U.S. Department of the Interior
U.S. Geological Survey

EFFECTS OF LAND USE AND TRAVEL TIME ON THE DISTRIBUTION OF NITRATE IN THE KIRKWOOD-COHANSEY AQUIFER SYSTEM IN SOUTHERN NEW JERSEY

Water-Resources Investigations Report 01-4117

National Water-Quality Assessment Program

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By Leon J. Kauffman, Arthur L. Baehr, Mark A. Ayers, and Paul E. Stackelberg

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U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 01-4117

NATIONAL WATER-QUALITY ASSESSMENT PROGRAM

West Trenton, New Jersey

2001

science for a changing world

U.S. DEPARTMENT OF THE INTERIOR

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Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Volume	
million gallons (Mgal)	3,785	cubic meter
	Flow	
gallon per day (gal/d)	0.003785	cubic meter per day
	Temperature	
degree Fahrenheit (°F)	°C = 5/9 x (°F-32)	degree Celsius (°C)
	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
N -nitrogen

FOREWORD

The U.S. Geological Survey (USGS) is committed to serve the Nation with accurate and timely scientific information that helps enhance and protect the overall quality of life, and facilitates effective management of water, biological, energy, and mineral resources. Information on the quality of the Nation's water resources is of critical interest to the USGS because it is so integrally linked to the long-term availability of water that is clean and safe for drinking and recreation and that is suitable for industry, irrigation, and habitat for fish and wildlife. Escalating population growth and increasing demands for the multiple water uses make water availability, now measured in terms of quantity *and* quality, even more critical to the long-term sustainability of our communities and ecosystems.

The USGS implemented the National Water-Quality Assessment (NAWQA) Program to support national, regional, and local information needs and decisions related to water-quality management and policy. Shaped by and coordinated with ongoing efforts of other Federal, State, and local agencies, the NAWQA Program is designed to answer: What is the condition of our Nation's streams and ground water? How are the conditions changing over time? How do natural features and human activities affect the quality of streams and ground water, and where are those effects most pronounced? By combining information on water chemistry, physical characteristics, stream habitat, and aquatic life, the NAWQA Program aims to provide science-based insights for current and emerging water issues. NAWQA results can contribute to informed decisions that result in practical and effective water-resource management and strategies that protect and restore water quality.

Since 1991, the NAWQA Program has implemented interdisciplinary assessments in more than 50 of the Nation's most important river basins and aquifers, referred to as Study Units. Collectively, these Study Units account for more than 60 percent of the overall water use and population served by public water supply, and are representative of the Nation's major hydrologic landscapes, priority ecological resources, and agricultural, urban, and natural sources of contamination.

Each assessment is guided by a nationally consistent study design and methods of sampling and analysis. The assessments thereby build local knowledge about water-quality issues and trends in a particular stream or aquifer while providing an understanding of how and why water quality varies regionally and nationally. The consistent, multi-scale approach helps to determine if certain types of water-quality issues are isolated or pervasive, and allows direct comparisons of how human activities and natural processes affect water quality and ecological health in the Nation's diverse geographic and environmental settings. Comprehensive assessments on pesticides, nutrients, volatile organic compounds, trace metals, and aquatic ecology are developed at the national scale through comparative analysis of the Study-Unit findings.

The USGS places high value on the communication and dissemination of credible, timely, and relevant science so that the most recent and available knowledge about water resources can be applied in management and policy decisions. We hope this NAWQA publication will provide you the needed insights and information to meet your needs, and thereby foster increased awareness and involvement in the protection and restoration of our Nation's waters.

The NAWQA Program recognizes that a national assessment by a single program cannot address all water-resource issues of interest. External coordination at all levels is critical for a fully integrated understanding of watersheds and for cost-effective management, regulation, and conservation of our Nation's water resources. The Program, therefore, depends extensively on the advice, cooperation, and information from other Federal, State, interstate, Tribal, and local agencies, non-government organizations, industry, academia, and other stakeholder groups. The assistance and suggestions of all are greatly appreciated.

Robert M. Hirsch

Robert M. Hirsch
Associate Director for Water

EFFECTS OF LAND USE AND TRAVEL TIME ON THE DISTRIBUTION OF NITRATE IN THE KIRKWOOD-COHANSEY AQUIFER SYSTEM IN SOUTHERN NEW JERSEY

By Leon J. Kauffman, Arthur L. Baehr, Mark A. Ayers, and Paul E. Stackelberg

ABSTRACT

Residents of the southern New Jersey Coastal Plain are increasingly reliant on the unconfined Kirkwood-Cohansey aquifer system for public water supply as a result of increasing population and restrictions on withdrawals from the deeper, confined aquifers. Elevated nitrate concentrations above background levels have been found in wells in the surficial aquifer system in agricultural and urban parts of this area. A three-dimensional steady-state ground-water-flow model of a 400-square-mile study area near Glassboro, New Jersey, was used in conjunction with particle tracking to examine the effects of land use and travel time on the distribution of nitrate in ground and surface water in southern New Jersey.

Contributing areas and ground-water ages, or travel times, of water at ground-water discharge points (streams and wells) in the study area were simulated. Concentrations of nitrate were computed by linking land use and age-dependent nitrate concentrations in recharge to the discharge points. Median concentrations of nitrate in water samples collected during 1996 from shallow monitoring wells in different land-use areas were used to represent the concentration of nitrate in aquifer recharge since 1990. On the basis of upward trends in the use of nitrogen fertilizer, the concentrations of nitrate in aquifer recharge in agricultural and urban areas were assumed to have increased linearly from the background value in 1940 (0.07 mg/L as N) to the 1990 (2.5-14 mg/L as N) concentrations.

Model performance was evaluated by comparing the simulation results to measured nitrate concentrations and apparent ground-water ages. Apparent ground-water ages at 32 monitoring wells in the study area determined from tritium/helium-3 ratios and sulfur hexafluoride concentrations favorably matched simulated travel times to these wells. Simulated nitrate concentrations were comparable to concentrations measured in 27 water-supply wells in the study area. A time series (1987-98) of nitrate concentrations at base-flow conditions in three streams that drain basins of various sizes and with various land uses was compared to simulated concentrations in these streams. In all three of the streams, a reasonable fit to the measured concentrations was achieved by multiplying the simulated concentration by 0.6. Because nitrate appeared to move conservatively (not degraded or adsorbed) in ground water to wells, the apparent non-conservative behavior in streams indicates that about 40 percent of the nitrate in aquifer recharge is removed by denitrification in the aquifer near the streams and (or) by in-stream processes.

The model was used to evaluate the effects of various nitrate management options on the concentration of nitrate in streams and water-supply wells. Nitrate concentrations were simulated under the following management alternatives: an immediate ban on nitrate input, reduction of input at a constant rate, and fixed input at the current (2000) level. The time required for water to move through the aquifer results in a time lag between the reduction of nitrate input in recharge and the reduction of nitrate concentration in streams and

wells. In the gradual-reduction alternative, nitrate concentrations in streams and wells continued to increase for several years after the reduction was enacted. In both the immediate-ban and gradual-reduction alternatives, nitrate concentrations remained elevated above background concentrations long after nitrate input ceased. In the fixed-use alternative, concentrations in streams and wells continued to increase for 30 to 40 years before reaching a constant level.

The spatial distributions of simulated nitrate concentrations in streams in 2000 and 2050 were examined with the assumption of no change in land use, nitrate concentration in recharge, or ground-water withdrawals. As expected, nitrate concentrations were highest in agricultural areas and lowest in largely undeveloped areas. Changes in concentrations over time were greatest in streams in areas where the aquifer is thick and in streams that flow mostly through areas that are undeveloped but whose contributing areas contain agricultural or urban land distant from the stream. Results of the computer simulations indicate that nitrate concentrations in typical domestic or public-supply wells installed in most of the study area would increase over the next 50 years. The extremes in nitrate concentration (high and low) and magnitude of change in nitrate concentration occurred in domestic wells rather than public-supply wells because the domestic wells intercept water derived from small contributing areas with fairly uniform land use and ground-water-age composition. Nitrate concentrations in water from public-supply wells were less extreme than in domestic wells because the public-supply wells' contributing areas supply water from multiple land uses and ground-water-age classes.

INTRODUCTION

Residents of the southern New Jersey Coastal Plain are increasingly reliant on the unconfined Kirkwood-Cohansey aquifer system for public water supply as a result of increasing population and restrictions on withdrawals from the deeper, confined aquifers. Elevated nitrate concentrations above background levels have been found in wells in the surficial aquifer system in agricultural and urban parts of this area.

The study area encompasses approximately 400 mi^2 in the Philadelphia metropolitan area near Glassboro, New Jersey (fig. 1), and is underlain by the Kirkwood-Cohansey aquifer system. In this report, this area is referred to as the Glassboro study area. Population growth in this area has resulted in increased ground-water withdrawals from the Kirkwood-Cohansey aquifer system. The primary objective of the study was to provide a detailed understanding of the relation among land use, ground-water flow, and the evolution of water quality in a heavily used surficial aquifer at a scale applicable to the evaluation of water-management alternatives. Three-dimensional numerical simulations of ground-water flow and particle transport were linked to data sets in a geographical information system (GIS) to describe the source and age of water currently (2000) within and discharging from the aquifer system. (In this report, ground-water age refers to the time elapsed since the water was recharged to the saturated zone of the aquifer system.) Although the ground-water-flow model could be used to study the movement of any surface-introduced contaminant, the scope of the application of the model was limited to simulating nitrate concentrations in streams and wells given current land use and three hypothetical nitrate-management alternatives.

The Kirkwood-Cohansey aquifer system is the principal surficial (unconfined) aquifer system in the New Jersey Coastal Plain (Zapecza, 1989). The aquifer, a major source of drinking water, is tapped by both domestic wells and large public-supply wells (Nawyn and Clawges, 1995). Ground water affects stream ecology in this area because 80 percent or more of streamflow is derived from ground-water discharge. The quality of the water in the aquifer, especially water discharging to wells and streams, is, therefore, of great interest for human health and aquatic life.

Surficial aquifers in urbanized and agricultural areas are vulnerable to contamination because they receive recharge across the entire land

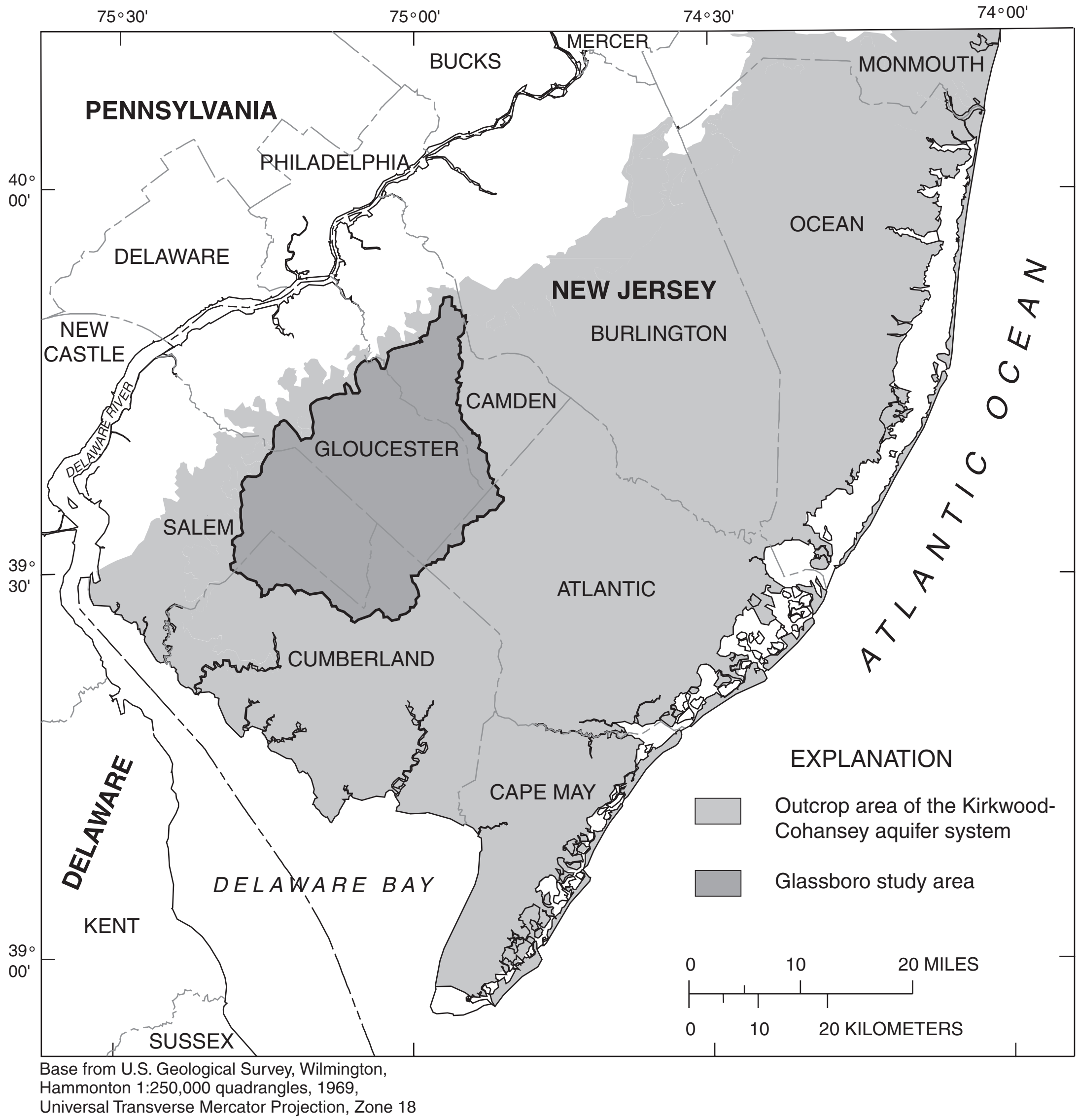

Figure 1. Location of Glassboro study area, New Jersey.

surface, allowing for downward migration of compounds, such as nutrients, pesticides, and volatile organic compounds, that are used at the land surface. The Kirkwood-Cohansey aquifer system particularly is vulnerable because it consists of highly permeable, unconsolidated sands and gravels, contains little organic matter, and generally has a shallow water table (average 15 ft below land surface). Sources of nitrate (for example, residential and agricultural fertilizers and rainfall) are widespread, and concentrations of nitrate greater than background levels were measured in ground water in observation wells (Stackelberg and others, 1997; Szabo and others, 1997), domestic wells (MacLeod and others, 1995), and public-supply wells (Stackelberg and others, 2000) throughout the Glassboro study area. The background concentration is considered to be the median concentration of nitrate in shallow wells in undeveloped areas. Similar findings were obtained in many other regions of the country in investigations conducted as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) Program (Nolan and Stoner, 2000).

To evaluate the effect of water quality in the shallow part of the Kirkwood-Cohansey aquifer system on the quality of water discharging to streams and wells, movement through the aquifer system must be considered. Because the path of the water through the aquifer varies in length and direction, the water discharging from the aquifer to streams and wells has a variety of sources and ages. Ground-water age can affect the concentration of a contaminant various ways. The concentration at the time of recharge (initial concentration) may change as a result of changes in chemical use over time, may be reduced through degradation or sorption, or may increase as the contaminant is formed through degradation of another contaminant.

This report (1) describes the ground-water-flow model of the study area; (2) describes the age and land-use signature of water in the Kirkwood-Cohansey aquifer system and water discharging to streams and wells in the study area; (3) presents the results of a simulation of the effects of several management alternatives on nitrate concentrations in the study area; and (4) evaluates the performance of the model by comparing measured and simulated water levels, ground-water ages, and nitrate concentrations.

Approach

This investigation was conducted as part of the Long Island-New Jersey (LINJ) NAWQA study unit. The data-collection and modeling approach used was a unique integration of ground-water components of NAWQA studies referred to as "land-use surveys" and "flow-path studies." This integration allowed current water-quality conditions to be related to information on current and historical land and chemical use to determine potential future water-quality conditions in an aquifer that is important for water supply and whose recharge area encompasses multiple land uses.

In a land-use survey, water in shallow observation wells is sampled to assess the quality of recently recharged ground water associated with a particular land use. Results of land-use surveys conducted in the Glassboro study area (Stackelberg and others, 1997) were used to determine water-quality conditions associated with urban, agricultural, and undeveloped areas.

Flow-path studies completed as a part of NAWQA study units across the country generally can be characterized as cross-sectional studies (see, for example, Burow and others, 1999; Cowdery, 1997; Mullaney and Grady, 1997; Saad and Thorstenson, 1998; Tesoriero and others, 2000) in which observation wells are located along a single perceived ground-water-flow path to conduct a detailed investigation of processes of transport from a single source. Wells sequenced in a cross-section provide water-quality information for ground water of different ages originating from a small recharge area.

The flow-path studies in the LINJ study differed from the cross-sectional studies used in many other NAWQA studies. In this study, a 10- to 15-year age group sampling program (Stackelberg and others, 2000) was designed based on simulated ground-water ages from a three-dimensional flow model to locate the screened depths of 30 observation wells beneath urbanized land in the Glassboro study area. This flow-path study was similar to a land-use survey, except that water from these wells was sampled to assess the quality of ground water recharged in urban areas 10 to 15 years prior to sampling. In contrast to the approach used in a typical NAWQA flow-path study, the approach used here results in water-quality information for ground water in a single age group over a large recharge area. In the second part of the LINJ flow-path study, water from public-supply wells in the area was sampled to assess the quality of water discharging from the aquifer (Baehr and others, 1999; Stackelberg and others, 2000).

The data-collection and modeling approach used in this study can be thought of as a regional flow-path study. Samples of water at the beginning (land-use surveys), middle (age-cohort sampling), and end (public-supply wells) of flow paths through the aquifer were collected and analyzed.

The three-dimensional flow model was used to relate the concentrations of contaminants in water from observation wells to the concentrations of contaminants in water discharged to streams and wells. The modeling approach provided a way to investigate past and future trends in water quality.

The ground-water modeling approach used in this study fundamentally is different from that of traditional quasi-three-dimensional plan-view ground-water flow models, which are designed primarily to estimate basin-wide water budgets. These models typically use the vertical dimension to represent distinct geologic layers. Such a model encompassing most of the Glassboro study area, with a focus on the Maurice River Basin, has been constructed (Stephen Cauller, U.S. Geological Survey, written commun., 2000). In the modeling approach used here, however, model layers in the vertical dimension are added, not to represent distinct geologic layers, but to discretize the vertical dimension in order to refine model definition of flow paths and travel times from point of recharge to point of discharge.

Previous Investigations

Zapecza (1989) described the hydrogeologic framework of the New Jersey Coastal Plain. Watt and Johnson (1992), Lacombe and Rosman (1995), Johnson and Charles (1997), and Charles and others (2001) provide information on the hydrogeologic framework and geochemistry of, water levels, water use, and base flow in, and a general hydrologic budget for various parts of the surficial aquifer system underlying the study area. Martin (1998) simulated flow in the entire New Jersey Coastal Plain with an emphasis on water budget. Stephen Cauller (U.S. Geological Survey, written commun., 2000) simulated ground-water flow in the Kirkwood-Cohansey aquifer system in the Glassboro study area to investigate the effect of ground-water withdrawals on base flow. This model was designed to focus on ground-water flow to the Maurice River and its tributaries.

Rice and Szabo (1997) used two-dimensional ground-water-flow models of three vertical sections in the Glassboro study area to simulate ground-water-flow paths and travel times. The simulations were used to determine stratification of ground-water age and its relation to concentrations of nitrate and radium concentrations in the aquifer system.

Modica and others (1998) simulated ground-water flow in the Kirkwood-Cohansey aquifer system in the Cohansey River Basin to determine the source and residence time of ground-water flow to streams. In this study, contributing areas to six stream transects were delineated and the age distribution of the ground-water discharge along two transects was defined. Ground-water ages, estimated from chlorofluorocarbon (CFC) concentrations in water extracted from about 2 ft below the streambed, corroborated the simulated age distribution of ground-water flow to the stream transects. The relation of the fraction of ground-water flow to the stream transects affected by nitrate contamination to time was shown for the case where contamination continues and for the case where the source of contamination is eliminated.

DESCRIPTION OF STUDY AREA

The northwestern boundary of the study area closely follows the outcrop of the Kirkwood Formation. The remaining boundaries are formed by the basins that drain to the following surface-water data-collection sites: Cohansey River at Seeley, Maurice River at Millville, Hospitality Branch near Folsom, and Great Egg Harbor River at Folsom. Thirty-five municipalities lie at least partly within the study area (fig. 2). The largest towns in the area by population are Vineland City and Glassboro Borough.

Hydrogeology

The Kirkwood-Cohansey aquifer system consists of a southeastward-dipping wedge of unconsolidated sediments, which include gravel, sand, silt, and clay. The thickness of the aquifer system in the study area ranges from less than 25 ft at the northwestern boundary to 300 ft in the southeast. Within the Glassboro study area, the Grenloch Sand Member of the Kirkwood Formation, the Cohansey Sand, and, where present, the overlying Bridgeton Formation are hydraulically connected and function together as the unconfined Kirkwood-Cohansey aquifer system (Zapecza,

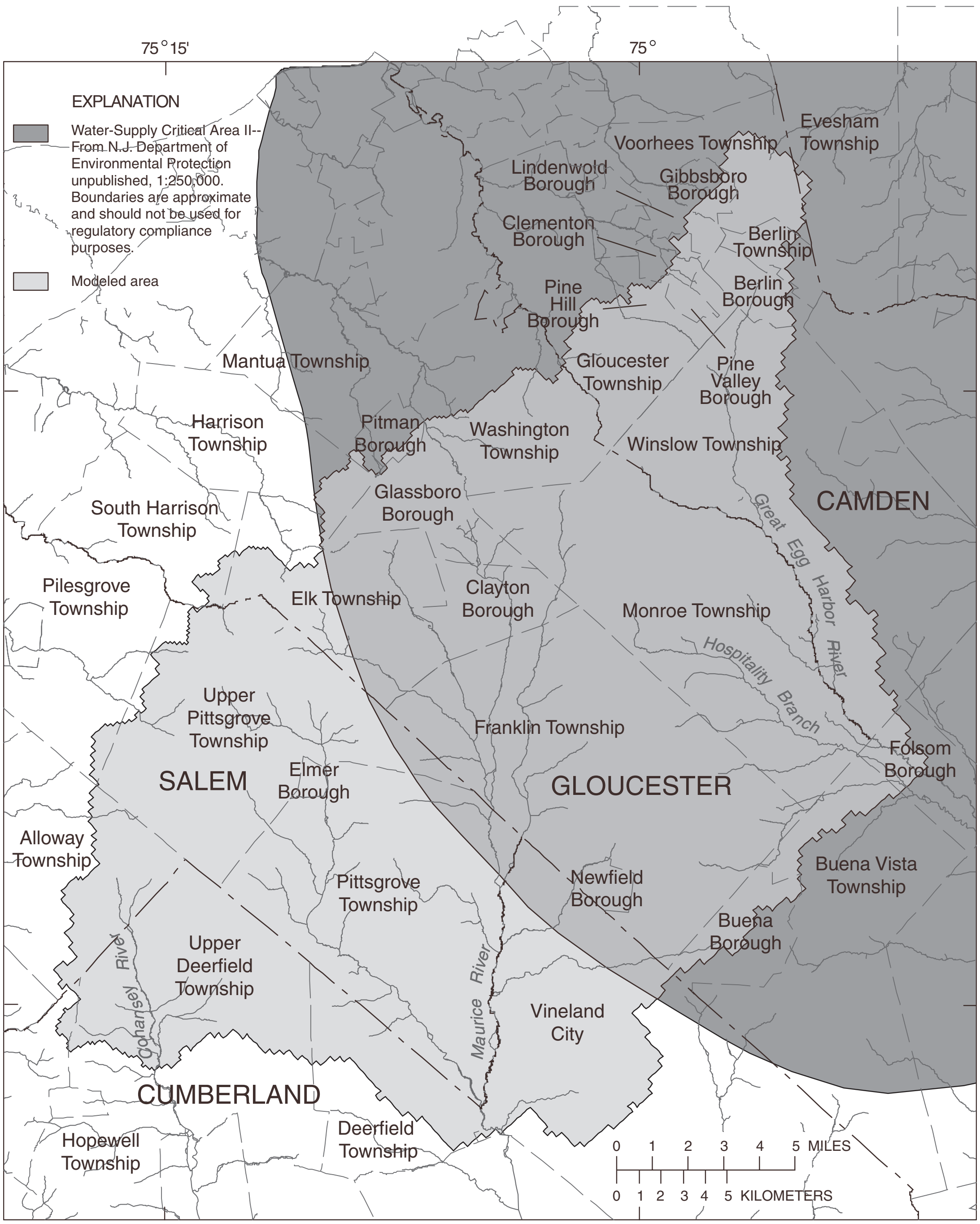

Figure 2. Extent of modeled area and approximate extent of New Jersey Department of Environmental Protection Water-Suppy Critical Area II in the Glassboro study area, New Jersey.

