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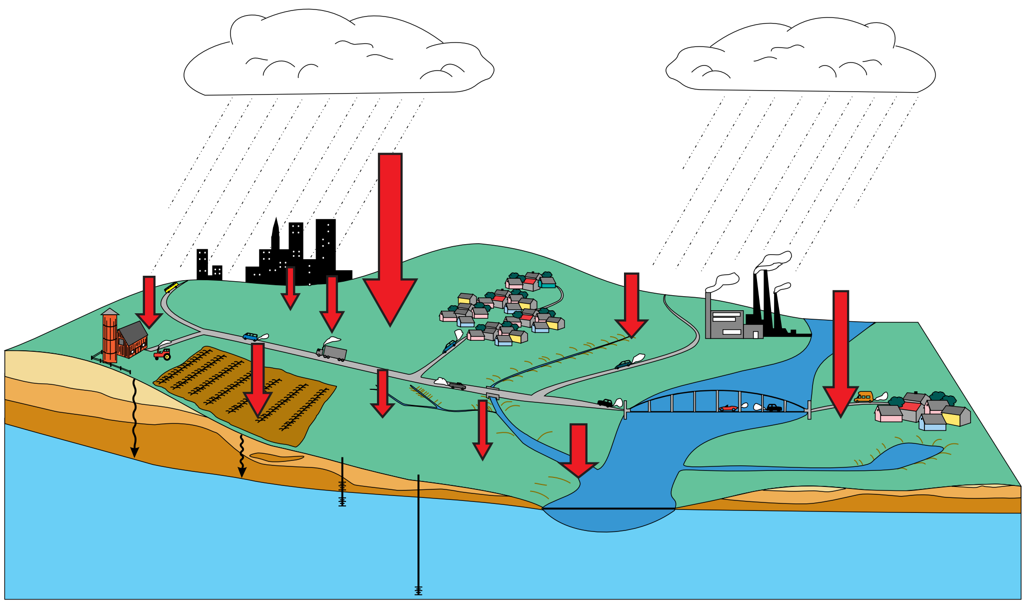
ESTIMATING SPATIAL VARIABILITY OF RECHARGE IN SOUTHERN NEW JERSEY FROM UNSATURATED-ZONE MEASUREMENTS

Water-Resources Investigations Report 02-4288



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By Arthur L. Baehr, Leon J. Kauffman, Kimberlie Perkins, and Bernard T. Nolan

U.S. GEOLOGICAL SURVEY

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West Trenton, New Jersey

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science for a changing world

U.S. DEPARTMENT OF THE INTERIOR

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CONVERSION FACTORS AND ABBREVIATIONS

MULTIPLY	BY	TO OBTAIN
micron (mm)	0.00003937	inches
centimeter (cm)	0.3937	inches
square kilometer (km^2)	0.3861	square miles
cubic centimeter (cm^3)	0.061	cubic inches

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ABSTRACT

Spatial variability of recharge in southern New Jersey was studied by sampling the unsaturated zone at 48 sites distributed over approximately 930 square kilometers. Samples of unsaturated-zone sediment were collected during the summer and fall of 1996. Unsaturated flow was calculated using moisture-content data and estimates of conductivity and matric potential derived from sediment-size data. Matric forces were found to be important at about 70 percent of the sites despite the expectation that unsaturated flow in a humid climate is gravity driven. Upward water movement occurred at about 17 percent of the sites. The lower sediment layer at these sites consisted of sandy loam, indicating that upward movement can occur at depth only where the sediments are relatively fine-grained. At the other extreme, calculated flow at about 17 percent of the sites exceeded 250 centimeters per year. Because of the uncertainty inherent in unsaturated-flow calculations, the method provides only a scaling of recharge variability; however, the median calculated flow of 29.1 centimeters per year compares favorably with recharge estimates from previous water-budget studies. A map developed by spatial analysis of the recharge estimates identified an agricultural part of the study area where recharge was known to be low relative to recharge in other basins.

INTRODUCTION

Recharge, the rate at which water moves across the water table, is typically quantified at the watershed scale by considering its relation to more readily measurable components of the water budget. For example, in the case of a surficial aquifer,

$$R = Q_0 - Q_i + Q_p , \qquad (1)$$

where R is recharge, Q_0 is stream outflow, Q_i is stream inflow, and Q_p is water use. By using this equation, a single value for recharge across the watershed can be calculated. This method of estimating recharge is described by Rutledge (1997).

Although an average value of recharge for a watershed serves to quantify the bulk movement of water through the hydrologic cycle, information on its spatial variability is needed to estimate contaminant loading to an aquifer because chemical use varies within the watershed (fig. 1). The relation of recharge at a particular location to topography, stormwater-management practices, and the hydraulic properties of the unsaturated zone, however, cannot be determined without additional data. Soils maps of a watershed, even if available, do not characterize unsaturated-zone sediments at depths greater than a few feet. Furthermore, the moisture content through the unsaturated zone generally is unknown.

The U.S. Geological Survey (USGS) conducted a study of the unsaturated zone in southern New Jersey to estimate the spatial variability of recharge to an unconfined aquifer. During July 30-October 24, 1996, samples of unsaturated-zone sediments were collected during the installation of 48 observation wells in the Kirkwood-Cohansey aquifer system over an area of approximately 930 km^2. The installation of the observation wells provided an opportunity to map unsaturated-zone sediment properties, collect core samples for analysis, and obtain one-time moisture-content data at these locations. Pedotransfer functions were used to estimate hydraulic conductivity and matric potential on the basis of sediment size-distribution data. Darcy's Law was applied to compute unsaturated flow within a sediment layer encountered below the soil zone at each site. These flow values are assumed to provide a "snapshot" of spatial variations in recharge over the study area. Because the flow

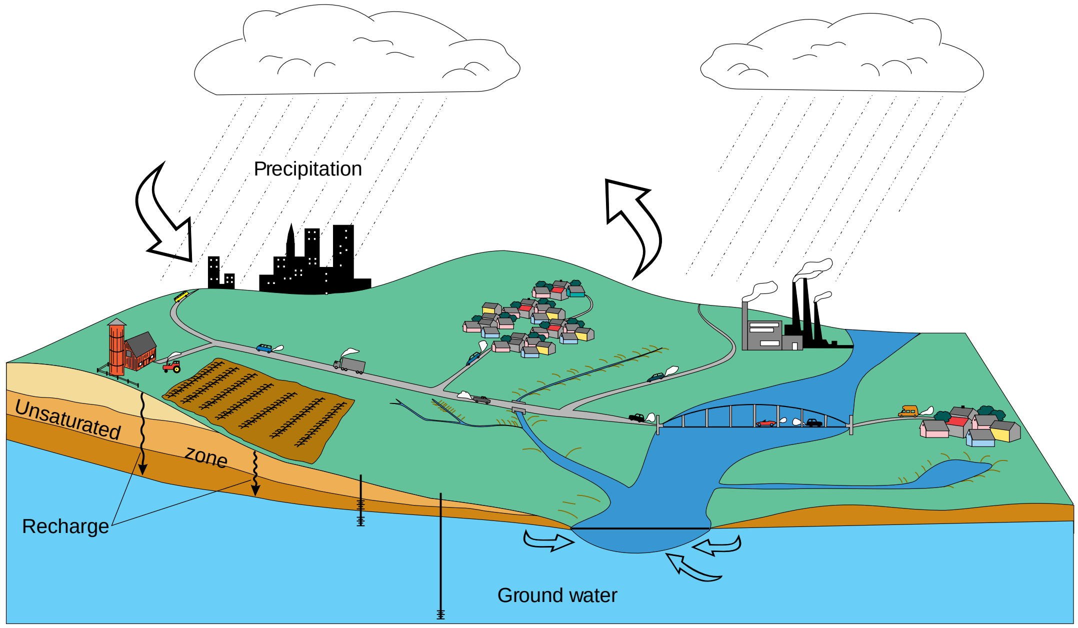
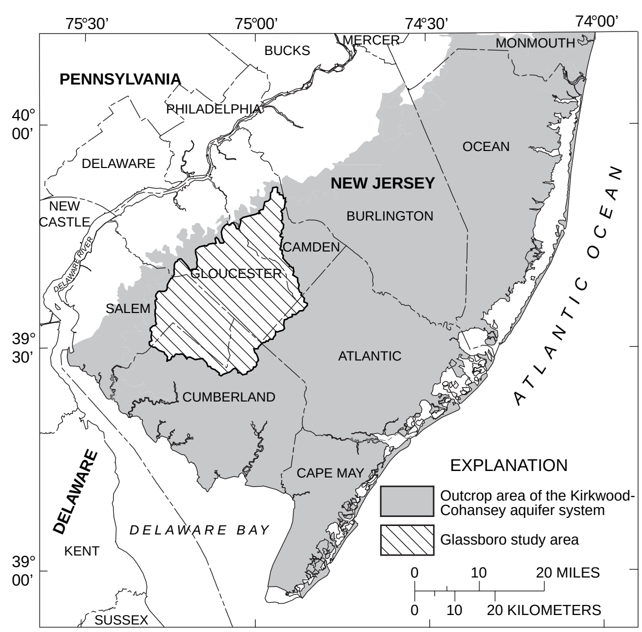


Figure 1. The hydrologic cycle in a watershed with various land uses.



Base from U.S. Geological Survey, Wilmington,
Hammonton 1:250,000 quadrangles, 1969,
Universal Transverse Mercator Projection, Zone 18

Figure 2. Location of unsaturated-zone sampling sites, Glassboro study area.

values are based on unsaturated-zone observation, they incorporate the effects of variable sediment properties and of other factors that can cause recharge to vary spatially, such as topography and stormwater-management practices.

This report presents the results of the unsaturated-zone study. It includes a summary of unsaturated-zone sediment properties, an evaluation of pedotransfer function parameters, and a map of the study area showing areas of relatively high and low recharge. The results of this study can be used in conjunction with land-use information to develop a conceptual understanding of the spatial variation of movement of chemicals into the Kirkwood-Cohansey aquifer system.

STUDY AREA

The study area (fig. 2) consists of approximately 930 km^2 in the Coastal Plain Physiographic Province encompassing Glassboro in southern New Jersey (hereafter called the Glassboro study area). The population in the study area, estimated from census data, was about 50,000 in 1940, 100,000 in 1960, 180,000 in 1980, and 250,000 in 2000. Water pumped from the surficial Kirkwood-Cohansey aquifer system (hereafter called the aquifer) has increased in recent years as communities meet the water demands associated with the rapid suburban growth. The outcrop of the Kirkwood Formation, a confining unit about 30 m thick, forms the northwestern boundary of the study area and underlies the aquifer, which consists of unconsolidated sand and gravel. The aquifer thickens to the southeast and is about 75 m thick at the southeastern boundary of the study area (Zapecza, 1989).

Most of the unsaturated zone is made up of the Cohansey Sand, which was was deposited during the Miocene Age. Its depositional history is one of inner shelf, nearshore, and beach environments during a slow retreat of the sea. The sediments of the Cohansey Sand, like those of similarly deposited formations of the New Jersey Coastal Plain, generally coarsen upward (Zapecza, 1989). In some areas, the Bridgeton Formation overlies the Cohansey Sand. Coarse, pebbly, orange sands that were deposited under continental conditions during the late Tertiary and Quaternary Periods characterize this formation. Where present in the study area, the Bridgeton Formation generally is less than 3 m thick.

Annual recharge to the aquifer in several watersheds in southern New Jersey has been estimated by water-budget methods through a program of surficial-aquifer studies conducted by the USGS (Watt and Johnson, 1992; Watt and others, 1994; Johnson and Watt, 1997; Johnson and Charles, 1997; Charles and others, 2001). These estimates range from 33.1 to 49.3 cm/yr. Average annual precipitation in the study area is about 109.3 cm, of which 25.4, 29.1, 29.1, and 25.8 cm falls during winter, spring, summer, and fall respectively. Although precipitation is nearly evenly distributed throughout the year, the average daily temperature varies seasonally (0.8, 11.1, 23.2, and 13.7 ^{o}C during winter, spring, summer, and fall, respectively). Estimated seasonal potential evapotranspiration obtained by the Thornthwaite method (Thornthwaite and Mather, 1957) is 0.7, 14.9, 41.5, and 16.2 cm, respectively.

STUDY METHODS

Unsaturated-zone sediment was sampled at 48 sites during the installation of shallow-ground-water observation wells in summer and fall 1996 (fig. 3). Unsaturated flow was calculated using moisture-content data and estimates of conductivity and matric potential derived from sediment-size data.

