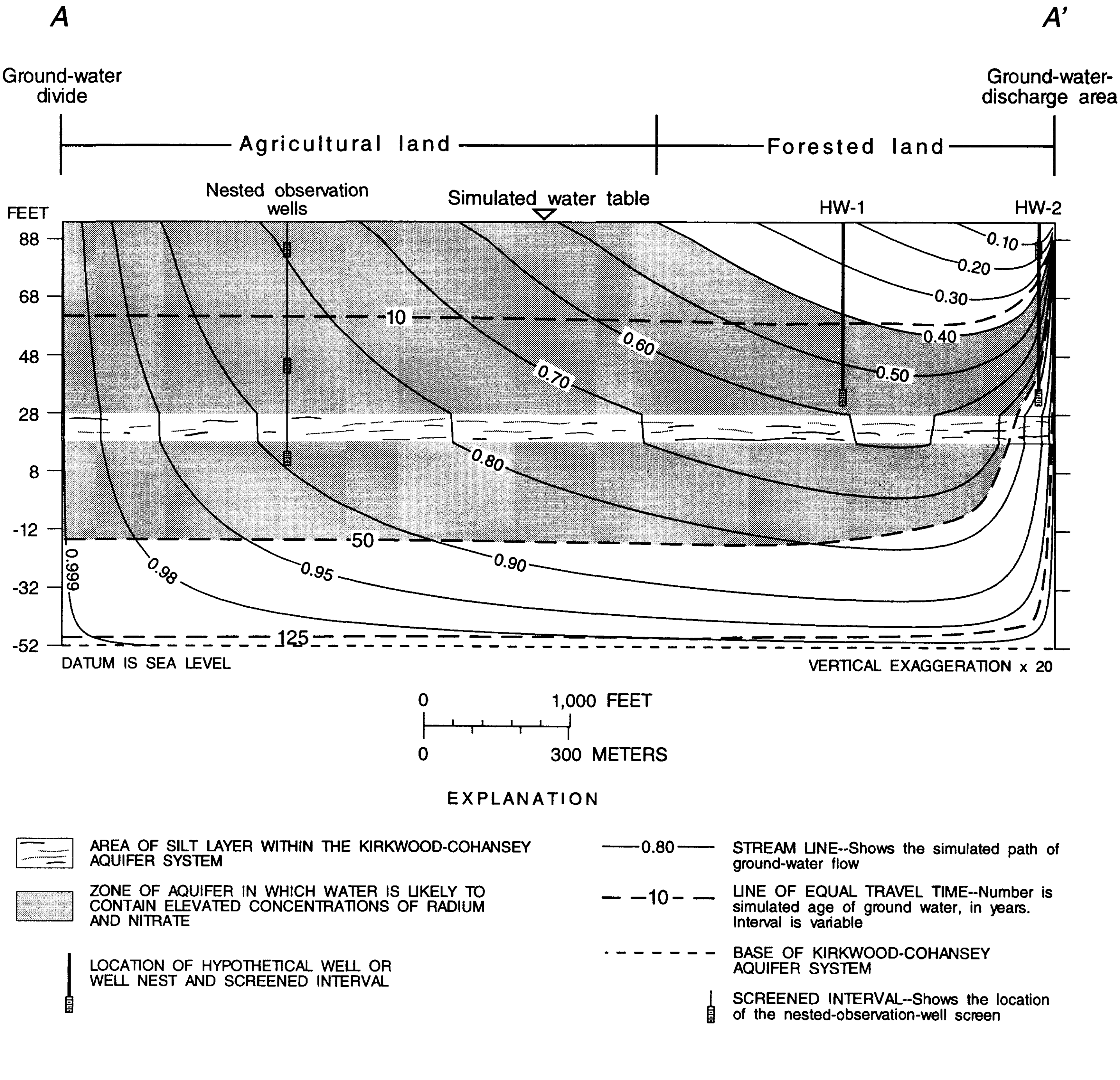


Figure 10. Schematic hydrologic section with predicted location of water containing elevated concentrations of radium and nitrate, along section *A-A'* near Seabrook, Cumberland County, New Jersey.

Water below this boundary in the aquifer will not contain modern agricultural chemicals whether or not it originated as recharge in an agricultural area. The depth from the water table to the 50-year line of equal travel time at the ground-water divide is 103 ft, 81 ft, and 85 ft in the Seabrook, Cross Keys, and southern Washington Township sections, respectively (figs. 9 and 10).