1989). The Grenloch Sand Member in this area is fine to medium sand and silty sand (Zapecza, 1989). The Cohansey Sand is predominantly medium- to coarse-grained sand with some gravel and silt and interbedded clay (Rhodehamel, 1973). The Bridgeton Formation is discontinuous throughout the study area, and is found on topographic highs. The Bridgeton Formation is coarse-grained sand and gravel. The Alloway Clay Member of the Kirkwood Formation underlies the Kirkwood-Cohansey aquifer system throughout the study area and functions as a continuous and competent confining bed (Nemickas and Carswell, 1976).

Average annual precipitation is about 44 in/yr and is distributed nearly uniformly throughout the year. About 3 in/yr of precipitation runs off directly into streams; the remainder is accounted for by evapotranspiration (ET) or recharge to ground water. The average annual ET is about 25 in/yr. ET is highest in the summer months, when the temperature is highest and plant growth is greatest. About 18 in/yr of water is recharged to the ground water (Lacombe and Rosman, 1995). Streams in the study area generally are gaining streams--that is, ground water flows into the streams.

Population and Land Use

The population of the Glassboro study area during 1930-90 (fig. 3) was estimated from U.S. Census data (New Jersey Department of Labor, 2000). Population data are available for individual municipalities at 10-year intervals. Many of the municipalities lie on the boundary of the study area; in these cases, the population of the municipality was scaled by the percentage of the municipality that lies within the study area.

Since 1960, the population of the townships in the study area has grown faster than the population of the boroughs and Vineland City (fig. 3). The boroughs and the city tend to be more densely populated, whereas townships historically are more rural and less densely populated.

Areas of urban, agricultural, and undeveloped land are distributed throughout the study area (fig. 4); however, the western part of the study area is predominantly agricultural and the northeastern

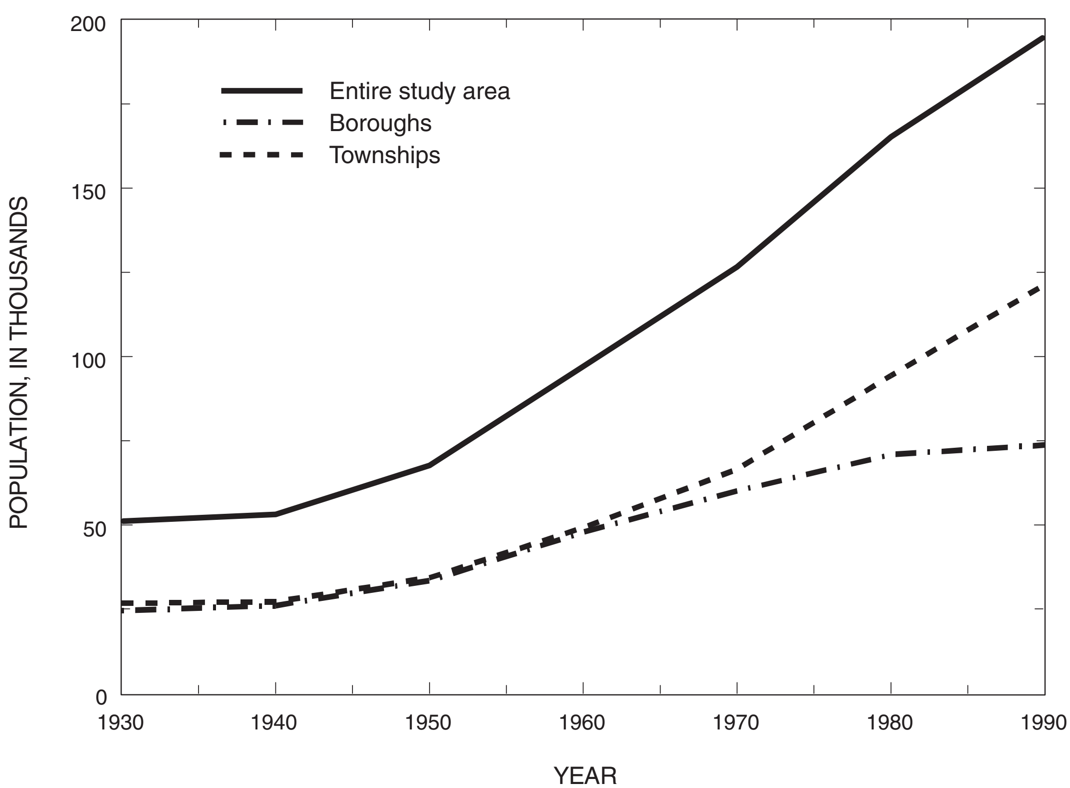

Figure 3. Population in the Glassboro study area, New Jersey, 1930-90. (Data from New Jersey Department of Labor, 2000)

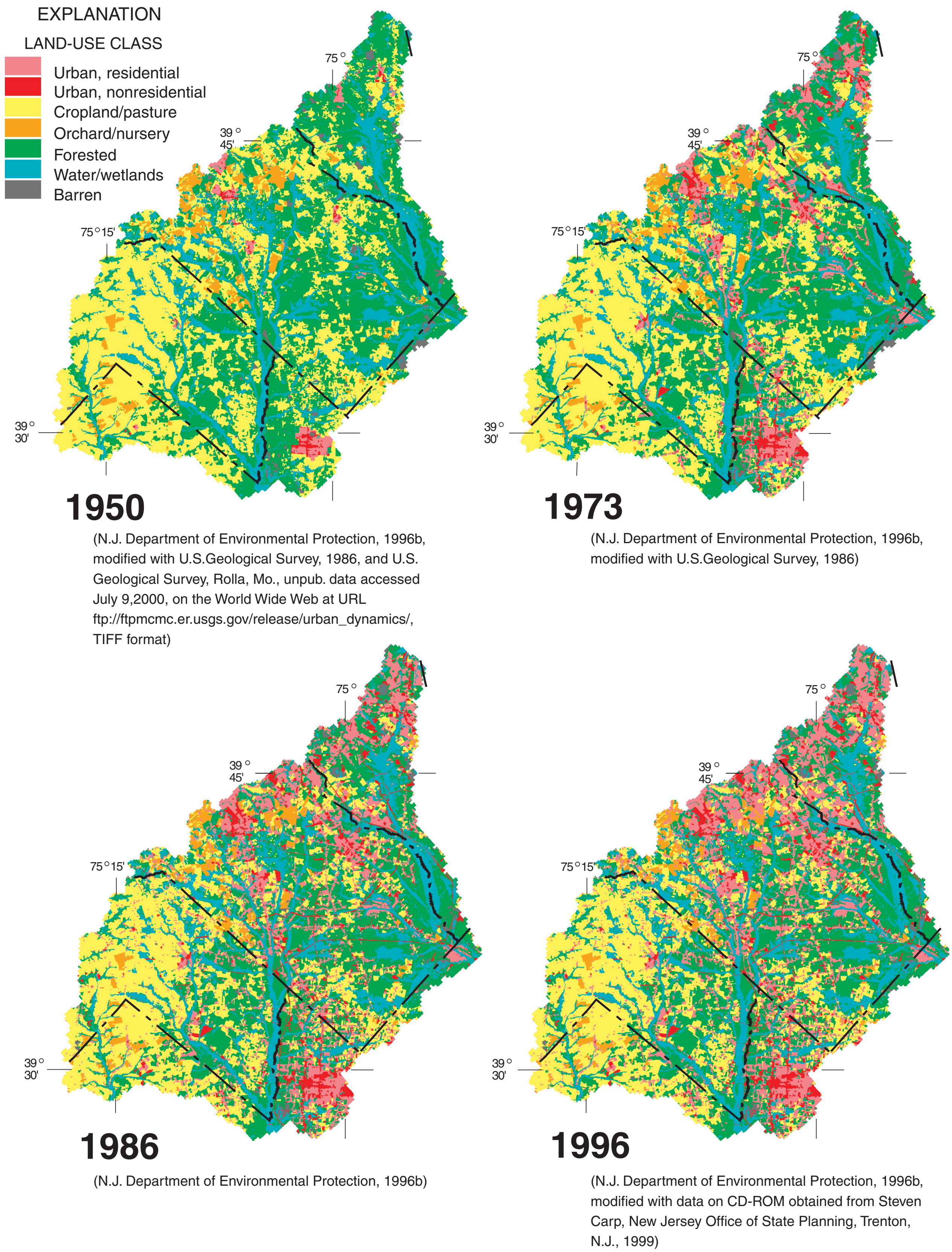

Figure 4. Land use in the Glassboro study area, New Jersey, 1950, 1973, 1986, and 1996.

part is predominantly urban land developed during the past 25 years. Vineland City in the southern part of the study area is another major tract of urban land. The largest tracts of undeveloped land are in the southeastern part of the study area.

The land-use data sets used in this investigation are based largely on the New Jersey Integrated Terrain Unit (ITU) GIS digital data set from 1986 (N.J. Department of Environmental Protection, 1996b). The ITU data set was based on interpretation of digital aerial photography. To look at change in land use over time, three additional land-use digital data sets were used to identify areas of land-use change: land cover from 1950's USGS topographic quadrangle sheets (U.S. Geological Survey, Rolla, Mo., unpub. data accessed July 9, 2000, on the World Wide Web at URL ftp://ftp-mcmc.er.usgs.gov/release/urban_dynamics/, TIFF format); the Geographic Information Retrieval and Analysis System (GIRAS) land-use digital data set from the early 1970's (U.S. Geological Survey, 1986); and a digital data set of areas developed between 1986 and the mid-1990's (data on CD-ROM obtained from Steven Carp, New Jersey Office of State Planning, Trenton, N.J., 1999).

The GIRAS land-use data were mapped at a scale of 1:250,000 and, therefore, are much coarser than the ITU data (mapped at a scale of 1:24,000). The coarse scale results in overestimation of the amount of agricultural and urban area and underestimation of the amount of undeveloped area in GIRAS. Because the difference in scale did not allow direct comparison of the ITU and GIRAS data sets, the GIRAS data set was used only to modify the ITU data set to represent 1973 land use. To create the 1973 land-use data set, the land-use designations from GIRAS were used when (1) ITU land use was urban and GIRAS was agricultural, forested, wetlands, or barren; (2) GIRAS land use was agricultural and ITU was brushland; (3) GIRAS land use was barren and ITU was agricultural, forested, or artificial lake; and (4) ITU land use was barren and GIRAS was agricultural or forested. For all other cases (areas in which land use likely did not change from 1973 to 1986), the land-use designations from the ITU data set were used.

The 1950 land-use data set was created by modifying the 1973 land-use data set described above on the basis of data from the scanned USGS topographic quadrangle sheets from the 1950's. Areas were delineated as urban, forested, water, or open (assumed to be agricultural). Only land use classified as urban in 1973 that was not urban in the 1950 data set was changed to the land use from the 1950 data set. Otherwise, the 1973 land use was used. This method likely results in underestimating the amount of urban land and overestimating the amount of agricultural land because the method of extracting land use from topographic sheets identifies urban land only in the town centers and not in more rural areas. The method also does not take into account changes in land use other than the change to urban land.

Areas of new development were added to the 1986 land-use data set to create the 1996 land-use data set. The digital data set of new development, created by using digital orthophoto quadrangles (DOQ's) from 1995 and 1997, was obtained from the New Jersey Office of State Planning, Trenton, N.J. To create the 1996 land-use data set, the areas of new development were assumed to be residential land; all other areas were assigned the value from the 1986 data set.

Comparison of the four land-use data sets (figs. 4 and 5) shows an increase in the amount of urban land (21 percent) and a corresponding decrease in the amount of agricultural (12 percent) and undeveloped (forested and water/wetlands) land (9 percent). Not including water and wetlands, the study area changed from a fairly even mix of agricultural and forested land use in 1950 to a fairly even mix of agricultural, forested, and urban land use in the mid-1990's. The large increase in urban land use between 1973 and 1986 in areas distant from the town centers corresponds with the period of rapid growth in population of the townships (fig. 3). The land-use percentages for the study area shown in figure 4 are listed in table 1.

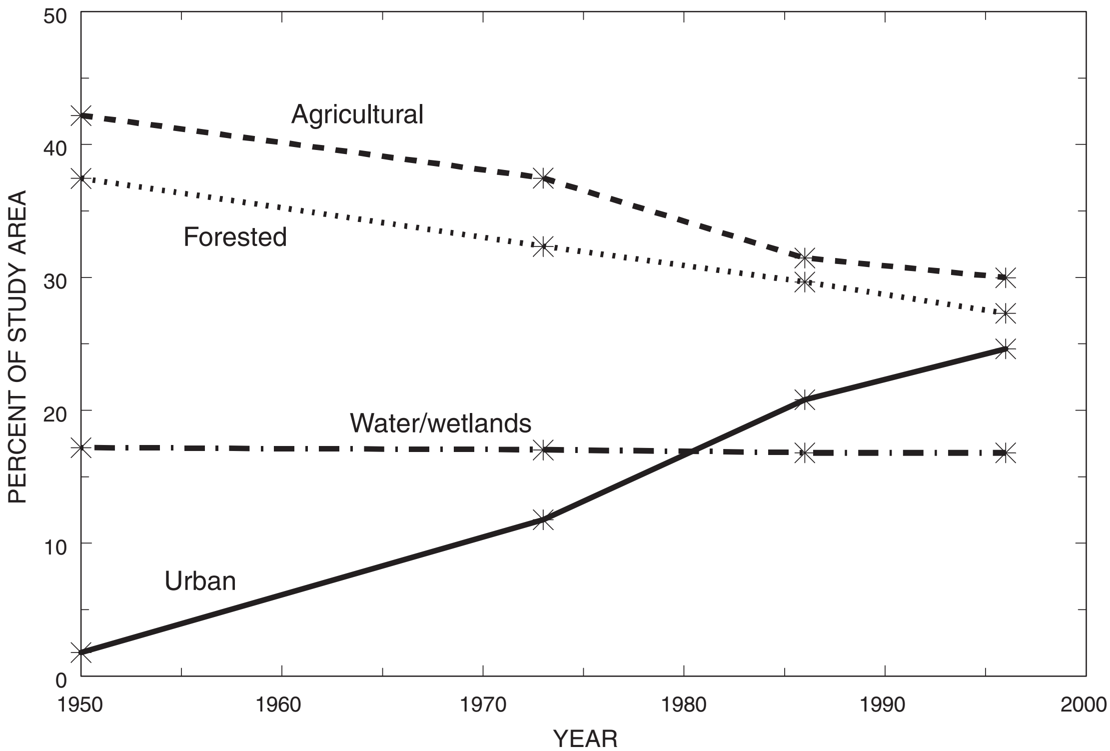

Figure 5. Land use in the Glassboro study area, New Jersey, 1950-96. [The asterisks denote times for which land-use data sets are available. (N.J. Department of Environmental Protection, 1996b; U.S. Geological Survey, Rolla, Mo., unpub. data accessed July 9, 2000, on the World Wide Web at URL ftp://ftpmcmc.er.usgs.gov/release/urban_dynamics/, TIFF format; U.S. Geological Survey, 1986; data on CD ROM obtained from Steven Carp, New Jersey Office of State Planning, Trenton, N.J., 1999)]

Water-Supply Issues and Ground-Water Use

The New Jersey Department of Environmental Protection (NJDEP) has recommended increased development of the Kirkwood-Cohansey aquifer system in the study area to meet a portion of the water demand caused by suburban growth and reduced pumping from deeper, confined aquifers (N.J. Department of Environmental Protection, 1996a). Part of the study area lies within NDJEP Water-Supply Critical Area II (fig. 2). The critical-area designation was made as a result of the presence of a large water-level depression in the underlying Potomac-Raritan-Magothy aquifer system caused by years of appreciable ground-water withdrawals. As part of the critical-area mandate, water allocations from the Potomac-Raritan-Magothy aquifer system within the Critical Area were reduced by an average of 20 percent. As a result of increasing population and, to a lesser degree, restricted pumping from deeper aquifers in the 1990's, withdrawals from the Kirkwood-Cohansey aquifer system in the study area increased by about 2,000 Mgal/yr from 1981 to 1996 (fig. 6).

Ground-water-use data were obtained from computer files supplied by the NJDEP Bureau of Water Allocation. Water use from three sources is reported: wells, ponds created by excavating soil beneath the water table, and water that is part of the surface drainage system (streams and ponds created by impounding or diverting surface water). In this report, the first two sources are considered to be ground-water withdrawals. The locations of the withdrawals in the study area are shown in

Table 1. Land use and change in land use in the Glassboro study area, New Jersey, 1950-96

[Data from N.J. Department of Environmental Protection, 1996b; U.S. Geological Survey, Rolla, Mo., unpub. data accessed July 9, 2000, on the World Wide Web at URL ftp://ftpmcmc.er.usgs.gov/release/urban_dynamics/, TIFF format; U.S. Geological Survey, 1986; data on CD-ROM obtained from Steven Carp, New Jersey Office of State Planning, Trenton, N.J., 1999]

Land-use category	Anderson Level 2 classification[1]	Percent of study area				Percent from year indicated to 1996		
		1950	1973	1986	1996	1950	1973	1986
Total urban		1.79	11.75	20.80	24.63	18.04	10.58	3.83
Residential	11	1.33	8.78	15.54	19.36	1.30	.39	.00
Commercial	12	.26	1.17	1.56	1.56	.59	.25	.00
Industrial	13	.08	.42	.67	.67	1.16	.79	.00
Transportation	14	.01	.39	1.17	1.17	.02	.00	.00
Industrial/commercial	15		.01	.02	.02	.00	.00	.00
Mixed urban	16	.00	.00	.00	.00	.99	.57	.00
Other urban	17	.07	.49	1.06	1.06	.74	.30	.00
Recreational	18	.04	.49	.78	.78	-12.21	-7.50	-1.48
Total agricultural		42.18	37.48	31.46	29.98	-11.01	-6.31	-1.03
Cropland	21	37.37	32.67	27.40	26.37	-.88	-.88	-.37
Orchard	22	4.03	4.03	3.51	3.15	-.24	-.24	.00
Feedlot	23	.25	.25	.01	.01	-.08	-.08	-.08
Other agricultural	24	.54	.54	.54	.46	-1.64	-5.38	-2.35
Total undeveloped		56.03	50.77	47.74	45.39	-2.09	-2.09	-.90
Deciduous	41	13.75	13.75	12.56	11.66	-.52	-.52	-.25
Coniferous	42	4.59	4.59	4.32	4.07	-8.47	-3.35	-.85
Mixed forest	43	17.08	11.96	9.47	8.61	.93	.93	-.34
Brushland	44	2.03	2.03	3.31	2.96	.00	.00	.00
River	51	.08	.08	.08	.08	.00	.00	.00
Lake	52	.03	.03	.03	.03	-.09	.05	.00
Artificial lake	53	1.13	.98	1.03	1.03	-.28	-.28	.00
Wetland	62	15.88	15.88	15.60	15.60	.00	.00	.00
Beaches	71	.00	.00	.00	.00	.41	.41	.00
Mining	73	.40	.40	.81	.81	.13	.13	.00
Altered land	74	.17	.17	.30	.30	-.34	-.34	.00
Transitional	75	.42	.42	.09	.09	-.33	-.33	.00
Undifferentiated barren	76	.39	.39	.07	.07	.00	.00	.00
Modified wetlands	80	.07	.07	.07	.07	.00	.00	.00

[1] Anderson and others, 1976.

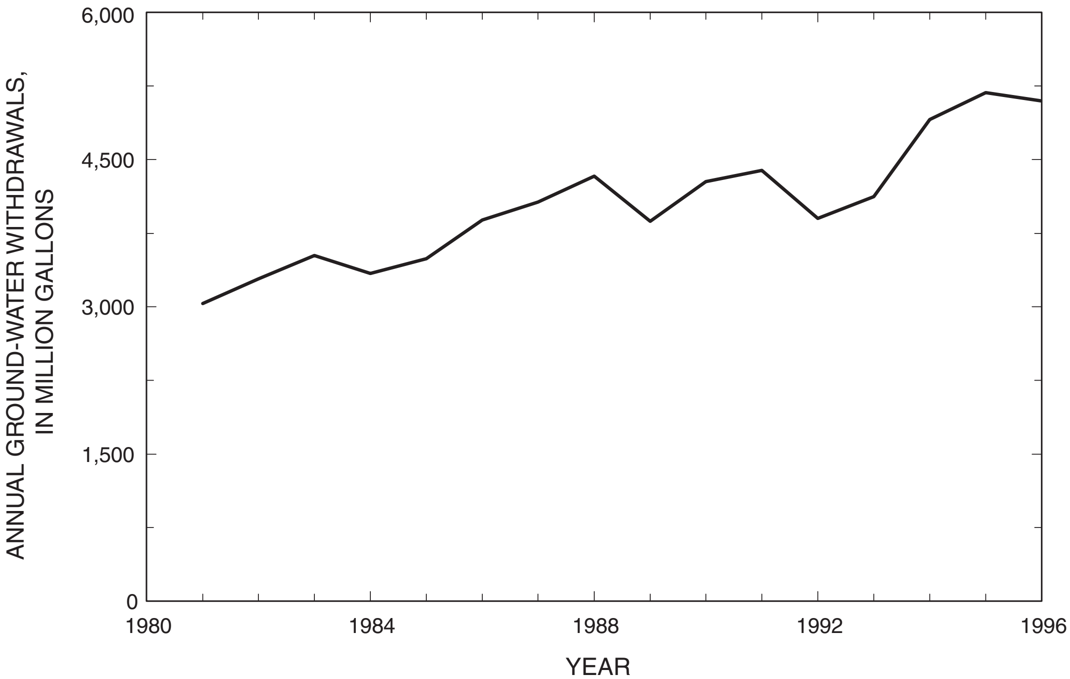

Figure 6. Ground-water withdrawals from public-supply wells in the Kirkwood-Cohansey aquifer system, Glassboro study area, New Jersey, 1981-96. (Unpublished data on file at U.S. Geological Survey office, West Trenton, N.J.)

figure 7. The water-use data are compiled for four types of users: agricultural irrigation wells, public-supply systems with allocations greater than 100,000 gal/d, other ground-water users with allocations greater than 100,000 gal/d (mostly industrial), and users with allocations less than 100,000 gal/d (small public-supply systems, fire companies, schools, and small industry). Water use is not reported for domestic wells serving individual households; however, the amount of water withdrawn from domestic wells was estimated by multiplying the number of people served by private wells, determined from 1990 census data (U.S. Bureau of the Census, 1992), by a per capita coefficient of 82 gal/d (Nawyn, 1998).

