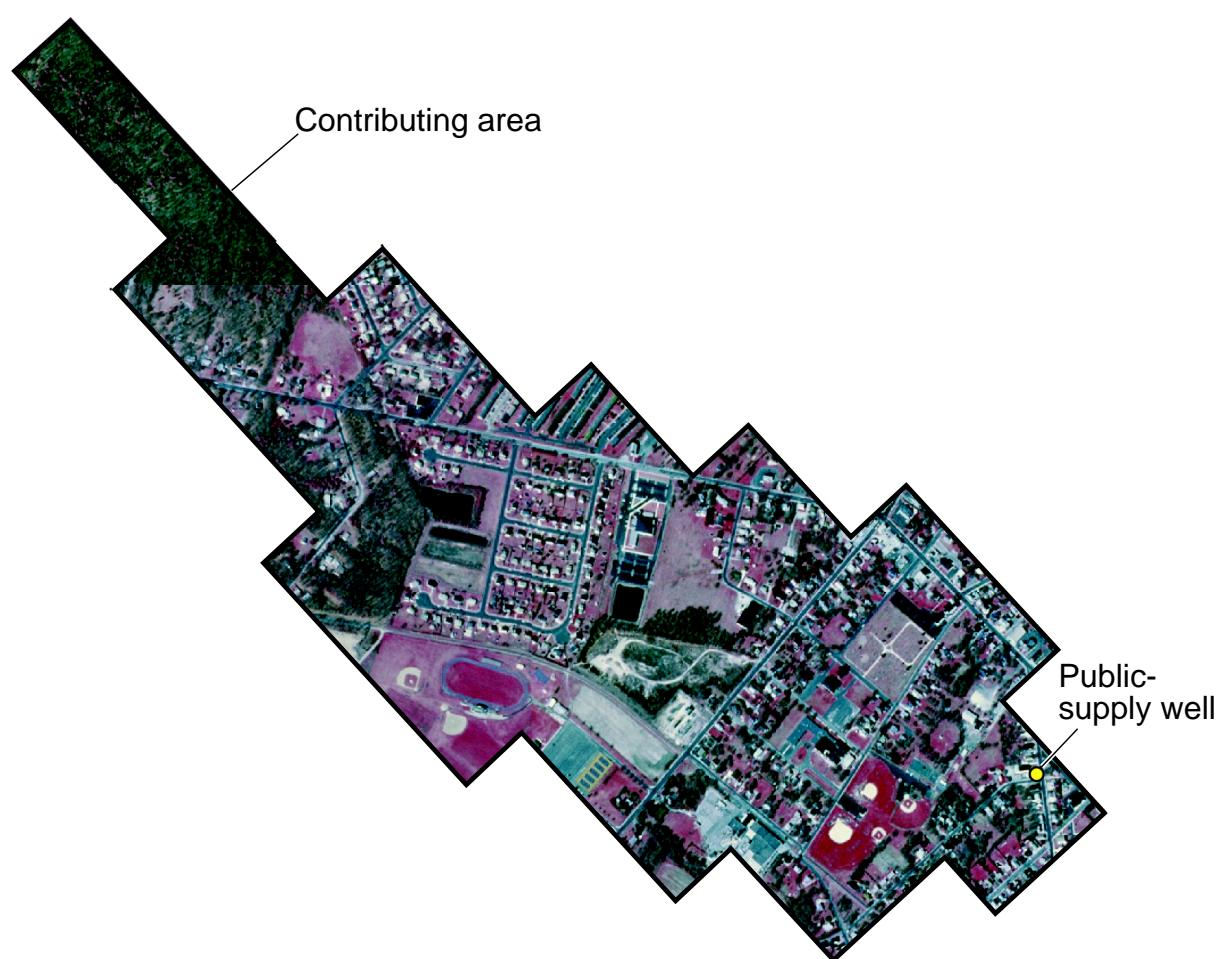


COMPARISON OF NITRATE, PESTICIDES, AND VOLATILE ORGANIC COMPOUNDS IN SAMPLES FROM MONITORING AND PUBLIC-SUPPLY WELLS, KIRKWOOD-COHANSEY AQUIFER SYSTEM, SOUTHERN NEW JERSEY

Water-Resources Investigations Report 00-4123



National Water-Quality Assessment Program

COMPARISON OF NITRATE, PESTICIDES, AND VOLATILE ORGANIC COMPOUNDS IN SAMPLES FROM MONITORING AND PUBLIC-SUPPLY WELLS, KIRKWOOD-COHANSEY AQUIFER SYSTEM, SOUTHERN NEW JERSEY

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

U.S. GEOLOGICAL SURVEY

Water-Resources Investigations Report 00-4123

National Water-Quality Assessment Program

West Trenton, New Jersey

2000

U.S. DEPARTMENT OF THE INTERIOR

BRUCE BABBITT, *Secretary*

U.S. GEOLOGICAL SURVEY

Charles G. Groat, *Director*

The use of firm, trade, and brand names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

For additional information
write to:

District Chief
U.S Geological Survey
Mountain View Office Park
810 Bear Tavern Road, Suite 206
West Trenton, NJ 08628

Copies of this report can be
purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286

CONTENTS

	Page
Abstract	1
Introduction	2
Simulation of ground-water flow	5
Well networks	5
Shallow monitoring wells	5
Moderate-depth monitoring wells	10
Public-supply wells	11
Comparison of nitrate, pesticides, and volatile organic compounds	12
Constituent properties, sources, occurrence, and fate.....	13
Nitrate	13
Pesticides	16
Volatile organic compounds	30
Transferability of water-quality results.....	42
Fate and significance of nitrate, pesticides, and VOCs in the Kirkwood-Cohansey aquifer system.....	44
Summary and conclusions	46
References cited.....	47
Appendixes	
1. Well-construction data for wells in the three well networks and depth to water at time of well installation, Glassboro study area, N.J.	52
2. Concentrations of pesticide compounds detected in one or more selected samples from the three well networks during September 1996-December 1998, Glassboro study area, N.J.	55
3. Concentration of volatile organic compounds detected in one or more selected samples from the three well networks during September 1996-December 1998, Glassboro study area, N.J.	61

ILLUSTRATIONS

Figure 1. Map showing location of Glassboro, New Jersey, study area	2
2. Graph showing volume of water withdrawn from the Kirkwood-Cohansey aquifer system by public-supply wells in the Glassboro study area, 1981-98	4
3. Maps showing:	
(a) simulated ground-water flow paths,	6
(b) simulated ground-water travel times, and	7
(c) residence times of water in the Kirkwood-Cohansey aquifer system in the Glassboro study area	8
4. Map showing land use and well locations in the Glassboro study area	9
5. Graph showing distribution of apparent age of water samples from monitoring wells and simulated age of water discharging from public-supply wells, Glassboro study area	11
6. Map showing simulated area contributing water to a public-supply well, Glassboro study area	13
7-14. Graphs showing:	
7. Cumulative frequency of nitrate concentrations in water samples from four well networks in and outside the Glassboro study area.....	15
8. Cumulative frequency of pesticide concentrations in water samples from all three well networks, Glassboro study area.....	24

ILLUSTRATIONS

Page

Figure 9. Concentration and frequency of detection of selected pesticides in water samples from all three well networks, Glassboro study area	26
10. Cumulative frequency of total volatile organic compound concentrations in water samples from four well networks within and outside the Glassboro study area	37
11. Concentration and frequency of detection of selected volatile organic compounds in water samples from all three well networks, Glassboro study area	39
12. Distribution of values of general characteristics of public-supply wells in and outside the Glassboro study area	43
13. Infiltration rate of soils within and outside the Glassboro study area	44
14. Total concentration and number of pesticides and volatile organic compounds per sample in water samples from all three well networks, Glassboro study area	45

TABLES

Table 1. Percentage of land use within simulated contributing areas of monitoring and public-supply wells, Glassboro study area, New Jersey	10
2. Use of selected pesticides as reported by licensed applicators in the State of New Jersey	17
3. Pesticide compounds analyzed for in samples from all three well networks, Glassboro study area	18
4. Pesticides that constitute 10 percent or more of use by category as reported by licensed applicators but not analyzed for in samples from all three well networks, Glassboro study area	19
5. Physical and chemical characteristics of selected pesticides.	21
6. Concentrations and detection frequencies of the most frequently detected pesticides in samples from all three well networks, Glassboro study area	23
7. Production amounts of selected volatile organic compounds for selected years from 1930 to 1994, as reported to the U.S. International Trade Commission	31
8. Volatile organic compounds analyzed for in samples from all three well networks, Glassboro study area	32
9. Physical and chemical properties of selected volatile organic compounds	35
10. Concentrations and detection frequencies of volatile organic compounds detected in more than 10 percent of samples from at least one of the well networks, Glassboro study area	36

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

<u>Multiply</u>	<u>By</u>	<u>To obtain</u>
<u>Length</u>		
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
<u>Weight</u>		
pound	0.4536	kilogram
<u>Area</u>		
acre	4,047	square meter
square mile (mi ²)	2,590	square kilometer
<u>Volume</u>		
million gallons (Mgal)	3,785	cubic meter
<u>Flow</u>		
inch per year (in./yr)	25.4	millimeter per year
foot per day (ft/d)	0.3048	meter per day
million gallons per day (Mgal/d)	0.04381	cubic meter per second
<u>Temperature</u>		
degree Fahrenheit (°F)	$^{\circ}\text{C} = 5/9 \times (^{\circ}\text{F} - 32)$	degree Celsius (°C)
<u>Hydraulic conductivity</u>		
foot per day (ft/d)	0.3048	meter per day
<u>Transmissivity</u>		
square foot per day (ft ² /d) ¹	0.09290	square meter per day

Vertical datum: 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
 µg/L - micrograms per liter
 mS/cm - microsiemens per centimeter at 25 degrees Celsius
 VOC - volatile organic compound

¹This unit is used to express transmissivity, the capacity of an aquifer to transmit water. Conceptually transmissivity is cubic feet (of water) per day per square foot (of aquifer area) times feet (of aquifer thickness), or (ft³/d)/ft² × ft. In this report, this expression is reduced to its simplest form, ft²/d.

FOREWORD

The mission of the U.S. Geological Survey (USGS) is to assess the quantity and quality of the earth resources of the Nation and to provide information that will assist resource managers and policy-makers at Federal, State, and local levels in making sound decisions. Assessment of water-quality conditions and trends is an important part of this overall mission.