Unsaturated-Zone Sampling

Site locations were selected at random within major land-use categories to assess ambient shallow-ground-water quality (Stackelberg and others, 1997). Core samples were collected throughout the unsaturated zone by driving a 61-cm-long by 5.1-cm- diameter split-spoon sampler with a drill rig hammer. A sediment sample of about 30 cm^3 was removed from the bottom end of each core to obtain values of moisture content and bulk density through use of gravimetric methods. Sediment layers, evidenced by visible changes in color and texture, were noted and the core samples were stored. Site locations and unsaturated-zone thickness are listed in table 1. Moisture contents as a function of depth at the sites are listed in table 2.

Figure 3. Location of unsaturated-zone sampling sites, Glassboro study area.

Table 1. Unsaturated-zone sampling sites, southern New Jersey

Site name	Altitude of site (meters above sea level)	Latitude	Longitude	Unsaturated-zone thickness (meters)	Date of water-level measurement[1]
AG01	36.6	393415.4	745635.1	4.5	8/06/1996
AG02	42.7	394302.6	751012.4	6.9	8/02/1996
AG03	43.3	393915.5	751220.9	3.6	8/02/1996
AG04	40.2	393627.0	751122.3	3.9	8/06/1996
AG09	38.1	393710.9	751209.8	2.0	9/11/1996
AG10	42.7	393413.2	751416.5	6.4	9/12/1996
AG11	39.6	393541.7	751102.9	2.7	9/12/1996
AG12	37.2	393158.9	751502.2	8.7	9/17/1996
AG13	29.0	393213.1	751556.2	3.4	9/17/1996
AG14	38.1	393051.7	751801.0	7.6	9/20/1996
AG15	26.8	393016.9	750544.0	5.8	10/08/1996
NU01	45.7	394326.7	750457.4	8.5	8/16/1996
NU02	43.3	394342.6	750400.6	2.3	8/16/1996
NU04	36.6	394458.0	750400.3	1.9	8/19/1996
NU06	53.3	394527.1	750039.5	13.1	8/20/1996
NU08	47.2	394338.9	750126.3	6.2	8/21/1996
NU09	44.2	394022.5	745909.1	6.1	8/22/1996
NU11	50.3	394604.5	750033.5	6.7	8/26/1996
NU12	47.2	394734.5	745641.2	2.5	8/27/1996
NU19	44.2	394254.5	745903.0	3.7	11/05/1996
NU21a	53.3	394640.0	745939.0	4.3	9/11/1996
NU22	44.2	394145.5	745913.3	3.0	11/14/1996
NU23	44.2	394154.0	750111.4	1.5	10/18/1996
NU24	42.7	394241.4	750506.2	4.7	9/24/1996
NU27	35.1	394942.0	745508.8	1.3	11/13/1996
NU29	36.6	394442.9	750307.4	2.4	11/06/1996
OU02	34.7	392919.8	750116.7	12.3	9/24/1996
OU03	48.2	394233.3	750136.2	5.4	10/02/1996
OU04	40.2	393917.1	750136.2	4.7	10/02/1996
OU05	22.9	393530.3	745237.8	2.8	10/03/1996
OU06	44.2	394104.1	745930.4	3.5	11/05/1996
OU07	27.4	392929.2	750159.1	4.9	11/21/1996
OU08	47.2	394747.9	745549.1	2.1	10/07/1996
OU10	29.3	392917.7	750036.7	6.4	11/19/1996
OU11	33.5	394351.0	750801.0	2.8	10/31/1996
OU13	39.6	394234.9	750713.4	2.1	10/31/1996
OU14	47.2	394645.5	745919.8	3.1	11/15/1996
OU15	29.0	392827.8	750138.3	8.1	9/16/1997
UN01	42.7	394141.8	745503.7	7.8	8/06/1996
UN02	15.2	392544.9	750507.7	4.3	9/13/1996
UN03	37.5	394023.3	750347.7	2.0	9/18/1996
UN05	38.7	393943.3	750304.9	2.5	10/03/1996
UN06	29.6	393751.8	745512.6	1.7	10/03/1996
UN07	30.2	393029.7	750907.3	4.6	11/2719/96
UN08	34.4	393339.4	745514.5	2.2	10/03/1996
UN09	30.5	393939.3	745341.5	1.1	10/03/1996
UN11	30.5	394710.0	750039.0	4.7	1/15/1996
UN12	25.9	393439.4	750431.0	1.5	11/04/1996

[1]Water level measured to determine unsaturated-zone thickness, typically on or shortly after date of well installation.

Table 2. Moisture content[1] at unsaturated-zone sampling sites

[--, depth below water table therefore moisture content not determined]

Site name	Date of moisture-content measurement[2]	Depth (meters below land surface)													
		0.6	1.2	1.8	2.4	3.0	3.7	4.3	4.9	5.5	6.1	6.7	7.3	7.9	8.5
AG01	7/31/1996	0.13	0.27	0.22	0.25	0.44	0.22	0.26	--	--	--	--	--	--	--
AG02	7/31/1996	0.15	0.19	0.10	0.28	0.08	0.12	0.12	0.12	0.09	0.09	0.10			
AG03	8/01/1996	0.42	0.24	0.10	0.08	0.20	--	--	--	--	--	--	--	--	--
AG04	8/01/1996	0.28	0.12	0.16	0.16	0.27	0.24	--	--	--	--	--	--	--	--
AG09	9/11/1996	0.09	0.11	--	--	--	--	--	--	--	--	--	--	--	--
AG10	9/12/1996	0.30	0.20	0.16	0.11	0.11	0.15	0.13	0.09	0.14	0.26	--	--	--	--
AG11	9/12/1996	0.05	0.09	0.07	0.15	--	--	--	--	--	--	--	--	--	--
AG12	9/17/1996	0.07	0.13	0.14	0.03	0.16	0.08	0.06	0.08	0.06	0.06	0.23	--	--	--
AG13	9/17/1996	0.37	0.17	0.13	0.10	--	--	--	--	--	--	--	--	--	--
AG14	9/17/1996	0.33	0.17	0.03	0.13	0.10	0.17	0.04	0.04	0.04	0.03	0.04	--	--	--
AG15	9/20/1996	0.10	0.03	0.03	0.14	0.12	0.06	0.06	0.07	0.18	--	--	--	--	--
NU01	8/14/1996	0.14	0.13	0.14	0.06	0.09	0.07	0.05	0.08	0.23	0.14	0.13	0.12	0.09	0.11
NU02	8/15/1996	0.13	0.04	0.12	--	--	--	--	--	--	--	--	--	--	--
NU04	8/19/1996	0.04	0.22	0.32	--	--	--	--	--	--	--	--	--	--	--
NU06	8/20/1996	0.09	0.35	0.16	0.07	0.18	0.17	0.17	0.14	0.07	0.11	0.17	0.07	0.06	
NU08	8/21/1996	0.15	0.10	0.13	0.13	0.10	0.10	0.16	0.11	0.12	0.14	--	--	--	--
NU09	8/22/1996	0.24	0.32	0.07	0.05	0.09	0.05	0.08	0.04	--	--	--	--	--	--
NU11	8/26/1996	0.05	0.07	0.07	0.05	0.03	0.04	0.03	0.05	0.05	0.03	--	--	--	--
NU12	8/27/1996	0.14	0.04	0.06	0.16	--	--	--	--	--	--	--	--	--	--
NU19	9/10/1996	0.11	0.21	0.19	0.17	0.14	0.29	--	--	--	--	--	--	--	--
NU21a	9/11/1996	0.06	0.10	0.08	0.04	0.05	0.05	0.08	--	--	--	--	--	--	--
NU22	9/23/1996	0.10	0.05	0.12	0.16	--	--	--	--	--	--	--	--	--	--
NU23	9/23/1996	0.21	0.25	--	--	--	--	--	--	--	--	--	--	--	--
NU24	9/24/1996	0.10	0.13	0.12	0.17	0.04	0.13	0.32	--	--	--	--	--	--	--
NU27	9/25/1996	0.15	--	--	--	--	--	--	--	--	--	--	--	--	--
NU29	10/10/1996	0.11	0.08	0.11	0.10	--	--	--	--	--	--	--	--	--	--
OU02	9/24/1996	0.15	0.46	0.17	0.16	0.16	0.16	0.17	0.07	0.10	0.15	0.11	0.14	0.14	0.08
OU03	9/25/1996	0.17	0.12	0.14	0.20	0.26	0.23	0.06	--	--	--	--	--	--	--
OU04	9/25/1996	0.16	0.21	0.06	0.05	0.14	0.18	0.22	--	--	--	--	--	--	--
OU05	9/26/1996	0.03	0.03	0.02	0.14	--	--	--	--	--	--	--	--	--	--

Table 2. Moisture content[1] at unsaturated-zone sampling sites, southern New Jersey--Continued

Site name	Date of moisture-content measurement[2]	Depth (meters below land surface)													
		0.6	1.2	1.8	2.4	3.0	3.7	4.3	4.9	5.5	6.1	6.7	7.3	7.9	8.5
OU06	9/26/1996	0.19	0.11	0.09	0.07	0.12	--	--	--	--	--	--	--	--	--
OU07	10/29/1996	0.06	0.15	0.09	0.22	0.19	0.21	--	--	--	--	--	--	--	--
OU08	10/07/1996	0.07	0.10	0.27	--	--	--	--	--	--	--	--	--	--	--
OU10	10/09/1996	0.13	0.06	0.12	0.10	0.15	0.20	0.19	0.09	0.21	0.16	--	--	--	--
OU11	10/23/1996	0.15	0.04	0.12	0.25	--	--	--	--	--	--	--	--	--	--
OU13	10/23/1996	0.12	0.21	--	--	--	--	--	--	--	--	--	--	--	--
OU14	10/24/1996	0.12	0.11	0.09	0.29	0.29	--	--	--	--	--	--	--	--	--
OU15	9/16/1997	0.16	0.15	0.13	0.12	0.08	0.16	0.11	0.18	0.13		--	--	--	--
UN01	7/30/1996	--	0.19	--	--	0.16	0.18	--	--	0.12	--	0.08	--	--	--
UN02	9/13/1996	0.01	0.002	0.03	0.03	0.05	--	--	--	--	--	--	--	--	--
UN03	9/18/1996	0.09	0.06	0.24	--	--	--	--	--	--	--	--	--	--	--
UN05	9/19/1996	0.10	0.19	0.19	0.22	--	--	--	--	--	--	--	--	--	--
UN06	9/19/1996	0.12	0.18	--	--	--	--	--	--	--	--	--	--	--	--
UN07	9/24/1996	0.12	0.11	0.47	0.25	0.30	0.30	--	--	--	--	--	--	--	--
UN08	9/26/1996	0.06	0.06	0.12	--	--	--	--	--	--	--	--	--	--	--
UN09	9/26/1996	0.10	--	--	--	--	--	--	--	--	--	--	--	--	--
UN11	10/10/1996	0.14	0.14	0.12	0.09	0.07	0.34	0.32	--	--	--	--	--	--	--
UN12	10/24/1996	0.09	0.20	--	--	--	--	--	--	--	--	--	--	--	--

[1]Moisture content (θ) is dimensionless. Its value is calculated as follows:

$\theta = (W)(BD)$ where W is the weight of water in the sample divided by the dry weight of the sample and BD is the dry bulk density of the sample (see table 3). If BD is not given for a layer, the value for the adjacent lower layer is used.

[2]Moisture content measured on date of well installation.

To map sediment-size distribution for the layers encountered, samples of about 50 cm^3 were taken from 109 cores. Samples were analyzed by optical diffraction using a Coulter LS-230 Particle Size Analyzer. This method allows for the partitioning of particle sizes ranging from 0.04 to 2,000 µm into about 120 bins. Particles larger than 2,000 µm (gravel) were sieved out and then integrated into the size-distribution results. The fraction smaller than 2,000 µm was disaggregated if necessary with a mortar and rubber-tipped pestle, then split with a riffle splitter to obtain appropriate random samples for analysis. The material was sonicated in suspension for 60 seconds prior to each run.

Sediment properties, including layer description, bulk density, porosity, and textural classification, are summarized in table 3. Particle-size distributions (table 4) were determined from samples representing many of the layers. The sediments were mostly sands according to textural classification. Descriptions of layers in the saturated zone between the water table and the bottom of the well, where listed, are approximate and are based on observations of drill cuttings, not core samples. The average unsaturated-zone thickness at the 48 sites was 4.4 m.

Flow Calculation

Darcy's Law for unsaturated-zone flow is as follows:

$$q = -K\left[1 - \frac{d\psi}{dz}\right] , \qquad (2)$$

where q is the rate of flow (cm/d), K is the hydraulic conductivity (cm/d), ψ is the matric potential (cm), and z is the vertical coordinate (cm), which is positive upward. Both K and ψ are functions of moisture content, θ. The matric potential is defined according to the model of van Genuchten (1980) as follows:

$$\psi = \frac{1}{\alpha}[S_e^{n/(1-n)} - 1]^{1/n} , \qquad (3)$$

where α (1/cm) and n (dimensionless) are curve-fitting parameters. The parameter $1/\alpha$ is referred to as the air entry pressure. The relative saturation S_e is defined as follows:

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} , \qquad (4)$$

where θ_r and θ_s are residual and saturated moisture contents, respectively.