Public (38 percent) and domestic (13 percent) water supply together account for about half of the water withdrawn from the Kirkwood-Cohansey aquifer system (fig. 8). The remaining 49 percent is withdrawn for industrial and irrigation purposes.

METHODS

In this section, the methods used to simulate ground-water flow and nitrate concentrations are described. Results of the ground-water-flow simulation were used as input to a particle-tracking program which, together with results of GIS land-use analysis, allowed simulation of nitrate concentrations in ground water from wells and streams.

Simulation of Ground-Water Flow

A numerical model, the USGS three-dimensional finite-difference code MODFLOW-96 (Harbaugh and McDonald, 1996a, 1996b), was used to simulate ground-water flow and head distributions across the study area. The results of this simulation were used as input to the particle-tracking program MODPATH (Pollock, 1994) that is used to delineate recharge areas and compute travel times through the aquifer.

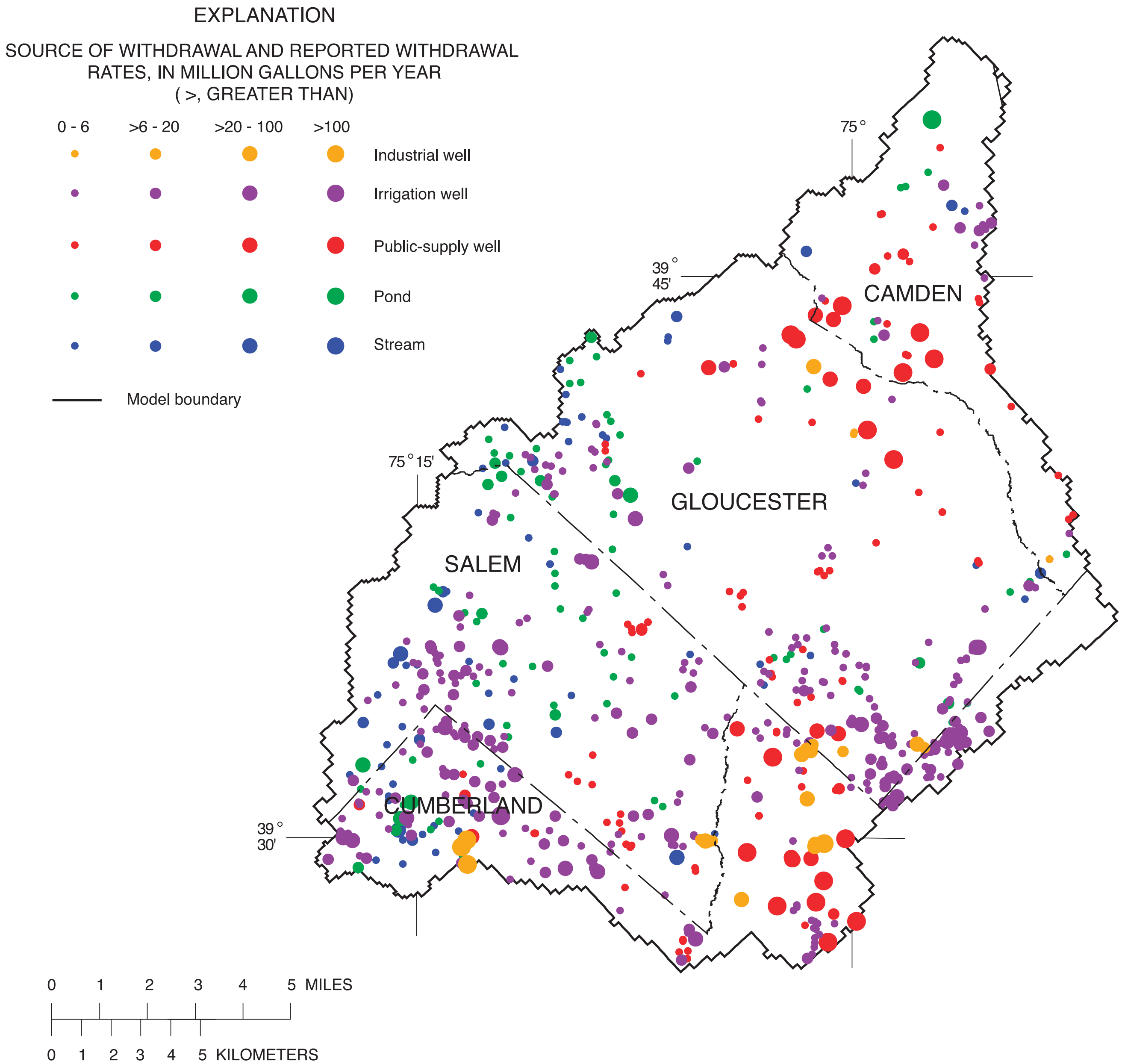

Figure 7. Location and average annual volume of water withdrawals from streams and from the Kirkwood-Cohansey aquifer system in the Glassboro study area, New Jersey, 1992-96. (Unpublished data on file at U.S. Geological Survey office, West Trenton, N.J.)

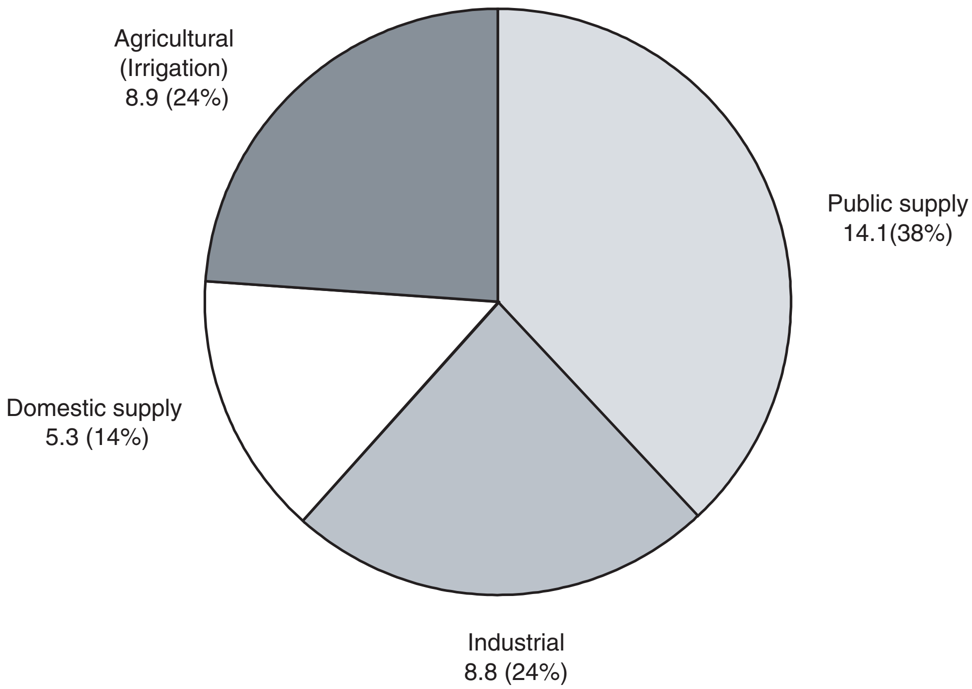

Figure 8. Average reported ground-water withdrawals from the Kirkwood-Cohansey aquifer system by water-use category, Glassboro study area, New Jersey, 1992-96. (Values are in million gallons per day; %, percent; unpublished data on file at the U.S. Geological Survey office, West Trenton, N.J.)

Model Discretization

The aquifer is represented in the numerical model by a three-dimensional grid of cells that consists of 343 columns, 214 rows, and 12 layers. The cells are 492 ft by 492 ft in the horizontal dimension and range from 20 to 80 ft in the vertical dimension (fig. 9) depending on their position in the aquifer system. The cells near the top of the model are thin for the purpose of simulating the vertical component of flow induced by recharge and topographic relief. Model layers in the vertical dimension are added not to represent geologic layers but to discretize the model in the vertical direction to refine the locations of flow paths in the aquifer system originating at land surface. The grid was aligned approximately with the north-eastern study-area boundary to minimize the total number of model cells required.

Each cell in the model was determined to be either active or inactive. The modeled area consists of all active cells. Ground water is not simulated to flow through inactive cells. Active cells meet the following three conditions: (1) the cell is within the study-area boundary, (2) the elevation of the top of the cell is greater than the elevation of the bottom of the Kirkwood-Cohansey aquifer system, and (3) the elevation of the bottom of the cell is lower than the land-surface elevation.

Boundary Conditions and Model Stresses

All external boundaries of the modeled area are modeled as no-flow boundaries. On the north-western perimeter of the modeled area, the boundary closely follows the outcrop of the Kirkwood Formation (fig. 9a). The boundary was

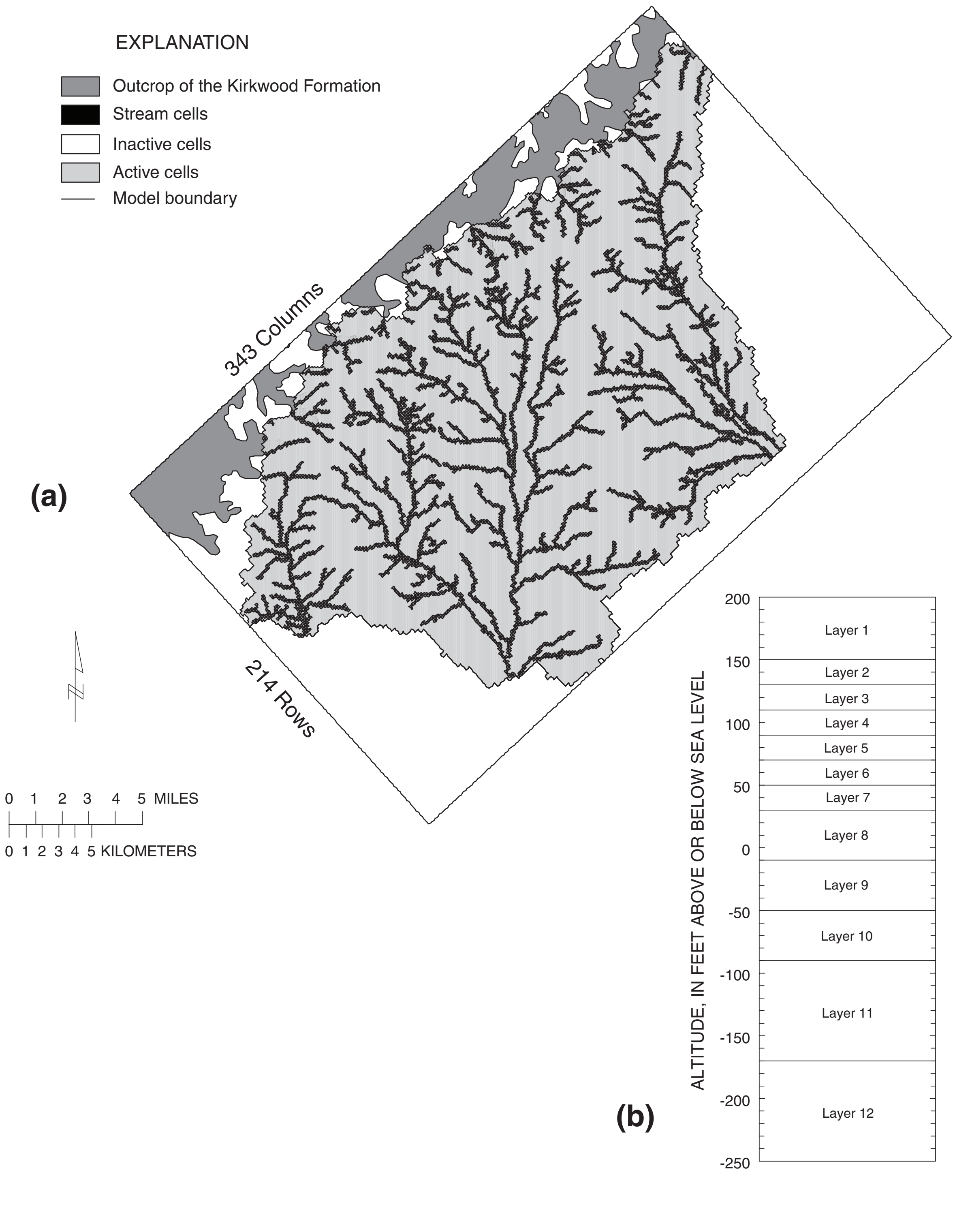

Figure 9. Ground-water-flow model of the Glassboro study area, New Jersey, showing (a) horizontal discretization and location of active, inactive, and stream cells, and (b) vertical discretization.

established by combining the drainage boundaries for the points on each stream where the stream elevation was equal to the elevation of the bottom of the aquifer system. On the other three sides, the boundaries of the modeled area are surface-water divides. These surface-water divides are considered to be surrogates for ground-water divides. The assumption of the co-location of the surface- and ground-water divides may be inappropriate under some conditions. Major pumping near the divides may cause the ground-water divide to shift away from the surface-water divide. If the vertical head gradient at the ground-water divide is sufficiently large, ground-water flow may have a regional component and water would flow under the local ground-water divide. Given the aquifer thickness in this area, this type of flow likely occurs only if a locally extensive layer of low-permeability material is present.

Recharge to the aquifer is modeled by applying the source to the uppermost active layer of the model. The location of the uppermost active layer depends on the simulation. If the head in a cell in the uppermost active layer is lower than the elevation of the bottom of the cell, then the cell is dry and is designated as an inactive cell. Recharge then is applied to the next lower cell. The base of the surficial aquifer system, defined as the elevation of the bottom of the sand layer of the Kirkwood Formation, is assumed to be a no-flow boundary. Although flow may occur across this boundary to or from the underlying confined aquifer, this component of flow is considered to be negligible.

Recharge to the aquifer was specified as a uniform flux of 0.004 ft/d (17.5 in/yr). Lacombe and Rosman (1995) reported a recharge value of 18.6 in/yr for the Maurice River Basin. Watt and Johnson (1992) reported a recharge value of 18.3 in/yr for the Great Egg Harbor River Basin. Charles and others (2001) computed a value of 16.3 in/yr for the Maurice River Basin and 14.1 in/yr for the Cohansey River Basin. Rice and Szabo (1997) used a value of 18 in/yr in their models of flow in the Maurice and Cohansey River Basins. Modica and others (1998) used a value of 15 in/yr for the Cohansey River Basin. Martin (1998) used 20 in/yr for the entire New Jersey Coastal Plain.

All wells with pumping rates greater than 6 Mgal/yr based on average yearly withdrawals from 1992 to 1996 reported to the NJDEP Bureau of Water Allocation were included in the simulations (fig. 7). Water extracted from ponds not directly connected to streams also was included in the simulations. Ponds of this type were modeled as shallow, large-diameter wells. The ponds are constructed by excavating beneath the water table. Similar to rates of pumping from wells, the pumping rates were set equal to the average yearly withdrawals from 1992 to 1996 reported to the NJDEP Bureau of Water Allocation. The locations of the wells were determined from latitudes and longitudes obtained from the NJDEP Bureau of Water Allocation. These locations were verified with 7.5-minute USGS topographic quadrangles (1:24,000 scale) and aerial photography. If the reported position was not at a pond, the location of the nearest pond was used. The topographic quadrangles also were used to determine whether the pond was connected to a stream.

Streams in the study area were modeled with the MODFLOW drain package. A drain simulates base flow by allowing water to enter a stream when the head in the aquifer is greater than the stage of the stream. The elevation or stage of the stream is held constant and the discharge to the stream is determined by multiplying the difference between the head in the aquifer and stream stage by the conductance of the streambed. The conductance of the streambed is the hydraulic conductivity of the material in the streambed multiplied by the stream area in the cell divided by the thickness of the streambed. The drain package does not allow for flow from a stream into the aquifer.

A model cell was designated a stream cell if a stream passed through any part of the model cell. The stage for stream cells that coincided with lakes or places where the 10-ft topographic contours crossed streams on the 7.5-minute USGS topographic quadrangles was set equal to the value of the elevation of lake or the contour line crossing the stream; all other stream cells were assigned stages on the basis of linear interpolation between these points.

Determination of Ground-Water Age and Contributing Areas to Wells and Streams

The particle-tracking model MODPATH (Pollock, 1994) was used to calculate travel times and discharge points for water entering the aquifer at the water table. MODPATH uses the cell-by-cell flow values from MODFLOW to simulate the path of a particle of water through the aquifer. Travel times along the paths are computed by using the magnitude of the cell-by-cell flows, the porosity of the aquifer, and the model cell dimensions. A porosity of 0.3 was used in this simulation.

Both forward and backward tracking approaches were used in simulation. In the forward tracking approach, one particle was started at the water table in the center of each cell that intersected the water table. The particle then was tracked forward until it discharged at a stream or well. Particles were stopped at weak sinks (see discussion of weak sinks below). Given uniform recharge and cell size, each particle represents the same volume of water. This approach was used to determine the contributing areas and travel times for water entering streams and wells with high pumping rates, such as public-supply and irrigation wells.

In the backward tracking approach, particles were started at locations within the aquifer and tracked backward until they reached the water table, or location of recharge (contributing area). Particles were allowed to pass through weak sinks. The backward tracking approach was used to determine the contributing areas and travel times for points in the aquifer or water entering wells with low pumping rates, such as domestic or monitoring wells.

Weak sinks are cells that contain a sink that does not capture all of the water entering the cell; water flows out at least one of the cell faces. When the backward particle tracking approach was used, particles were allowed to pass through weak sinks so they eventually would reach the water table. When the forward tracking approach was used, however, particles were stopped at weak sink cells. This approach may cause the simulated contributing area for that cell to be larger than the actual contributing area. Subsequently, simulated contributing areas of cells downgradient from a weak sink may be smaller than the actual contributing area. Particles were stopped at weak sinks in forward-tracking runs to be conservative with respect to wells (which are more likely than streams to be weak sinks)--that is, overestimating rather than underestimating the size of the contributing area.

Determination of Nitrate Concentration at Discharge Points

The concentration of nitrate in recharge entering the aquifer at the water table was assumed to be a function of the land use at the site of recharge and the year in which the recharge took place. The results of the MODPATH simulations provide information on the recharge location and time required for each particle to reach its discharge location. Each particle is assigned a concentration corresponding to the land use in the year that the recharge took place. For example, if the concentration is being computed for the year 2000 and MODPATH simulates a travel time of 20 years, and the starting location of the particle as the cell at column 200, row 100, the particle is given the concentration corresponding to the land use at that point in 1980. If the concentration in 2020 is being computed, the particle would be given the concentration corresponding to the land use at that point in 2000. The percentage of each land use in 1950, 1973, 1986, and 1996 was calculated for all cells in the model. Land-use percentages between these years were linearly interpolated. Land-use data for 1950 were used for all years before 1950 and land-use data for 1996 were used for all years after 1996.

To compute the concentration at a particular discharge point, the average of the concentrations associated with all the particles that flow to that particular discharge point is used. Because recharge and cell size are uniform, each particle represents an equal amount of water and, thus, an average is appropriate. If recharge and cell size were not uniform, a weighted average would be required.

The transport of nitrate in the aquifer is assumed to be conservative. Because nitrogen neither forms insoluble minerals that could precipitate nor is appreciably adsorbed under aquifer conditions, the only means of in-situ nitrate removal from ground water is by reduction (Appelo and Postma, 1996). Dissolved oxygen concentrations in the ground water generally are greater than 3 mg/L (Szabo and others, 1997); therefore, reduction of nitrogen is unlikely to occur. Nitrate reduction does take place on a local scale in this aquifer. Samples from 2 of 37 monitoring wells sampled for dissolved gas in the study area contained excess dissolved nitrogen greater than 1 mg/L (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.). The amount of dissolved argon is used to determine the amount of nitrogen expected to be dissolved in water in equilibrium with the atmosphere; any nitrogen in excess of this amount is attributed to nitrate reduction (Dunkle and others, 1993; Rowe and others, 1999).

Estimation of Nitrate Concentration in Recharge Over Time

In order to compute the concentrations of nitrate as outlined above, it was necessary to develop a history of nitrate concentrations in recharge for the land uses of interest (fig. 10). The current value for nitrate concentration was based on median values from three networks of shallow monitoring wells designed to characterize the quality of water beneath agricultural, urban, and undeveloped land. These median values were 14 mg/L as N for cropland and pasture, 10 mg/L as N for orchards and nurseries, 2.5 mg/L as N for urban land, and 0.07 mg/L as N for undeveloped

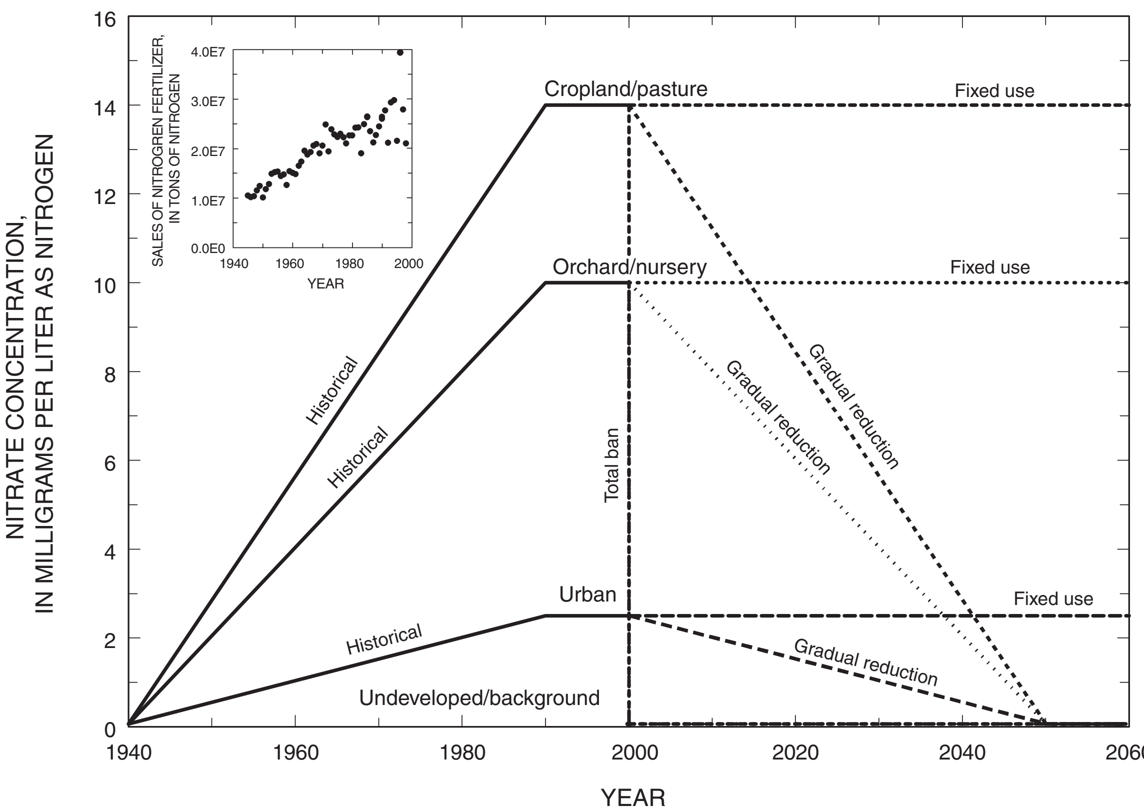

Figure 10. Mean concentration of nitrate in recharge to aquifer from four land-use types, 1940-2000 (solid lines), and for three water-management alternatives (dotted lines) used in model simulations, Glassboro study area, New Jersey. [Inset shows reported sales of nitrogen fertilizer in New Jersey, 1945-98 (Alexander and Smith, 1990; Battaglin and Goolsby, 1994; David Lorenz, U.S. Geological Survey, written commun., 2000)]

land (Stackelberg and others, 1997). On the basis of trends in the use of nitrogen fertilizer and reconstructed concentrations of nitrate in recharge in the Coastal Plain of New Jersey (Modica and others, 1998) and Maryland (Bohlke and Denver, 1995), the concentrations of nitrate in aquifer recharge in agricultural and urban areas were assumed to increase linearly from the background value of 0.07 mg/L as N in 1940 to the respective 1990 concentrations. Prior to 1940, the nitrate concentration in recharge from all land uses was assumed to be at the background level.