One of the greatest challenges faced by water-resources scientists is acquiring reliable information that will guide the use and protection of the Nation's water resources. That challenge is being addressed by Federal, State, interstate, and local water-resource agencies and by many academic institutions. These organizations are collecting water-quality data for a host of purposes that include: compliance with permits and water-supply standards; development of remediation plans for specific contamination problems; operational decisions on industrial, wastewater, or water-supply facilities; and research on factors that affect water quality. An additional need for water-quality information is to provide a basis on which regional- and national-level policy decisions can be based. Wise decisions must be based on sound information. As a society we need to know whether certain types of water-quality problems are isolated or ubiquitous, whether there are significant differences in conditions among regions, whether the conditions are changing over time, and why these conditions change from place to place and over time. The information can be used to help determine the efficacy of existing water-quality policies and to help analysts determine the need for and likely consequences of new policies.

To address these needs, the U.S. Congress appropriated funds in 1986 for the USGS to begin a pilot program in seven project areas to develop and refine the National Water-Quality Assessment (NAWQA) Program. In 1991, the USGS began full implementation of the program. The NAWQA Program builds upon an existing base of water-quality studies of the USGS, as well as those of other Federal, State, and local agencies. The objectives of the NAWQA Program are to:

- Describe current water-quality conditions for a large part of the Nation's freshwater streams, rivers, and aquifers.

- Describe how water quality is changing over time.

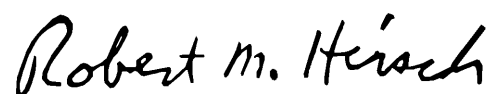
- Improve understanding of the primary natural and human factors that affect water-quality conditions.

This information will help support the development and evaluation of management, regulatory, and monitoring decisions by other Federal, State, and local agencies to protect, use, and enhance water resources.

The goals of the NAWQA Program are being achieved through ongoing and proposed investigations of 59 of the Nation's most important river basins and aquifer systems, which are referred to as study units. These study units are distributed throughout the Nation and cover a diversity of hydrogeologic settings. More than two-thirds of the Nation's freshwater use occurs within the 59 study units and more than two-thirds of the people served by public water-supply systems live within their boundaries.

National synthesis of data analysis, based on aggregation of comparable information obtained from the study units, is a major component of the program. This effort focuses on selected water-quality topics using nationally consistent information. Comparative studies will explain differences and similarities in observed water-quality conditions among study areas and will identify changes and trends and their causes. The first topics addressed by the national synthesis are pesticides, nutrients, volatile organic compounds, and aquatic biology. Discussions on these and other water-quality topics will be published in periodic summaries of the quality of the Nation's ground and surface water as the information becomes available.

This report is an element of the comprehensive body of information developed as part of the NAWQA Program. The program depends heavily on the advice, cooperation, and information from many Federal, State, interstate, Tribal, and local agencies and the public. The assistance and suggestions of all are greatly appreciated.



Robert M. Hirsch
Chief Hydrologist

COMPARISON OF NITRATE, PESTICIDES, AND VOLATILE ORGANIC COMPOUNDS IN SAMPLES FROM MONITORING AND PUBLIC-SUPPLY WELLS, KIRKWOOD-COHANSEY AQUIFER SYSTEM, SOUTHERN NEW JERSEY

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

ABSTRACT

The number and total concentration of volatile organic compounds (VOCs) per sample were significantly greater in water from public-supply wells than in water from shallow and moderate-depth monitoring wells in the surficial Kirkwood-Cohansey aquifer system in the Glassboro area of southern New Jersey. In contrast, concentrations of nitrate (as nitrogen) and the number and total concentration of pesticides per sample were statistically similar in samples from shallow and moderate-depth monitoring wells and those from public-supply wells.

VOCs in ground water typically are derived from point sources, which commonly exist in urban areas and which result in spatially variable contaminant concentrations near the water table. Because larger volumes of water are withdrawn from public-supply wells than from monitoring wells, their contributing areas are larger and, therefore, they are more likely to intercept water flowing from VOC point sources. Additionally, public-supply wells intercept flow paths that span a large temporal interval. Public-supply wells in the Glassboro study area withdraw water flowing along short paths, which contains VOCs that recently entered the aquifer system, and water flowing along relatively long paths, which contains VOCs that originated from the degradation of parent compounds or that are associated with past land uses. Because the volume of water withdrawn from monitoring wells is small and because shallow monitoring

wells are screened near the water table, they generally intercept only relatively short flow paths. Therefore, samples from these wells represent relatively recent, discrete time intervals and contain both fewer VOCs and a lower total VOC concentration than samples from public-supply wells.

Nitrate and pesticides in ground water typically are derived from nonpoint sources, which commonly are found in both agricultural and urban areas and typically result in low-level, relatively uniform concentrations near the water table. Because nonpoint sources are diffuse and because processes such as degradation or sorption/dispersion do not occur at rates sufficient to prevent detection of these constituents in parts of the aquifer used for domestic and public supply in the study area, concentrations of nitrate and pesticides and numbers of pesticide compounds are likely to be similar in samples from shallow monitoring wells and samples from public-supply wells.

Results of a comparison of (1) the general characteristics of, and water-quality data from, public-supply wells in the Glassboro study area to available data from public-supply wells screened in the Kirkwood-Cohansey aquifer system outside the study area, and (2) land-use settings, soil characteristics, and aquifer properties in and outside the study area indicate that the findings of this study likely are applicable to the entire extent of the Kirkwood-Cohansey aquifer system in southern New Jersey.

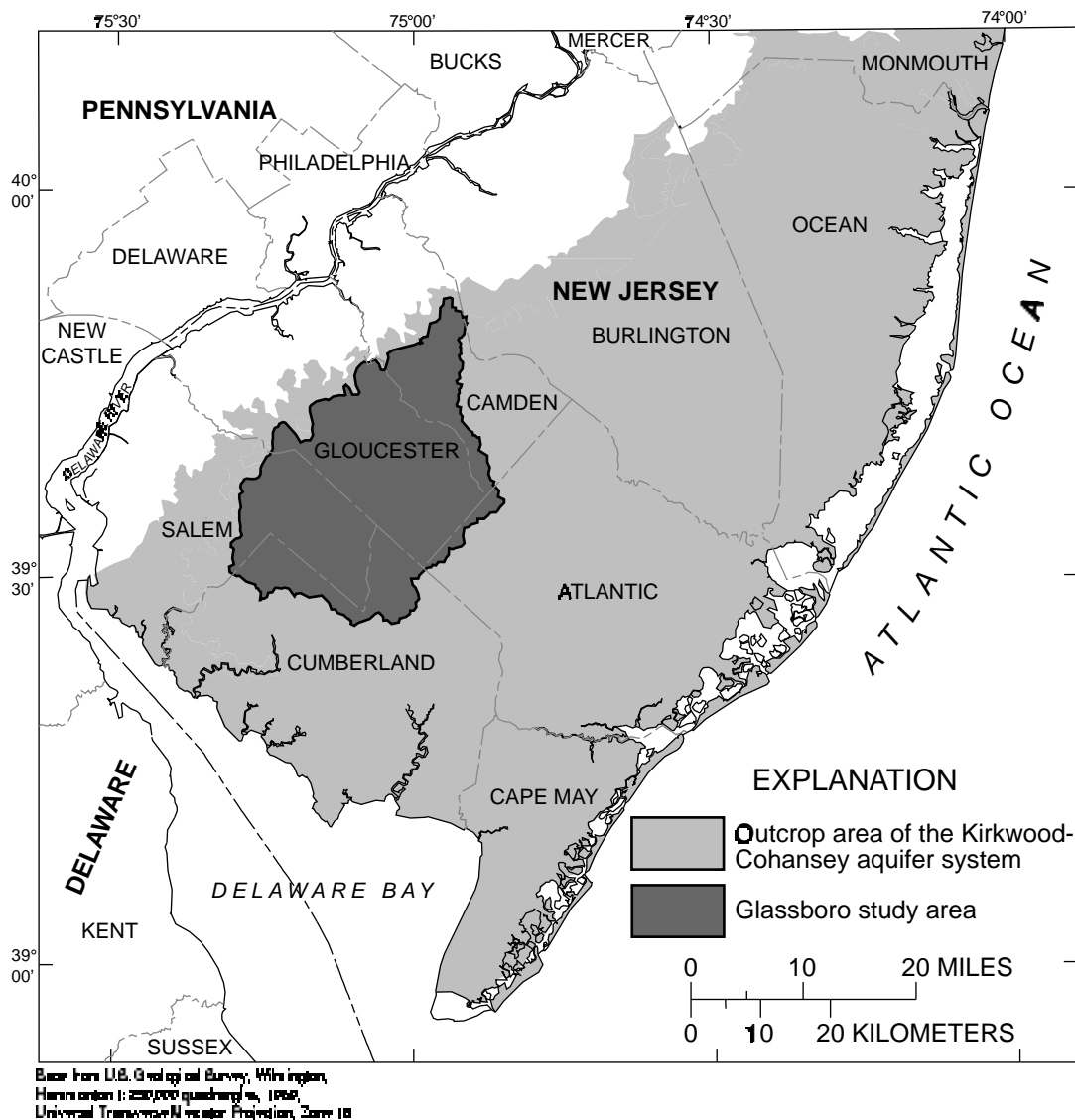


Figure 1. Location of Glassboro, New Jersey, study area.

INTRODUCTION

In ground-water sampling conducted as part of the U.S. Geological Survey's National Water-Quality Assessment (NAWQA) program, elevated concentrations of nitrate-nitrogen (hereafter referred to as nitrate) and generally low concentrations of pesticides and VOCs were frequently detected in recently recharged ground water from the surficial

Kirkwood-Cohansey aquifer system beneath the Glassboro area in southern New Jersey (fig. 1) (Stackelberg and others, 1997). Because this water was recently recharged and, therefore, vulnerable to contamination, it is rarely, if ever, intentionally targeted for domestic or public supply. With time, however, this water will migrate deeper into the aquifer system and, in the absence of complete degradation or substantial sorption and dispersion, will

eventually affect the quality of deeper ground water that is a current source of domestic and public supply. In addition, some of the water withdrawn by public-supply wells in the study area is young (less than 5 years old) (Kauffman and others, U.S. Geological Survey, unpub. data accessed August 15, 1999, on the World Wide Web at URL <http://nj.usgs.gov/nawqa/jpg/leonposter.agu.jpg>) even though this young water is not intentionally targeted as a source of domestic or public supply. The fate of nitrate, pesticides, and VOCs in recently recharged ground water and the likelihood that they will ultimately affect the quality of water used for domestic and public supplies are issues of concern as use of the surficial Kirkwood-Cohansey aquifer system increases to meet current and future water-supply demands.