The conceptual model of the distribution of elevated concentrations of radium and nitrate within the Kirkwood-Cohansey aquifer system in the study area (fig. 10), derived from results of the simulation of ground-water flow in the modeled sections, can be described as follows:

1. Travel time increases with depth in the Kirkwood-Cohansey aquifer system. Therefore, nitrate dissolved in the water (and associated elevated concentrations of radium) extends downward to a maximum depth of penetration that is determined by the length of time nitrate has been intensively applied. This depth is defined by the 50-year line of equal travel time.

2. Water at depth in the Kirkwood-Cohansey aquifer system can be more than 50 years old. Because this water predates the intensive application of nitrate it will not contain elevated concentrations of either radium or nitrate.

3. Ground-water flowpaths in the Kirkwood-Cohansey aquifer system that originate beneath agricultural land extend beneath downgradient nonagricultural land. Therefore, water containing elevated concentrations of radium and nitrate can be transported from agricultural to nonagricultural areas.

Use of Conceptual Model to Predict Distribution of Radium and Nitrate

The conceptual model illustrated in figure 10 indicates that, in general, water that is less than 50 years old and that originated in an agricultural area will contain elevated concentrations of dissolved radium and nitrate. For example, water moving along flowpaths intercepted by the nested wells at the Seabrook site originated in an agricultural area, has a travel time of less than 50 years, and contains elevated concentrations of radium and nitrate. The conceptual model illustrated in figure 10 also indicates, however, that elevated concentrations of radium and nitrate may be absent beneath agricultural land or present beneath nonagricultural land. Elevated concentrations of radium can be found in water from wells located in a nonagricultural (forested or low-density residential) area if the water has a travel time of less than 50 years and is downgradient from an agricultural area. Low concentrations of radium (radium-226 plus radium-228 <2.0 pCi/L[3]) can be found in water from deep wells in agricultural areas, and in water from shallow wells in nonagricultural areas immediately downgradient from agricultural areas.

Results of the simulations indicated that water recharging the aquifer through agricultural land (potentially bearing nitrate and leaching radium) flows toward the nearby stream, passing beneath downgradient, undeveloped land (fig. 10). Therefore, water in wells in nonagricultural areas downgradient from agricultural land may contain elevated concentrations of radium and nitrate. For example, hypothetical well HW-1 (fig. 10): (1) is located downslope and downgradient from agricultural land, (2) is located beneath nonagricultural land but not immediately adjacent to the discharge area (local stream or swamp), and (3) is screened at a depth where flowpaths to its

[3] This value is based on the median concentration of <1.73 pCi/L radium-226 plus radium-228 reported by Szabo and others (1997) for wells located in nonagricultural areas.