MODEL SIMULATION RESULTS

In this section, results of the model simulations are presented. The calibration procedure is discussed and model performance is evaluated. Ground water, both in the aquifer and discharging from the aquifer, is characterized with respect to age and land use in the recharge area.

Model Calibration and Evaluation

The flow model was calibrated by adjusting horizontal, vertical, and streambed hydraulic conductivities to achieve the closest possible match between simulated and observed heads. A single value of streambed hydraulic conductivity of 50 ft/d was used throughout the model. The horizontal and vertical conductivities were assigned on the basis of zones in areas with similar stratigraphy (see fig. 11) determined by using geophysical and driller's logs (Stephen Cauller, written commun., 2000). Additional, smaller zones were created in the northeastern part of the study area because satisfactory calibration could not be achieved with larger zones. Hydraulic conductivity was assumed to be constant with depth.

A map of the water table in the study area was created by using a GIS from water levels in 592 wells (data on file at U.S. Geological Survey, West Trenton, N.J.), the elevations of perennial streams, and water-level contours from results of surficial-aquifer studies in the area (Lacombe and Rosman 1995; Watt and Johnson 1992; Johnson and Charles 1997; Charles and others, 2001). This map was used to establish a target water level for each cell within the model. The hydraulic conductivities then were adjusted to minimize the sum of squares of the difference between the target water level and simulated water level in each cell. The final calibrated hydraulic conductivities and the locations of the conductivity zones are shown in figure 11.

The difference between the targeted and simulated water levels is shown in figure 12. Simulated water levels generally are within 5 ft of the target water levels. Most of the areas in which the difference is large are near the edge of the model and, therefore, are subject to boundary effects. In some of these areas, however, no measured water level is available and the poor match may be the result of the process used to create the water-table map.

The base flow simulated with the model was compared with measured base flows to evaluate the accuracy of the recharge value used. Charles and others (2001) report ground-water discharge to streams to be 15.6 and 13.1 in/yr for the Maurice and Cohansey Rivers, respectively. Base flow in the Great Egg Harbor River is 17.3 in/yr (Watt and Johnson, 1992). The simulated values for these rivers at the boundary of the model were 15.3 in/yr for the Maurice River, 16.1 in/yr for the Cohansey River, and 15.4 in/yr for the Great Egg Harbor River. The simulated ground-water discharge nearly was equal to the reported discharge for the Maurice River but was high for the Cohansey River and low for the Great Egg Harbor River. If the values are weighted by drainage area and combined, the measured ground-water discharge is 15.7 in/yr and the simulated ground-water discharge is 15.4 in/yr.

To evaluate the performance of the model with respect to simulation of travel time and to calibrate the value of porosity, the model-simulated ground-water age and the age determined by analyses for environmental tracers in ground water from monitoring wells were compared (table 2, fig. 13). The travel times to monitoring wells were estimated by using the ratios of tritium to helium-3 (3H/3He) (for example, Eckwurzel and others, 1994; Szabo and others, 1996) and sulfur hexafluoride (SF_6) concentrations (Busenberg and Plummer, 2000). Ages were determined by $^3H/^3He$ and (or) SF_6 analyses for 55 monitoring wells in the study area. Simulated travel times to

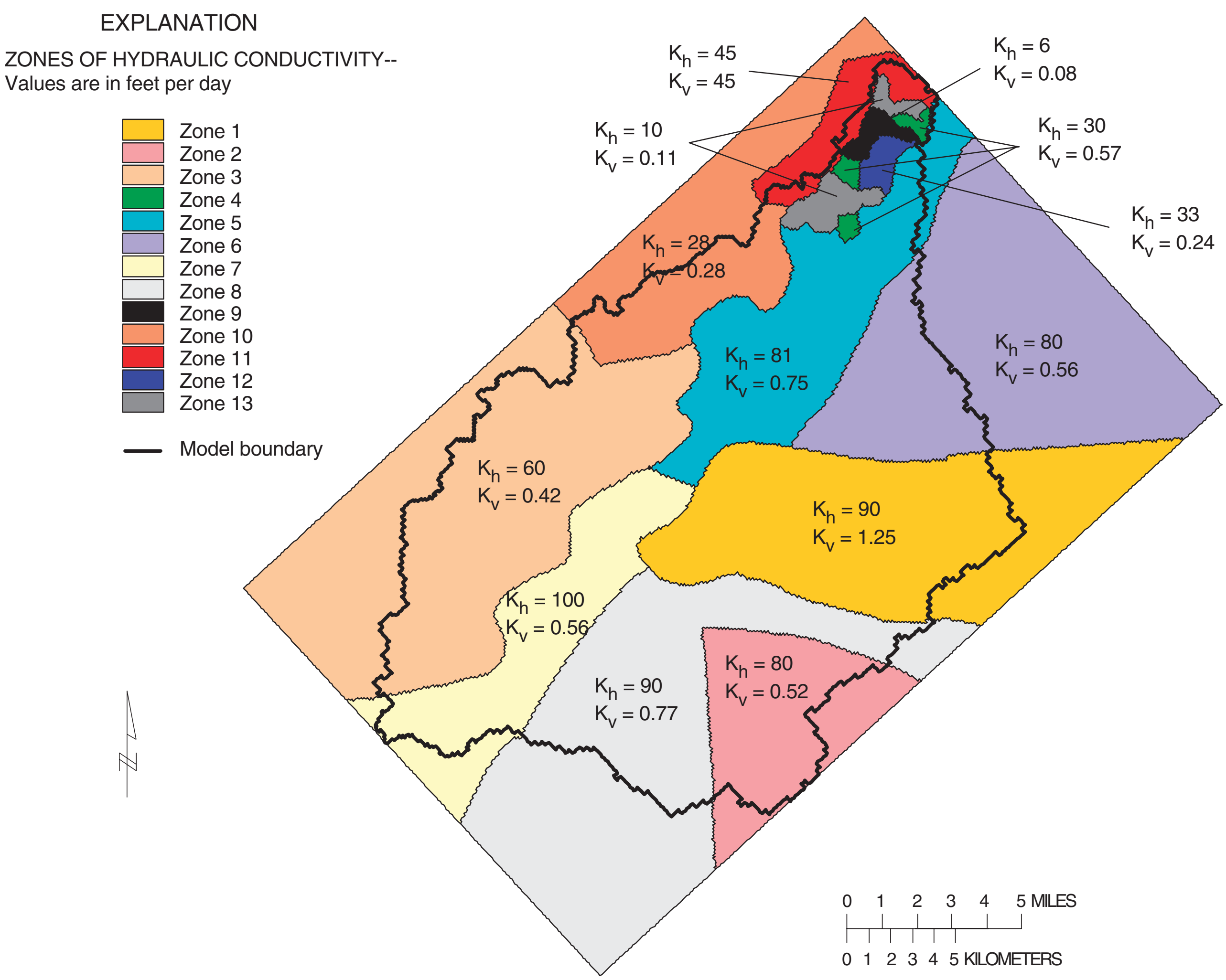

Figure 11. Zones of hydraulic conductivity used in model calibration and final calibrated horizontal (K_h) and vertical (K_v) hydraulic conductivities in the modeled area, Glassboro study area, New Jersey.

the monitoring wells were determined by starting particles at the center of the screened interval and tracking them backward to the water table.

The value of porosity to be used in the model was the value at which the sum of squares of the difference between the $^3H/^3He$ ages and the simulated ages was minimal. This value was determined to be 0.30 (table 3). Use of this value resulted in a reasonable match between the simulated and geochemically interpreted ages.

Age of Water in the Aquifer and Relation to Land Use in the Recharge Area

The model was used to simulate the length of time that the water has been in the aquifer and the land use in the area where the water entered the aquifer in order to obtain a general indication of current (2000) water-quality conditions in the aquifer. The Kirkwood-Cohansey aquifer system in the study area contains about 3 trillion gallons of water if a porosity of 0.3 is assumed. The average age of this water is 49 years; however, the small

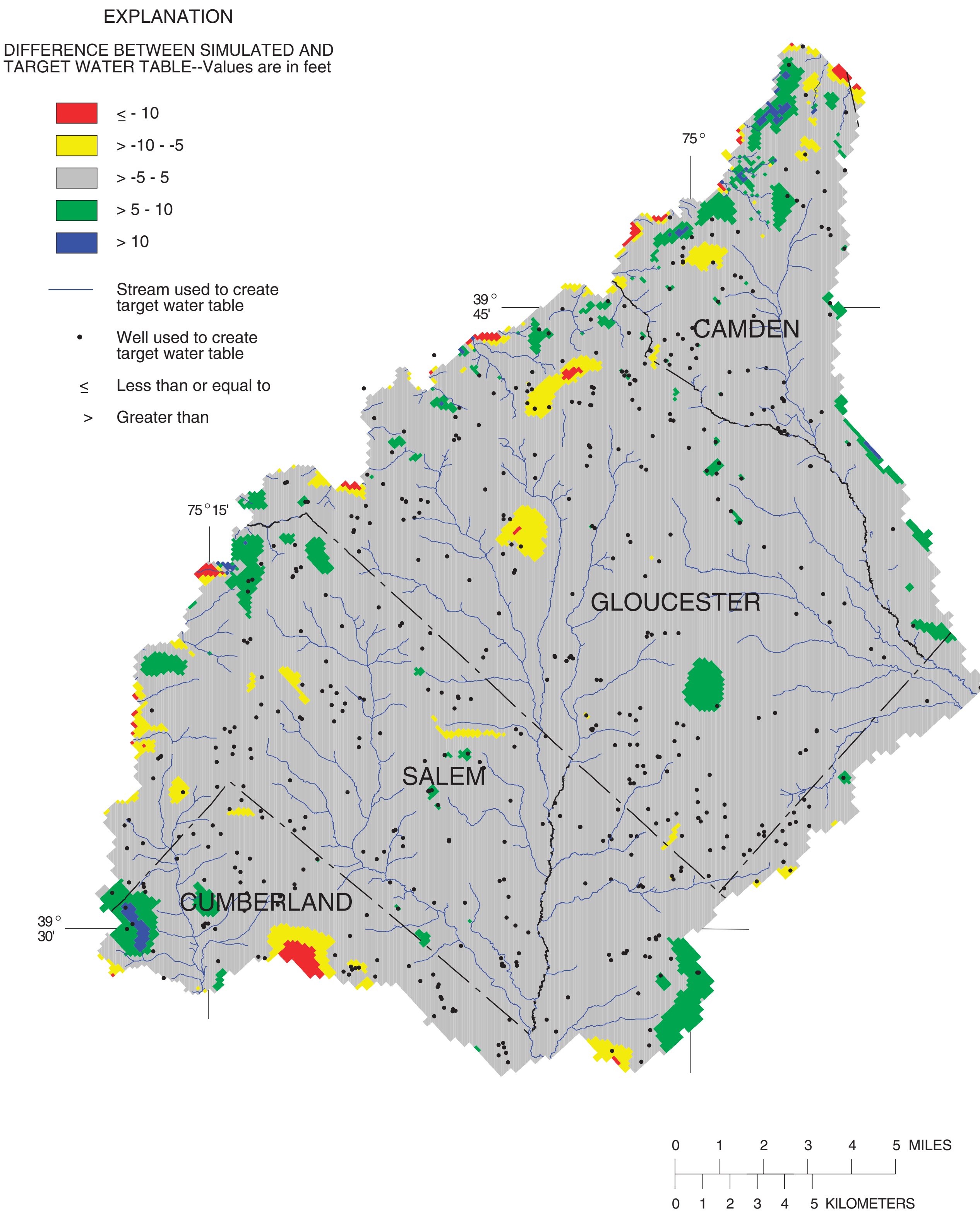

Figure 12. Difference between simulated and target water levels in the modeled area, Glassboro study area, New Jersey.

Table 2. Geochemical and simulated ages of water samples from monitoring wells in the Glassboro study area, New Jersey
[--, data not available]

Well name	U.S. Geological Survey well number	Latitude	Longitude	Depth to top of screened interval (in feet)	Depth to bottom of screened interval (in feet)	Date helium-tritium sample collected	Helium-tritium age (in years)	Date sulfur hexa-fluoride sample collected	Sulfur hexa-fluoride age (in years)	Simulated age to top of screen (in years)	Simulated age to middle of screen (in years)	Simulated age to bottom of screen (in years)
AG06	11-0692	39°30’58.5”	75°12’19.1”	33	38	4/28/1992	6.1	--	--	1.8	2.4	2.9
AG08	33-0822	39°35’24.9”	75°13’23.2”	29	31	2/18/1998	1.5	2/23/1999	5.6	1.3	1.5	1.8
AG09	33-0820	39°37’10.9”	75°12’09.8”	17	19	2/19/1998	4.7	2/19/1998	1.1	2.1	2.4	2.6
AG11	33-0819	39°35’41.7”	75°11’02.9”	20	22	12/4/1996	1.8	--	--	2.5	2.8	3.0
AG12	11-0889	39°31’58.9”	75°15’02.2”	37	39	1/21/1998	.6	1/21/1998	4.2	1.2	1.3	1.5
NU01-TEN	15-1266	39°43’26.7”	75°04’57.2”	55.5	58	1/09/1998	23.0	--	--	6.0	6.5	7.0
NU02	15-1210	39°43’42.6”	75°04’00.6”	17.5	19.5	2/11/1998	1.4	2/11/1998	1.7	2.3	2.6	2.8
NU02-TEN	15-1267	39°43’42.6”	75°04’00.7”	40.5	43	11/11/1997	21.0	2/11/1998	13.7	9.9	10.4	10.9
NU06	7-0841	39°45’27.1”	75°00’39.5”	52	54	1/29/1998	--	1/29/1998	4.1	1.6	1.8	2.0
NU06-TEN	7-0867	39°45’27.1”	75°00’39.5”	77.5	80	6/06/1997	11.5	1/29/1998	7.6	9.0	9.5	10.0
NU08	15-1220	39°43’38.9”	75°01’26.3”	28.5	30.5	12/09/1996	5.3	--	--	1.8	2.0	2.3
NU09	15-1219	39°40’22.5”	74°59’09.1”	29	31	12/16/1997	.3	1/27/1998	1.0	2.1	2.3	2.5
NU09-TEN	15-1264	39°40’22.4”	74°59’09.3”	50.5	53	12/16/1997	13.3	1/27/1998	15.6	7.0	7.3	7.6
NU10-TEN	15-1277	39°39’48.2”	74°58’28.8”	47	49	1/22/1998	21.3	1/22/1998	14.0	8.4	8.6	8.9
NU11	7-0836	39°46’04.5”	75°00’33.5”	30	37	9/09/1997	7.5	2/22/1999	4.2	2.2	3.2	4.0
NU11-TEN	7-0868	39°46’04.4”	75°00’33.4”	67.5	70	11/06/1997	30.1	1/29/1998	29.1	14.2	14.7	15.3
NU13-TEN	7-0870	39°43’46.7”	74°59’49.6”	52.5	55	1/06/1998	5.6	--	--	6.3	6.7	7.0
NU16-TEN	7-0869	39°42’33.8”	74°57’42.4”	45.5	48	1/08/1998	2.6	--	--	8.3	8.6	8.9
NU19-TEN	7-0887	39°42’54.5”	74°59’03”	49.5	52	1/08/1998	20.5	--	--	6.5	6.8	7.2
NU22-TEN	15-1280	39°41’50.2”	74°59’00.8”	43	45	1/12/1998	36.9	2/24/1999	30.0	8.2	8.4	8.7
NU26-TEN	7-0879	39°47’04”	74°56’16.2”	38.5	41	12/17/1997	26.2	2/21/1999	13.1	10.9	11.4	11.8
NU27-TEN	7-0886	39°49’42”	74°55’08.8”	33.5	35.5	12/09/1997	6.8	2/21/1999	4.6	17.0	18.4	19.1
NU29	15-1258	39°44’42.9”	75°03’07.4”	17	19	12/11/1996	4.3	--	--	1.3	1.6	1.8
NU29-TEN	15-1268	39°44’42.9”	75°03’07.4”	32.5	35	12/04/1997	2.1	2/12/1998	1.6	5.6	6.1	6.5
NU30	15-1260	39°45’08.9”	75°02’35”	50	52	2/11/1998	3.2	1/07/1998	4.1	2.2	2.5	2.8
NU30-TEN	15-1271	39°45’08.9”	75°02’34.9”	64.5	67	1/07/1998	14.3	2/11/1998	10.7	8.2	8.9	9.8
OU01-TEN	33-0844	39°35’32.5”	75°10’11”	37	39.5	2/18/1998	10.9	2/18/1998	12.1	9.7	10.3	10.8
OU02-TEN	11-0937	39°29’19.9”	75°01’16.8”	67	69.5	11/18/1997	6.3	1/21/1998	17.0	5.6	5.9	6.2
OU04	15-1214	39°39’17.1”	75°05’35.2”	25	27	--	--	1/22/1998	3.1	1.7	2.0	2.2
OU04-TEN	15-1262	39°39’16.9”	75°05’35.3”	47	49.5	1/22/1998	8.6	2/23/1999	11.7	7.7	8.1	8.6

Table 2. Geochemical and simulated ages of water samples from monitoring wells in the Glassboro study area, New Jersey--Continued

Well name	U.S. Geological Survey well number	Latitude	Longitude	Depth to top of screened interval (in feet)	Depth to bottom of screened interval (in feet)	Date helium-tritium sample collected	Helium-tritium age (in years)	Date sulfur hexa-fluoride sample collected	Sulfur hexa-fluoride age (in years)	Simulated age to top of screen (in years)	Simulated age to middle of screen (in years)	Simulated age to bottom of screen (in years)
OU05-TEN	1-1243	39°35’30.3”	74°52’37.8”	37.5	40	12/05/1997	19.5	2/12/1998	11.1	14.8	16.4	18.1
OU06	15-1248	39°41’04.1”	74°59’30.4”	19.5	21.5	12/18/1997	.2	1/27/1998	2.5	1.8	2.0	2.2
OU06-TEN	15-1265	39°41’04.1”	74°59’30.6”	46	48.5	12/18/1997	14.8	1/27/1998	12.1	7.6	7.9	8.2
OU07-TEN	11-0938	39°29’29.3”	75°01’59”	53	55.5	--	--	1/20/1998	17.1	6.2	6.4	6.7
OU08-TEN	7-0880	39°47’49.3”	74°55’53.8”	37.5	40	12/17/1997	7.6	2/24/1999	29.0	7.8	8.2	8.5
OU09-TEN	15-1263	39°42’09.9”	75°06’37.5”	40	42.5	2/12/1998	20.0	2/12/1998	10.1	8.1	8.5	8.9
OU10	11-0927	39°29’17.7”	75°00’36.7”	30	32	12/16/1996	4.4	--	--	1.5	1.7	1.9
OU10-TEN	11-0936	39°29’17.6”	75°00’36.9”	47.5	50	--	--	1/20/1998	7.1	5.2	5.5	5.8
OU14-TEN	7-0885	39°46’45.7”	74°59’19.9”	44.5	47	--	--	2/22/1999	26.0	10.3	10.7	11.1
OU15-TEN	11-0935	39°28’27.8”	75°01’38.4”	67.5	70	11/18/1997	8.6	--	--	9.1	9.4	9.7
OU16-TEN	15-1270	39°45’01.7”	75°02’04.7”	67.5	69.5	1/07/1998	12.4	2/22/1999	30.0	26.0	28.6	31.8
OU17-TEN	7-0882	39°48’19.9”	74°57’01.7”	68	70	12/10/1997	27.9	2/21/1999	28.0	12.0	12.3	12.7
OU18-TEN	7-0884	39°48’41.6”	74°56’25.1”	67	69	12/09/1997	26.8	2/21/1999	31.0	12.3	12.6	12.8
OU19-TEN	15-1279	39°41’37.3”	75°00’04”	59.5	61.5	2/12/1998	14.1	--	--	10.2	10.5	10.8
OU20-TEN	15-1282	39°42’25.5”	75°00’38.9”	50	52	1/08/1998	9.1	2/24/1999	7.0	8.7	8.9	9.2
UN09	7-0842	39°39’39.3”	74°53’41.5”	12	14	--	--	2/17/1998	2.1	1.8	2.0	2.2
RUTGERS-MED	11-0693	39°31’04”	75°12’21”	73	78	4/28/1992	24.3	--	--	11.3	12.0	12.7
RUTGERS-DEEP	11-0694	39°31’04”	75°12’21”	105	110	4/28/1992	36.3	--	--	22.5	24.5	26.5
TPE-SHALLOW	15-1057	39°42’42”	75°03’29”	22	27	4/29/1992	3.5	--	--	1.7	2.3	2.9
TPE-MED-SH	15-1063	39°42’42”	75°03’29”	35	40	4/29/1992	7.2	--	--	5.0	5.7	6.4
TPE-MED-DE	15-1058	39°42’42”	75°03’29’	70	75	4/29/1992	24.4	--	--	18.4	19.9	21.5
TPE-DEEP	15-1059	39°42’42”	75°03’29”	95	100	4/29/1992	33.3	--	--	44.9	51.2	60.3
WTMUA-SHALLOW	15-1051	39°43’14”	75°01’44”	22	27	4/30/1992	2.5	--	--	2.6	3.1	3.7
WTMUA-MEDIUM	15-1052	39°43’14”	75°01’44”	60	65	4/30/1992	12.9	--	--	15.8	17.1	18.6
WTMUA-DEEP	15-1053	39°43’14”	75°01’44”	92	97	4/30/1992	39.8	--	--	46.5	52.0	59.4

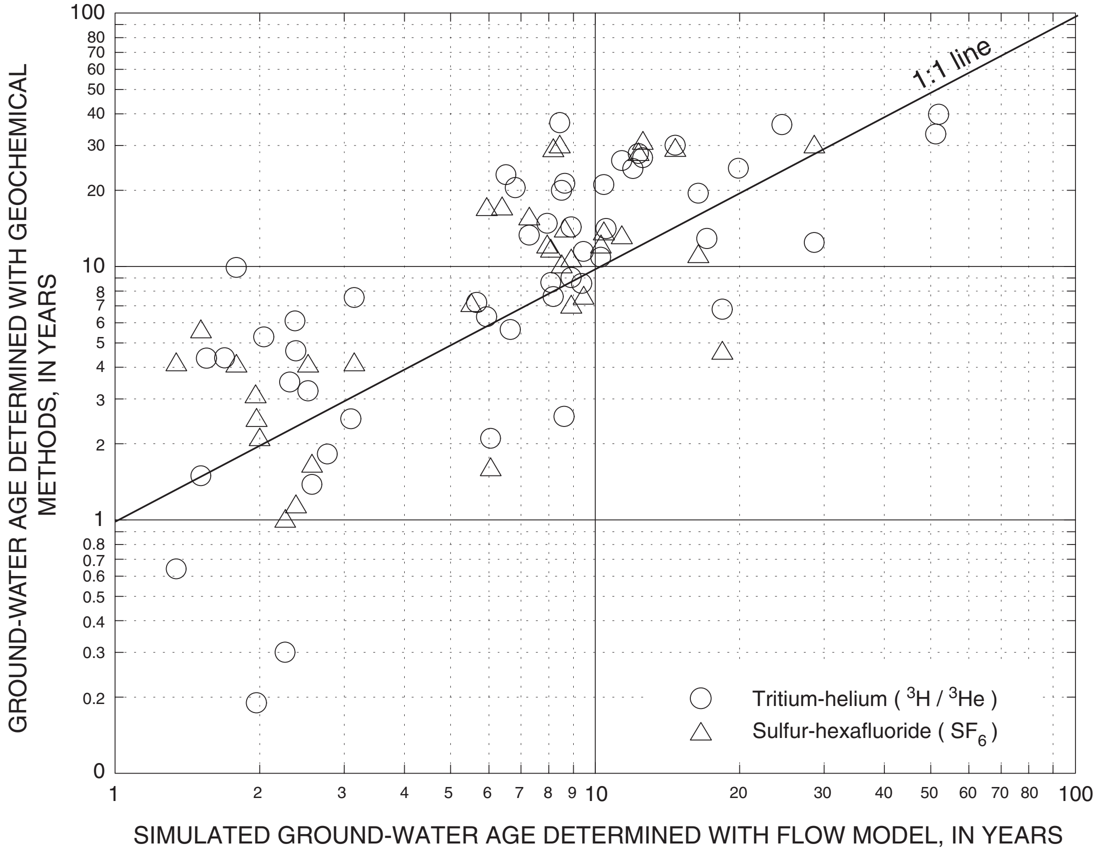

Figure 13. Ground-water age determined with geochemical methods (^{3}H-^{3}He and (or) SF_6) and simulated ground-water age, where a sample was collected, Kirkwood-Cohansey aquifer system, Glassboro study area, New Jersey.