Historically, much of the study area has relied on the confined Potomac-Raritan-Magothy aquifer system for most of its public supply; however, excessive pumping from this aquifer system has resulted in substantial water-level declines. These water-level declines prompted the New Jersey Department of Environmental Protection (NJDEP) to identify this part of the State as a Water-Supply Critical Area (N.J. Department of Environmental Protection, 1993) and to restrict further withdrawals from the Potomac-Raritan-Magothy aquifer system. Water supply is a critical issue in this area, one of the fastest growing regions in the State, where suburban development is expanding outward from the metropolitan Philadelphia area. The population of this area in 1990 was estimated to be 250,000 (N.J. Department of Environmental Protection, 1993). The growing population and State-imposed restrictions on withdrawals from the Potomac-Raritan-Magothy aquifer system have caused local water managers to seek alternative sources of water supply. One alternative is further development of the surficial Kirkwood-Cohansey aquifer system. Water withdrawals from this aquifer system for

public supply in the Glassboro study area have nearly doubled since 1980 (fig. 2). Since 1989, 15 public-supply wells have been installed in the Glassboro study area. Each of these wells withdraws, on average, 86 Mgal/yr from the Kirkwood-Cohansey aquifer system (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.). During this same period, more than 1,500 domestic-supply wells were completed in the Kirkwood-Cohansey aquifer system in the study area (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.).

Because the Kirkwood-Cohansey aquifer system consists of highly permeable, unconsolidated sands and gravels and has a generally shallow water table, it is vulnerable to contamination introduced at or near land surface. Contaminants can enter the aquifer system from either point or nonpoint sources. (In this report, a “contaminant” is any manmade compound detected or any compound that occurs naturally but whose concentration is greater than can be attributed to natural sources.) Point sources are local sources of contaminants, such as leaking underground storage tanks, sewer lines, effluent from cesspools and landfills, accidental spills, and areas where chemicals have been disposed of improperly. Individual point sources typically contaminate relatively small volumes of an aquifer system; however, they may introduce a wide variety of chemicals at highly elevated concentrations to the ground-water system. Nonpoint sources, in contrast, are areally extensive sources of contaminants, such as the widespread application of fertilizers and pesticides in agricultural areas and automobile emissions in urban areas. Nonpoint sources typically contaminate large, areally extensive volumes of the aquifer with low-level concentrations of specific compounds.

On occasion, water-quality problems have been recognized in water withdrawn for public

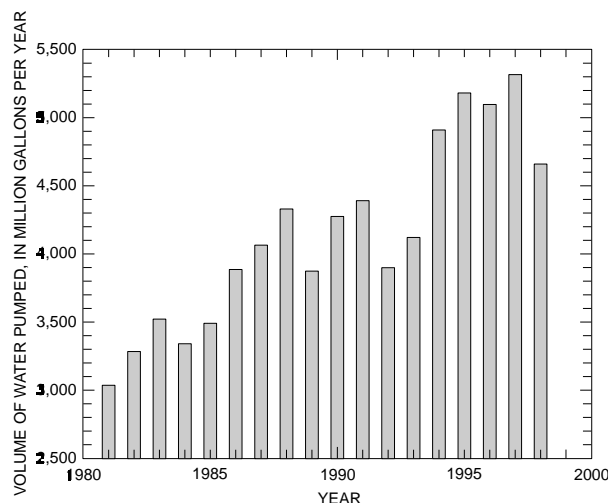


Figure 2. Volume of water withdrawn from the Kirkwood-Cohansey aquifer system by public-supply wells in the Glassboro study area, N.J., 1981-98. (Unpublished data on file at the U.S. Geological Survey office, West Trenton, N.J.)

supply in the study area. When water-quality problems are encountered, remedial actions are taken to ensure a safe drinking-water supply. These remedial actions have included the blending of waters from multiple sources and the retrofitting of public-supply wells with air strippers or carbon filters to reduce contaminant concentrations. In a few cases, however, public-supply wells in the study area have had to be abandoned as a result of severe water-quality problems. Because of the potential for contamination, some purveyors in the study area proactively install air strippers or carbon filters on new supply wells. These systems are expensive and can substantially increase the cost of producing and distributing public-supply water. Therefore, water purveyors need information on the occurrence of contaminants within the aquifer system, the factors governing their distribution, and the vulnerability of current and future domestic and public supplies so that they can anticipate water-quality problems.

Results of laboratory analyses of water samples collected from three well networks were coupled with a three-dimensional

computer model of ground-water flow in the Kirkwood-Cohansey aquifer system in the Glassboro study area to assess the occurrence and fate of nitrate, pesticides, and VOCs on a regional scale to facilitate management decisions regarding the continued development of the aquifer system as a source of drinking-water supply. The transferability of the water-quality findings of this study to the entire outcrop area of the Kirkwood-Cohansey aquifer system in southern New Jersey was evaluated by comparing (1) the construction and water-quality characteristics of public-supply wells in the Glassboro study area to those of more than 180 public-supply wells throughout the Kirkwood-Cohansey aquifer system and (2) the land-use settings, soil characteristics, and aquifer properties of the study area to those outside the study area.

This study, conducted as part of the USGS's NAWQA program, is part of an ongoing investigation of the occurrence and movement of contaminants throughout the hydrologic system and the effects of their presence on the use of ground water for domestic and public supplies in the Glassboro study area. This report (1) describes the chemical quality of water from shallow and moderate-depth monitoring wells and public-supply wells in the Kirkwood-Cohansey aquifer system; (2) examines the fate of contaminants as they migrate from the water table to parts of the aquifer system used for domestic and public supply; (3) relates the occurrence of selected constituents to current and historical use, mode of introduction (point or nonpoint), and source-area and well-type characteristics; and (4) evaluates the transferability of these findings to the entire area of the Kirkwood-Cohansey aquifer system in southern New Jersey. The report focuses on residential and urban parts of the study area because most of the existing and proposed public-supply wells are located in these areas.

SIMULATION OF GROUND-WATER FLOW

Patterns and rates of ground-water flow must be known in order to relate the occurrence of contaminants to source-area and well-type characteristics and to determine the vulnerability of current and future domestic and public supplies to contamination introduced at or near the water table. Therefore, a three-dimensional ground-water flow model of the study area (Kauffman and others, 1998), developed by using a three-dimensional finite-difference model (MODFLOW) (McDonald and Harbaugh, 1988) coupled with a particle-tracking program (MODPATH) (Pollock, 1989), was used to simulate ground-water flow rates and paths and to estimate ground-water residence times in the study area. The finite-difference grid consists of 343 rows and 214 columns; each grid cell is 492 by 492 ft. The Kirkwood-Cohansey aquifer system was modeled as one hydrogeologic unit with 12 model layers used to provide vertical discretization. Model parameters were uniform among all 12 model layers. The model is bounded on the bottom by a composite confining unit, which ranges in thickness from 50 to 600 ft within the study area (Zapoczka, 1989) and which serves as a continuous and competent confining unit. It is bounded on the northwestern edge by the outcrop of the aquifer and on the remaining sides by ground-water divides, which are represented as no-flow boundaries. The water-table boundary is represented by a uniform recharge rate of 17 in/yr. The model was calibrated by comparing simulated and observed water levels and base flows.

The ground-water flow model was used to approximate (1) the rates and paths of ground-water movement through the aquifer system, and (2) the time required for water to move from the water table at the point of recharge to the point of discharge at a stream or

well. Results are shown in figure 3 (a, b, and c). A plane view of select ground-water flow patterns in the study area is shown in figure 3a. Flow patterns were developed by starting a particle in each grid cell and tracking the particle forward until it discharged at a stream or well. In this way, the discharge point of ground water originating at any location on the water table in the study area was approximated. The rate of flow along each flow path also can be determined; thus, the amount of time required for water to flow from the water table to its discharge point also could be approximated (fig. 3b). A vertical section through the modeled area (fig. 3c) shows the distribution of ground-water residence times with depth in the aquifer system.

WELL NETWORKS

This section describes the monitoring- and public-supply well networks from which water samples were collected as part of this investigation. Details on the procedures and protocols used for selecting the well sites and installing the monitoring wells are described in Squillace and Price (1996) and Lapham and others (1995) and are summarized below. Well-construction data for wells sampled during this study and the depth to water at the time of well installation are presented in appendix 1.

Shallow monitoring wells

Fifty shallow monitoring wells were installed in the study area to provide data representative of the chemical quality of water recharging the Kirkwood-Cohansey aquifer system in areas of urban development (fig. 4). Thirty of these wells were installed in areas of residential and commercial development less than 30 years old (new urban) and 20 were installed in areas where urban development was more than 30 years old (old urban). New-