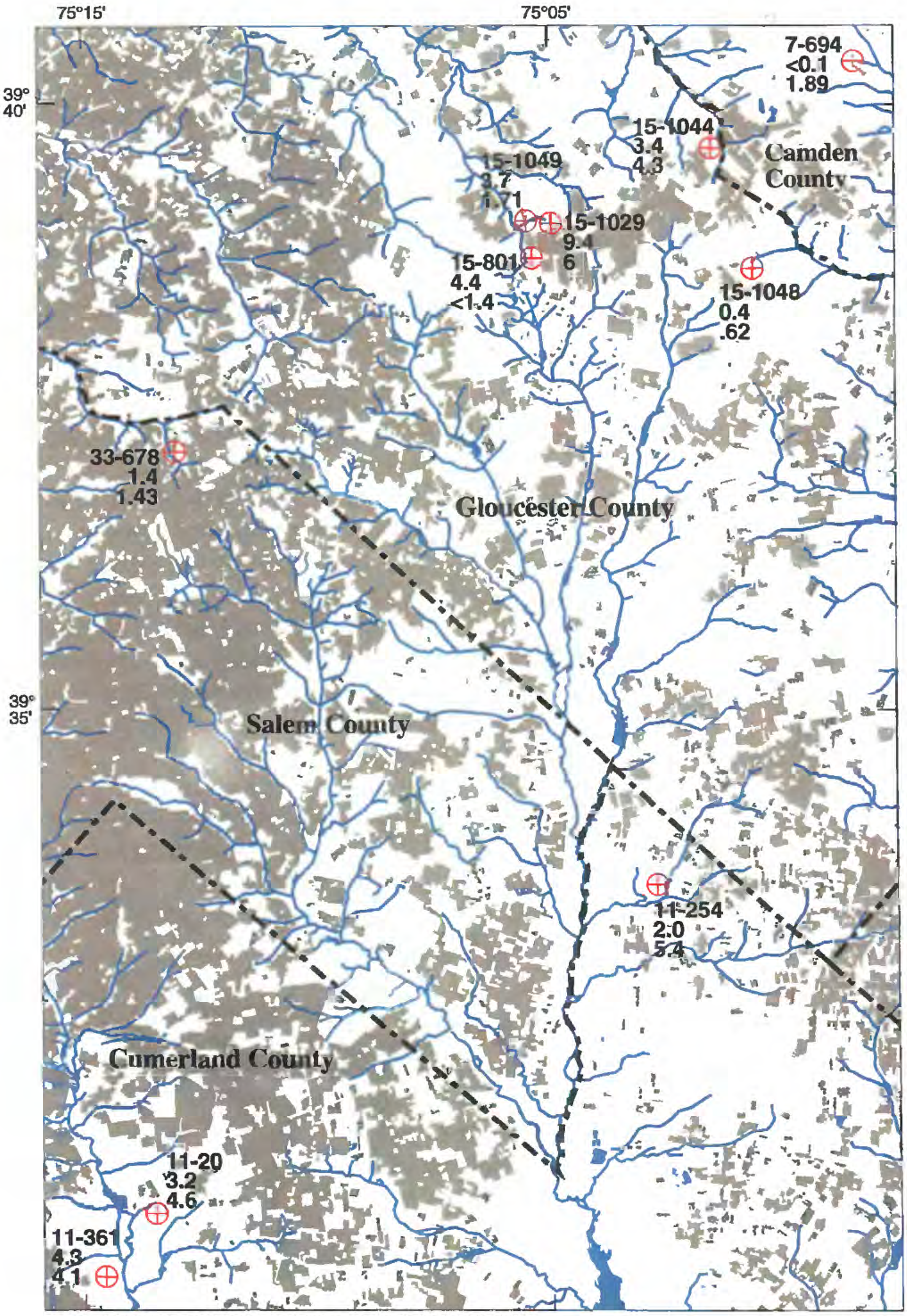
screen originate in an agricultural recharge area. Therefore, water from this well is expected to contain elevated concentrations of radium and nitrate. A well screen placed at this depth intercepts water that is likely to have been recharged through the adjacent upgradient agricultural land within the last 50 years, especially if the well (a public-supply well, for example) is pumped at a high rate. For example, samples collected by Kozinski and others (1995, app. 2) from unused public-supply well 15-1029 (fig. 11) located in an undeveloped area immediately downgradient from agricultural land contained elevated concentrations of radium (radium-226 plus radium-228 6.0 pCi/L) and nitrate (9.4 mg/L).

In practice, this simple conceptual model cannot predict with certainty every well in which concentrations of both radium and nitrate will be elevated. The use of precise numbers to define elevated concentrations of radium and nitrate is a limitation of the conceptual model. Examples of wells at similar locations and depths as well HW-1 in which radium or nitrate concentrations are not precisely consistent with those predicted by the conceptual model are public-supply wells 11-20, 11-254, and 11-361 (Kozinski and others, 1995, app. 2) and domestic well 15-1044 (Szabo and others, 1997, app. 1B). Each of these wells contains elevated concentrations of either radium or nitrate; but the concentration of the other constituent does not meet the definition of elevated. Factors not considered in the conceptual model that could locally affect the concentrations of radium and (or) nitrate in water include (1) the pumping rate of the well, (2) changes in the application rate of fertilizer (nitrate) over time, (3) spatial differences in the radium concentration of aquifer material, and (4) changes in land use over time.

Land use in the study area is changing rapidly from agricultural to residential. The southern Washington Township nested-well site is an area where such a change occurred. As the amount of agricultural land decreases over time, the number of flowpaths within the aquifer that originate in an agricultural recharge area that reach wells similar to well HW-1 also will decrease, resulting in decreasing concentrations of radium and nitrate in the water.