Table 3. Relation of porosity to difference between simulated and geochemical ground-water ages in flow model of Glassboro study area, New Jersey

Porosity	Sum of squares of the difference between simulated and geochemical ages
0.25	3,289
.26	3,197
.27	3,124
.28	3,072
.29	3,038
.30[1]	3,025
.31	3,031
.32	3,057
.33	3,102
.34	3,167
.35	3,252

[1] Value used in model simulation.

percentage of very old water (>210 years) skews the average age. Fifty percent of the water is less than 22 years old, and 25 percent of the water is less than 10 years old.

A histogram of the age classes of water currently in the Kirkwood-Cohansey aquifer system in the study area is shown in figure 14. Each bar in the histogram is shaded to demonstrate the amount of water that is being contributed from different land-use classes. The age classes are equal intervals of the logarithm of age. The land-use class was assigned on the basis of the land use at the time the water recharged the aquifer.

The spatial variability in the time required for water to travel from the point of recharge to the point of discharge is shown in figure 15. Water that is recharged near streams moves relatively quickly to the streams, whereas water that is recharged at locations distant from streams, such as along surface-water divides, can take hundreds of years to move through the aquifer. Changes in land use and (or) chemical use (for example, establishing riparian buffer zones) in areas near streams can have a relatively quick effect on streamwater quality. On the other hand, chemicals entering the aquifer at areas distant from the streams can affect water quality for tens to hundreds of years.

The simulated age of water in vertical sections along columns 230 and 231 of the model is shown in figure 16. The age increases with depth in the aquifer. As the aquifer thickens, in general, the amount of water in a given age class increases, especially for the older age classes.

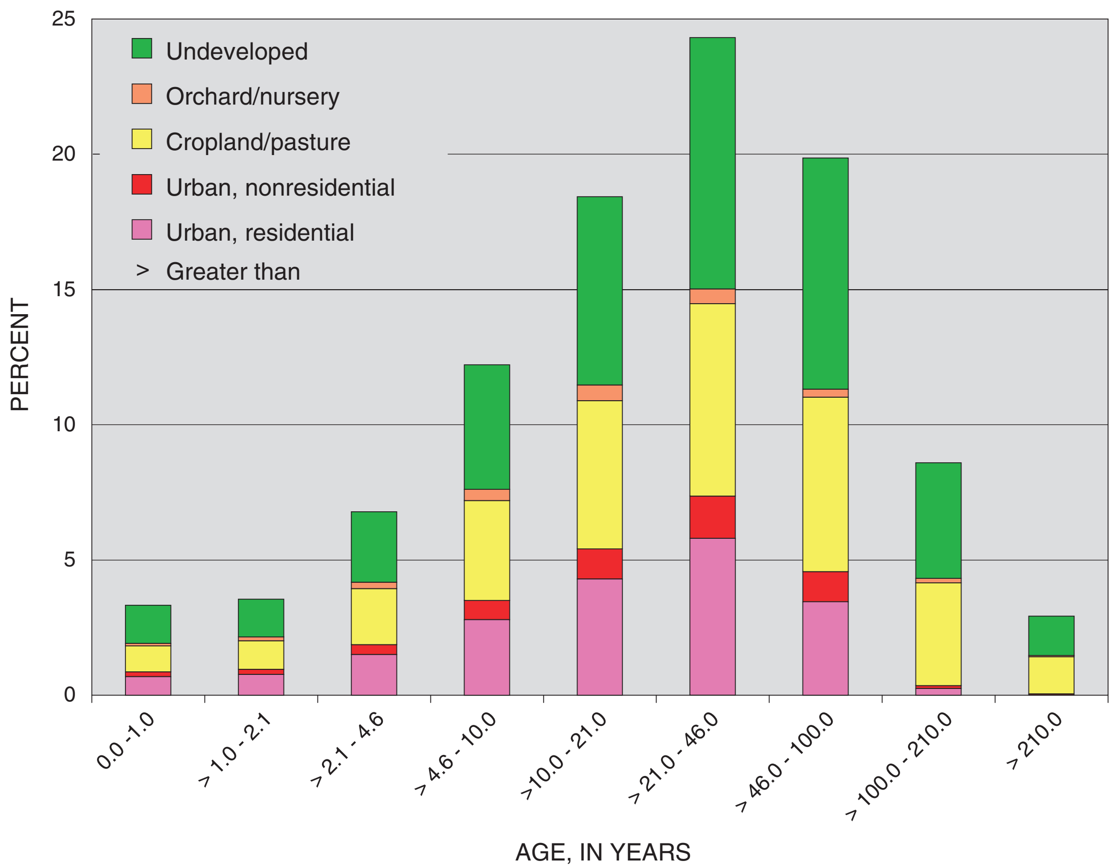

Figure 14. Distribution of land use at the point of recharge by ground-water age for water in the Kirkwood-Cohansey aquifer system, Glassboro study area, New Jersey.

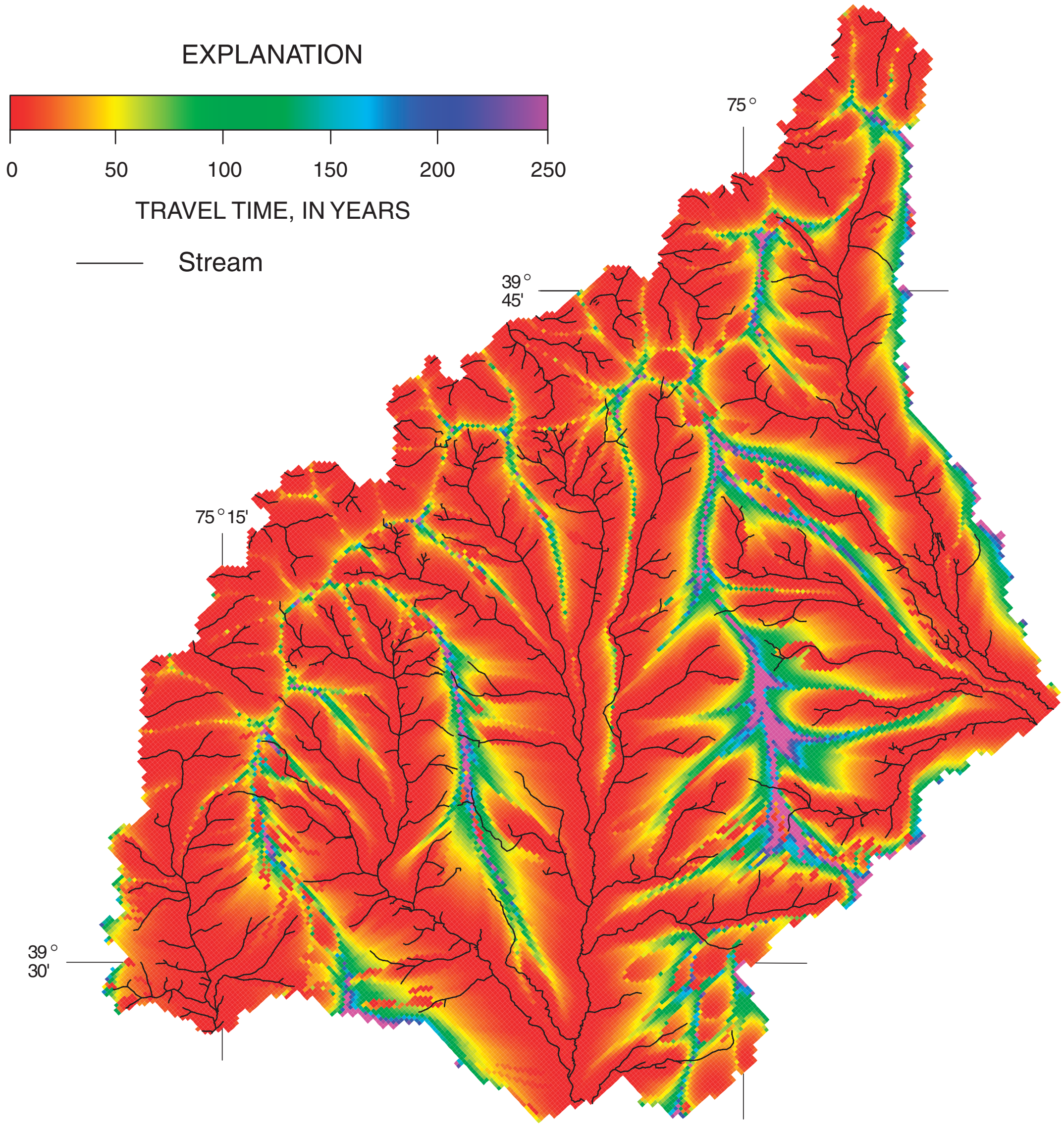

Figure 15. Travel time required for water that recharges the surficial aquifer at a given location to reach its discharge point (stream or well), Glassboro study area, New Jersey.

Near streams, water from all age classes converges upward to discharge to the stream, with younger water entering near the edge of a stream and older water discharging near the center (Modica and others, 1998).

Near wells, water from all age classes converges toward the well screen. In general, old water enters near the bottom of the screen, whereas younger water enters at the top. A "cone of age depression" is present around wells that withdraw large amounts of water from an unconfined aquifer. This cone could be important where, for example, a low-volume domestic well is near a large-volume well. The domestic well might be installed at a depth that normally would intercept 25- to 50-year-old water; however, the effects of pumping from a nearby large-volume well might cause the domestic well to intercept water that is 0 to 10 years old instead.

The spatial distribution of the vertically averaged age of water in the aquifer is shown in figure 17. The average age was computed by (1) simulating the ground-water age at 10-ft intervals, (2) integrating age values within each 10-ft interval by assuming an exponential model (Solomon and others, 1995) for increase in age with depth, and finally (3) summing the integrated ages for each 10-ft interval and dividing by the total depth. The average age increases with the thickness of the aquifer. The average age also is greatest beneath streams because the older water is converging upward to the stream. High-volume withdrawals can increase or decrease the average age of water in the aquifer around the well depending on the location of the well screen. If the screen is near the bottom of the aquifer, young water will be drawn downward and the average age will decrease; if the screen is in the upper part of the aquifer, old water will be pulled upward and the average age will increase.

Age of Ground-Water Discharge and Relation to Land Use in the Recharge Area

The model was used to characterize ground water discharging from the aquifer to wells and streams with respect to age and land use in the recharge area. This water is a mixture of water of various ages that was recharged in areas with

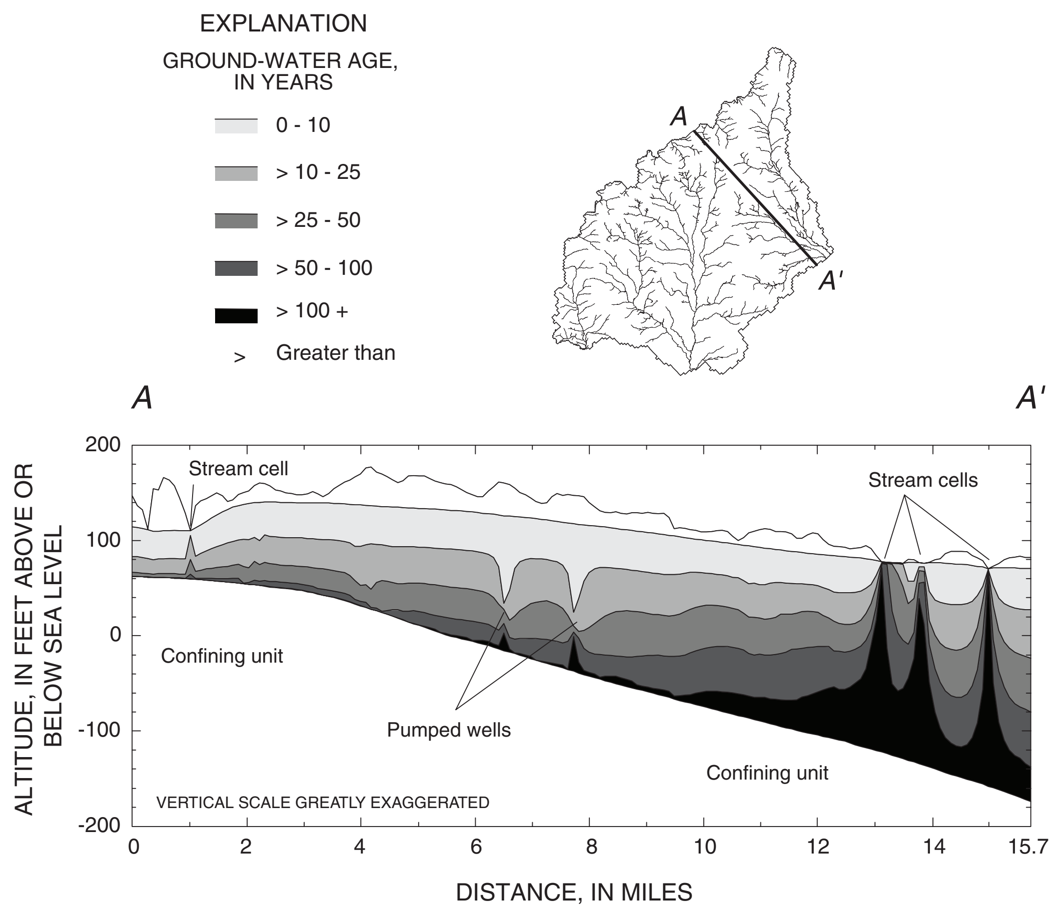

Figure 16. Vertical section showing the distribution of simulated ground-water age along profile *A-A'*, Glassboro study area, New Jersey.

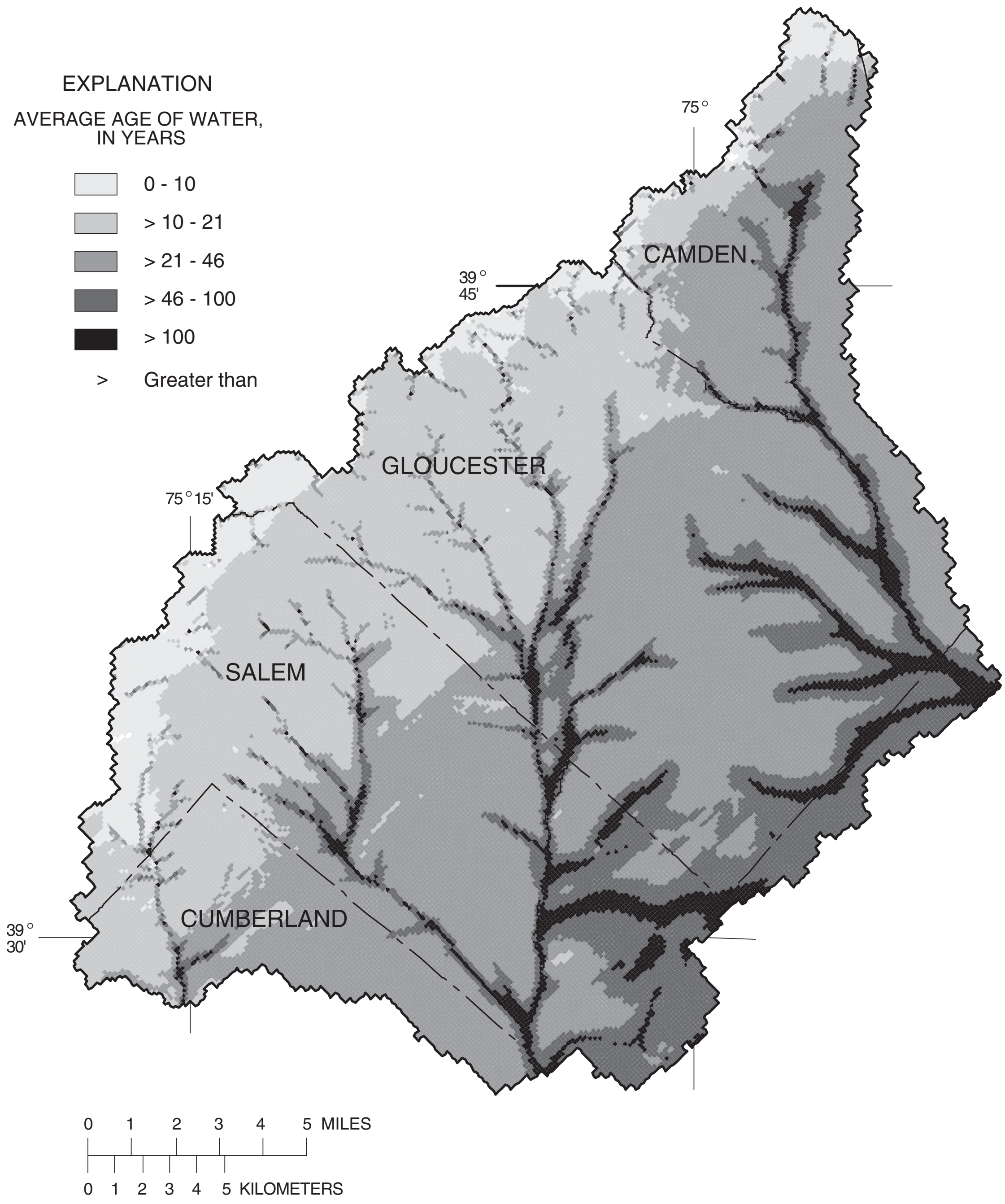

Figure 17. Vertically averaged age of water in the Kirkwood-Cohansey aquifer system, Glassboro study area, New Jersey.

different land uses. The endpoint files from MODPATH were linked to digital land-use data sets with a GIS to quantify the amount of water from different land-use and age classes for each discharge location. The combination of land use and age was used to estimate concentrations of nitrate in the aquifer. In addition to characterizing the current quality of water discharging to wells and streams, the model was used to simulate the future response to possible changes in land use and nitrate concentration in recharge.

The first step was to determine the areas where the water was recharged to the aquifer, or the contributing areas, for various wells and streams (fig. 18). Ninety-three percent of the water that recharges the aquifer discharges to streams. Contributing areas to wells in surficial aquifers tend to be elongated areas that extend upgradient from each well (fig. 19). Contributing areas to wells near a ground-water divide are more rounded. For the most part, the effect of pumping wells in an unconfined, highly permeable aquifer is to slightly lower the water table over a broad area rather than to radically change the hydraulic-head gradient in the vicinity of the well. In some cases, the contributing area to a well does not include the actual well location. This case is most likely to occur where pumping rates are low, the well is screened near the bottom of the aquifer, and (or) the well is near a stream. To simulate this case with a ground-water-flow model, the vertical discretization must be sufficiently fine. Given a uniform recharge rate, the size of the contributing area to a well is linearly proportional to the pumping rate of the well.

Simulating contributing areas with a numerical model is subject to certain limitations. Model accuracy may be affected by the discretization of the model, generalization of aquifer properties, and changes in source and sink strength over time (for example, changing pumping rates or variations in recharge). The accuracy with which a contributing area can be simulated increases with the size of the contributing area. For example, the simulated contributing area to the entire Maurice River in the study area will be more accurate than the contributing area to Still Run (a tributary to the Maurice River), which likely will be more accurate than the contributing area to a public-supply well, which, in turn, will be more accurate than the contributing area to a domestic well. Despite these limitations, a ground-water-flow model can provide a more accurate approximation of a contributing area than other methods in which circular buffer zones, simple analytical models, or surface-water divides, for example, are used.

The fraction of water entering streams and wells from various land-use classes is shown by age class in figure 20. The age classes again are equal intervals of logarithm of age. Water discharging to all streams and water discharging to all wells is grouped to allow a general comparison of the age and land-use derivation of water entering wells and streams. Water that discharges to wells (fig. 20a) is more likely to originate in urban and agricultural areas and travel longer through the aquifer than water that discharges to streams (fig. 20b) because most wells are located in urban and agricultural areas and generally are screened in the bottom part of the aquifer.

The differences in the composition of water in different types of wells reflect the differences in the location and construction characteristics of the wells (fig. 20c-f). Public-supply wells and industrial wells contain water of similar composition. A large proportion of water withdrawn by irrigation wells originates from agricultural land, reflecting the use of the water. In addition, water in irrigation wells is younger than water in public-supply wells because the screened interval is shallower. Water from ponds in the study area is used mostly for agricultural purposes (especially orchards), and its composition reflects the large proportion of water recharged in agricultural areas. In contrast to the wells, the ponds contain younger water because they are shallower with respect to ground-water discharge. Compared to the streams (similar depth of discharge), little water older than 20 years discharges to the ponds because, unlike streams, they are not necessarily located at natural topographic lows, where water of all ages converges.