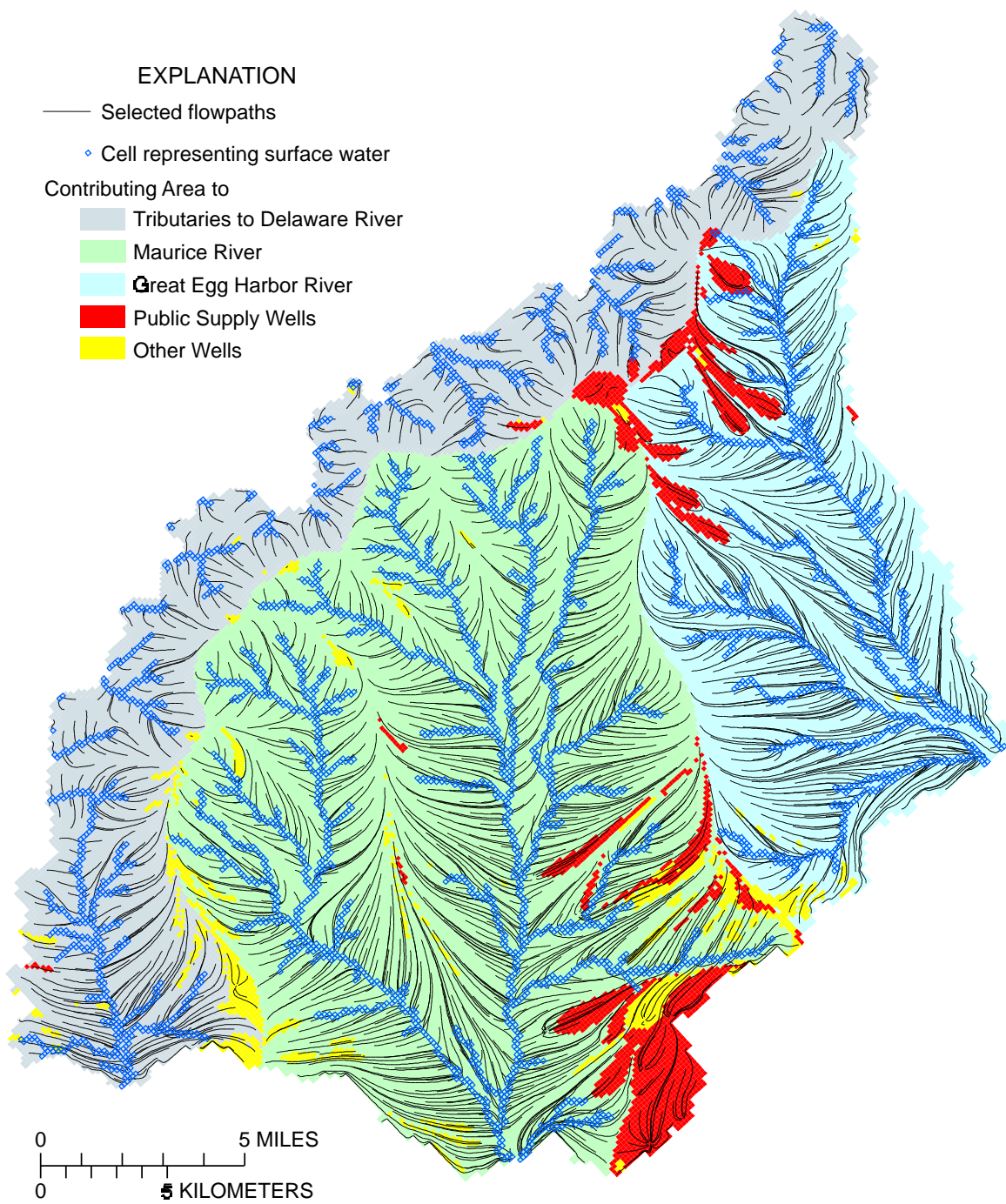


Figure 3a. Simulated ground-water flow paths in the Glassboro study area, N.J. (Location of study area shown in fig.1)

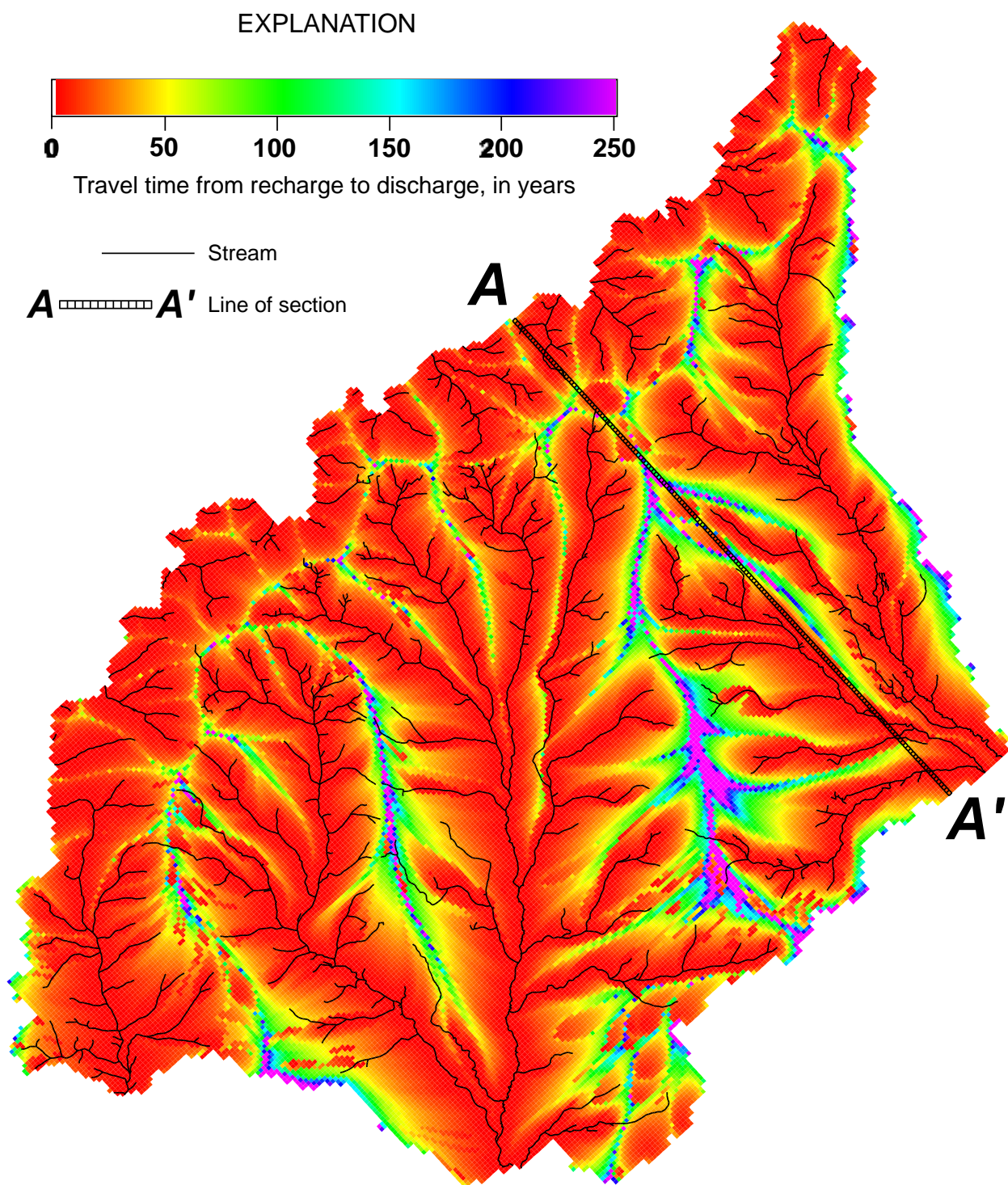


Figure 3b. Simulated ground-water travel times in the Glassboro study area, N.J. (Location of study area shown in fig. 1)

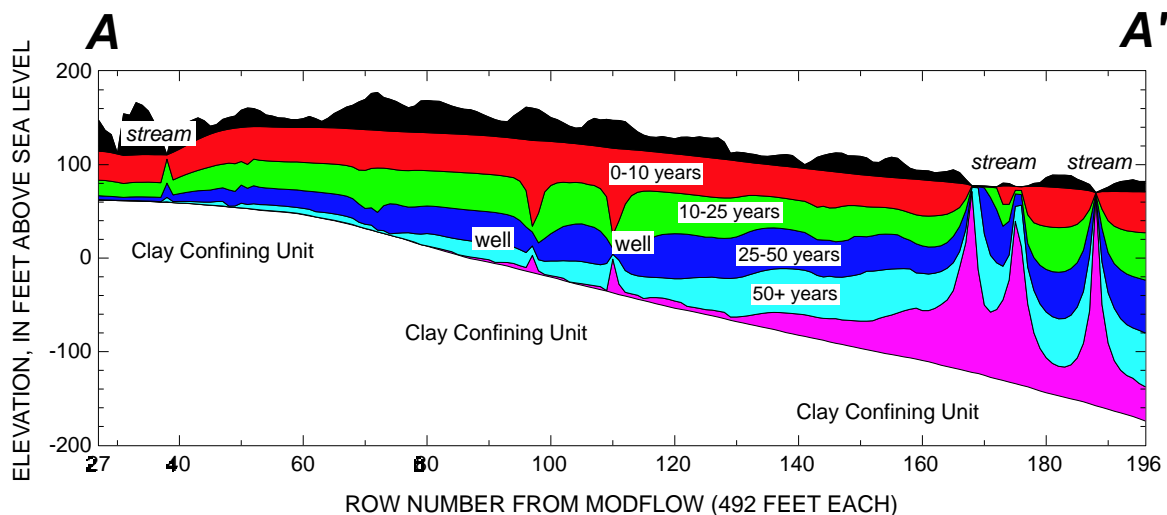


Figure 3c. Simulated residence times of water in the Kirkwood-Cohansey aquifer system in the Glassboro study area, N.J. (Line of section shown in fig. 3b)

urban wells were located in areas where development was at least 5 years old; more recently developed areas were avoided to ensure that water samples would be representative of current rather than previous land uses. Well locations were selected randomly by using a grid-based random site-selection program (Scott, 1990) to ensure that water-quality data collected from the network would be unbiased. Well locations were separated by at least 1,000 meters (3,280 ft) to ensure sample independence and to avoid spatial autocorrelation (Barringer and others, 1990). Land use within a 500-meter- (1,640-ft-) radius zone surrounding each well site is predominantly urban, further ensuring that samples from the shallow network are representative of the chemical quality of recently recharged water underlying urban land. Each well is constructed with 2-in-diameter threaded polyvinyl chloride (PVC) pipe and typically is screened over a 2-ft interval about 10 ft below the water table. Because well sites in the study area that met criteria for well-site selection were limited, two shallow monitoring wells were installed outside the study-area boundary (fig. 4).

Shallow monitoring wells screened over a short interval near the water table are designed to provide samples of water that was recharged in close proximity to the well site during a relatively discrete, recent time interval. These assumptions are supported by the results of particle-tracking and by tritium/helium-3 ($^3\text{H}/^3\text{He}$) age estimates determined from water samples. The ratio of ^3H to ^3He concentrations provides reliable estimates of the time elapsed since a water sample was recharged and isolated from the atmosphere (referred to as the apparent age of the sample) (Plummer and others, 1993; Ekwurzel and others, 1994; Szabo and others, 1996; Cook and Solomon, 1997). Samples for $^3\text{H}/^3\text{He}$ age dating were collected at nine of the shallow monitoring wells. Apparent ages ranged from less than 1 to 7.5 years (fig. 5) with a median of 1.4 years, confirming that the samples collected from the network of shallow monitoring wells were young.