Results of the simulation indicate that the lines of equal ground-water travel time are more closely spaced vertically near the ground-water-discharge area (local stream or swamp) than at points upgradient from the discharge area (fig. 8). Hypothetical well nest HW-2 is located adjacent to a stream beneath nonagricultural land (fig. 10) with the deepest well screened the same distance below the water table as well HW-1 (fig. 10). The water intercepted by the deepest well at nest HW-2 originates far upgradient in an agricultural area, but the travel time at the point on the flowpath intercepted by the well indicates that the time of recharge predates the intensive application of fertilizer (nitrate); therefore, water from this well likely does not contain elevated concentrations of radium or nitrate. For example, samples from well 33-678 in a similar location and depth as the deep well in nest HW-2 contained low concentrations of radium (radium-226 plus radium-228, <1.46 pCi/L) and nitrate (1.4 mg/L) (Szabo and others, 1997, app. 1B). An additional example of a well with a similar location and depth with low concentrations of radium is well 15-1048 (Szabo and others, 1997, app. 1B).

A shallow well near a discharge area, such as the shallowest well in nest HW-2, would intercept water along flowpaths recharged from nonagricultural land; water from such a well also would not contain elevated concentrations of radium or nitrate. Well 7-694 is in a similar location and depth as the shallow well in nest HW-2, and water from this well contained low concentrations of radium (radium 226 plus radium 228, 1.89 pCi/L) and nitrate (<0.1 mg/L).



Base from New Jersey Department of Environmental Protection digital data, 1:24,000, 1988, Universal Transverse Mercator Projection, Zone 18. Agricultural land-use polygons modified from New Jersey Department of Environmental Protection digital data, 1:24,000, 1986.

0 1 2 3 4 MILES

0 1 2 3 4 KILOMETERS

EXPLANATION

Agricultural land

County boundary

Stream

15-801 4.4 <1.4 WELL--Top number is U.S. Geological Survey well number. Middle number is nitrate concentration, in milligrams per liter. Bottom number is sum of radium-226 and radium-228 concentrations, in picocuries per liter (< = less than)

Figure 11. Concentrations of nitrate and the sum of radium-226 and radium-228 in water samples from wells in the Kirkwood-Cohansey aquifer system, southwestern New Jersey.

SUMMARY AND CONCLUSIONS

In a study of the hydrologic processes that control the distribution of radium in water in the Kirkwood-Cohansey aquifer system in the southern Coastal Plain of New Jersey, 15 nested observation wells and two piezometers were installed at five sites in agricultural areas near ground-water divides. Water levels measured in the wells and piezometers at three of the sites were used to calibrate two-dimensional finite-difference ground-water-flow models constructed through three of the nested-observation-well sites. Water-quality samples from the nested wells and piezometers were analyzed for radium and nitrate.

Ground-water flowpaths and travel times were calculated from the simulation results. Flowpaths in the modeled sections extended downward from the divide, across the section, and upward to the discharge area. Ground-water travel times were predicted to increase with depth in the Kirkwood-Cohansey aquifer system. Travel times to each well approximately matched the ranges of apparent ages of ground water determined by tritium age-dating.

The flowpaths and travel times predicted from simulation results were used to develop a conceptual model of the distribution of modern agricultural chemicals and elevated concentrations of radium within the aquifer. The conceptual model can be described as follows:

1. Travel time increases with depth in the Kirkwood-Cohansey aquifer system. Therefore, nitrate dissolved in the water (and associated elevated concentrations of radium) extends downward to a maximum depth of penetration which is determined by the length of time nitrate has been intensively applied. This depth is defined by the 50-year line of equal travel time.

The maximum depth of penetration of 50-year-old water in the modeled sections ranged from 80 to 105 ft below the water table. The maximum concentrations of dissolved radium and nitrate generally were found in water predicted to have a travel time less than 50 years, ranging in depth from near the water table to about 80 ft below land surface.

2. Water at depth in the Kirkwood-Cohansey aquifer system can be more than 50 years old. Because this water predates the intensive application of nitrate it will not contain elevated concentrations of either radium or nitrate.

In general, water from the deep nested observation wells contained lower concentrations of radium-226 plus radium-228 and nitrate than water from the shallower wells.

3. Ground-water flowpaths in the Kirkwood-Cohansey aquifer system that originate beneath agricultural land extend beneath downgradient nonagricultural land. Therefore, water containing elevated concentrations of radium and nitrate can be transported from agricultural to beneath nonagricultural areas.

The conceptual model can be used to predict the aquifer areas that may contain elevated concentrations of radium and nitrate. These aquifer areas are found beneath agricultural areas where travel time is less than 50 years and beneath forested land adjacent to agricultural areas where ground water was recharged through agricultural land and has a travel time of less than 50 years. The conceptual model can also predict aquifer areas that do not contain elevated concentrations of radium and nitrate. These aquifer areas would be located deep beneath agricultural areas or adjacent nonagricultural areas where ground water was recharged through an agricultural area but has a travel time greater than 50 years, and beneath nonagricultural areas where shallow ground water was not recharged through an adjacent agricultural area.