Older water generally is of better quality than younger water in the aquifer system, although exceptions can be found. Compounds that degrade over time are less likely to be detected the longer the water has been in the aquifer. Most contaminants have been available only in the last 50 years;

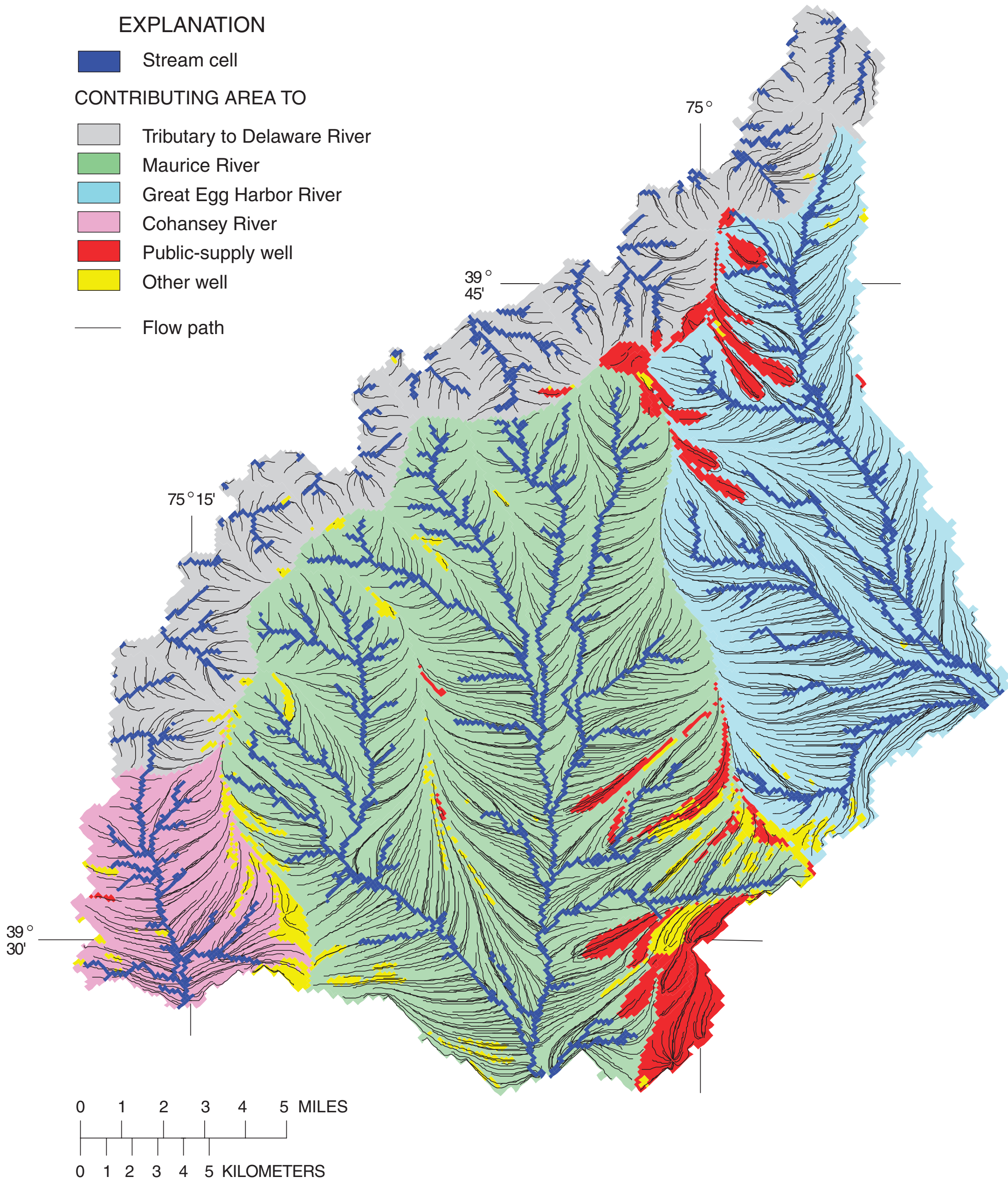

Figure 18. Simulated contributing areas to wells and streams and selected simulated flow paths in the Glassboro study area, New Jersey.

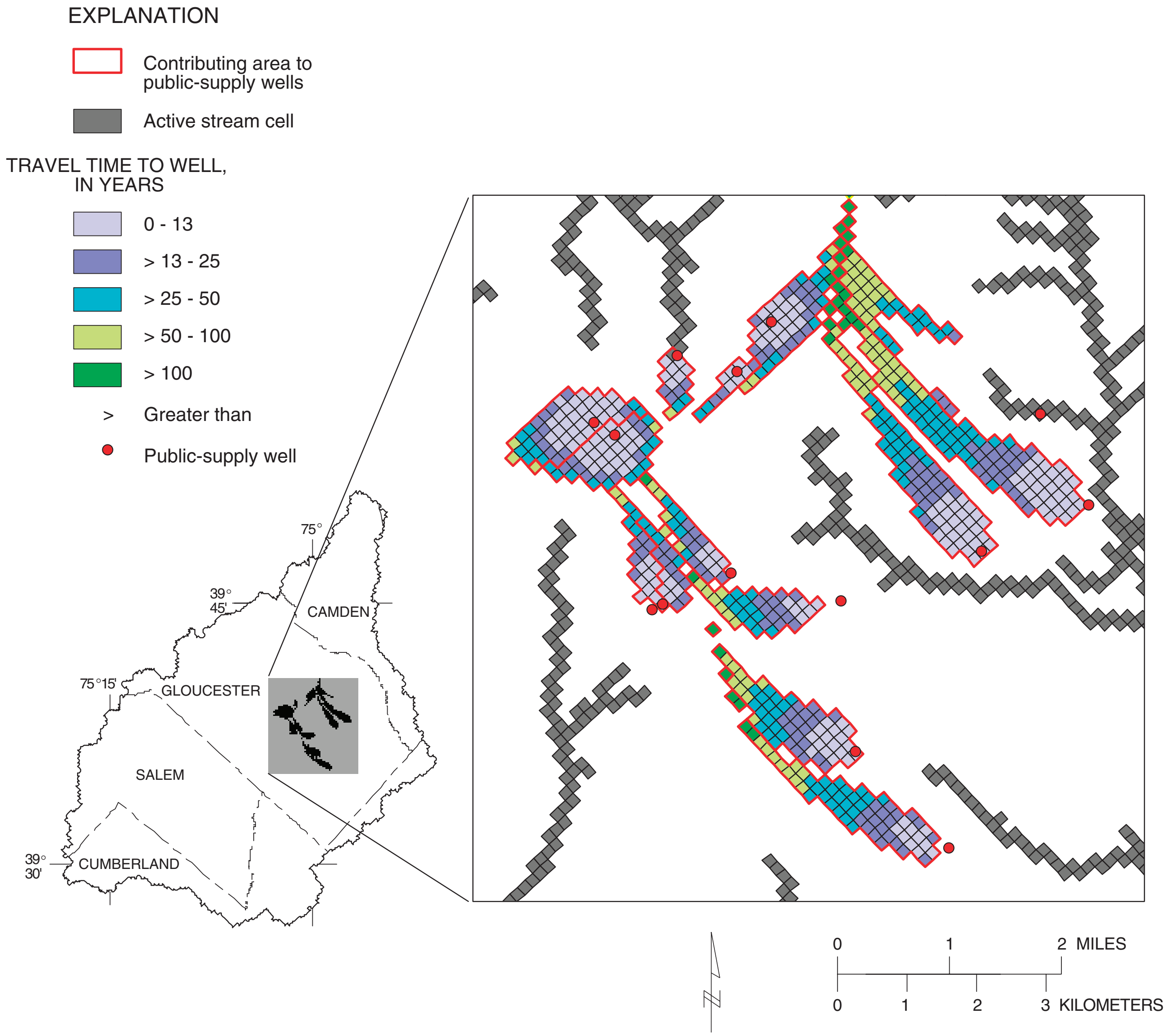

Figure 19. Simulated contributing areas to selected public-supply wells in the Glassboro study area, New Jersey, and associated travel times from recharge area to well.

thus, concentrations of these compounds tend to be higher in recently recharged water than in older water. Concentrations of compounds that are breakdown products of another compound and compounds that were used in greater amounts in the past also tend to be higher in older water than in younger water.

EFFECTS OF LAND USE AND TRAVEL TIME ON DISTRIBUTION OF NITRATE

Concentrations of nitrate in water discharging to streams and wells were simulated to demonstrate the effects of land use and travel time on water quality. Nitrate concentrations commonly are elevated above background levels in shallow ground water in the Kirkwood-Cohansey aquifer

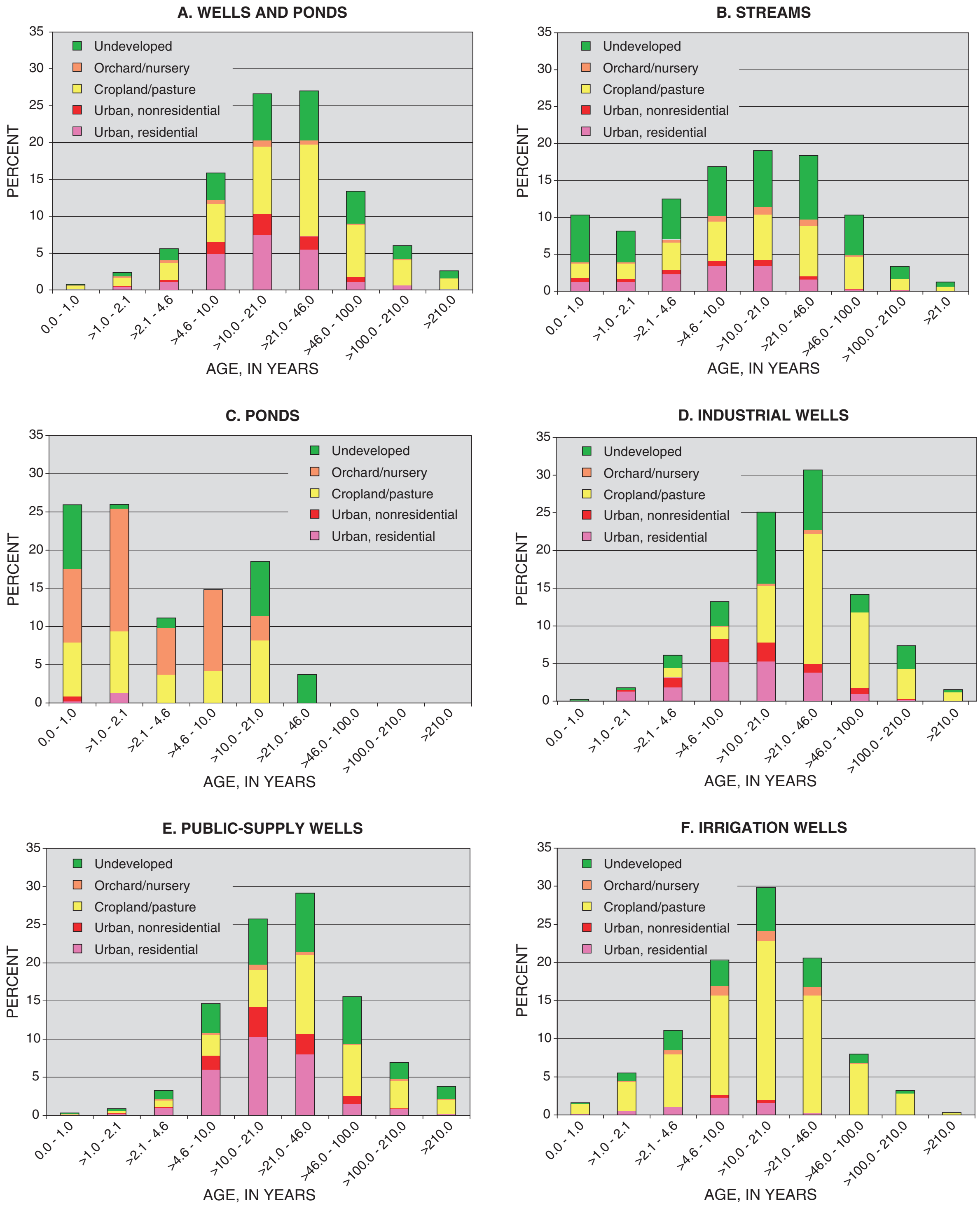

Figure 20. Distribution of land use at the point of recharge by ground-water age for water discharging to (a) all wells and ponds, (b) streams, (c) ponds, (d) industrial wells, (e) public-supply wells, and (f) irrigation wells, Glassboro study area, New Jersey. (>, greater than)

system beneath agricultural and urban areas in southern New Jersey (Stackelberg and others, 1997). Over the past 60 years, the use of nitrogen fertilizers in agricultural and urban areas has increased, and nitrate concentrations in recharge in the Atlantic Coastal Plain also have increased over the same time period (Bohlke and Denver, 1995). In an aerobic ground-water-flow system like most of the Kirkwood-Cohansey aquifer system, nitrate behaves conservatively. Its widespread and increasing use, relevance to ground- and surface-water quality, largely conservative behavior, and availability of data make nitrate a good choice for demonstrating effects of age and land use on water quality in this study.

Comparison of Simulated and Measured Nitrate Concentrations

Nitrate concentrations were simulated for 27 public-supply wells in the study area (locations shown in fig. 21) that were sampled in 1998 (Baehr and others, 1999; Stackelberg and others, 2000) and were compared to the measured values (fig. 22). Generally, the simulated nitrate concentrations were within 2.0 mg/L as N of the measured concentrations, a reasonable fit for the intended purpose. Five of the sampled wells with larger errors were near the boundary of the model and the simulated contributing areas likely are affected by the model boundary conditions. The close agreement between the simulated and measured values indicates that nitrate, for the most part, moves conservatively through the aquifer to these wells.

The comparison to measured data from streams is less straightforward than from wells. The model simulates only the portion of streamflow that is derived from ground water; therefore, the stream samples whose nitrate concentrations are most appropriate for comparison with the simulated nitrate concentrations are those collected when flow and chemical input derived from sources other than ground water (for example, runoff or discharge from a wastewater-treatment plant) are minimal. Three sites in the study area were used to compare simulated and measured nitrate concentrations: Great Egg Harbor River near Sicklerville, Maurice River at Norma, and Cohansey River at Seeley. The basins that drain to these three sites differ in size and land-use composition (see fig. 21). Nitrate concentrations for these sites were retrieved from the U.S. Geological Survey's National Water Information System database with two restrictions: (1) streamflow at the time the sample was collected was classified as base flow, and (2) no appreciable point-source contributions of nitrate or flow were being made to the stream when the sample was collected. Streamflow was classified as base flow if the mean flow at both the Maurice River at Norma and Great Egg Harbor River at Folsom (sites for which long-term daily flow values were available) had not increased by more than 1 percent or decreased by more than 10 percent in the previous 3 days.

Comparison of nitrate concentrations for the three streams showed that the simulated nitrate concentrations consistently exceeded the measured concentrations. Given the conservative behavior of nitrate in water withdrawn by public-supply wells, this difference likely can be attributed to non-conservative behavior of nitrate in and (or) near streams. Reasons for non-conservative behavior may include denitrification in the relatively organic-rich sediments that make up the streambed or uptake by aquatic plants and algae in the water column. For the three streams, a 40-percent reduction in the simulated concentrations was needed to match the measured concentrations in the streams (fig. 23). The scatter in the measured concentrations may be a result of the variation in water temperature. Biological activity in the water column increases with the temperature of the streamwater; therefore, nitrate concentrations decrease with increasing temperature. A 40-percent loss in nitrate seems to be representative of the average amount of nitrate that is removed by in- or near-stream processes in the study area since 1990.

Because the method described above uses nitrate concentration in recharge based on the mean concentration in water associated with each land-use type, the reliability of the method for simulating nitrate concentration increases with the size of the contributing area to the discharge location—that is, the larger the area over which this "mean" is applied, the more likely it is to represent the actual concentration in the recharge.

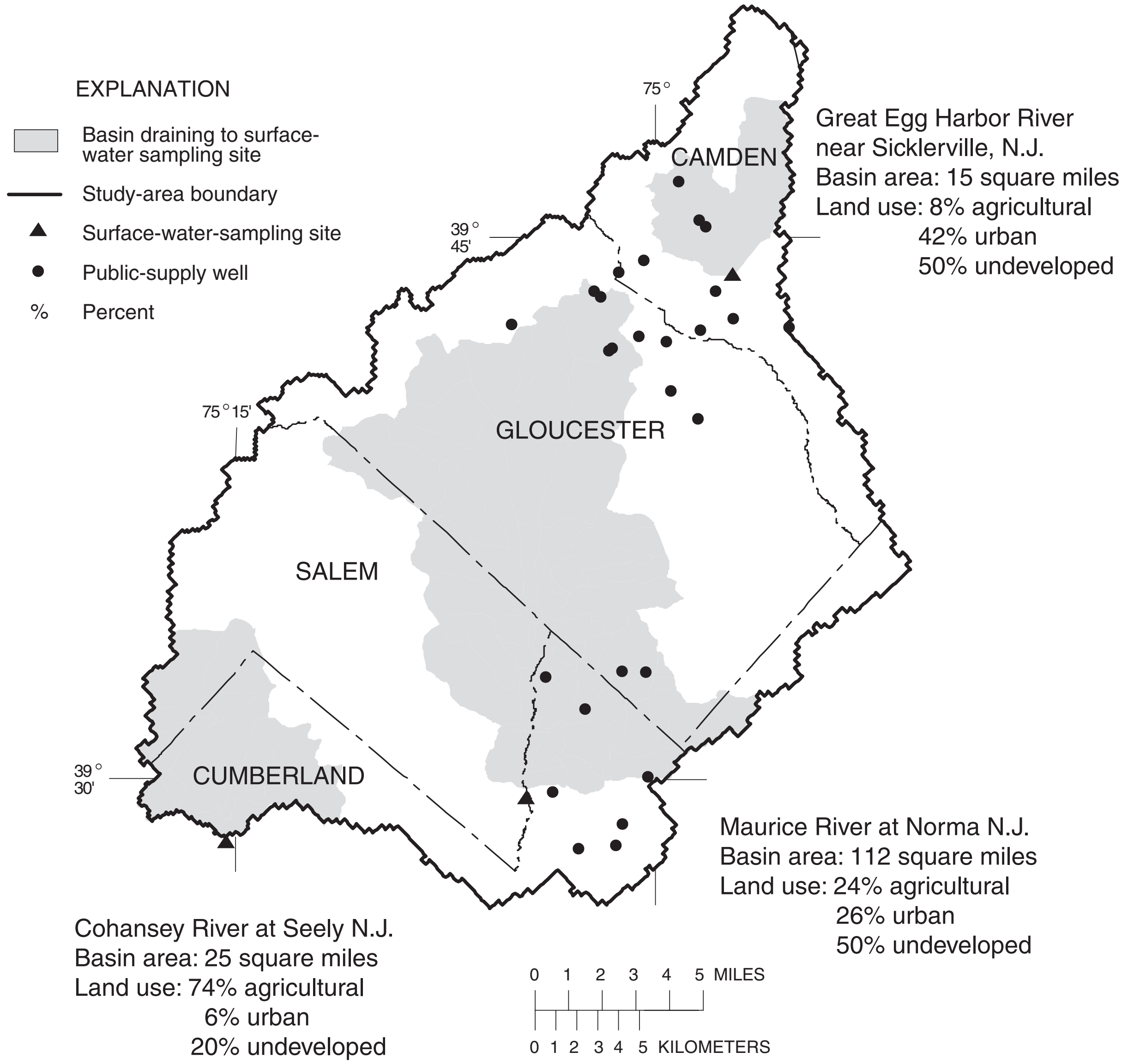

Figure 21. Location of ground-water and surface-water sampling sites and land use in basins draining to surface-water sites, Glassboro study area, New Jersey. [Land-use data are for 1996 (N.J. Department of Environmental Protection, 1996b; data on CD-ROM obtained from Steven Carp, New Jersey Office of State Planning, Trenton, N.J., 1999)]

Response to Management Alternatives

The model was used to evaluate the effects of various management alternatives on the concentration of nitrate in streams and public-supply wells. Nitrate concentrations were simulated under the following conditions: an immediate ban on nitrate input, a gradual reduction in input, and fixed input. Under the ban alternative, the nitrate concentration in recharge immediately would decrease to the background concentration. Under the gradual-reduction alternative, the nitrate concentration in recharge would be reduced at a constant rate over

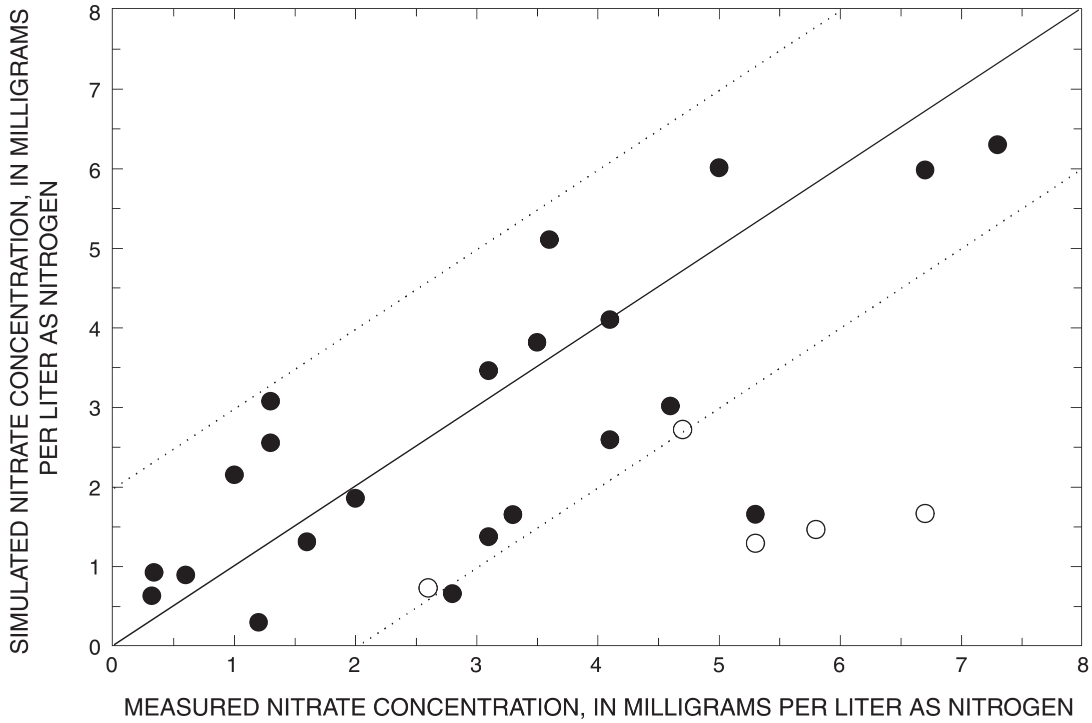

Figure 22. Simulated and measured nitrate concentrations in public-supply wells in the Glassboro study area, New Jersey. (Open circles represent sites near the model boundary. The solid line shows where the simulated concentration equals the measured concentration. The dotted lines show where the simulated concentration differs from the measured concentration by plus or minus 2 milligrams per liter as nitrogen.)