Equation (3) is used in conjunction with the pore-size-distribution model of Mualem (1976) to yield the van Genuchten-Mualem model (van Genuchten, 1980) for K:

$$K = K_0 S_e^L \left\{1 - [1 - S_e^{n/(n-1)}]^{1-1/n}\right\}^2 , \qquad (5)$$

where K_0 (cm/d) and L (dimensionless) are curve-fitting parameters.

Hydraulic properties can be estimated indirectly from sediment-texture data with quasi-empirical models known as pedotransfer functions. The models given by equations (3) and (5) were selected from among alternative formulations in order to use the pedotransfer functions incorporated in the program and database known as Rosetta (U.S. Department of Agriculture, 2002). Bulk density and the fractions of sand, silt, and clay were input to obtain estimates of the parameters θ_r, θ_s, α, n, K_0, and L for each layer for which texture data were collected (table 5). The pedotransfer functions are based on neural network analyses described by Schaap and Leij (1998), Schaap and others (1998), and Schaap and others (1999). The Rosetta program is discussed by Schaap and others (2001).

Table 3. Unsaturated-zone characteristics at sampling sites, southern New Jersey

[-- , not measured; BLS, below land surface; m, meters; g/cm^3, grams per cubic centimeter]

Site name	Unsaturated-zone thickness (m)	Layer interval[1] Top (m BLS)	Layer interval[1] Bottom (m BLS)	Field description[2]	Textural classification[3]	Bulk density (g/cm^3)	Porosity[4]
AG01	4.5	0.0	0.3	topsoil	--	--	--
		0.3	0.8	tan, coarse	loamy sand	1.9	0.30
		0.8	2.3	tan, finer	sandy loam	1.6	0.41
		2.3	7.3	orange	sandy loam	1.6	0.41
AG02	6.9	0.0	0.6	topsoil	--	--	--
		0.6	1.2	orange, coarse	sand	1.6	0.40
		1.2	5.5	orange, coarse	sand	1.7	0.39
		5.5	7.6	orange, coarse	sand	1.7	0.39
					sand	1.6	0.41
AG03	3.6	0.0	0.6	topsoil	--	--	--
		0.6	1.8	orange, coarse	sand	1.5	0.43
		1.8	6.7	gray, coarse	sand	1.7	0.36
					loamy sand	1.7	0.35
AG04	3.9	0.0	0.3	topsoil	--	--	--
		0.3	2.7	brown	sandy loam	1.8	0.33
		2.7	6.1	brown	loamy sand	2.0	0.27
AG09	2.0	0.0	0.2	topsoil	--	--	--
		0.2	1.8	orange	loamy sand	1.7	0.35
		1.8	2.1	gray, medium sand	--	--	--
		2.1	5.8	orange, medium coarse sand	--	--	--
AG10	6.4	0.0	2.1	brown	loamy sand	1.6	0.41
		2.1	4.9	orange, coarse with gravel	sand	1.6	0.42
		4.9	9.8	orange, coarse	sand	1.6	0.41
AG11	2.7	0.0	0.3	topsoil	--	--	--
		0.3	1.2	orange	sandy loam	1.8	0.34
		1.2	2.7	tan, medium with pebbles	sand	1.6	0.42
		2.7	3.7	orange, medium	sandy loam	1.5	0.45
		3.7	6.7	white, medium sand	--	--	--
AG12	8.7	0.0	0.2	topsoil	--	--	--
		0.2	1.8	red, clayey	sandy loam	1.6	0.39
		1.8	2.4	tan, coarse	sand	1.6	0.41
		2.4	4.6	med. tan	sand	1.6	0.39
		4.6	11.0	red, fine-medium	sand	1.4	0.45
		11.0	11.9	brown, medium			
AG13	3.4	0.0	0.3	topsoil	--	--	--
		0.3	3.4	red-brown, coarse	sand	1.4	0.49
		3.4	6.7	orange, medium	sand	1.5	0.45
AG14	7.6	0.0	0.3	topsoil			
		0.3	2.6	brown	loamy sand	1.7	0.36
		2.6	4.3	orange, fine-medium	sandy loam	1.7	0.38
		4.3	5.8	orange, coarse	sand	1.5	0.45
		5.8	7.0	yellow, medium sand	--	--	--
		7.0	10.4	orange, medium sand	--	--	--

Table 3. Unsaturated-zone characteristics at sampling sites, southern New Jersey--Continued

Site name	Unsaturated-zone thickness (m)	Layer interval[1]		Field description[2]	Textural classification[3]	Bulk density (g/cm³)	Porosity[4]
		Top (m BLS)	Bottom (m BLS)				
AG15	5.8	0.0	0.2	topsoil	--	--	--
		0.2	0.9	brown, clayey sand	--	--	--
		0.9	1.7	brown, medium sand	--	--	--
		1.7	2.7	brown, medium	sand	1.6	0.40
		2.7	8.8	brown, medium-coarse	sand	1.6	0.39
					sand	1.7	0.43
					sand	1.7	0.40
NU01	8.5	0.0	0.2	topsoil	--	--	--
		0.2	2.6		loamy sand	1.7	0.37
		2.6	3.4	orange fine sand	--		
		3.4	4.9	white, fine	sand	1.6	0.39
		4.9	7.6	orange	sandy loam	1.7	0.40
		7.6	10.7	orange	sandy loam	1.5	0.44
		10.7	12.2	red, coarse sand	--	--	--
NU02	2.3	0.0	0.3	topsoil	--	--	--
		0.3	2.0	tan, medium	sand	1.5	0.46
		2.0	2.4	fine	sand	1.7	0.36
		2.4	5.8	coarse sand	--	--	--
NU04	1.9	0.0	0.2	topsoil	--	--	--
		0.2	1.8	brown	sandy loam	1.5	0.43
		1.8	7.0	yellow, fine sand	--	--	--
NU06	13.1	0.0	0.2	topsoil	--	--	--
		0.2	2.4	orange	loamy sand	1.9	0.30
		2.4	4.9	orange, medium	sand	1.7	0.38
		4.9	12.2	brown, fine	sand	1.4	0.47
		12.2	15.8	orange, medium sand	--	--	--
NU08	6.2	0.0	0.2	topsoil	--	--	--
		0.2	0.6	tan, fine sand	--	--	--
		0.6	9.1	orange, fine-medium	sand	1.5	0.43
					sand	1.5	0.44
					sand	1.7	0.40
NU09	6.1	0.0	0.3	topsoil	--	--	--
		0.3	9.4	orange	sandy loam	1.8	0.37
					Sand	1.4	0.48
NU11	6.7	0.0	0.9	brown, coarse sand	--	--	--
		0.9	1.4	dark brown, coarse sand	--	--	--
		1.4	7.3	brown, coarse	sand	1.5	0.45
					sand	1.5	0.43
NU12	2.5	0.0	0.3	topsoil	--	--	--
		0.3	5.5	yellow, medium-coarse	sand	1.5	0.43
NU19	3.7	0.0	0.3	topsoil	--	--	--
		0.3	2.4	orange	sandy loam	1.5	0.44
		2.4	3.7	orange, fine-medium sand	--	--	--
		3.7	8.8	orange, fine sand	--	--	--

Table 3. Unsaturated-zone characteristics at sampling sites, southern New Jersey--Continued

Site name	Unsaturated-zone thickness (m)	Layer interval[1] Top (m BLS)	Layer interval[1] Bottom (m BLS)	Field description[2]	Textural classification[3]	Bulk density (g/cm^3)	Porosity[4]
NU21a	4.3	0.0	0.3	topsoil	--	--	--
		0.3	3.0	brown-coarse with pebbles	--	--	--
		3.0	3.7	orange, very coarse	sand	1.7	0.38
		3.7	4.3	rose, coarse	--	--	--
NU-22	3.0	0.0	0.3	topsoil	--	--	--
		0.3	0.6	orange, medium sand	--	--	--
		0.6	1.5	red, medium sand	--	--	--
		1.5	3.0	yellow	sandy loam	1.5	0.46
NU23	1.5	0.0	0.3	topsoil	--	--	--
		0.3	0.8	red, fine sand	--	--	--
		0.8	1.5	clayey	sandy loam	1.6	0.41
		1.5	2.4	orange, sandy clay	--	--	--
NU24	4.7	0.0	0.3	topsoil	--	--	--
		0.3	0.6	orange, medium sand	--	--	--
		0.6	1.5	red, medium	sand	1.4	0.47
		1.5	3.7	orange, medium	sand	1.5	0.44
		3.7	4.7	red, medium sand	--	--	--
NU27	1.3	0.0	0.3	topsoil	--	--	--
		0.3	1.2	brown, medium sand	--	--	--
		1.2	1.8	black	sand	1.7	0.36
		1.8	3.0	gray, fine sand	--	--	--
		3.0	4.3	brown, silty sand	--	--	--
NU29	2.4	0.0	0.2	topsoil	--	--	--
		0.2	5.8	brown, medium	sand	1.4	0.49
OU02	12.3	0.0	1.2	brown	loamy sand	1.8	0.33
		1.2	2.7	red	sandy loam	1.7	0.37
		2.7	4.0	gray	loamy sand	1.7	0.36
		4.0	8.8	tan, coarse	sand	1.6	0.41
		8.8	10.1	tan, medium sand	--	--	--
		10.1	10.7	gray, coarse sand	--	--	--
		10.7	15.5	orange fine-medium sand	--	--	--
OU03	5.4	0.0	1.8	brown	loamy sand	1.5	0.42
		1.8	2.4	fine sand	--	--	--
		2.4	3.4	orange	loam	1.9	0.31
		3.4	8.5	white	sandy loam	1.5	0.46
OU04	4.7	0.0	0.3	topsoil	--	--	--
		0.3	1.8	brown	sand	1.7	0.37
		1.8	2.7	tan, coarse	sand	1.4	0.47
		2.7	6.4	brown	sandy loam	1.6	0.40
		6.4	7.6	medium-fine sand	--	--	--
		7.6	8.2	white, coarse sand	--	--	--
OU05	2.8	0.0	1.5	gray-black	sand	1.7	0.37
		1.5	2.4	brown, medium sand	--	--	--
		2.4	5.8	tan, medium sand	--	--	--

Table 3. Unsaturated-zone characteristics at sampling sites, southern New Jersey--Continued

Site name	Unsaturated-zone thickness (m)	Layer interval[1]		Field description[2]	Textural classification[3]	Bulk density (g/cm[3])	Porosity[4]
		Top (m BLS)	Bottom (m BLS)				
OU06	3.5	0.0	0.2	topsoil	--	--	--
		0.2	1.5	brown	sand	1.9	0.29
		1.5	4.0	brown	loam	1.7	0.37
		4.0	6.7	orange, coarse sand	--	--	--
OU07	4.9	0.0	0.2	topsoil			
		0.2	0.9	brown, fine	sand	1.6	0.42
		0.9	3.4	brown	sandy loam	1.5	0.45
		3.4	4.9	orange	sandy loam	1.5	0.45
		4.9	5.8	yellow	loam	1.3	0.53
		5.8	6.1	brown, medium sand	--	--	--
		6.1	6.7	brown, sandy clay	--	--	--
OU08	2.1	0.0	0.3	topsoil	--	--	--
		0.3	0.6	black clay	--	--	--
		0.6	1.5	brown, medium sand	--	--	--
		1.5	1.8	black	sandy loam	1.1	0.59
		1.8	5.8	clayey gray sand	--	--	--
OU10	6.4	0.0	0.3	topsoil	--	--	--
		0.3	2.1	brown, coarse	sand	1.5	0.43
		2.1	2.7	white coarse sand	--	--	--
		2.7	3.4	orange, medium	sand	1.8	0.34
		3.4	4.9	white, coarse	sand	1.9	0.28
		4.9	9.8	yellow, coarse sand	--	--	--
OU11	2.8	0.0	0.3	topsoil	--	--	--
		0.3	2.1	gravelly sand	--	--	--
		2.1	5.8	orange	sandy loam	1.6	0.42
OU13	2.1	0.0	0.3	topsoil	--	--	--
		0.3	0.8	orange, fine-medium sand	--	--	--
		0.8	5.2	brown	sandy loam	1.4	0.46
				brown	sandy loam		
OU14	3.1	0.0	0.2	topsoil	--	--	--
		0.2	2.1	brown, coarse	sand	1.7	0.38
		2.1	5.8	brown medium	sand	1.3	0.50
OU15	8.1	0.0	0.3	topsoil	--	--	--
		0.3	3.0	orange, coarse sand	sand	1.7	0.37
		3.0	4.3	yellow, medium	sand	1.7	0.35
		4.3	6.1	orange, fine-medium	sand	1.8	0.34
		6.1	7.9	red, medium sand	--	--	--
		7.9	11.3	orange, fine-medium sand	--	--	--
UN01	7.8	0.0	0.3	topsoil	--	--	--
		0.3	3.4	brown,coarse sand	--	--	--
		3.4	7.8	white, coarse	sand	1.7	0.36
UN02	4.3	0.0	0.3	topsoil	--	--	--
		0.3	4.6	orange, coarse	sand	1.7	0.35
		4.6	7.9	red, coarse sand	--	--	--