Monitoring wells are pumped only during sampling (and then at very low rates) and, thus, capture water that originates in relatively small areas at land surface. To determine the area

EXPLANATION

Land use in 1986--

- Urban
- Agricultural
- Undeveloped
- Water bodies and wetlands

Well location--

- Shallow monitoring well
- Co-located shallow and moderate-depth monitoring wells
- Public-supply well

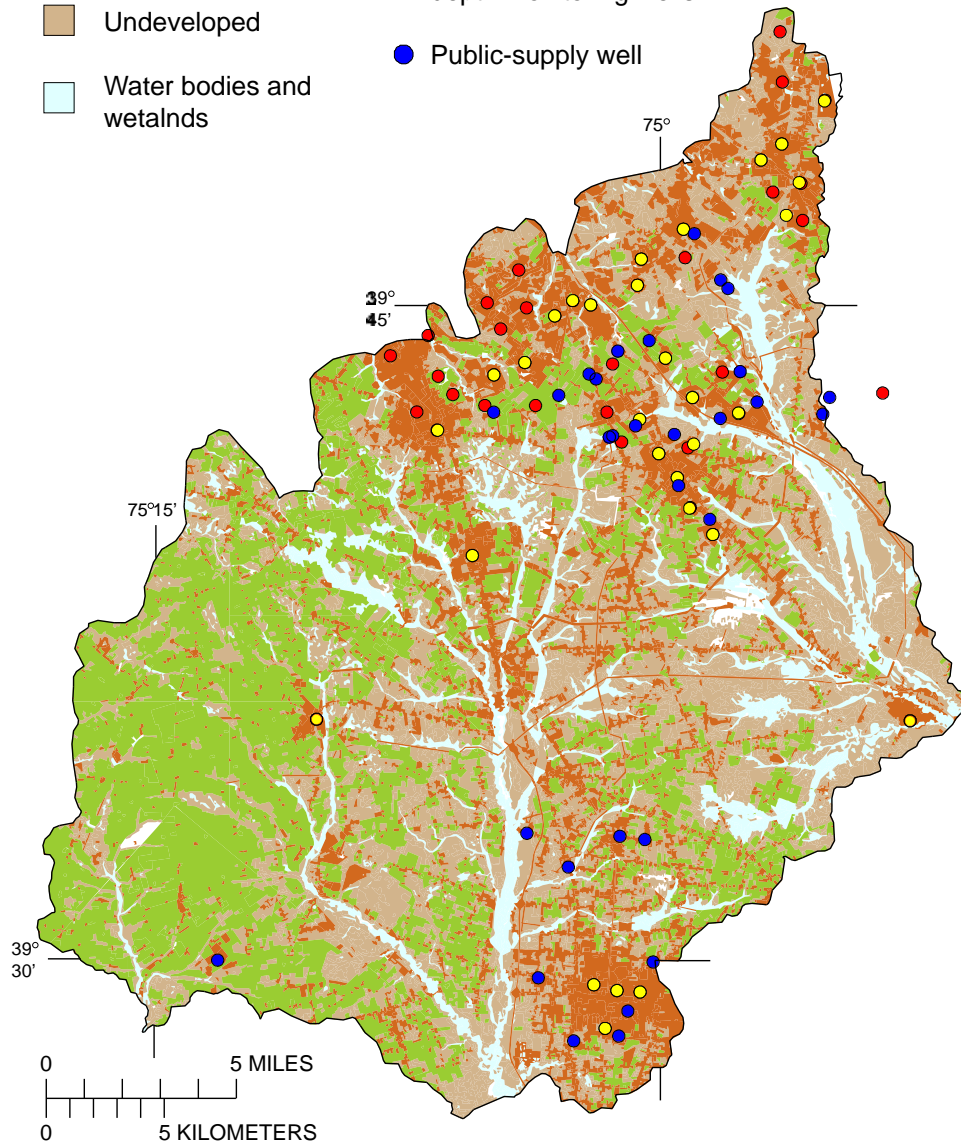


Figure 4. Land use and well locations in the Glassboro study area, N.J.
(Land-use data from New Jersey Department of Environmental Protection, 1996)

Table 1. Percentage of land use within simulated contributing areas of monitoring and public-supply wells, Glassboro study area, N.J.
[Average area of simulated contributing areas shown in parentheses; --, none reported]

Land-use category	Shallow monitoring wells (1.2 acres)	Moderate- depth monitoring wells (1.8 acres)	Public-supply wells (230 acres)
URBAN			
Residential	67.03	77.38	33.49
Commercial and services	5.61	5.40	3.16
Industrial	6.74	--	.65
Other (miscellaneous) urban	9.97	10.82	2.81
Transportation, communication, and utilities	--	--	1.40
Total	89.35	93.6	41.51
AGRICULTURAL			
Cropland and pastureland	3.65	6.15	21.09
Orchards	--	.08	3.74
Total	3.65	6.23	24.83
UNDEVELOPED			
Open park, recreational, and athletic fields	--	--	.77
Forest, brushland, and wooded wetlands	7.00	.17	31.59
Altered wetlands, reservoir, marsh	--	--	.14
Total	7.00	0.17	32.50

most likely contributing water to each of the shallow monitoring wells, particles were placed along the screened interval of each well and tracked back to the location of recharge. The traces of particles at land surface were buffered by 50 meters (164 ft) to accommodate uncertainties in precise recharge location. In all cases, the simulated particle paths indicate that recharge is derived from within the 500-meter- (1,640-ft-) radius zone surrounding each well site, confirming that samples obtained from the shallow monitoring wells were recharged near the well site in areas of urban development

(table 1).

Moderate-depth monitoring wells

Thirty moderate-depth monitoring wells were installed in the study area (fig. 4). These wells were (1) co-located with shallow monitoring wells in areas where urban development was known to be more than 20 years old, (2) constructed with 2-in-diameter threaded PVC pipe, and (3) typically screened over a 2- to 2.5-ft interval. The screened

intervals of the moderate-depth monitoring wells were located to capture water that recharged the aquifer system about 15 years ago in areas of urban development. Well-screen depths were selected by using the ground-water flow model and particle tracking. The chemical quality of 15-year-old water is of concern because particle-tracking results indicate that water withdrawn from the Kirkwood-Cohansey aquifer system for domestic and public supply is composed partly of water from this age interval and because it is an indicator of the fate of contaminants known to be contributing to the contaminant load at the water table in areas of urban development.

Samples for $^3\text{H}/^3\text{He}$ age dating were collected from 12 of the moderate-depth monitoring wells. Apparent ages ranged from 6.3 to 30 years (fig. 5) with a median of 14 years, illustrating the utility of the ground-water flow model and particle tracking in approximating the rate of ground-water movement and the time elapsed since recharge. To determine the area most likely contributing water to each of the moderate-depth monitoring wells, particles were placed along each well's screened interval and tracked back to the location of recharge. The traces of particles at land surface were buffered by 50 meters (164 ft) to accommodate uncertainties in precise recharge location. In most cases, the particle-tracking results indicate that recharge was derived from within the 500-meter- (1,640-ft-) radius zone surrounding each well site where land use has been urban for at least 20 years. For those sites where particles apparently recharge from beyond the 500-meter-radius zone, land use near the site of apparent recharge also had been urban for at least 20 years. Thus, samples from the moderate-depth monitoring wells (1) are representative of the chemical quality of water that recharged the aquifer system about 15 years ago in areas of urban development (fig. 5, table 1), (2) are representative of the chemical quality of water

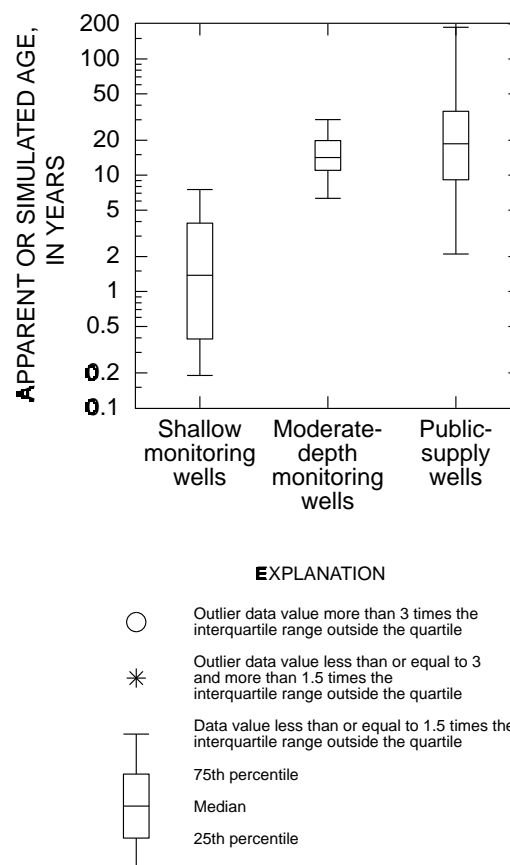


Figure 5. Distribution of apparent age of water samples from monitoring wells and simulated age of water discharging from public-supply wells, Glassboro study area N.J.

in parts of the aquifer system that are used for domestic and public supplies, and (3) are indicative of the fate of contaminants known to be contributing to the contaminant load at the water table.

Public-supply wells

Thirty public-supply wells, located in the same vicinity as the monitoring-well networks (fig. 4), were included in this investigation to provide data representative of the chemical quality of water in parts of the aquifer system from which water is withdrawn for public supply. Samples from these public-supply wells

were collected prior to any water-treatment procedures and thus consisted of raw, untreated water. The 25th-, 50th-, and 75th-percentile depths of these public-supply wells are 97, 142, and 160 ft below land surface, respectively; the 25th-, 50th-, and 75th-percentile screen lengths are 25, 30, and 33 ft, respectively.

Unlike monitoring wells, public-supply wells withdraw large volumes of water from the aquifer system. The average pumping rate for these public-supply wells was 97 Mgal/yr during 1992-96 (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.). Consequently, these wells capture recharge from relatively large areas at land surface. For instance, if a regional recharge rate of 17 in/yr is assumed, the resulting contributing area for a well producing 100 Mgal/yr would be about 200 acres (Baehr and others, 1999b). Water discharging at public-supply wells, therefore, typically is a mixture of waters of different ages that were recharged beneath various land-use settings (Franke and others, 1998).

Because pumping public-supply wells generally integrates waters of different ages, it is difficult to obtain a meaningful age estimate by using environmental tracers such as ³H/³He. Ground-water flow modeling and particle tracking, however, can be used instead of environmental tracers to estimate the age of water discharging to public-supply wells and to determine the area most likely contributing water to these wells. To determine these areas, a particle was placed at the water table in each model cell and tracked forward to the location of discharge--in this case, the screened interval of each public-supply well. The particle-tracking results indicate that recharge generally is derived from large, elongate contributing areas (fig. 6). Flow paths defined by forward-tracking particles and captured by public-supply wells contain water that ranges in age from less than 3 to more than 180 years with a

median age of 19 years (fig. 5), demonstrating the wide range of ages of water withdrawn from public-supply wells. A full continuum of land uses may be present in these contributing areas, including undeveloped, agricultural, and urban settings (table 1; fig. 6).