50 years until reaching the background concentration. Under the fixed-input alternative, the nitrate concentration in recharge would remain constant at the concentration in 2000. The response of the aquifer system to these management alternatives is shown in figure 24.

Immediate Ban. Under the immediate-ban alternative, the concentration at the discharge locations will start to decrease almost immediately but will not be reduced to background levels for about 15 years for streams and about 30 years for wells. The decrease in concentration in discharge will begin when the water recharged after the ban reaches the discharge point. For streams, this time will be very short, because water recharged near streams flows quickly to the stream. The time likely will be longer for wells, especially those with low pumping rates and (or) screened near the bottom of the aquifer.

Gradual reduction. Under the gradual-reduction alternative, the nitrate concentration continues to increase for about 10 years in streams and 15 years in wells before eventually decreasing to the background concentration. The continued increase in concentration during the initial years after the reduction in input is a result of the influx of water that was recharged before the reduction. The presence of older water will cause the concentration in the discharge to remain above background levels (<1 mg/L as N) for about 50 years for streams and about 70 years for wells.

Fixed Input. Under a fixed-input alternative, concentrations eventually will approach a constant value. The time until the constant value is reached will depend on the age composition of the discharge. In the short term, concentrations will continue to increase over time as the proportion of post-1950 water increases. As more of the dis-

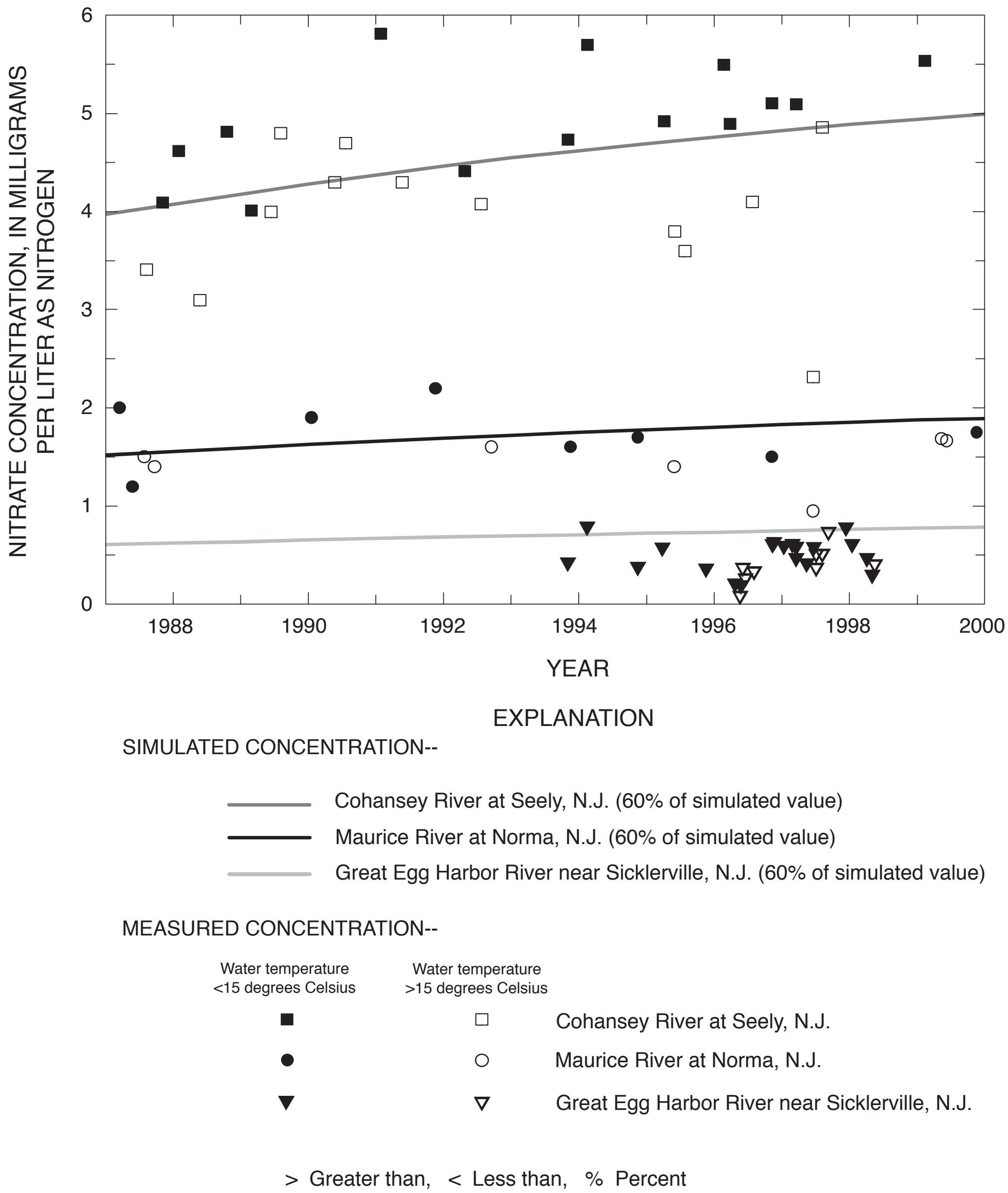

Figure 23. Simulated and measured nitrate concentrations at three surface-water sites, Glassboro study area, New Jersey, 1987-99.

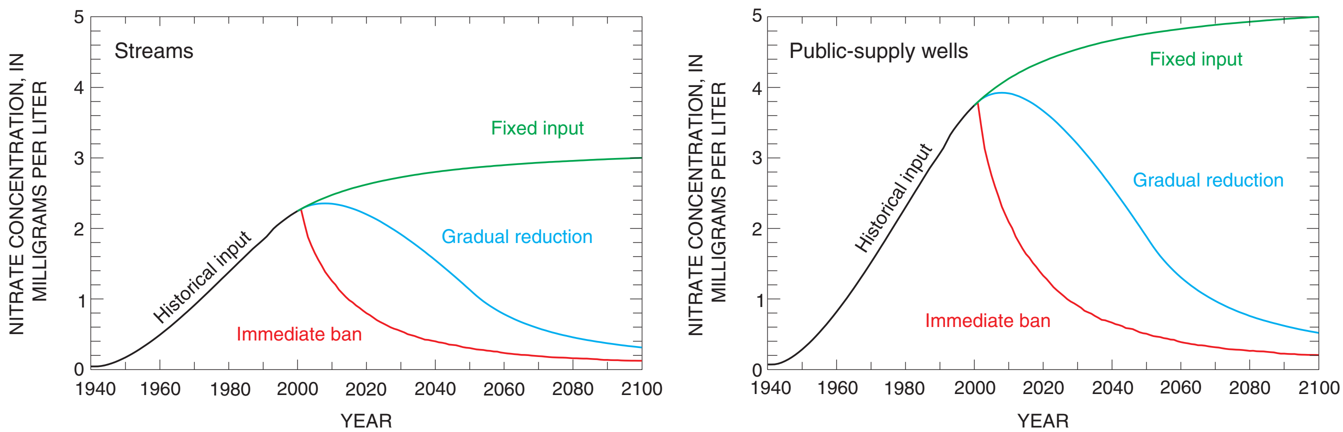

Figure 24. Simulated nitrate concentrations in streams and public-supply wells determined from historical nitrate input and simulated response to three management alternatives (fixed input, gradual reduction, and immediate ban) for future nitrate input in recharge, Glassboro study area, New Jersey.

charging water reaches the constant recharge concentration, the overall concentration will approach a constant value. The higher the percentage of young water at the discharge point, the more rapidly the concentration will approach the constant value. The constant concentration of nitrate that eventually is reached will be the nitrate concentration in recharge from each land use multiplied by the percentage of that land use in the contributing area.

Spatial Distribution of Changes in Nitrate Concentrations

Concentrations of nitrate in streams (reduced by 40 percent to account for non-conservative behavior in and near streams) in 2000 and 2050 were simulated with the assumption of constant land use, withdrawal rates and locations, and recharge concentration during the period (fig. 25). Currently (2000), nitrate concentrations are highest in streams in the agricultural areas, mostly in the western part of the study area. Concentrations are lowest in the Great Egg Harbor River and in some other small tributaries that drain mostly undeveloped areas. As discussed in the fixed-input alternative above, concentrations generally will increase over the next 50 years. The magnitude of these changes is shown in figure 26. The absolute changes are largest in the western and south-southeastern parts of the study area, where agricultural inputs of nitrate are high. The percent changes are largest in the eastern and southern parts of the study area, where streams flow through wetlands and the flow paths of recharge that originates in agricultural and urban areas are longer.

Nitrate concentrations in 2000 and 2050 in a “typical” domestic well installed in the Kirkwood-Cohansey aquifer system were simulated (fig. 27). A “typical” domestic well was defined as a well anywhere in the study area screened at a depth from 90 to 100 ft below land surface or over the bottom 10 ft of the aquifer if the total thickness is less than 100 ft. Higher nitrate concentrations indicate where agricultural land and to a lesser degree urban land is located. Nitrate concentrations generally are highest in agricultural and, to a smaller degree, urban areas, and along surface-water divides, where the unsaturated zone is thickest, because water moves more rapidly through the unsaturated zone than through the saturated zone of the aquifer. If land use, withdrawal rates and locations, and recharge concentration are assumed to be constant, the area in which nitrate concentrations exceed the maximum contaminant level (10 mg/L as N) is considerably

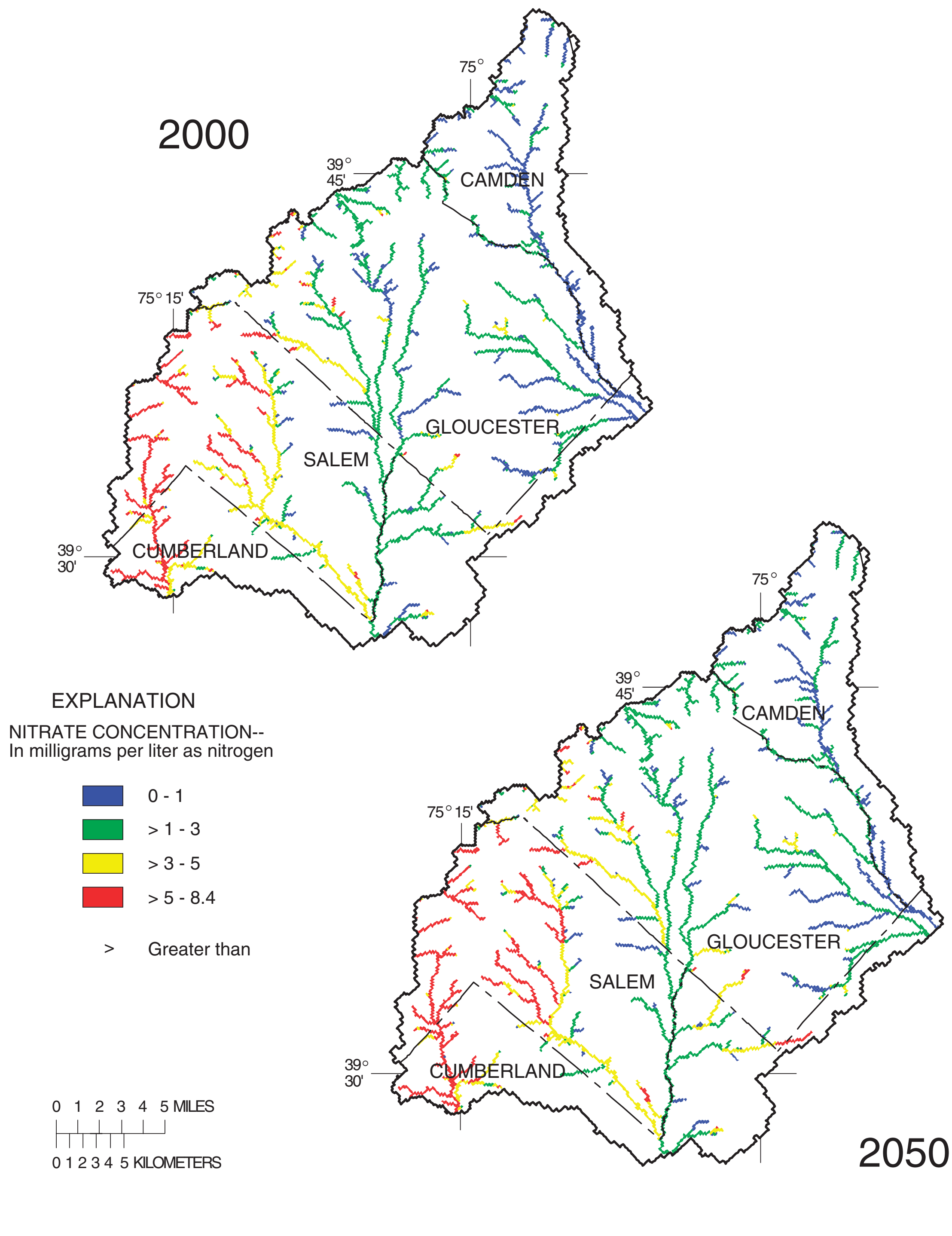

Figure 25. Simulated nitrate concentration in streams in the Glassboro study area, New Jersey, in 2000 and in 2050 with the assumption of no future change in land use, withdrawals, or nitrate concentration in recharge during the period.

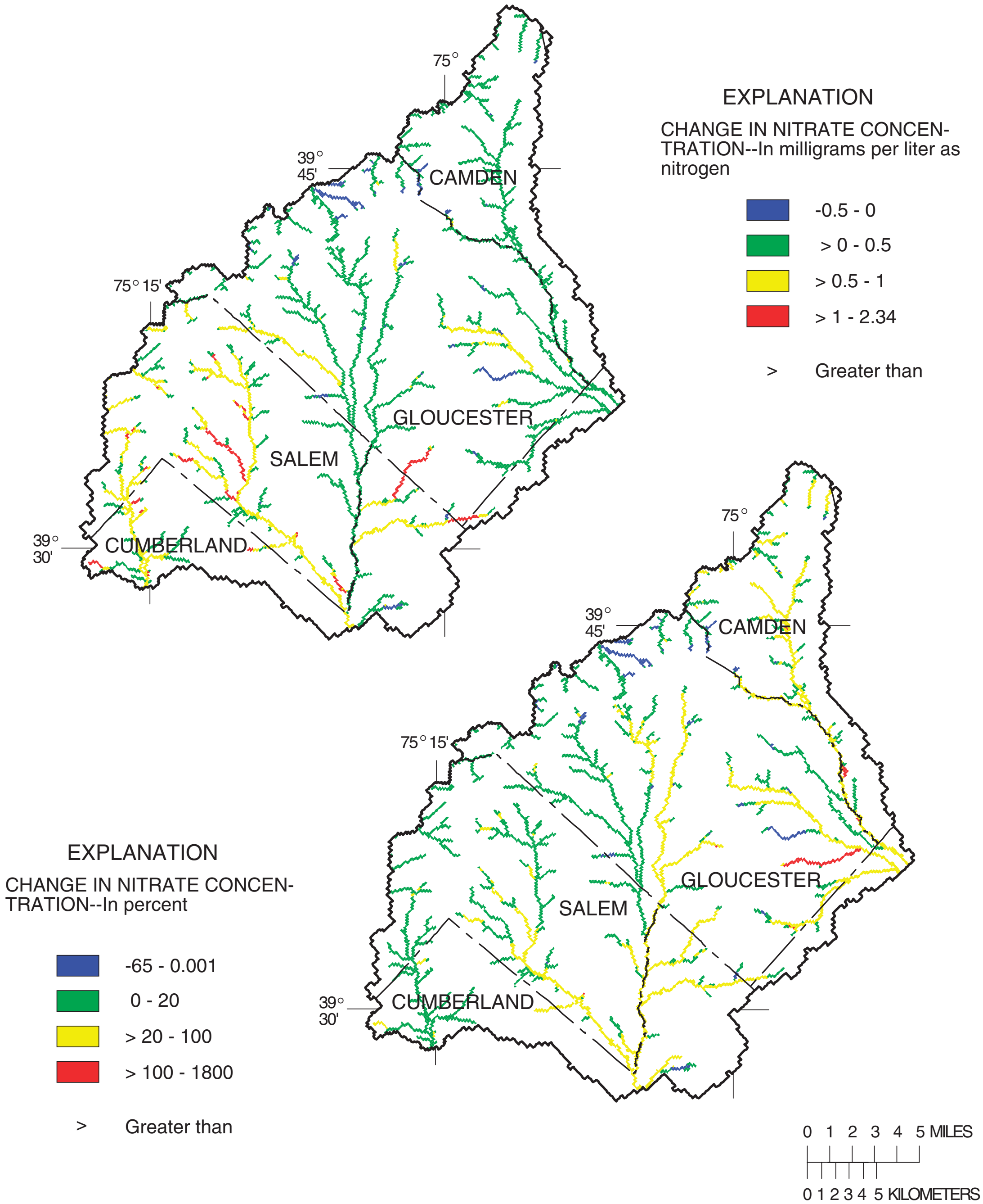

Figure 26. Change in simulated nitrate concentration in streams in the Glassboro study area, New Jersey, from 2000 to 2050 with the assumption of no future change in land use, withdrawals, or nitrate concentration in recharge during the period.

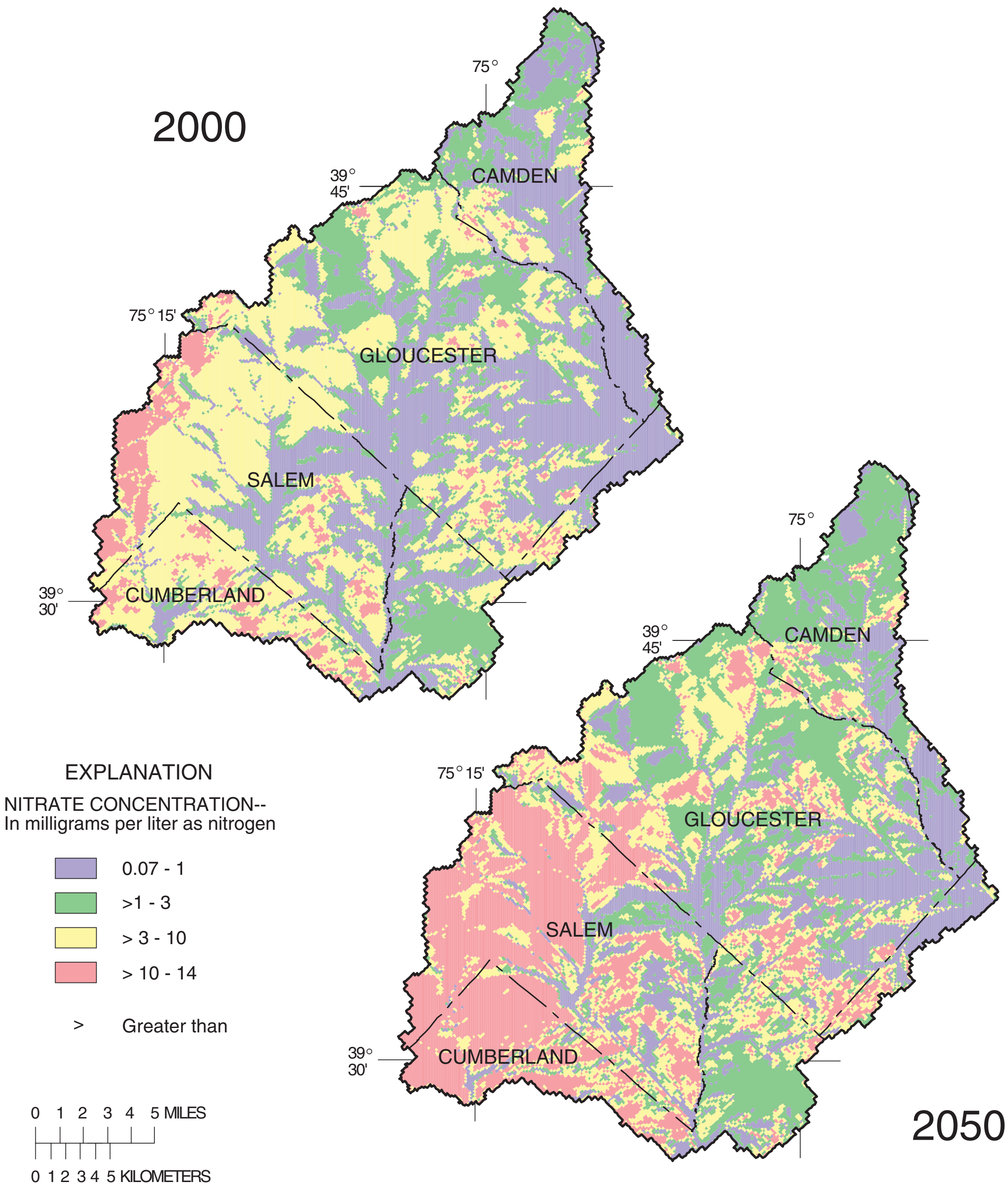

Figure 27. Simulated nitrate concentration in a "typical" domestic well installed in the Kirkwood-Cohansey aquifer system in the Glassboro study area, New Jersey, in 2000 and in 2050 with the assumption of no future change in land use, withdrawals, or nitrate concentration in recharge during the period. (A "typical" domestic well is defined as having a screened interval from 90 to 100 feet, or at the bottom 10 feet of the aquifer if the aquifer is less than 100 feet thick.)

higher in 2050 than in 2000. Moreover, the area in which nitrate concentrations are at background levels (<1 mg/L as N) is much lower in 2050 than in 2000. In some areas where land use changed from agricultural to urban, however, concentrations would be lower in 2050 than in 2000 because the nitrate inputs associated with urban land use are lower than those associated with agricultural land use.

Nitrate concentrations in 2000 and 2050 in a "typical" public-supply well installed in the Kirkwood-Cohansey aquifer system were simulated in the model (fig. 28). A "typical" public-supply well was defined as a well screened in the bottom 30 ft of the aquifer system anywhere in the study area and with a pumping rate of 0.6 Mgal/d. The nitrate concentrations reflect the density of agricultural and, to a lesser degree, urban land use. The simulated areas of high and low nitrate concentrations in 2000 and 2050 generally are similar to those simulated for domestic wells. Because their contributing areas are larger, extreme concentrations in the public-supply wells are less common than in the domestic wells. Compared to streams, wells receive a higher percentage of "older" water; therefore, nitrate concentrations in wells will change more dramatically than those in streams over the 50-year period (with no change in input).

The change in nitrate concentration from 2000 to 2050 for typical public- and domestic-supply wells is shown in figure 29. The changes are largest in domestic wells, especially in the agricultural areas. In some areas, nitrate concentration decreases in water from both public-supply and domestic wells as a result of a change in land use from agricultural to urban. The changes in concentration at public-supply wells are largest in the thick parts of the aquifer where some agricultural land is present.

The results demonstrate the effect of the characteristics of the contributing areas to domestic and public-supply wells on water quality. The extremes in nitrate concentration (high and low) and the largest changes in nitrate concentration from 2000 to 2050 occurred in domestic wells rather than public-supply wells because the domestic wells intercept water derived from small contributing areas with fairly uniform land use and ground-water-age composition. Nitrate concentrations in public-supply wells were less extreme and increased less compared to domestic wells because contributing areas supply water derived from multiple land uses and ground-water-age classes for public-supply wells.