Table 3. Unsaturated-zone characteristics at sampling sites, southern New Jersey--Continued

Site name	Unsaturated-zone thickness (m)	Layer interval[1] Top (m BLS)	Layer interval[1] Bottom (m BLS)	Field description[2]	Textural classification[3]	Bulk density (g/cm^3)	Porosity[4]
UN03	2.0	0.0	0.3	topsoil	--	--	--
		0.3	1.5	brown, medium	sand	1.7	0.38
		1.5	3.0	brown, silty	sand	1.6	0.38
		3.0	5.5	yellow, clayey sand	--	--	--
UN05	2.5	0.0	0.2	topsoil	--	--	--
		0.2	2.1		--	--	--
		2.1	2.7	orange	sandy loam	1.6	0.40
		2.7	5.8	orange	loam	1.6	0.40
		5.8	6.7	yellow, sand	--	--	--
UN06	1.7	0.0	0.3	topsoil	--	--	--
		0.3	4.6		sand	1.6	0.41
UN07	4.6	0.0	0.3	topsoil	--	--	--
		0.3	1.8	red, medium coarse	sand	1.5	0.44
		1.8	3.0	white-orange	loam	1.4	0.47
		3.0	3.7	clayey sand	--	--	--
		3.7	4.6	red, sand	--	--	--
		4.6	5.5	orange sand	--	--	--
		5.5	6.1	brown, medium-coarse sand	--	--	--
UN08	2.2	0.0	0.3	topsoil	--	--	--
		0.3	3.4	brown, medium	sand	1.6	0.40
		3.4	4.3	fine sand	--	--	--
UN09	1.1	0.0	0.3	topsoil	--	--	--
		0.3	4.0	gray, medium	sand	1.7	0.36
UN11	4.7	0.3	4.6	brown, medium	sand	1.4	0.49
		4.6	6.1	fine-medium	sand	1.4	0.46
		6.1	7.0	gray, silty sand	--	--	--
UN12	1.5	0.0	0.3	topsoil	--	--	--
		0.3	4.6	brown, coarse	sand	1.5	0.44

[1]Visual description from field notes. Descriptions of layers in the saturated zone between the water table and the bottom of the well, where listed, are approximate and are based on observations of drill cuttings, not core samples.

[2]Color is based on moist-sediment appearance. Layers were identified visually without size-distribution data; therefore, the textural descriptions are useful for comparison of layers at a particular site, but may not be consistent between sites. Only size-distribution data should be used to compare sediments collected at different sites.

[3]U.S. Department of Agriculture description based on percent (by weight) of sand, silt, and clay. Textural classification provided only if size analysis available (see table 4).

[4]Porosity was computed from the measured bulk density by assuming a grain density of 2.67 g/cm^3.

Table 4. Particle-size distribution in samples from unsaturated-zone sampling sites, southern New Jersey

[BLS, below land surface; m, meter; µm, micron; <, less than; >, greater than; rep, replicate sample]

Site name	Sample depth[1] (m BLS)	Percent (by weight) of sample in size range										
		Clay (<2µm)	Silt (2-50 µm)	Very fine sand (50-100 µm)	Fine sand (100-250 µm)	Medium sand (250-500 µm)	Coarse sand (500-1,000 µm)	Very coarse sand (1,000-2,000 µm)	Gravel (>2,000 µm)	[2]d_{50} (µm)	[3]Cu	[4]Cg
AG01	0.6	3.3	16.0	5.4	14.4	13.3	15.5	11.3	20.9	436	61.0	2.6
	1.8	6.0	27.3	6.3	24.9	29.4	5.8	0.2	0.0	176	54.4	1.4
	3.7	8.0	33.3	5.4	26.1	23.2	3.8	0.2	0.0	130	67.9	0.8
AG02	1.2	2.4	11.7	3.9	4.1	4.3	19.8	40.6	13.2	1032	59.6	9.7
	2.1	2.2	11.2	4.9	7.0	11.6	22.9	28.7	11.4	762	32.7	4.0
	4.3	1.0	5.4	2.9	4.2	10.8	36.6	34.0	5.2	831	7.5	3.0
	6.1	0.9	4.1	1.6	3.6	8.2	31.9	40.4	9.7	949	4.8	2.3
AG03	1.2	1.2	6.5	3.1	8.3	13.3	28.2	31.6	7.9	784	11.7	2.6
	2.4	1.1	4.2	1.8	4.2	13.8	26.0	25.4	23.4	923	6.7	1.5
	3.7	3.5	16.0	5.1	4.4	5.9	20.7	27.1	17.2	833	78.2	5.8
AG04	1.8	4.0	26.6	5.6	10.4	25.0	20.2	7.8	0.5	265	42.2	0.7
	3.7	3.6	20.0	6.0	19.9	21.9	14.0	12.7	1.9	237	29.3	2.9
AG09	1.2	2.6	19.7	5.5	8.7	17.9	25.3	17.6	2.8	419	38.1	1.9
AG10	1.8	1.9	15.4	5.2	5.3	6.8	22.8	16.3	26.3	882	44.9	4.2
	4.3	1.7	10.4	3.1	6.0	16.3	20.8	20.6	21.1	822	30.4	4.0
	6.1	1.1	6.4	2.2	4.2	8.5	32.6	33.8	11.2	877	10.3	3.7
AG11	0.6	4.4	33.3	13.3	11.0	11.1	14.4	6.6	5.9	94	27.5	0.8
	1.8	1.1	4.3	2.2	5.5	14.6	38.1	26.1	8.1	759	5.6	2.0
	3.0	5.3	20.8	4.1	12.9	51.8	5.0	0.1	0.0	263	63.4	5.7
AG12	1.2	2.2	22.1	9.5	5.1	8.6	21.0	16.5	14.9	536	45.5	0.4
	2.4	0.4	1.8	1.0	2.6	6.5	33.4	54.3	0.0	991	2.6	1.4
	3.7	0.7	2.4	1.2	4.1	9.1	40.3	40.5	1.7	874	3.4	1.7
	4.9	1.9	7.1	4.0	52.7	31.5	2.9	0.0	0.0	210	3.6	1.9
AG13	1.8	1.8	9.4	4.3	11.9	25.7	33.9	10.5	2.4	461	14.5	3.1
	3.7	2.4	11.5	6.4	60.0	14.5	4.9	0.4	0.0	156	6.8	3.1
AG14	1.8	2.6	16.1	4.3	7.1	11.1	15.3	16.1	27.5	740	62.4	2.7
	3.7	4.5	38.1	19.2	38.2	0.0	0.0	0.0	0.0	64	14.7	1.5
	5.5	0.9	2.7	1.3	2.7	24.8	58.1	9.5	0.0	595	2.1	1.2

Table 4. Particle-size distribution in samples from unsaturated-zone sampling sites, southern New Jersey--Continued

Site name	Sample depth[1] (m BLS)	Percent (by weight) of sample in size range										
		Clay (<2µm)	Silt (2-50 µm)	Very fine sand (50-100 µm)	Fine sand (100-250 µm)	Medium sand (250-500 µm)	Coarse sand (500-1,000 µm)	Very coarse sand (1,000-2,000 µm)	Gravel (>2,000 µm)	$^{2}d_{50}$ (µm)	$^{3}C_u$	$^{4}C_g$
AG15	1.8	1.0	3.5	5.2	26.4	27.5	22.3	11.3	2.9	337	4.7	0.9
	2.4	2.0	10.2	4.2	3.7	7.3	31.5	22.2	18.8	809	27.7	8.5
	3.0	2.2	11.5	3.9	11.7	18.4	25.0	17.6	9.7	531	26.9	3.2
	4.9	1.5	7.4	2.8	9.3	18.5	29.6	21.7	9.2	680	13.7	2.4
NU01	1.8	2.6	17.2	5.3	15.3	23.8	18.4	8.1	9.3	314	23.9	2.8
	4.3	0.4	1.6	1.2	3.3	7.9	49.2	35.7	0.8	832	2.5	1.4
	5.5	3.5	27.6	10.5	44.2	2.9	4.7	4.9	1.7	112	16.6	1.8
	6.7	3.5	22.0	13.1	49.7	7.3	3.4	0.1	1.0	113	13.1	3.5
NU02	1.2	1.3	4.4	2.0	6.2	21.1	48.8	15.5	0.6	672	4.7	2.0
	2.4	1.1	4.6	2.2	6.0	11.6	27.9	21.1	25.5	883	7.7	2.0
NU04	1.8	3.8	24.0	12.9	49.7	6.0	2.2	0.5	0.8	111	16.0	3.1
NU06	1.8	3.8	16.5	6.6	6.5	11.9	23.4	15.8	15.3	575	54.1	1.7
	4.3	2.0	9.2	5.6	6.6	8.5	29.8	31.4	6.9	787	23.1	5.6
	7.9	1.4	4.7	3.5	33.5	54.1	2.9	0.0	0.0	249	2.8	1.6
NU08	1.8	1.5	9.8	3.1	3.2	6.7	25.0	34.9	14.0	929	28.5	7.7
	3.7	0.7	4.4	2.1	2.4	10.1	30.4	30.8	19.1	948	4.0	1.4
	5.5	1.1	6.5	2.8	3.1	9.4	28.0	32.0	17.1	940	13.1	4.3
NU09	0.6	3.4	23.1	13.2	18.3	10.4	11.9	4.1	15.7	200	16.0	0.6
	3.7	1.2	5.8	2.3	7.0	38.1	37.9	6.9	0.8	466	4.8	2.0
NU11	3.7	0.7	3.3	1.3	2.4	6.5	45.9	39.3	0.5	864	2.5	1.4
	6.1	0.5	1.8	0.7	1.6	3.4	35.7	53.6	2.7	1010	2.0	1.1
NU12	1.8	0.8	7.6	2.5	8.5	27.1	34.0	18.7	0.7	541	9.4	2.3
NU19	1.8	3.5	24.8	3.8	46.2	12.3	1.9	7.5	0.0	156	25.7	3.2
NU21a	3.0	1.4	6.2	3.0	3.8	8.8	52.1	23.4	1.3	724	10.0	5.0
NU-22	2.4	3.1	26.3	4.1	55.4	9.3	1.7	0.0	0.0	135	19.1	2.3
NU23	1.2	5.3	27.1	3.7	29.5	18.9	4.1	10.1	0.5	177	38.0	1.1

Table 4. Particle-size distribution in samples from unsaturated-zone sampling sites, southern New Jersey--Continued