COMPARISON OF NITRATE, PESTICIDES, AND VOLATILE ORGANIC COMPOUNDS

Sampling and analytical methods recently developed by the USGS allow for the quantification of pesticide concentrations at 0.01 µg/L and less and VOC concentrations at 0.1 µg/L and less in samples of environmental water. Protocols and procedures used for sample collection during this study are described in Koterba and others (1995); analytical methods are described in Zaugg and others (1995) and Connor and others (1998). Quality-assurance samples, including blanks, spikes, replicates, duplicates, and surrogates, were collected in the field (Koterba and others, 1995) and (or) the laboratory (Zaugg and others, 1995; Connor and others, 1998) to ensure the integrity of environmental data. Review of results of analyses of quality-assurance samples indicates that chemical results reported herein are reproducible and that field and laboratory procedures did not introduce contamination to environmental samples (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.).

In accordance with procedures described in Zaugg and others (1995) and Connor and others (1998), concentrations of compounds that were confirmed to be detected but were below minimum reporting levels (MRLs) were estimated. These estimated concentrations of confirmed detections are included in figures and tables in this report and in the calculation of detection frequencies. Results of analyses of



Figure 6. Simulated area contributing water to a public-supply well, Glassboro study area, N.J.

water samples for pesticides and VOCs are shown in appendixes 2 and 3, respectively.

Constituent properties, sources, occurrence, and fate

The potential for nitrate, pesticides, or VOCs to leach to ground water depends on many factors, including (1) their use and manner of introduction to the environment, (2) their physical and chemical characteristics, and (3) the characteristics of the soil and aquifer materials they penetrate. This section provides a general discussion of these factors and describes the occurrence and fate of these

constituents in all three well networks.

Nitrate

Nitrate is a stable species of nitrogen in oxygenated subsurface environments and was the most frequently detected nutrient in samples from the three well networks. Concentrations of other nitrogen species, such as nitrite, were negligible (generally less than 0.02 mg/L) and are not discussed further in this report.

Natural sources of nitrogen, such as precipitation and plant residue, generally contribute small amounts of nitrate to ground

water. Nitrate concentrations in 41 samples of precipitation collected in the Glassboro study area from December 1996 to May 1999 ranged from 0.05 to 2.6 mg/L (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.). The 25th-, 50th-, and 75th-percentile concentrations were 0.2, 0.4, and 0.6 mg/L, respectively, indicating that nitrate concentrations in ground water due to precipitation generally are less than 1.0 mg/L. Nitrate concentrations in 13 samples of recently recharged ground water underlying undeveloped (forested) land in the Glassboro study area ranged from less than 0.05 mg/L to 0.33 mg/L with a median concentration of 0.07 mg/L (Stackelberg and others, 1997), providing additional evidence that natural sources of nitrogen in the study area result in nitrate concentrations less than 1.0 mg/L in ground water.

Human sources of nitrogen, such as agricultural fertilizers, lawn and garden fertilizers, and effluent from leaking sewer lines, cesspools, and septic tanks, can significantly increase nitrate concentrations in ground water beneath agricultural and urban areas. Concentrations of nitrate greater than 10 mg/L in drinking water can pose a health threat to infants, whose digestive systems convert nitrate to nitrite, which reduces the oxygen-carrying capacity of blood and results in the disease methemoglobinemia (“blue-baby syndrome”). The U. S. Environmental Protection Agency (USEPA), therefore, has established a maximum contaminant level (MCL) for nitrate of 10 mg/L as nitrogen in water that is delivered to any user of a public-supply system (U. S. Environmental Protection Agency, 1996). In addition, nitrate concentrations of 4 mg/L or more in rural drinking-water supplies have been associated with increased risk of non-Hodgkin’s lymphoma (Ward and others, 1996).

The cumulative distributions of nitrate concentrations in samples from the three well networks are shown in figure 7. This graph can be used to compare constituent-concentration distributions among the well networks. The percentage of samples from each network of wells in which nitrate concentrations were less than (or greater than) a given concentration can be determined by locating the point on the y-axis at which the cumulative-distribution curve intersects the given concentration. The relations shown were calculated by ranking the constituent concentrations from smallest ($i=1$) to largest ($i=n$, where n is the number of samples in the data set) (Helsel and Hirsch, 1992) and then plotting them along the horizontal axis. Cumulative frequency, a function of the rank i and the sample size n , is calculated by using the formula

$$p_i = i / (n + 1)$$

(Helsel and Hirsch, 1992). Concentrations reported as “less than” are assigned a concentration value of zero. When the above formula is used, two or more samples with the same reported concentration are assigned different positions on the vertical axis, forming vertical slopes. Samples with nearly equal concentrations form nearly vertical slopes. For example, nitrate concentrations in most of the samples from each of the three well networks are between 1 and 8 mg/L; therefore, the cumulative-distribution slopes in this range are steep (fig. 7). In contrast, a large gap between two reported concentrations will result in a nearly horizontal slope. For example, one sample from both monitoring-well networks contained a nitrate concentration greater than 30 mg/L. The next highest reported nitrate concentrations for the two networks were between 8 and 12 mg/L; therefore, the slopes of the cumulative-frequency curves between these samples are nearly horizontal (fig. 7).

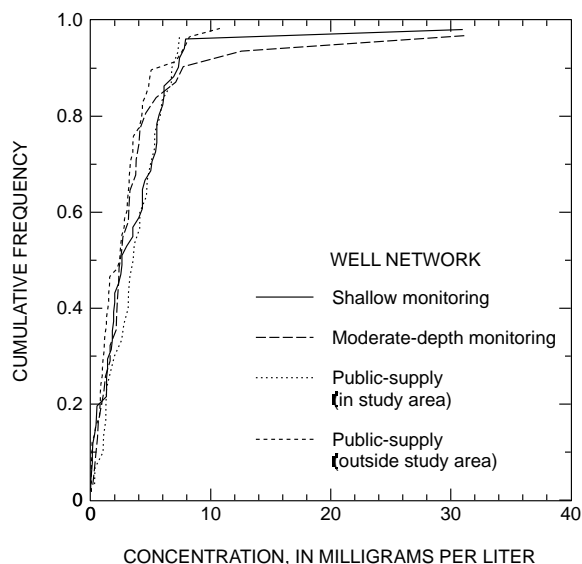


Figure 7. Cumulative frequency of nitrate concentrations in water samples from four well networks in and outside the Glassboro study area, N.J.

The cumulative distribution of nitrate concentrations in samples from 57 public-supply wells located throughout the entire Kirkwood-Cohansey outcrop area in New Jersey (fig. 1) but excluding the study area also is shown in figure 7. These data are included to show how the concentrations of nitrate in samples from public-supply wells in the Glassboro study area compare with those in samples from other public-supply wells in the Kirkwood-Cohansey aquifer system. Nitrate-concentration data were considered to be appropriate for comparison if the public-supply well from which the sample was collected was located in an unconfined part of the aquifer system and the analysis had been performed after 1987. In addition, nitrate-concentration data were not considered for comparison if the associated dissolved-oxygen concentration was less than 1.5 mg/L. Samples with dissolved-oxygen concentrations less than 1.5 mg/L were considered to be anoxic and subject to denitrification, a process that would deplete nitrate concentrations.

The median nitrate concentrations in samples from the shallow and moderate-depth monitoring wells and public-supply wells in and outside the study area were 2.6, 2.45, 3.5, and 2.4 mg/L, respectively. Results of analysis of variance (ANOVA) on rank-transformed nitrate concentrations indicate that mean ranked nitrate concentrations are similar among the four well networks at a 95-percent confidence level. ANOVA on rank-transformed data is a robust, nonparametric method that is insensitive to outlying values and assumptions of equal variance or normality (Helsel and Hirsch, 1992). The concentrations of nitrate in samples from the Glassboro study area public-supply wells, therefore, are similar to those in samples from the shallow and moderate-depth monitoring wells and those in samples from public-supply wells located throughout the Kirkwood-Cohansey aquifer system. Nitrate concentrations in only four samples—one from the shallow monitoring wells, two from the moderate-depth monitoring wells, and one from a public-supply well outside the Glassboro study area—exceeded the USEPA MCL of 10 mg/L.

Because public-supply wells withdraw water that was recharged in a variety of land-use settings (table 1), the concentration of nitrate in a given sample represents a composite concentration from all areas that contribute water to the public-supply well. For instance, whereas the concentration of nitrate in samples of water withdrawn from shallow monitoring wells located in undeveloped areas generally is less than 1.0 mg/L, the median concentrations of nitrate in samples of water withdrawn from shallow monitoring wells located in agricultural and urban areas were 13 and 3.0 mg/L, respectively (Stackelberg and others, 1997). The median concentration of nitrate in samples of water withdrawn from public-supply wells for this study was 3.5 mg/L.

Pesticides

Synthetic organic pesticides were first introduced in the 1940's; however, reliable records on their manufacture and use were not compiled until the 1960's. Since then, their manufacture and use have increased steadily (Smith and others, 1988; Barbash and Resek, 1996). Pesticides have long been used in agricultural settings but, in the last several decades, their use in nonagricultural settings, such as urban and undeveloped areas, has increased as well. Pesticides are used in urban settings to control insects, weeds, and fungi on lawns and golf courses, in cemeteries, parks and private and public gardens, and in and around homes and commercial buildings. They are also used to control vegetation on railroad, transmission-line, and roadway rights-of-way. Insecticides are used to control mosquito and other pest populations in urban and undeveloped areas for the protection of public health and for nuisance reduction (Barbash and Resek, 1996). More than 10,000 products containing more than 400 major active ingredients are currently registered for use as pesticides in New Jersey (Hamilton and Meyer, 1994).

As part of its Pesticide Control Program, the NJDEP has monitored the types and amounts of pesticides applied by licensed applicators in New Jersey since the mid-1980's. Data for selected pesticides compiled by the NJDEP (table 2) indicate trends in pesticide use for agricultural purposes and current pesticide use for the maintenance of lawns, golf courses, and rights-of-way, and the control of termites and mosquitoes. The pesticides listed in table 2 are those detected in 10 percent or more of samples from at least one of the well networks, excluding degradation byproducts. Information summarized in table 2 is from licensed applicators only and does not take into account the use of pesticides that are available to and used by non-licensed applicators (for example, homeowners).

In New Jersey, agriculture accounts for the largest use of pesticides by volume by licensed applicators. More than 1.6 million pounds of active ingredients was applied to New Jersey crops in 1994 (New Jersey 1994 Agricultural Pesticide Use Survey; unpublished data on file at N.J. Department of Environmental Protection, Pesticide Control Program, Trenton, N.J.). Residential lawn care accounts for the second largest use of pesticides in New Jersey by licensed applicators. More than 370,000 pounds of active pesticide ingredient, mostly herbicides with smaller amounts of insecticides and fungicides, were applied in 1995 (New Jersey 1995 Lawn Care Pesticide Use Survey; unpublished data on file at N.J. Department of Environmental Protection, Pesticide Control Program, Trenton, N.J.). Maintenance of golf courses, termite and mosquito control, and control of weeds in right-of-way areas account for most of the remaining pesticide use in New Jersey by licensed applicators.