REFERENCES CITED

Bauersfeld, W.R., Jones, W.D., and Pustay, E.A., 1992, Water resources data, New Jersey, water year 1991, volume 2. ground-water data: U.S. Geological Survey Water-Data Report NJ-91-2, 182 p.

Bauersfeld, W.R., Jones, W.D., and Gurney, C.E., 1993, Water resources data, New Jersey, water year 1992, volume 2. ground-water data: U.S. Geological Survey Water-Data Report NJ-91-2, 182 p.

Bradbury, K.R., 1991, Tritium as an indicator of ground-water age in central Wisconsin: Ground Water, v. 29, p. 398-404.

Brown, L.R., 1970, Human food production as a process in the biosphere: Scientific American, v. 223, no. 3, p. 158-169.

Buxton, H.T., and Modica, Edward, 1992, Patterns and rates of ground-water flow on Long Island, New York: Ground Water, v. 30, no. 6, p. 857-866.

Claassen, H.C., 1982, Guidelines and techniques for obtaining water samples that accurately represent the water chemistry of an aquifer: U.S. Geological Survey Open-File Report 82-1024, 49 p.

Cothern, C.R., 1987, Estimating the health risks of radon in drinking water: American Water Works Association Journal, v. 79, no. 4, p. 153-158.

Delwiche, C.C., 1970, The nitrogen cycle: Scientific American, v. 223, no. 3, p. 137-146.

Farlekas, G.M., Nemickas, Bronius, and Gill, H.E., 1976, Geology and ground-water resources of Camden County, New Jersey: U.S. Geological Survey Water-Resources Investigations 76-76, 146 p.

Fishman, M.J., and Friedman, L.C., 1985, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 709 p.

Hardt, W.F., and Hilton, G.S., 1969, Water resources and geology of Gloucester County, New Jersey: State of New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report No. 30, 130 p.

Hendry, M.J., 1988, Do isotopes have a place in ground-water studies?: Ground Water, v. 26, no. 4, p. 410-415.

Johnson, M.E., 1950, Geologic map of New Jersey, revised: New Jersey Department of Conservation and Economic Development, scale 1:250,000.

Johnson, J.H., 1978, Soil survey of Atlantic County, New Jersey: U.S. Department of Agriculture, Soil Conservation Service, 61 p.

REFERENCES CITED--Continued

Kozinski, Jane, Szabo, Zoltan, Zapecza, O.S., and Barringer, T.H., 1995, Natural radioactivity in, and inorganic chemistry of, ground water in the Kirkwood-Cohansey aquifer system in southern New Jersey: U.S. Geological Survey Water-Resources Investigations Report 92-4144, 130 p.

Krieger, H.L., and Whitaker, E.L., 1980, Prescribed procedures for measurement of radioactivity in drinking water: U.S. Environmental Protection Agency, Manual EPA-600/4-80-032, 111 p.

Lacombe, Pierre, and Rosman, Robert, 1995, Hydrology of the unconfined aquifer system, upper Maurice River Basin and adjacent areas in Gloucester County, New Jersey, 1986-87: U.S. Geological Survey Water-Resources Investigations Report 92-4128, 5 sheets.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, 528 p.

Martin, Mary, in press, Ground-water flow in the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-H.

Martino, R.L., 1981, The sedimentology of the late Tertiary Bridgeton and Pensauken Formations in southern New Jersey: New Brunswick, N.J., Rutgers University, unpublished Ph.D. dissertation, 299 p.

Mays, C.W., Rowland, R.E., and Stehney, A.F., 1985, Cancer risk from the lifetime intake of Ra and U isotopes: Health Physics, v. 48, no. 5, p. 635-647.

Nemickas, Bronius, and Carswell, L.D., 1976, Stratigraphic and hydrologic relation of the Piney Point aquifer and the Alloway Clay member of the Kirkwood Formation in New Jersey: U.S. Geological Survey Journal of Research, v. 4, no. 1, p. 1-7.