Site name	Sample depth[1] (m BLS)	Percent (by weight) of sample in size range: Clay (<2µm)	Silt (2-50 µm)	Very fine sand (50-100 µm)	Fine sand (100-250 µm)	Medium sand (250-500 µm)	Coarse sand (500-1,000 µm)	Very coarse sand (1,000-2,000 µm)	Gravel (>2,000 µm)	[2]d_{50} (µm)	[3]Cu	[4]Cg
NU24	1.2	1.7	12.7	2.2	20.5	24.7	21.6	6.8	9.9	327	20.2	3.5
	3.0	1.3	6.2	2.4	13.6	10.6	51.1	14.6	0.0	668	7.9	2.0
NU27	1.2	1.1	7.0	4.0	17.5	18.2	27.5	23.2	1.2	541	10.3	1.2
NU29	1.8	1.6	7.6	4.7	14.7	28.6	27.9	5.5	9.2	420	9.5	2.1
OU02	0.6	2.4	17.3	5.1	6.7	21.8	24.8	10.2	11.8	449	33.3	4.5
	1.8	3.1	23.7	0.7	0.0	0.8	37.9	17.0	16.7	753	78.5	30.8
	3.0	2.0	14.6	6.9	5.3	7.6	34.5	26.7	2.4	690	33.6	4.1
	5.5	1.4	8.0	2.9	2.8	8.8	36.3	32.9	6.9	822	17.8	6.8
OU03	1.2	2.1	18.2	9.0	19.7	43.1	8.0	0.0	0.0	250	14.1	1.8
	3.0	5.5	44.9	8.2	15.7	19.6	5.6	0.5	0.0	48	27.8	1.0
	4.3	4.0	18.3	6.7	22.1	41.4	5.2	0.8	1.6	230	28.0	3.6
OU04	1.8	1.5	7.6	2.7	4.7	12.3	30.5	27.6	13.1	786	15.8	4.6
	2.4	1.1	5.1	2.4	5.6	17.6	45.8	22.3	0.0	668	5.9	2.4
	3.7	6.4	13.0	1.9	5.9	10.1	26.0	34.6	2.0	752	225.3	25.0
OU05	1.2	0.8	1.6	1.3	19.6	48.7	26.4	1.6	0.0	349	2.4	1.0
OU06	1.2	1.4	11.0	4.6	5.7	10.0	19.8	11.4	36.2	870	36.1	4.0
	2.4	10.7	47.0	15.5	26.8	0.0	0.0	0.0	0.0	37	26.0	2.5
OU07	0.6	2.2	10.7	2.6	13.3	16.8	18.8	10.1	25.2	574	31.5	3.2
	2.4	3.9	27.3	4.7	42.4	12.7	7.1	1.9	0.0	151	25.1	1.5
	2.4 rep	3.6	22.1	4.0	40.5	14.5	8.5	6.4	0.2	171	24.8	5.7
	5.5	8.0	42.8	4.0	33.0	8.1	4.1	0.0	0.0	44	42.0	0.5
OU08	1.8	3.2	30.9	21.9	25.5	10.5	6.4	0.9	0.7	80	10.3	1.7
OU10	1.2	0.8	3.9	1.6	3.5	14.8	39.6	28.5	7.2	786	3.7	1.5
	3.0	2.2	11.7	4.4	6.1	10.5	40.3	22.0	2.0	664	28.3	7.6
	3.7	1.8	8.7	3.6	4.6	7.4	18.3	12.7	42.8	1370	56.5	3.4
OU11	3.0	5.2	22.0	7.1	27.0	22.8	13.1	1.3	0.8	161	44.4	3.8
OU13	1.2	5.6	15.8	10.7	56.5	8.9	2.5	0.0	0.0	124	15.8	5.9
	1.2 rep	6.7	15.2	9.4	52.1	10.8	5.1	0.6	0.0	129	25.2	8.5

Table 4. Particle-size distribution in samples from unsaturated-zone sampling sites, southern New Jersey--Continued

Site name	Sample depth[1] (m BLS)	Percent (by weight) of sample in size range: Clay (<2µm)	Silt (2-50 µm)	Very fine sand (50-100 µm)	Fine sand (100-250 µm)	Medium sand (250-500 µm)	Coarse sand (500-1,000 µm)	Very coarse sand (1,000-2,000 µm)	Gravel (>2,000 µm)	[2]d_{50} (µm)	[3]Cu	[4]Cg
OU14	1.2	0.7	2.7	2.3	13.7	15.4	22.3	21.9	20.8	786	7.4	1.1
	2.4	2.5	9.0	4.1	56.4	25.1	3.0	0.0	0.0	183	6.4	3.3
OU15	2.4	2.8	12.3	3.5	5.5	12.8	29.2	27.5	6.5	693	44.5	8.7
	3.7	3.0	10.9	3.0	7.8	12.5	17.5	12.7	32.7	790	66.3	4.3
	5.5	1.4	7.3	2.8	12.3	7.6	19.9	22.6	26.2	921	18.1	2.4
UN01	5.5	1.7	5.8	2.3	6.6	20.0	36.9	19.8	6.7	638	7.5	2.4
UN02	1.8	0.4	1.1	0.7	2.5	16.1	45.8	23.8	9.7	766	2.5	1.1
UN03	1.2	0.7	2.9	1.8	6.9	22.4	34.5	7.3	23.4	653	4.0	1.3
	2.4	1.1	3.2	5.0	24.1	34.3	30.7	1.6	0.0	340	4.4	1.1
UN05	2.4	3.5	24.4	5.7	16.0	42.4	8.1	0.0	0.0	240	36.3	1.7
	3.7	7.6	45.7	6.6	28.3	7.2	3.7	0.8	0.0	36	30.7	0.5
UN06	1.2	0.9	4.3	7.1	16.6	26.8	35.4	8.4	0.6	439	6.9	1.4
UN07	1.2	1.1	5.9	3.8	6.0	15.6	39.1	26.6	1.8	685	9.9	3.4
	2.4	9.6	51.7	12.0	22.9	3.8	0.0	0.0	0.0	27	23.0	0.9
UN08	1.2	0.6	1.7	1.7	13.0	32.2	43.2	6.6	0.8	495	3.4	1.2
UN09	1.2	1.5	7.1	4.4	18.6	30.1	29.4	7.7	1.2	382	7.5	1.6
UN11	1.2	1.3	3.4	4.2	54.5	28.0	8.2	0.3	0.0	190	2.3	1.0
	2.4	1.7	3.2	5.3	65.1	20.1	4.6	0.0	0.0	172	2.1	1.0
UN12	1.2	0.5	1.1	0.5	2.3	28.3	56.1	8.6	2.4	600	2.1	1.1

[1] The depth reported is the depth of the bottom of the core sample from which the 30-cm^3 sample was collected. The sample is assumed to be representative of the layer (see table 3) from which it was taken.

[2] Grain-size diameter of 50 percent of the sample (by weight) is less than d_{50}.

[3] $C_u = d_{60}/d_{10}$ is the uniformity index. If C_u is less than 2, then the sediment is considered uniform.

[4] $C_g = d_{30}^2/(d_{60}d_{10})$ is the coefficient of gradation: the higher the value, the more graded the sample (the wider the distribution of particle sizes).

Table 5. Input to and pedotransfer function parameters from the Rosetta program for unsaturated-zone sampling sites, southern New Jersey

[m BLS, meters below land surface; g/cm^3, grams per cubic centimeter; m, meters; cm, centimeters; µm, microns cm/d, centimeters per day; <, less than; >, greater than; rep, replicate sample]

			Input data (percent by weight)[1]			Pedotransfer function parameters[2]						
Site name	Sample depth (m BLS)	Bulk density (g/cm^3)	Clay (<2 µm)	Silt (2-50 µm)	Sand (>50 µm)	θr (cm^3/cm^3)	θs (cm^3/cm^3)	α log_{10} (1/cm)	n log_{10}	[3]Ks log_{10} (cm/d)	Ko log_{10} (cm/d)	L (dimension-less)
AG01	0.6	1.9	3.3	16.0	80.7	0.036	0.283	-1.288	0.231	1.578	1.575	-1.110
	1.8	1.6	6.0	27.3	66.7	0.034	0.348	-1.382	0.156	1.590	1.385	-1.249
	3.7	1.6	8.0	33.3	58.7	0.035	0.345	-1.516	0.144	1.440	1.192	-1.171
AG02	1.2	1.6	2.4	11.7	85.8	0.041	0.349	-1.380	0.349	2.236	1.545	-0.867
	2.1	1.7	2.2	11.2	86.5	0.041	0.337	-1.377	0.356	2.222	1.548	-0.872
	4.3	1.7	1.0	5.4	93.7	0.047	0.336	-1.452	0.508	2.681	1.440	-0.867
	6.1	1.6	0.9	4.1	95.4	0.049	0.357	-1.479	0.561	2.859	1.427	-0.882
AG03	1.2	1.5	1.2	6.5	92.4	0.048	0.378	-1.448	0.498	2.753	1.438	-0.881
	2.4	1.7	1.1	4.2	94.6	0.047	0.325	-1.462	0.513	2.684	1.430	-0.857
	3.7	1.7	3.5	16.0	80.5	0.037	0.318	-1.308	0.242	1.789	1.568	-1.050
AG04	1.8	1.8	4.0	26.6	69.4	0.030	0.296	-1.203	0.139	1.339	1.549	-1.720
	3.7	2.0	3.6	20.0	76.4	0.033	0.264	-1.233	0.183	1.282	1.592	-1.305
AG09	1.2	1.7	2.6	19.7	77.6	0.034	0.315	-1.269	0.216	1.705	1.599	-1.122
AG10	1.8	1.6	1.9	15.4	82.7	0.039	0.360	-1.351	0.306	2.168	1.605	-0.877
	4.3	1.6	1.7	10.4	87.9	0.043	0.366	-1.403	0.399	2.442	1.513	-0.850
	6.1	1.6	1.1	6.4	92.5	0.047	0.363	-1.449	0.500	2.713	1.433	-0.883
AG11	0.6	1.8	4.4	33.3	62.2	0.028	0.300	-1.244	0.119	1.291	1.463	-2.035
	1.8	1.6	1.1	4.3	94.7	0.050	0.370	-1.474	0.548	2.862	1.417	-0.893
	3.0	1.5	5.3	20.8	73.9	0.038	0.390	-1.396	0.196	1.969	1.486	-0.950
AG12	1.2	1.6	2.2	22.1	75.6	0.033	0.338	-1.290	0.212	1.815	1.593	-1.076
	2.4	1.6	0.4	1.8	97.8	0.052	0.366	-1.502	0.620	3.042	1.467	-0.874
	3.7	1.6	0.7	2.4	96.9	0.050	0.345	-1.490	0.580	2.915	1.430	-0.873
	4.9	1.4	1.9	7.1	91.0	0.047	0.370	-1.442	0.463	2.633	1.430	-0.875
AG13	1.8	1.4	1.8	9.4	88.7	0.045	0.426	-1.384	0.371	2.666	1.619	-0.794
	3.7	1.5	2.4	11.5	86.2	0.043	0.389	-1.394	0.356	2.429	1.551	-0.830

Table 5. Input to and pedotransfer function parameters from the Rosetta program for unsaturated-zone sampling sites, southern New Jersey--Continued

Site name	Sample depth (m BLS)	Bulk density (g/cm^3)	Input data (percent by weight)[1] Clay (<2 µm)	Silt (2-50 µm)	Sand (>50 µm)	Pedotransfer function parameters[2] θr (cm^3/cm^3)	θs (cm^3/cm^3)	α log_{10} (1/cm)	n log_{10}	[3]Ks log_{10} (cm/d)	Ko log_{10} (cm/d)	L (dimension-less)
AG14	1.8	1.7	2.6	16.1	81.3	0.037	0.325	-1.314	0.265	1.895	1.598	-0.986
	3.7	1.7	4.5	38.1	57.5	0.028	0.317	-1.395	0.130	1.404	1.320	-1.539
	5.5	1.5	0.9	2.7	96.4	0.051	0.376	-1.492	0.589	2.977	1.435	-0.889
AG15	1.8	1.6	1.0	3.5	95.6	0.049	0.351	-1.480	0.558	2.857	1.418	-0.884
	2.4	1.6	2.0	10.2	87.8	0.044	0.369	-1.406	0.395	2.444	1.506	-0.850
	3.0	1.7	2.2	11.5	86.3	0.040	0.320	-1.364	0.341	2.116	1.566	-0.890
	4.9	1.7	1.5	7.4	91.1	0.045	0.340	-1.427	0.451	2.519	1.464	-0.863
NU01	1.8	1.7	2.6	17.2	80.2	0.036	0.330	-1.309	0.255	1.886	1.601	-0.997
	4.3	1.6	0.4	1.6	98.1	0.051	0.348	-1.501	0.608	2.997	1.452	-0.866
	5.5	1.7	3.5	27.6	68.9	0.030	0.325	-1.276	0.157	1.562	1.511	-1.386
	6.7	1.5	3.5	22.0	74.6	0.035	0.366	-1.343	0.205	1.908	1.542	-1.015
NU02	1.2	1.5	1.3	4.4	94.3	0.051	0.401	-1.465	0.531	2.907	1.443	-0.877
	2.4	1.7	1.1	4.6	94.3	0.047	0.325	-1.458	0.508	2.668	1.437	-0.856
NU04	1.8	1.5	3.8	24.0	72.1	0.034	0.363	-1.352	0.188	1.840	1.502	-1.066
NU06	1.8	1.9	3.8	16.5	79.7	0.036	0.282	-1.280	0.214	1.503	1.561	-1.167
	4.3	1.7	2.0	9.2	88.7	0.043	0.337	-1.403	0.398	2.351	1.504	-0.859
	7.9	1.4	1.4	4.7	93.9	0.050	0.406	-1.456	0.517	2.896	1.458	-0.868
NU08	1.8	1.5	1.5	9.8	86.9	0.044	0.374	-1.410	0.419	2.529	1.503	-0.851
	3.7	1.5	0.7	4.4	94.9	0.050	0.384	-1.471	0.557	2.921	1.445	-0.887
	5.5	1.7	1.1	6.5	92.4	0.045	0.336	-1.438	0.482	2.600	1.456	-0.863
NU09	0.6	1.8	3.4	23.1	73.5	0.032	0.302	-1.227	0.168	1.480	1.575	-1.383
	3.7	1.4	1.2	5.8	93.0	0.049	0.420	-1.428	0.479	2.875	1.520	-0.839
NU11	3.7	1.5	0.7	3.3	96.0	0.051	0.400	-1.475	0.574	3.007	1.472	-0.876
	6.1	1.5	0.5	1.8	97.7	0.052	0.379	-1.502	0.620	3.062	1.473	-0.877
NU12	1.8	1.5	0.8	7.6	91.5	0.046	0.377	-1.434	0.483	2.711	1.463	-0.873
NU19	1.8	1.5	3.5	24.8	71.7	0.034	0.369	-1.360	0.186	1.882	1.501	-1.045
NU21a	3.0	1.7	1.4	6.2	92.4	0.046	0.340	-1.443	0.481	2.608	1.440	-0.869
NU22	2.4	1.5	3.1	26.3	70.5	0.033	0.377	-1.380	0.179	1.937	1.484	-1.025