Forty-seven pesticides and pesticide degradation byproducts were analyzed for in samples from all three well networks to obtain a comprehensive analysis of the occurrence, distribution, and concentration of pesticides in the Kirkwood-Cohansey aquifer system in the Glassboro study area (table 3). Pesticides selected for analysis were targeted because of their widespread use in the United States and (or) concerns about their effects on human health, and their amenability to measurement with available analytical techniques (Zaugg and others, 1995). Although this list is comprehensive, these pesticides do not account for all pesticide use within New Jersey and, thus, some pesticides whose use is significant were not analyzed for in samples from all three well networks. Pesticides that account for 10 percent or more of total use by category in New Jersey as reported by licensed applicators but that were not analyzed for in samples from all three well networks are listed in table 4. Four of

Table 2. Use of selected pesticides as reported by licensed applicators in the State of New Jersey [Data on file at N.J. Department of Environmental Protection, Pesticide Control Program, Trenton, N.J.; --, none reported; <, less than; H, herbicide; I, insecticide]

Compound	Use, in pounds of active ingredient (percent of category)									
	Agriculture			Lawn care		Rights-of-way	Termites		Mosquitos	Golf courses
	1985	1988	1991	1994	1995		1992	1993		
Atrazine (H)	58,857 (12.6)	45,813 (10.2)	57,128 (12.0)	58,790 (11.7)	18 (<1)	3 (<1)	--	--	--	--
Simazine (H)	8,866 (1.9)	3,311 (<1)	4,691 (<1)	5,846 (1.2)	51 (<1)	1,833 (3.4)	--	--	--	--
Prometon (H)	267 (<1)	92 (<1)	24 (<1)	85 (<1)	866 (<1)	246 (<1)	--	--	--	--
Metolachlor (H)	72,691 (15.5)	98,379 (22.0)	144,418 (30.4)	137,387 (27.3)	132 (<1)	--	--	2 (<1)	137,521	
Dieldrin (I)	--	--	--	--	--	--	--	--	--	--
Alachlor (H)	84,462 (18.0)	49,050 (11.0)	35,323 (7.4)	48,945 (9.7)	--	--	--	--	48,945	
Terbacil (H)	3,450 (<1)	13,193 (2.9)	4,585 (1.0)	2,318 (<1)	--	--	--	--	2,318	
Carbaryl (I)	21,922 (5.4)	16,910 (3.2)	16,768 (4.0)	16,331 (4.3)	9,563 (10.2)	--	--	--	2,650 (8.0)	28,544
Carbofuran (I)	33,492 (8.2)	29,954 (5.6)	19,956 (4.8)	10,353 (2.7)	--	--	--	--	--	10,353

¹Total use = 1994 agricultural use plus use data from other non-agricultural surveys.

Table 3. Pesticide compounds analyzed for in samples from all three well networks, Glassboro study area, N.J.

[CAS, Chemical abstract service number; MRL, minimum reporting level; µg/L, micrograms per liter]

Compound	CAS	MRL (µg/L)	Compound	CAS	MRL (µg/L)
Herbicides			Insecticides		
Acetochlor	34256-82-1	0.002	Azinphos-methyl	86-50-0	.001
Alachlor	15972-60-8	.002	Carbaryl	63-25-2	.003
Atrazine	1912-24-9	.001	Carbofuran	1563-66-2	.003
Benfluralin	1861-40-1	.002	Chlorpyrifos	2921-88-2	.004
Butylate	2008-41-5	.002	Diazinon	333-41-5	.002
Cyanazine	21725-46-2	.004	Dieldrin	60-57-1	.001
Dacthal	1861-32-1	.002	Disulfoton	298-04-4	.017
EPTC	759-94-4	.002	Ethoprophos	13194-48-4	.003
Ethalfuralin	55283-68-6	.004	Fonofos	944-22-9	.003
Linuron	330-55-2	.002	Lindane	58-89-9	.004
Metolachlor	51218-45-2	.002	Malathion	121-75-5	.005
Metribuzin	21087-64-9	.004	Parathion	56-38-2	.004
Molinate	2212-67-1	.004	Parathion-methyl	298-00-0	.006
Napropamide	15299-99-7	.003	cis-Permethrin	52774-45-7	.005
Pebulate	1114-71-2	.004	Phorate	298-02-2	.002
Pendimethalin	40487-42-1	.004	Propargite	2312-35-8	.013
Prometon	1610-18-0	.018	Terbufos	13071-79-9	.013
Pronamide	23950-58-5	.003	Degradation Byproducts		
Propachlor	1918-16-7	.007	2,6-Diethylaniline	579-66-8	.003
Propanil	709-98-8	.004	Deethylatrazine	6190-65-4	.002
Simazine	122-34-9	.005	alpha-HCH	319-84-6	.002
Tebuthiuron	34014-18-1	.010	p,p'-DDE	72-55-9	.006
Terbacil	5902-51-2	.007			
Thiobencarb	28249-77-6	.002			
Triallate	2303-17-5	.001			
Trifluralin	1582-09-8	0.002			

Table 4. Pesticides that constitute 10 percent or more of use by category as reported by licensed applicators but not analyzed for in all samples from all three well networks, Glassboro study area, N.J.
[Data on file at N.J. Department of Environmental Protection, Pesticide Control Program, Trenton, N.J.; percent of category shown in parentheses; --, none]

Agriculture (1994)	Lawn care (1995)	Rights-of-way (1992)	Termite control (1992)	Mosquito control (1993)	Golf-course maintenance (1993)
Herbicides					
--	2,4-D (19) Mecoprop (13) MCPA (12)	Diuron (56) Glyphosate (24)	--	--	Bensulide (12) Mecoprop (11)
Insecticides					
Sodium aluminoflur (31) Oil (20)	Trichlorfon (34)	--	Isophenphos (26)	Oil (53)	Trichlorfon (34) Bendiocarb (25)
Fungicides					
Sulfur (40) Chlorothalonil (16) Captan (15)	Chlorothalonil (38) Iprodione (12)	--	--	--	Chlorothalonil (38)

these compounds (2,4-D, MCPA, diuron, and chlorothalonil) were analyzed for in samples from the 50 shallow monitoring wells. 2,4-D, MCPA, and chlorothalonil were not detected in any of these samples and diuron was detected in only 2 (4 percent) of the 50 samples. Although these results indicate that these compounds probably would not be frequently detected in samples of shallow ground-water from the Kirkwood-Cohansey aquifer system, they may be present in samples from the moderate-depth monitoring wells, which represent the chemical quality of water that recharged the aquifer system about 15 years ago in urban areas, or in samples from the public-supply wells, which represent the chemical quality of water that is a mixture of waters of different ages that were recharged beneath various land-use settings, including agricultural areas (table 1).

Because pesticides are applied to large tracts of land in agricultural, suburban, and urban settings, pesticides generally are considered to have a diffuse or nonpoint

source. Introduction of pesticides, however, is likely a process that is intermediate between the diffuse introduction of nitrate and the predominantly point-source introduction of VOCs. For instance, whereas most agricultural fields are treated with nitrogen to enhance productivity, not all agricultural fields are treated with each pesticide compound. Rather, the application of pesticides tends to be crop- and (or) season-specific. In areas such as New Jersey where a wide variety of crops is grown, the application of pesticides also is diversified and results in diffuse, nonpoint-source introduction of contaminants characterized by alternating and overlapping application of various pesticide compounds. In addition, differences in land use may result in the introduction of different pesticide compounds (pesticides applied in urban areas may differ from those applied in agricultural settings), further increasing the type and number of pesticides introduced to the environment. Finally, accidental spills, improper disposal, and (or) the rinsing of tanks used for storing or

applying pesticides may result in the introduction of pesticides from point sources in areas otherwise dominated by nonpoint sources.

Atmospheric deposition is another potential diffuse, nonpoint source by which pesticides can be introduced to the environment. Pesticides applied at or near land surface can be introduced to the atmosphere by spray drift and (or) evaporation. The amount of a pesticide that is volatilized to the atmosphere during spray drift or by evaporation depends on many factors, including the physical and chemical properties of the pesticide, the manner in which it is applied, and weather conditions (Majewski and Capel, 1995). Recent studies indicate that, under certain conditions, 75 percent or more of a pesticide applied at land surface may be lost to the atmosphere (Majewski and Capel, 1995) and that even a small percentage of certain high-use pesticides lost to the atmosphere may constitute a substantial quantity. Once in the atmosphere, pesticides can be reintroduced to land surface through either wet (precipitation) or dry (the deposition of vapors or pesticide particles) deposition. Precipitation, therefore, can introduce pesticides in the atmosphere to land areas where they were not directly applied. Because dry deposition of pesticides and other constituents was not measured as part of this investigation, it is not discussed further in this report.

Precipitation as a potential nonpoint source of pesticides in shallow ground water in the Glassboro study area is currently being evaluated (A.L. Baehr, U.S. Geological Survey, oral commun., 1999). Thirty-four samples of precipitation collected from December 1996 to May 1999 were analyzed for the same 47 pesticide compounds as ground-water samples (table 3). Many of the pesticides detected most frequently in ground water also were detected in precipitation

samples, and at similar concentrations. The occurrence of pesticides in precipitation was seasonal, however, with most of the detections coinciding with spring and early summer pesticide applications. Samples from the 50 shallow monitoring wells were collected once during two sampling events in late summer to early winter (September-December 1996 or November 1997). These samples were collected about 10 ft below the water table and had a median apparent age of 1.4 years (fig. 5); therefore, they are inappropriate for evaluating potential seasonal fluxes of pesticides at the water table.