SUMMARY AND CONCLUSIONS

The Kirkwood-Cohansey aquifer system is the principal unconfined aquifer system in the southern New Jersey Coastal Plain. The properties of the soils and aquifer materials (sandy, permeable, and low organic-matter content) contribute to the vulnerability of the aquifer system to contamination. The presence of contaminants in recharge commonly is related to the land use in the area in which precipitation recharges the aquifer. The land use in the recharge area, along with travel time through the aquifer, is used to explain the quality of water at streams and wells, the locations of ground-water discharge. As part of the USGS's NAWQA Program, a data-collection and ground-water-modeling study was conducted to characterize ground-water age and nitrate concentration in the Glassboro area in southern New Jersey with respect to land use in the recharge area at the time and place of recharge. Nitrate concentrations were simulated as an example of how the land-use signature and age of water affect water quality.

A three-dimensional ground-water flow model was developed for a 400-mi^2 area of the Kirkwood-Cohansey aquifer system in the southern New Jersey Coastal Plain. The aquifer system consists of unconfined, unconsolidated sands and gravels with some interbedded clays. Land use in the study area currently (2000) is a mixture of urban, agricultural, and forest (25-30 percent each), with the remainder consisting mostly of wetlands. Most of the urban development has occurred since 1950 on land that previously was either agricultural or forested. An increase in urban land and the corresponding increase in population created the need for increased water supply. For many years most of the water used for public supply came from deeper, confined aquifers below the Kirkwood-Cohansey aquifer system. In recent years, however, restric-

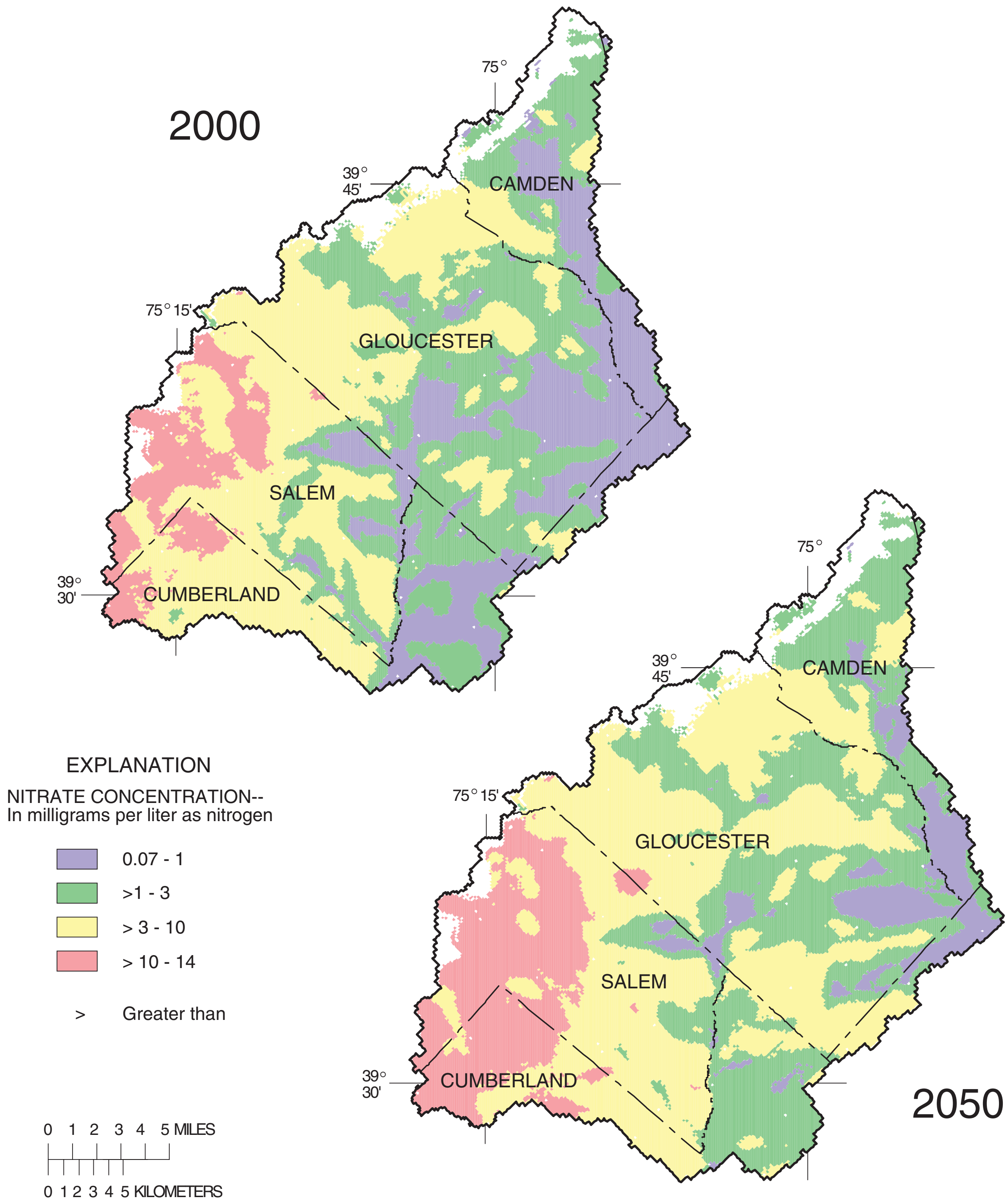

Figure 28. Simulated nitrate concentration in a "typical" public-supply well installed in the Kirkwood-Cohansey aquifer system in the Glassboro study area, New Jersey, in 2000 and in 2050 with the assumption of no future change in land use, withdrawals, or nitrate concentration in recharge during the period. (A "typical" public-supply well is defined as having a screened interval at the bottom 30 feet of the aquifer with a pumping rate of 0.6 million gallons per day. Areas where the "typical" well would dewater the aquifer are shown in white.)

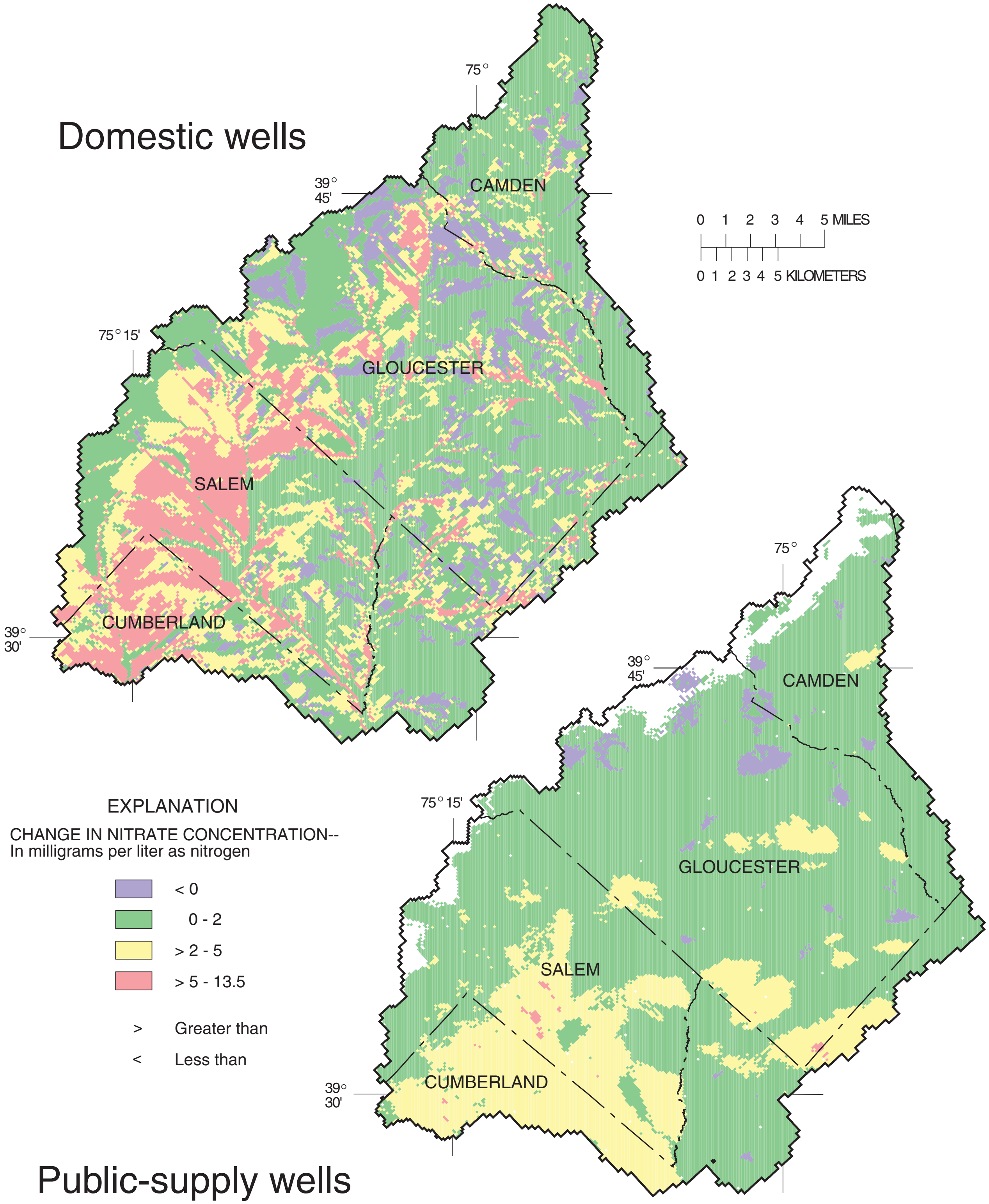

Figure 29. Change in simulated nitrate concentration from 2000 to 2050 in "typical" domestic and public-supply wells installed in the Kirkwood-Cohansey aquifer system in the Glassboro study area, New Jersey, with the assumption of no future change in land use, withdrawals, or nitrate concentration in recharge during the period. (A "typical" domestic well is defined as having a screened interval from 90 to 100 feet, or at the bottom 10 feet of the aquifer if the aquifer is less than 100 feet thick. A "typical" public-supply well is defined as having a screened interval at the bottom 30 feet of the aquifer with a pumping rate of 0.6 million gallons per day. Areas where the "typical" well would dewater the aquifer are shown in white.)

tions placed on withdrawals from the confined aquifers have necessitated increased withdrawals from the Kirkwood-Cohansey aquifer system.

Results of numerical simulations of ground-water flow and transport were integrated with a GIS to characterize ground water with respect to its land-use source at the time and place of recharge and the age of the water. Ground-water flow was simulated with the computer program MODFLOW. These results were used as input to the computer program MODPATH, whose output consists of contributing areas and travel times from locations of recharge to locations of discharge. A GIS was used to organize the model input and output data and relate the recharge locations to land-use data sets. Simulated ages approximately matched the ages of water samples from monitoring wells measured by using tritium-helium and sulfur hexafluoride age-dating techniques.

The average age of water in the aquifer system in the study area is approximately 50 years; however, most of the water is younger. Volumetrically, 50 percent of the water is less than 20 years old and 25 percent is less than 10 years old. The time required for water to move from recharge to discharge is shortest near streams. Water entering the aquifer system near wells from which large volumes of water are withdrawn also has a relatively short travel time through the system. Travel times are longest for water recharged near ground-water divides. The age of water increases with depth in the aquifer, with the exception of water in areas near streams where the water flows upward to discharge to the stream. The vertically averaged age of water increases as the aquifer thickens and in the vicinity of streams.

Water that discharges to streams and wells is a mixture of water of different ages derived from areas with different land uses. Water that discharges to streams generally is younger than water that discharges to wells. Wells draw a greater percentage of water from agricultural and urban areas than streams because they typically are located in those areas.

Nitrate was chosen to demonstrate the effects of age and land use on water quality because of its widespread and increasing use, presence in ground- and surface-water systems, mostly conservative (not degraded or adsorbed) behavior, and availability of data. Based on estimates of nitrate concentrations in recharge over time for each land-use type together with the age and land-use distributions for various discharge points, nitrate concentrations were computed. Simulated nitrate concentrations in water from 27 public-supply wells compared favorably to measured concentrations, indicating that nitrate transport to these wells is conservative. Simulated and measured nitrate concentrations compared favorably for time-series data at three surface-water sites after simulated concentrations were decreased by 40 percent. This difference is attributed to the non-conservative behavior of nitrate in the aquifer near streams (for example, denitrification) and in the water column of the stream itself (for example, uptake by aquatic plants).

The model was used to evaluate the effects of various management alternatives on the concentration of nitrate in streams and public-supply wells under the assumption of no future changes in land use or withdrawal rates or locations. The time required for water to move through the aquifer results in a time lag between the reduction of nitrate input in recharge and the reduction of nitrate concentrations in streams and water from wells. In the gradual-reduction alternative, nitrate concentrations in streams and wells continued to increase for 10 to 15 years after the reduction was enacted. In both the immediate-ban and gradual-reduction alternatives, nitrate concentrations remained elevated for decades after nitrate input ceased. In the fixed-use alternative, concentrations in streams and wells continued to increase for 30 to 40 years before reaching a constant level.

The simulated spatial distribution of nitrate in streams in 2000 and 2050 was examined under the assumption of no future changes in land use, withdrawal rates or locations, or recharge concentration. As expected, concentrations were highest in agricultural areas and lowest in largely undeveloped areas. In general, the simulated nitrate concentrations increased over time, especially in streams in areas where the aquifer is thick and in streams with mostly undeveloped land nearby (short flow paths) and agricultural or urban land in the more distant parts of the contributing area (longer flow paths).

Results of the computer model simulations indicate that in most of the study area, given the same assumption of no future changes in land use, withdrawal rates or locations, or recharge concentration, nitrate concentrations in a typical domestic or public-supply well will increase over the next 50 years (from 2000 to 2050). Nitrate concentrations likely will decrease in some areas where agricultural land has been converted to urban land. Nitrate concentrations in domestic wells will vary most because these wells intercept water derived from small contributing areas with fairly uniform land use and ground-water travel times. Nitrate concentrations in public-supply wells are between the highest and lowest concentrations in domestic wells because their contributing areas are larger and water is integrated from multiple age classes and land uses.

REFERENCES CITED

Anderson, J.R., Hardy, E.E., Roach, J.T., and Witmer, R.E., 1976, A land use and land cover classification for use with remote sensor data: U.S. Geological Survey Professional Paper 964, 8 p.

Appelo, C.A.J., and Postma, D., 1996, Geochemistry, groundwater and pollution: Rotterdam, Netherlands, A.A. Balkema, 536 p.

Alexander, R.B., and Smith, R.A., 1990, County-level estimates of nitrogen and phosphorus fertilizer use in the United States, 1945 to 1985: U.S. Geological Survey Open-File Report 90-130, 12 p.

Baehr, A.L., Kauffman, L.J., Charles, E.G., Baker, R.J., Stackelberg, P.E., Ayers, M.A., and Zapecza, O.S., 1999, Sampling throughout the hydrologic cycle to characterize sources of volatile organic compounds in ground water, in Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the technical meeting, Charleston, S.C., March 8-12, 1999--Volume 3 of 3--Subsurface contamination from point sources: U.S. Geological Survey Water-Resources Investigations Report 99-4018C, p. 21-35.

Battaglin, W.A., and Goolsby, D.A., 1994, Spatial data in geographic information system format on agricultural chemical use, land use, and cropping practices in the United States: U.S. Geological Survey Water-Resources Investigations Report 94-4176, 87 p.

Bohlke, J.K., and Denver, J.M., 1995, Combined use of groundwater dating, chemical, and isotopic analysis to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic Coastal Plain, Maryland: Water Resources Research, v. 31, no. 9, p. 2319-2340.

Burow, K.R., Pahsin, S.Y., Dubrovsky, N.M., Vanbrocklin, Daniel, and Fogg, G.E., 1999, Evaluation of processes affecting 1,2-dibromo-3-chloropropane (DBCP) concentrations in ground water in the eastern San Joaquin Valley, California: Analysis of chemical data and ground-water flow and transport simulations: U.S. Geological Survey Water-Resources Investigations Report 99-4059, 57 p.

Busenberg, Eurybiades, and Plummer, L.N., 2000, Dating young groundwater with sulfur hexafluoride: Natural and anthropogenic sources of sulfur hexafluoride: Water Resources Research, v. 36, no. 10, p. 3011-3030.

Charles, E.G., Storck, D.A., and Clawges, R.A., 2001, Hydrology of the unconfined aquifer system, Maurice River area: Maurice and Cohansey Rivers, New Jersey, 1994-95: U.S. Geological Survey Water-Resources Investigations Report 01-4229, 5 sheets.

Cowdery, T.K., 1997, Shallow ground-water quality beneath cropland in the Red River of the North Basin, Minnesota and North Dakota, 1993-95: U.S. Geological Survey Water-Resources Investigations Report 97-4001, 52 p.

Dunkle, S.A., Plummer, L.N., Busenberg, E., Phillips, P.J., Denver, J.M., Hamilton, P.A., Michel, R.L., and Coplen, T.B., 1993, Chlorofluorocarbons (CCl_3F and CCl_2F_2) as dating tools and hydrologic tracers in shallow groundwater of the Delmarva Peninsula, Atlantic Coastal Plain, United States: Water Resources Research, v. 29, no. 12, p. 3837-3860.

Eckwurzel, Brenda, Schlosser, Peter, Smethie, W.M., Jr., Plummer, L.N., Busenberg, Eurybiades, Michel, R.L., Weppernig, Ralf, and Stute, Martin, 1994, Dating of shallow groundwater--Comparison of the transient tracers 3H/3He, chlorofluorocarbons, and 85Kr: Water Resources Research, v. 30, no. 6, p. 1693-1708.

Harbaugh, A.W., and McDonald, M.G., 1996a, User's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-485, 56 p.

Harbaugh, A.W., and McDonald, M.G., 1996b, Programmer's documentation for MODFLOW-96, an update to the U.S. Geological Survey modular finite-difference ground-water flow model: U.S. Geological Survey Open-File Report 96-486, 220 p.

Johnson, M.L., and Charles, E.G., 1997, Hydrology of the unconfined aquifer system, Salem River area: Salem River, Raccoon, Oldmens, Alloway, and Stow Creek basins, New Jersey, 1993-94: U.S. Geological Survey Water-Resources Investigations Report 96-4195, 5 sheets.

Lacombe, P.J., and Rosman, Robert, 1995, Hydrology of the unconfined aquifer system in the 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.

Martin, Mary, 1998, Ground-water flow in the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-H, 146 p.

MacLeod, C.L., Barringer, T.H., Vowinkel, E.F., and Price, C.V., 1995, Relation of nitrate concentrations in ground water to well depth, well use, and land use in Franklin Township, Gloucester County, New Jersey, 1970-85: U.S. Geological Survey Water-Resources Investigations Report 94-4174, 29 p.

Modica, Edward, Buxton, H.T., and Plummer, L.N., 1998, Evaluating the source and residence times of groundwater seepage to streams, New Jersey Coastal Plain: Water Resources Research, v. 34, no. 11, p. 2797-2810.

Mullaney, J.R., and Grady, S.J., 1997, Hydrogeology and water quality of a surficial aquifer underlying an urban area, Manchester, Connecticut: U.S. Geological Survey Water-Resources Investigations Report 97-4195, 40 p.

Nawyn, J.P., 1998, Withdrawals of ground water and surface water in New Jersey, 1991-92: U.S. Geological Survey Open-File Report 98-282, 57 p.

Nawyn, J.P., and Clawges, R.M., 1995, Withdrawals of ground water and surface water in New Jersey, 1989-90: U.S. Geological Survey Open-File Report 95-324, 52 p.

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.

New Jersey Department of Environmental Protection, 1996a, Water for the 21st century: The vital resource: New Jersey Statewide Water Supply Plan, chap. VI, 46 p.

New Jersey Department of Environmental Protection, 1996b, New Jersey geographic information system: Trenton, N.J., CD-ROM series 1, v. 2.

New Jersey Department of Labor, accessed February 2, 2000, Labor fast facts: Census data tables on the World Wide Web at URL http://www.wnjpin.state.nj.us/OneStopCareerCenter/LaborMarketInformation/lmi01/.

Nolan, B.T., and Stoner, J.D., 2000, Nutrients in ground waters of the conterminous United States, 1992-1995: Environmental Science and Technology, v. 34, no. 7, p. 1156-1165.

Pollock, D.W., 1994, User’s guide to MODPATH/MODPATH_PLOT, version 3—A particle tracking post-processing package for MODFLOW, the U.S. Geological Survey modular three-dimensional finite-difference ground-water-flow model: U.S. Geological Survey Open-File Report 94-464 (variously paged).

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 36, 58 p.

Rice, D.E., and Szabo, Zoltan, 1997, 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: U.S. Geological Survey Water-Resources Investigations Report 96-4165B, 41 p.

Rowe, G.L., Shapiro, S.D., and Schlosser, Peter, 1999, Use of environmental tracers to evaluate ground-water age and water-quality trends in a buried-valley aquifer, Dayton area, southwestern Ohio: U.S. Geological Survey Water-Resources Investigations Report 99-4113, 81 p.

Saad, D.A., and Thorstenson, D.C., 1998, Flow and geochemistry along shallow ground-water flowpaths in an agricultural area in southeastern Wisconsin: U.S. Geological Survey Water-Resources Investigations Report 98-4179, 62 p.

Solomon, D.K., Poreda, R.J., Cook, P.G., and Hunt, A., 1995, Site characterization using $^{3}H/^{3}He$ ground-water ages, Cape Cod, MA: Ground Water, v. 33, no. 6, p. 988-996.

Stackelberg, P.E., Hopple, J.A., and Kauffman, L.J., 1997, Occurrence of nitrate, pesticides, and volatile organic compounds in the Kirkwood-Cohansey aquifer system, southern New Jersey: U.S. Geological Survey Water-Resources Investigations Report 97-4241, 8 p.

Stackelberg, P.E., Kauffman, L.J., Baehr, A.L., and Ayers, M.A., 2000, Comparison of nitrate, pesticides, and volatile organic compounds in samples from monitoring and public-supply wells, Kirkwood-Cohansey aquifer system, southern New Jersey: U.S. Geological Survey Water-Resources Investigations Report 00-4123, 78 p.

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

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, 1990-91: U.S. Geological Survey Water-Resources Investigations Report 96-4265A, 119 p.

Tesoriero, A.J., Liebscher, Hugh, and Cox, S.E., 2000, The mechanism and rate of denitrification in an agricultural watershed: Electron and mass balance along groundwater flow paths: Water Resources Research, v. 36, no. 6, p. 1545-1560.

U.S. Bureau of the Census, 1992, Census of population and housing, 1990--Summary tape file 3A on CD-ROM (machine-readable data file): Washington, D.C., The Bureau (producer and distributor).

U.S. Geological Survey, 1986, Land use and land cover digital data from 1:250,000- and 1:100,000-scale maps: National Mapping Program technical instructions, Data users' guide 4, 36 p.

Watt, M.K., and Johnson, M.L., 1992, Water resources of the unconfined aquifer system of the Great Egg Harbor River Basin, New Jersey, 1989-90: U.S. Geological Survey Water-Resources Investigations Report 91-4126, 5 sheets.

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