Table 5. Input to and pedotransfer function parameters from the Rosetta program for unsaturated-zone sampling sites, southern New Jersey--Continued

Site name	Sample depth (m BLS)	Bulk density (g/cm^3)	Input data (percent by weight)[1] Clay (<2 µm)	Silt (2-50 µm)	Sand (>50 µm)	Pedotransfer function parameters[2] θr (cm^3/cm^3)	θs (cm^3/cm^3)	α log_{10} (1/cm)	n log_{10}	[3]Ks log_{10} (cm/d)	Ko log_{10} (cm/d)	L (dimension-less)
NU23	1.2	1.6	5.3	27.1	66.7	0.034	0.354	-1.377	0.156	1.633	1.397	-1.243
NU24	1.2	1.4	1.7	12.7	85.7	0.042	0.406	-1.372	0.336	2.485	1.621	-0.813
	3.0	1.5	1.3	6.2	92.3	0.048	0.382	-1.450	0.495	2.761	1.434	-0.882
NU27	1.2	1.7	1.1	7.0	91.7	0.045	0.325	-1.425	0.456	2.503	1.479	-0.852
NU29	1.8	1.4	1.6	7.6	90.6	0.047	0.426	-1.400	0.413	2.759	1.576	-0.810
OU02	0.6	1.8	2.4	17.3	80.2	0.035	0.303	-1.281	0.239	1.724	1.607	-1.069
	1.8	1.7	3.1	23.7	73.2	0.032	0.323	-1.263	0.181	1.631	1.563	-1.250
	3.0	1.7	2.0	14.6	83.4	0.038	0.324	-1.330	0.300	2.003	1.607	-0.928
	5.5	1.6	1.4	8.0	90.6	0.045	0.363	-1.430	0.457	2.594	1.456	-0.869
OU03	1.2	1.5	2.1	18.2	79.7	0.037	0.365	-1.336	0.262	2.084	1.614	-0.911
	3.0	1.9	5.5	44.9	49.6	0.026	0.276	-1.293	0.095	0.992	1.350	-2.829
	4.3	1.5	4.0	18.3	77.7	0.038	0.391	-1.370	0.228	2.099	1.565	-0.898
OU04	1.8	1.7	1.5	7.6	90.9	0.044	0.331	-1.421	0.442	2.467	1.479	-0.856
	2.4	1.4	1.1	5.1	93.8	0.050	0.412	-1.445	0.508	2.903	1.485	-0.858
	3.7	1.6	6.4	13.0	80.4	0.040	0.322	-1.350	0.221	1.714	1.459	-1.106
OU05	1.2	1.7	0.8	1.6	97.6	0.050	0.333	-1.496	0.582	2.914	1.425	-0.860
OU06	1.2	1.9	1.4	11.0	87.6	0.040	0.276	-1.372	0.356	1.954	1.594	-0.863
	2.4	1.7	10.7	47.0	42.3	0.036	0.315	-1.732	0.136	0.990	0.892	-0.987
OU07	0.6	1.6	2.2	10.7	86.8	0.043	0.360	-1.398	0.379	2.364	1.520	-0.853
	2.4	1.5	3.9	27.3	68.7	0.033	0.372	-1.400	0.172	1.858	1.435	-1.048
	2.4 rep	1.5	3.6	22.1	74.1	0.035	0.361	-1.336	0.200	1.864	1.535	-1.048
	5.5	1.3	8.0	42.8	49.3	0.041	0.399	-1.981	0.183	1.812	0.683	-0.039
OU08	1.8	1.1	3.2	30.9	65.9	0.035	0.455	-1.607	0.152	2.368	1.288	-0.551
OU10	1.2	1.5	0.8	3.9	95.2	0.050	0.382	-1.477	0.564	2.934	1.437	-0.890
	3.0	1.8	2.2	11.7	85.3	0.040	0.308	-1.346	0.313	1.991	1.572	-0.938
	3.7	1.9	1.8	8.7	89.3	0.042	0.274	-1.405	0.383	2.044	1.548	-0.833
OU11	3.0	1.6	5.2	22.0	72.2	0.037	0.364	-1.361	0.183	1.782	1.470	-1.099

Table 5. Input to and pedotransfer function parameters from the Rosetta program for unsaturated-zone sampling sites, southern New Jersey--Continued

Site name	Sample depth (m BLS)	Bulk density (g/cm^3)	Input data (percent by weight)[1] Clay (<2 µm)	Silt (2-50 µm)	Sand (>50 µm)	Pedotransfer function parameters[2] θr (cm^3/cm^3)	θs (cm^3/cm^3)	α log_{10} (1/cm)	n log_{10}	[3]Ks log_{10} (cm/d)	Ko log_{10} (cm/d)	L (dimension-less)
OU13	1.2	1.4	5.6	15.8	78.7	0.042	0.418	-1.401	0.223	2.195	1.552	-0.833
	1.2 rep		6.7	15.2	78.1	0.043	0.404	-1.417	0.225	2.087	1.493	-0.862
OU14	1.2	1.7	0.7	2.7	96.4	0.049	0.339	-1.483	0.566	2.874	1.428	-0.871
	2.4	1.3	2.5	9.0	88.5	0.046	0.428	-1.392	0.363	2.642	1.603	-0.788
OU15	2.4	1.7	2.8	12.3	84.9	0.040	0.332	-1.362	0.320	2.092	1.561	-0.903
	3.7	1.7	3.0	10.9	86.1	0.041	0.313	-1.367	0.324	2.038	1.543	-0.918
	5.5	1.8	1.4	7.3	91.4	0.044	0.309	-1.419	0.436	2.387	1.502	-0.836
UN01	5.5	1.7	1.7	5.8	92.3	0.046	0.323	-1.439	0.457	2.511	1.447	-0.856
UN02	1.8	1.7	0.4	1.1	98.6	0.049	0.319	-1.498	0.590	2.922	1.448	-0.832
UN03	1.2	1.7	0.7	2.9	96.3	0.049	0.336	-1.481	0.560	2.847	1.428	-0.867
	2.4	1.6	1.1	3.2	95.7	0.049	0.343	-1.481	0.551	2.830	1.413	-0.877
UN05	2.4	1.6	3.5	24.4	72.2	0.033	0.345	-1.313	0.185	1.743	1.524	-1.150
	3.7	1.6	7.6	45.7	46.7	0.033	0.324	-1.695	0.144	1.243	0.972	-0.921
UN06	1.2	1.6	0.9	4.3	94.8	0.049	0.360	-1.473	0.549	2.845	1.423	-0.888
UN07	1.2	1.5	1.1	5.9	93.0	0.048	0.387	-1.452	0.510	2.816	1.442	-0.881
	2.4	1.4	9.6	51.7	38.7	0.042	0.362	-2.078	0.193	1.431	0.511	-0.059
UN08	1.2	1.6	0.6	1.7	97.5	0.051	0.354	-1.500	0.602	2.990	1.438	-0.877
UN09	1.2	1.7	1.5	7.1	91.2	0.044	0.320	-1.422	0.438	2.436	1.483	-0.850
UN11	1.2	1.4	1.3	3.4	95.3	0.052	0.425	-1.451	0.525	2.982	1.506	-0.845
	2.4	1.4	1.7	3.2	95.0	0.052	0.405	-1.477	0.542	2.942	1.431	-0.877
UN12	1.2	1.5	0.5	1.1	98.3	0.053	0.382	-1.508	0.633	3.100	1.485	-0.872

[1]Fractions of coarse, medium, and fine sand are provided in table 2 for descriptive purposes; however, only the total sand fraction, along with silt and clay fractions and bulk density, was input to the Rosetta program.

[2]See equations 3, 4, and 5.

[3]The Rosetta program also can be used to estimate the saturated conductivity for the sediment, Ks. Ks is estimated independently from Ko, which is a curve-fitting parameter.

RECHARGE ESTIMATES

For each site, unsaturated flow was calculated from moisture-content data collected when the well was installed (table 6). The depth for which flow was calculated was selected such that the moisture-content gradient could be calculated from data associated with a single layer. For the 48 sites, the average depth for which flow was calculated was 3.1 m below land surface. The average unsaturated-zone thickness was 4.4 m; therefore, although the flow values generally were calculated for layers deep in the unsaturated zone, they were not calculated precisely at the water table. Although the computed flows technically are not recharge estimates, they are herein referred to as such and collectively are assumed to provide a measure of spatial recharge variability. In some cases, the calculation of the moisture-content gradient was determined to be unreliable and the recharge estimate was assumed to equal the conductivity. A positive value for recharge corresponds to downward flow to the aquifer; a negative value indicates upward water movement.

The median recharge rate (table 6) was 29.1 cm/yr (27 percent of average annual precipitation). As cited above, estimates of annual recharge to the aquifer based on water-budget calculations range from 33.1 to 49.3 cm/yr. Although there are uncertainties in the calculations (discussed below), the median compares favorably to the reported range; therefore, this approach to scaling recharge and its variability has an appropriate central tendancy. The moisture-content measurements were made during summer and fall, when potential evapotranspiration is highest. The recharge estimates vary considerably across the study area (fig. 4). The range from 6.5 to 74.2 cm/yr contains the middle third of the estimates and corresponds to 6 to 68 percent of the average annual precipitation rate. Recharge estimates for approximately 17 percent of the sites were very high--in excess of 250 cm/yr (2.3 times the average annual precipitation rate)--whereas at the other extreme, about 17 percent of the recharge estimates were negative, indicating upward movement. The interval $0 < R < 110$ cm/yr (bounded above by a value approximately equal to the average annual precipitation of 109.3 cm/yr) contains about 58 percent of the recharge estimates (fig. 4 inset).

Uncertainty of Calculations

Calculations of flow in unsaturated porous media are inherently uncertain because of the nonlinear dependence of K and ψ on moisture content and difficulty in measuring these hydraulic properties. The use of the Rosetta program introduces additional uncertainty because the data used to derive the functional relations are for sediment collected elsewhere. To evaluate the application of the Rosetta model, six sediment samples (AG02, AG12, AG14, AG15, NU01, and NU08) were selected for direct measurement of K and ψ and recalculation of recharge.

The steady-state centrifuge method (Nimmo and others, 1987; Conca and Wright, 1998) was used to measure K and ψ for the six samples selected. Samples for analysis were obtained by subcoring the original 5.1-cm (2-inch) cores to obtain an intact sample 4.9 cm long and 3.2 cm in diameter. Steady-state unsaturated flow is achieved relatively quickly through use of centrifugal force to drive flow. If appropriate flow rates controlled by a metering pump are chosen, K can be determined over a range of moisture contents. The measurements start from saturation and each step in the sequence produces data for a point on the drying curve. For each step, steady flow is verified by observing that moisture content and flux through the sample are constant. The moisture content is determined by weighing the sample between runs. The matric potential, ψ, associated with K and θ at the end of a steady-state run was measured with a nonintrusive touch tensiometer; however, measurements of ψ near the field moisture content were obtainable only for samples AG02 and NU08 because the presence of pebbles in samples AG12, AG14, AG15, and NU01 prohibited the measurement of ψ at values near the field moisture content.