Ostlund, H.G., and Dorsey, H.G., 1977, Rapid electrolytic enrichment and hydrogen gas proportional counting of tritium, *in* Low-radioactivity measurements and applications: Proceedings of the International Conference on Low-Radioactivity Measurements and Applications, October 6-10, 1975, The High Tatras, Czechoslovakia, Slovenske Pedagogicke Nakla date'stvo, Bratislava, Slovakia.

Owens, J.P., Bybell, L.M., Paulachok, Gary, Ager, T.A., Gonzalez, V.M., and Sugarman, P.J., 1988, Stratigraphy of the Tertiary sediments in a 945-foot-deep corehole near Mays Landing in the southeastern New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1484, 39 p.

Owens, J.P., and Minard, J.P., 1979, Upper Cenozoic sediments of the lower Delaware Valley and the northern Delmarva Peninsula: New Jersey, Pennsylvania, Delaware, and Maryland: U.S. Geological Survey Professional Paper 1067-D, 48 p.

Owens, J.P., and Sohl, N.F., 1969, Shelf and deltaic paleoenvironments in the Cretaceous-Tertiary formations of the New Jersey Coastal Plain, *in* Subitzky, Seymour, ed., Geology of selected areas in New Jersey and eastern Pennsylvania, and guidebook of excursions: New Brunswick, N.J., Rutgers University Press, p. 235-278.

Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 89-381, 188 p.

Remson, Irwin, 1954, Hydrologic studies at Seabrook, New Jersey: U.S. Geological Survey Open-File Report, 156 p.

Rhodehamel, E.C., 1973, Geology and water resources of the Wharton Tract and the Mullica River Basin in southern New Jersey: New Jersey Department of Environmental Protection, Division of Water Resources, Special Report No. 36, 58 p.

Rooney, J.G., 1971, Ground-water resources of Cumberland County, New Jersey: New Jersey Department of Environmental Protection, Division of Water Resources, Special Report No. 34, 83 p.

Rosenau, J.C., Lang, S.M., Hilton, G.S., and Rooney, J.G., 1969, Geology and ground-water resources of Salem County, New Jersey: State of New Jersey Department of Conservation and Economic Development, Division of Water Policy and Supply, Special Report No. 33, 142 p.

Rosman, Robert, Lacombe, P.J., and Storck, D.A., 1995, Water levels in major artesian aquifers of the New Jersey Coastal Plain, 1988: U.S. Geological Survey Water-Resources Investigations Report 95-4060, 74 p., 8 pl.

Severson, R.C., and Shacklette, H.T., 1988, Essential elements and soil amendments for plants: Sources and use for agriculture: U.S. Geological Survey Circular 1019, 48 p.

Szabo, Zoltan, Rice, D.E., Ivahnenko, Tamara, and Vowinkel, E.F., 1994, Delineation of the distribution of pesticides and nitrate in an unconfined aquifer in the New Jersey Coastal Plain by flow-path analysis, *in* Weigman, D.L., ed., New directions in pesticide research, development, management, and policy: Blacksburg, Va., Virginia Water Resources Center, p. 100-117.

Szabo, Zoltan, Rice, D.E., MacLeod, C.L., and Barringer, T.H.,1997, Relation of distribution of radium, nitrate, and pesticides to agricultural land use and depth, Kirkwood-Cohansey aquifer system, New Jersey Coastal Plain, 1990-92: U.S. Geological Survey Water-Resources Investigations Report 96-4165A, 119 p.

Szabo, Zoltan, Rice, D.E., Plummer, L.N., Busenberg, Eurybades, Drenkard, Stefan, and Schlosser, Peter, 1996, Age-dating of shallow ground water with chlorofluorocarbons, tritium/helium-3, and flow-path analysis in an unconfined aquifer of the southern New Jersey Coastal Plain: Water Resources Research, v. 32 no. 4, p. 1023-1038.

REFERENCES CITED--Continued

Vowinkel, E.F., and Szabo, Zoltan, 1996, Relation between land use and distributions of dissolved nitrogen species in shallow water in two New Jersey Coastal Plain aquifer systems, *in* Puckett, L.J., and Triska, F.J., eds., U.S. Geological Survey Nitrogen-Cycling Workshop: U.S. Geological Survey Open-File Report 96-477, p. 14.

Wood, W.W., 1976, Guidelines for collection and field analysis of ground-water samples for selected unstable constituents: U.S. Geological Survey Techniques of Water Resources Investigations, book 1, chap. D2, 24 p.

Zapecza, O.S., 1989, Hydrogeologic framework of the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-B, 49 p., 24 pl.