Table 6. Summary of flow calculations for unsaturated-zone sampling sites, southern New Jersey

[θ, moisture content; K, conductivity; dψ/dz, matric potential gradient; R, recharge; m, meters; BLS, below land surface; cm/yr, centimeters per year; --, unreliable moisture content gradient]

Site name	Flow depth (m BLS)	Unsaturated-zone thickness (m)	Ratio	θ (dimension-less)	K (cm/yr)	dψ/dz (dimension-less)	R[1] (cm/yr)
AG01	2.4	4.5	0.54	0.25	56.3	-0.06	59.7
AG02	6.1	6.9	0.89	0.09	102.2	-0.04	106.1
AG03	2.4	3.6	0.68	0.08	67.4	-0.16	77.9
AG04	2.4	3.9	0.63	0.16	19.4	0.13	16.8
AG09	1.2	2.0	0.61	0.11	14.9	1.88	-13.0
AG10	4.3	6.4	0.67	0.13	162.3	-0.09	176.9
AG11	1.8	2.7	0.67	0.07	23.2	-0.37	31.6
AG12	6.1	8.7	0.70	0.06	3.3	0.50	1.7
AG13	2.4	3.4	0.72	0.06	1.3	-2.37	4.3
AG14	5.5	7.6	0.72	0.04	0.0	--	0.0
AG15	4.9	5.8	0.84	0.07	9.5	0.52	5.6
NU01	6.7	8.5	0.79	0.13	11.7	0.44	5.6
NU02	1.8	2.3	0.80	0.12	281.6	--	281.6
NU04	1.2	1.9	0.63	0.22	53.2	--	53.2
NU06	7.6	13.1	0.58	0.06	1.7	-1.72	4.7
NU08	5.5	6.2	0.88	0.12	253.5	0.05	240.9
NU09	4.4	6.1	0.73	0.08	30.7	--	30.7
NU11	5.5	6.7	0.82	0.05	0.0	--	0.0
NU12	1.8	2.5	0.74	0.06	8.6	--	8.6
NU19	1.8	3.7	0.50	0.19	19.2	-0.42	27.3
NU21a	3.0	4.3	0.71	0.05	0.4	--	0.4
NU22	2.4	3.0	0.81	0.16	6.1	4.05	-18.5
NU23	1.2	1.5	0.83	0.25	54.2	1.21	-11.5
NU24	2.4	4.7	0.52	0.17	689.5	0.24	526.8
NU27	0.6	1.3	0.47	0.15	395.9	-0.21	478.9
NU29	1.8	2.4	0.76	0.11	79.1	0.65	27.5
OU02	7.9	12.3	0.64	0.14	298.7	0.01	297.1
OU03	3.7	5.4	0.68	0.23	554.1	-0.14	634.4
OU04	3.0	4.7	0.65	0.14	36.3	--	36.3
OU05	1.8	2.8	0.65	0.02	0.0	--	0.0
OU06	1.8	3.5	0.53	0.09	0.0	-65.04	0.5
OU07	3.0	4.9	0.62	0.19	54.0	-0.30	73.1
OU08	1.2	2.1	0.59	0.10	0.0	225.01	-1.8
OU10	4.3	6.4	0.67	0.19	1753.1	-0.05	1,835.0
OU11	1.8	2.8	0.66	0.12	1.6	--	1.6
OU13	1.2	2.1	0.58	0.21	75.4	--	75.4
OU14	1.8	3.1	0.60	0.09	133.5	-0.13	151.1
OU15	5.5	8.1	0.68	0.13	279.6	-0.18	330.8
UN01	6.7	7.8	0.86	0.08	30.4	-0.20	36.5
UN02	3.0	4.3	0.71	0.05	0.0	--	0.0
UN03	1.2	2.0	0.61	0.06	10.0	-0.68	16.7
UN05	1.8	2.5	0.73	0.19	20.4	0.08	18.7
UN06	1.2	1.7	0.71	0.18	1054.9	0.23	812.1
UN07	3.7	4.6	0.79	0.30	27.7	0.30	19.4
UN08	1.2	2.2	0.55	0.06	7.7	0.03	7.4
UN09	0.6	2.2	0.27	0.10	77.9	--	77.9
UN11	3.0	4.7	0.65	0.07	24.1	-0.34	32.3
UN12	0.6	1.5	0.41	0.09	148.6	--	148.6
Median	2.4	3.8	0.67	0.11	29.06		29.14

[1] R = -q (eq. 2) unless $\theta < \theta r$ in which case R=0 is assumed. R = K is assumed if dψ/dz is unavailable.

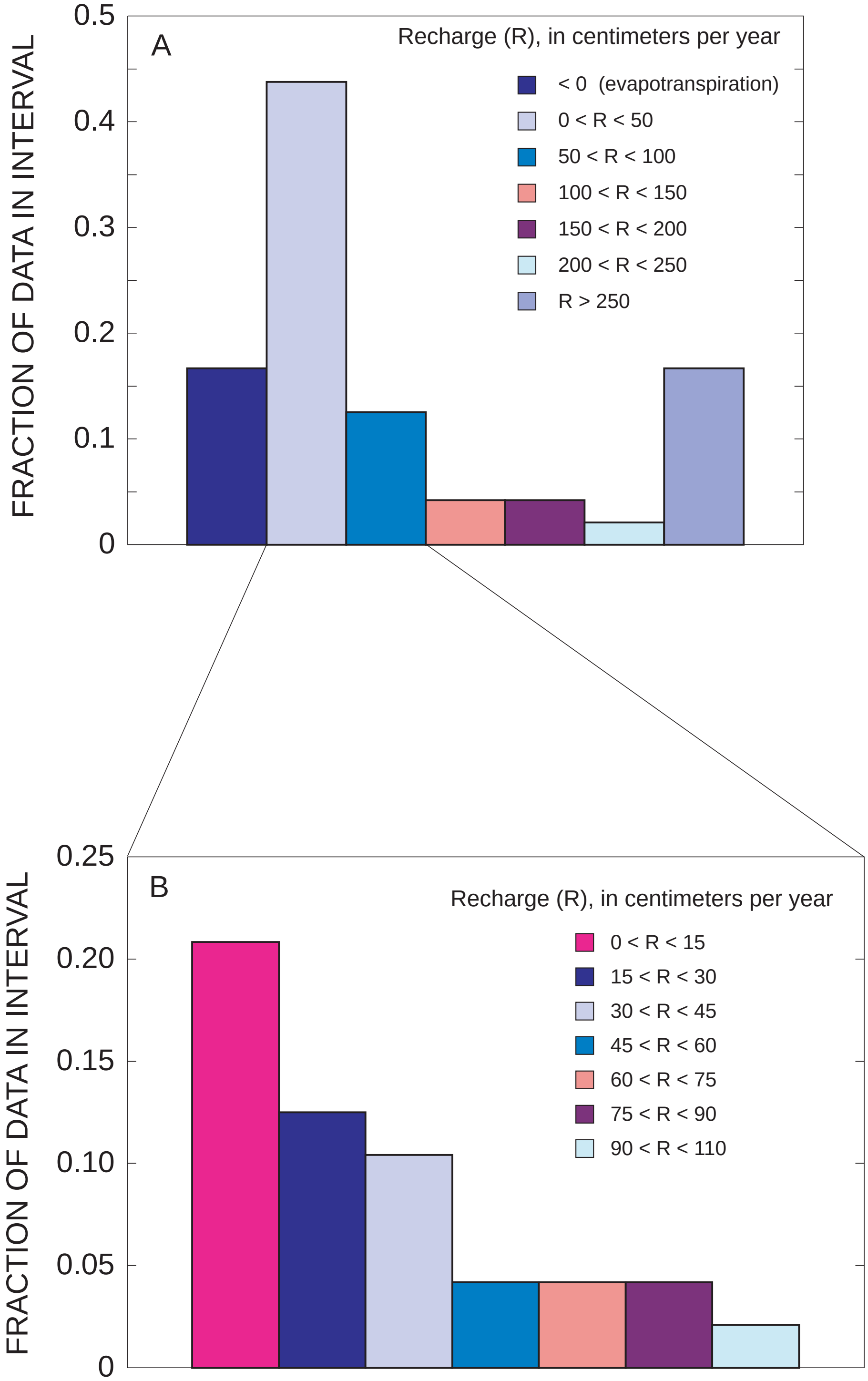


Figure 4. Distribution of (a) all recharge estimates and (b) recharge estimates between 0 and 110 centimeters per year for unsaturated-zone sampling sites, Glassboro study area.

The flow calculations are summarized in table 7 and figure 5. Linear interpolation was used to obtain values of K and ψ for field moisture contents between experimental points. Experimental values for ψ near the field moisture content were not attainable at some sites; in these cases, the conductivity values were plotted. The estimates vary considerably; in particular, the Rosetta-based estimates for sites AG02 and NU08 were much higher than the estimates based on measured values. The estimates, however, compare favorably in that both indicated relatively low recharge for four sites (AG12, (AG14, AG15, and NU01) and relatively high recharge for two sites (AG02 and NU08). Because of the uncertainty in flow calculations, the recharge estimates for 48 sites based on the Rosetta model provide only a scaling of recharge that allows site estimates to be ranked only into broad categories such as low, moderate, and high recharge.

Flow Regime

Unsaturated flow is gravity-dominated if

$$\left|\frac{R - K}{R}\right| < \delta \ , \qquad (6)$$

where δ is a specified relative error. If flow is gravity-dominated, then it can be approximated by conductivity because matric-potential gradients are negligible. For all sites where R and K were calculated in sand, flow is gravity-dominated if $R > 100$ cm/yr (fig. 6). The inset in figure 6 is rescaled to illustrate that matric forces must be considered in the flow calculations for the sites for which $R < 100$ cm/yr.

For the sites for which both R and K were calculated in sandy loams, matric forces are significant for the entire range of R (fig. 7). In particular, matric forces dominate gravity where the net movement of water is upward ($R < 0$). Upward water movement was not observed at any of the sites where the recharge calculation was made for sands (fig. 6). This finding indicates that net water loss from the aquifer can occur only at sites where the water table is located in sediment that is finer than sand.

Mapping Spatial Trends

If discernible, spatial trends in recharge at a watershed scale could be used in conjunction with land-use information to identify areas susceptible to contamination. Because the recharge estimates are categorical in nature, it is appropriate to consider maps based on transformed recharge estimates. If the value 0 is assigned to an estimated recharge less than the median (29.1 cm/yr) and the value 1 is assigned to an estimated recharge greater than the median, then the map showing the probability of exceeding the median recharge (fig. 8) is obtained by kriging the indicator transform.

The area of lower expected recharge plotted in the southwestern part of the study area is mostly agricultural land within the Cohansey River Basin. Annual average recharge in this basin has been estimated to be 37.1 cm/yr (Charles and others, 2001), which is the 25th percentile within the range (33.1–49.3 cm/yr) of reported recharge estimates based on water-budget studies. This finding is consistent with the recharge calculations, as the area is one where recharge can be expected to be less than the regional median (fig. 8).

Table 7. Flow calculations for six selected unsaturated-zone sampling sites, southern New Jersey

[m BLS, meters below land surface; θ, moisture content; K, conductivity; dψ/dz, matric potential gradient; q, flow; cm/yr, centimeters per year; --, measurement not possible]

			Flow calculation					
			With Rosetta program			With measured values[1]		
Site name	Depth (m BLS)	θ (dimensionless)	K (cm/yr)	dψ/dz (dimensionless)	q (cm/yr)	K (cm/yr)	dψ/dz (dimensionless)	q (cm/yr)
AG14	5.5	0.04	0.0	--	0.0	0.2	--	0.2
AG12	6.1	0.06	3.3	0.5	1.7	9.4	0.12	8.3
AG15	4.9	0.07	11.7	0.52	5.6	1.8	--	1.8
NU01	6.7	0.13	10.0	0.44	5.6	0.0	--	0.0
AG02	6.1	0.09	102.2	-0.04	106.1	35.7	-0.40	50.0
NU08	5.5	0.12	253.5	0.05	240.9	39.2	--	39.2

[1]Measurement of ψ not possible near field moisture content for samples AG14, AG15, NU01, and NU08; therefore, q is assumed to equal K for comparison purposes.

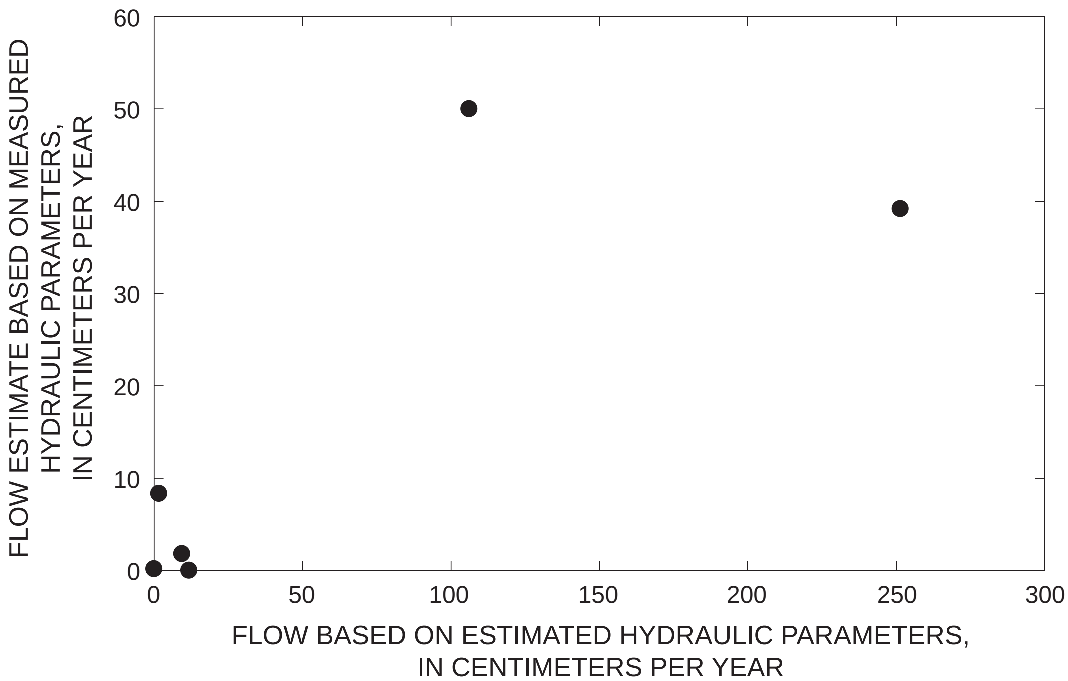


Figure 5. Relation of flow estimates based on measured hydraulic parameters to flow based on estimated hydraulic parameters for six selected unsaturated-zone sampling sites, Glassboro study area.

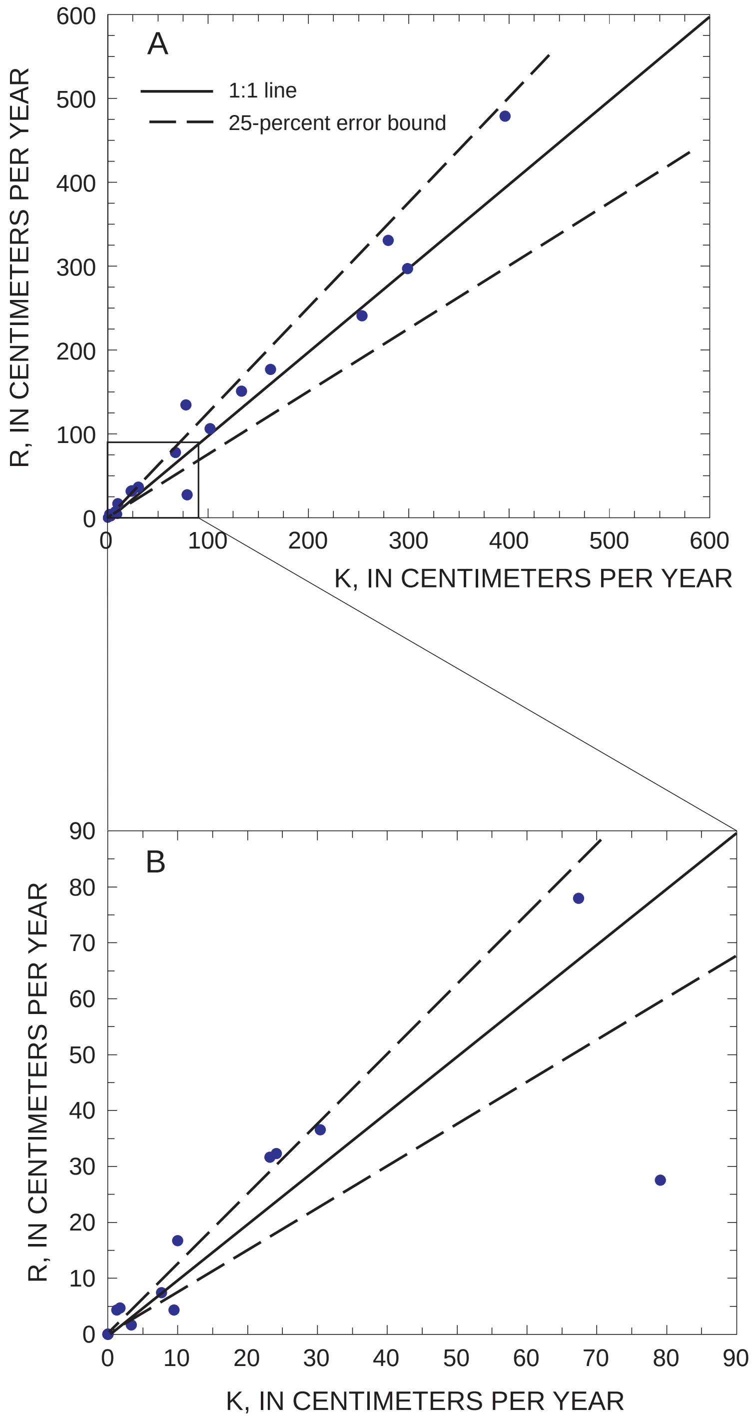


Figure 6. Relation of flow (R) to conductivity (K) for (a) all sands and (b) sands in which flow was less than 100 centimeters per year.

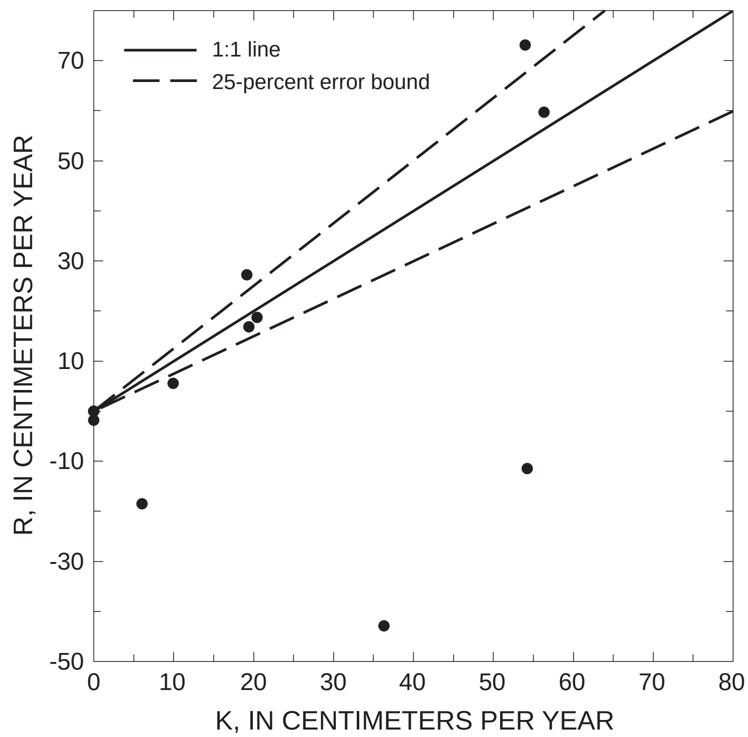


Figure 7. Relation of flow (R) to conductivity (K) for sandy loams.

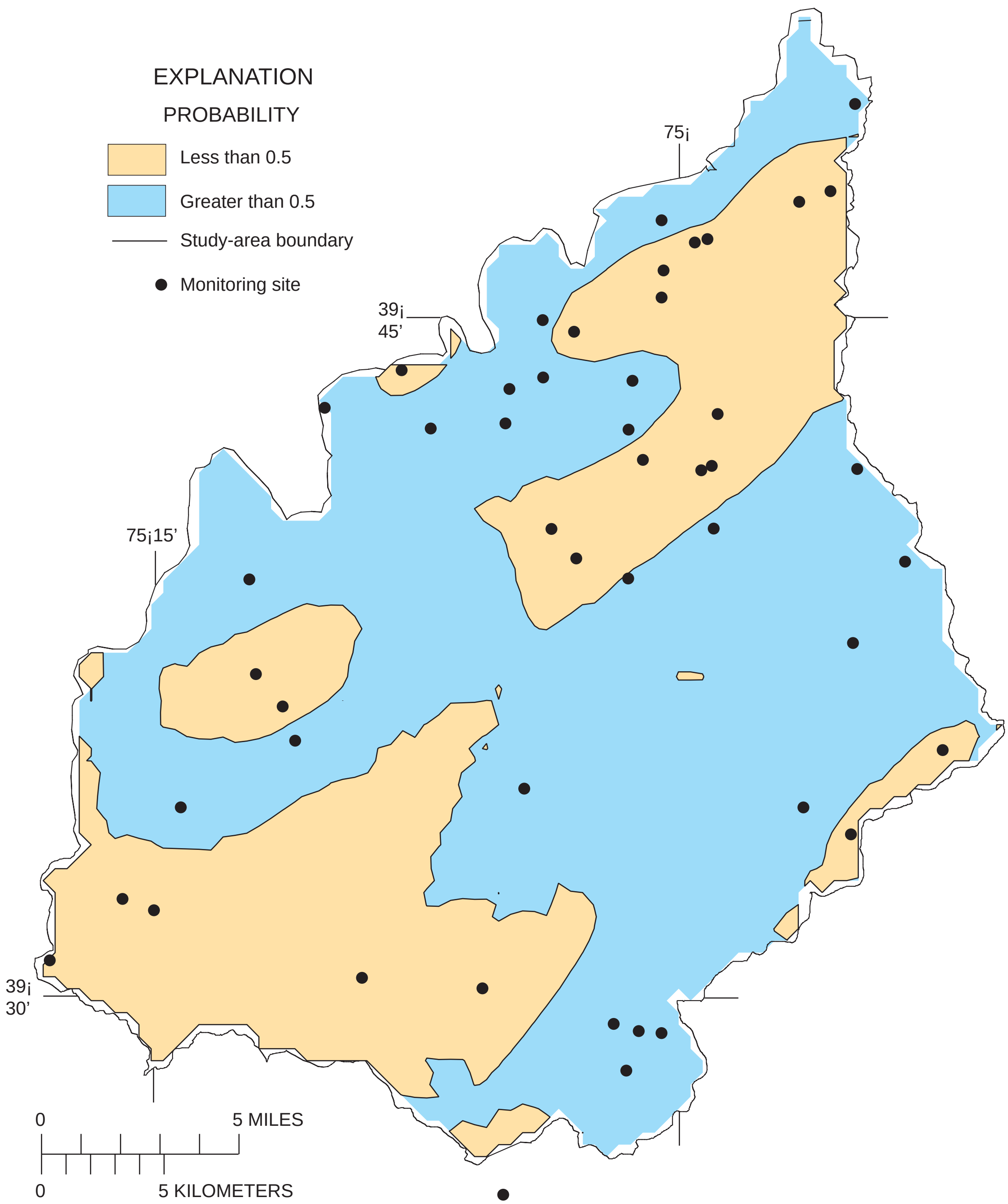


Figure 8. Probability of recharge exceeding 29.2 centimeters per year in the Glassboro study area.

SUMMARY AND CONCLUSIONS

Traditional water-budget methods can be used to obtain average values of recharge for a watershed, but information on variations in recharge over the watershed is needed to determine chemical loading to ground water. One approach for estimating recharge variability is to collect samples of unsaturated-zone sediment at sites throughout the watershed, estimate hydraulic properties, and calculate unsaturated flow. This method was applied by sampling the unsaturated zone at 48 sites over an area of approximately 930 km^2 in southern New Jersey during the summer and fall of 1996.

Unsaturated flow at the 48 sites was calculated at a median depth below land surface of 0.67 times the unsaturated-zone thickness. The calculated flow was assumed to equal recharge. The median recharge for the 48 sites was 29.1 cm/yr (27 percent of the average annual precipitation rate); this value compares favorably to estimates of annual recharge to the aquifer based on water-budget studies, which range from 33.1 to 49.3 cm/yr. The moisture content was measured during the summer and fall, when recharge would be expected to be lower than its annual average because of greater-than-average evapotranspiration.

Estimates of recharge varied across the study area, with the middle third of the values falling between 6.5 and 74.2 cm/yr (6 to 68 percent of the annual precipitation rate). The flow calculations, however, are uncertain as a result of the nonlinearity of conductivity and matric-potential functions and the application of Rosetta-derived pedotransfer functions to these particular sediments. The overall method, however, does provide a scaling of recharge variability that allows the sites to be ranked in broad categories, such as low, moderate, and high recharge.

Despite the general perception that unsaturated flow in a humid climate such as that of southern New Jersey is gravity-driven, matric forces were found to be important in the movement of water through the unsaturated zone at about 70 percent of the sites for which $R < 100$ cm/yr. At 15 percent of the sites, matric forces caused water to move upward ($R < 0$), but only in fine-grained sediments such as sandy loams (not in sand).

A map developed by kriging the indicator transform was used to delineate parts of the study area where recharge was more likely or less likely to exceed the median. The map was consistent in identifying a largely agricultural part of the study area where recharge previously was found to be low relative to recharge in other basins for which water budgets had been developed.

The method used here provides data needed to define the role of unsaturated-zone geology in recharge variability. The study is limited, however, because moisture content was determined only during a single season. Repeated measurements of moisture content throughout the year would allow determination of the nature of spatial variability during the other seasons.

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