Physical and chemical properties that determine, in part, the likelihood that a pesticide will leach to ground water for pesticides detected in 10 percent or more of the samples from at least one of the well networks are listed in table 5. Values listed for these properties are considered approximations and may vary greatly as a result of variations in soils, climate, and other site-specific characteristics. Nonetheless, they can be used to distinguish those pesticides most likely to contaminate ground water from those least likely. Pesticides that are highly water-soluble, poorly sorbed, and highly persistent pose the greatest risk of contaminating ground water. Each pesticide in table 5 is assigned a "movement rating" based on its persistence in soil (aerobic soil half-life) and its tendency to sorb to soil (Koc) by using the formula

$$\log_{10}(\text{soil half-life}) \times [4 - \log_{10}(\text{Koc})]$$

(Vogue and others, 1994). Pesticides with movement ratings less than 1 are classified as having an extremely low potential for leaching to ground water. Pesticides with movement ratings of 1 to 2 are classified as having a low potential, 2 to 3 as having a moderate potential, 3 to 4 as having a high potential, and greater than 4 as having a very high potential to leach to ground water (Vogue and others,

Table 5. Physical and chemical characteristics of selected pesticides

[Data from U.S. Department of Agriculture (1995b) unless otherwise noted; lbs a.i./acre: pounds active ingredient per acre; mg/L, milligrams per liter; mPa, millipascals; Pa m³/mol, Pascal cubic meter per mole; log Kow, logarithm of the octanol-water partition coefficient; Kd, soil-sorption coefficient; Koc, soil-sorption coefficient normalized to organic-carbon content; °C, degrees Celsius; --, no data]

Characteristic	Pesticide								
	Atrazine	Simazine	Prometon	Metolachlor	Dieldrin	Alachlor	Terbacil	Carbaryl	Carbofuran
Application rate ¹ (lbs a.i./acre)	1.6-4	1.6-9.6	² 10-60	1.25-4	--	1-4	0.4-8	0.53-6.4	0.13-2.0
Water solubility (mg/L)	33	6.2	720	488	.14	240	710	110	350
Vapor pressure (mPa at 20-25 °C)	.038	.003	1.028	4.2	.024	2.9	4.2	.156	.082
Henry's law constant (Pa m ³ /mol at 20-25 °C)	2.5x10 ⁻⁴	9.8x10 ⁻⁵	3.2x10 ⁻⁴	2.44x10 ⁻³	.065	2.1x10 ⁻³	1.2x10 ⁻⁵	2.8x10 ⁻⁴	5.2x10 ⁻⁵
Octanol-water partition coefficient (log Kow at 20-25 °C)	2.68	2.1	2.69	2.6	3.69	2.9	1.9	2.31	1.41
Soil sorption (Kd)	.2-2.46	.48-4.31	.38-2.9	1.54-10	--	.3-3.7	.39-1.3	.44-4.69	.096-1.25
Soil sorption (Koc) median (range)	147 (38-288)	140 (103-230)	95 (32-300)	70 (22-307)	12,000 (3,982- 38,700)	124 (43-209)	63 (41-120)	288 (26-1,054)	22 (9-158)
Hydrolysis rate (per day at 20-25 °C)	Stable	Stable	Stable	Stable	1.81x10 ⁻⁴	--	Stable	.066	.0024
Photolysis rate, soil (per day at 25 °C)	.015	4.5x10 ⁻³	.026	.087	--	--	.011	--	.0154
Photolysis rate, water (per day at 25 °C)	.002	1.8x10 ⁻³	Stable	.0097	--	.058	Stable	.0154	.124
Aerobic soil half- life (days)	146	91	932	26	³ 1,000	³ 15	520	17	³ 50
Anerobic soil half- life (days)	77	58	557	37	--	--	--	46	--
Movement rating ³	High	High	Very high	High	Extremely low	Moderate	Very high	Low	Very high

¹U.S. Geological Survey (1999)

²Capel and others (1999)

³Vogue and others (1994)

1994). Additional factors, such as current and historical use patterns, the classification of a pesticide as a general- or restricted-use compound, and other physical and chemical properties, most notably water solubility, may also be important in determining the likelihood that a pesticide will leach to ground water. Like the values listed for individual properties in table 5, each pesticide's movement rating is only an approximation and can appropriately be used only to distinguish those pesticides most likely to leach to ground water from those least likely.

Soil and aquifer characteristics that affect the movement of pesticides and other contaminants include soil texture, organic-matter content, number and size of pores in the soil, and depth to water from the land surface. A coarse-textured (sandy) soil low in organic matter will allow pesticides to move easily from the land surface to the underlying aquifer. Pesticides are more likely to reach ground water if the water table is shallow than if it is deep. Soils in the study area generally consist of sandy loams with organic-matter contents less than 1 percent (U.S. Department of Agriculture, 1995), and the organic-matter content of sediments in the unsaturated zone beneath the soil zone is likely even less. The average depth to water in the Glassboro study area is only about 15 ft; therefore, the Kirkwood-Cohansey aquifer system is considered to be vulnerable to contamination from pesticides and other chemicals introduced at or near land surface.

One or more pesticides were detected in 75 to 80 percent of samples from each of the three well networks. Concentrations, however, generally were low (less than 1.0 µg/L). The high detection frequencies result, in part, from the sensitive analytical methods recently developed by the USGS, which allow for the measurement of pesticide concentrations of 0.01 µg/L and less (Zaugg and others, 1995).

Ten pesticide or pesticide-degradation byproducts were detected in 10 percent or more of samples from at least one well network; these include atrazine, deethylatrazine, simazine, prometon, metolachlor, dieldrin, alachlor, terbacil, carbaryl, and carbofuran (table 6). The use of these pesticides (except deethylatrazine, a degradation byproduct) in New Jersey, as reported by licensed applicators, is listed in table 2.

Five of these pesticides (atrazine, simazine, metolachlor, dieldrin, and alachlor) are classified by the USEPA as probable or possible human carcinogens, and four (atrazine, simazine, alachlor, and carbofuran) have been assigned MCLs by the USEPA. Although enforceable Federal drinking-water regulations in the form of MCLs do not currently exist for deethylatrazine, metolachlor, prometon, dieldrin, terbacil, or carbaryl, four of these pesticides (metolachlor, prometon, terbacil, and carbaryl) have been assigned lifetime health advisories (HALs) by the USEPA. A HAL is the concentration of a chemical in drinking water that is not expected to cause any adverse carcinogenic effects over a lifetime (70 years) of exposure, with a margin of safety (U.S. Environmental Protection Agency, 1996). None of the samples contained a pesticide at a concentration greater than an established MCL or HAL (table 6).

Five of these pesticides (atrazine, simazine, dieldrin, alachlor, and carbofuran) have been assigned Ground Water Quality Criteria (GWQC) by the NJDEP (table 6). GWQCs are concentrations that, when not exceeded, will not prohibit or significantly impair the use of ground water for potable water or conversion to potable water through conventional water treatment (N.J. Department of Environmental Protection, 1999). GWQCs are human-health risk-based criteria based on the available evidence regarding each constituent's carcinogenicity or toxicity, as

Table 6. Concentrations and detection frequencies of the most frequently detected pesticides in samples from all three well networks, Glassboro study area, N.J. [$\mu\text{g/L}$, micrograms per liter; --, not established; <, less than; MRL, minimum reporting level; E, estimated concentration; MCL, maximum contaminant level; HAL, lifetime health advisory; B, probable human carcinogen; C, possible human carcinogen; D, not classifiable as to human carcinogenicity; E, no evidence of carcinogenicity in humans]

Compound	Common name	MRL ($\mu\text{g/L}$)	Percentage of wells in which compound was detected	Median detected concentration ($\mu\text{g/L}$)	Maximum detected concentration ($\mu\text{g/L}$)	Carcinogenic potential	Human health advisory ($\mu\text{g/L}$)	Ground- water quality criterion ($\mu\text{g/L}$)	Aquatic- life criterion ($\mu\text{g/L}$)
Herbicides									
Atrazine	AAtrex, Gesaprim	0.001	43.6	0.004	0.117	C	¹ ₃	3	³ ₂
Simazine	Aquazine, Princep, GESatop, Weedex	.005	36.4	.0225	.629	C	¹ ₄	1	³ ₁₀
Metolachlor	Dual, Pennant	.002	26.4	.004	.671	C	² ₇₀	--	³ ₈
Prometon	Gesagram, prometone	.018	19.1	.0446	4.83	D	² ₁₀₀	--	--
Terbacil	Sinbar	.007	7.3	.055	.0978	E	² ₉₀	--	--
Alachlor	Lasso	.002	6.4	.0109	.0671	B	¹ ₂	.43	--
Degradation byproducts									
Atrazine, deethyl-	Atrazine metabolite	.002	40.9	.003	.0694	--	--	--	--
Insecticides									
Dieldrin	Panoram D-31, Octalox, Compound 497	.001	24.5	.016	5.6	B	--	.002	⁴ ₀₆₂₅
Carbofuran	Furadan, Curaterr, Yaltox	.003	4.5	.0128	.173	E	¹ ₄₀	40	³ _{1.75}
Carbaryl	Sevin, Savit	.003	6.4	.0243	.781	D	² ₇₀₀	--	--

¹MCL (U.S. Environmental Protection Agency, 1996)

²HAL (U.S. Environmental Protection Agency, 1996)

³Canadian or Canadian interim aquatic-life criterion (Canadian Council of Resource and Environment Ministers, 1996)

⁴USEPA aquatic-life criterion (U.S. Environmental Protection Agency, 1986)

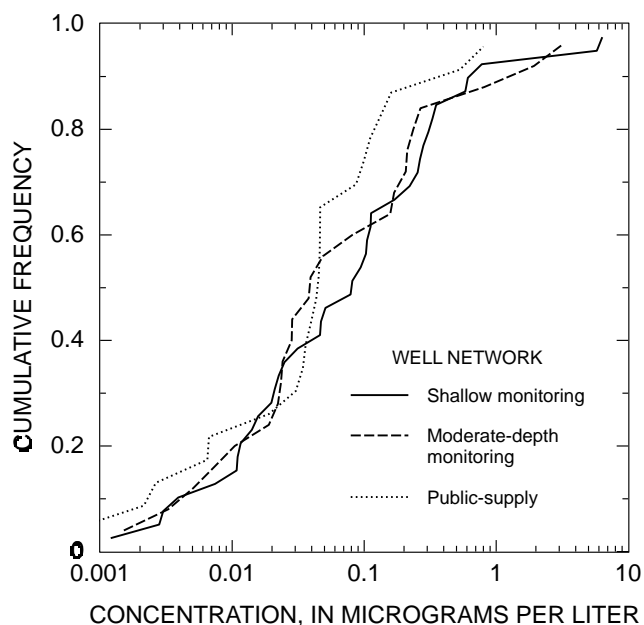


Figure 8. Cumulative frequency of pesticide concentrations in water samples from all three well networks, Glassboro study area, N.J.

appropriate for the protection of potable-water use. Because GWQCs are risk-based criteria, they sometimes are set at concentrations less than the analytical capabilities of routine laboratory procedures. In such cases a default standard is established at the practical quantitation limit (PQL), which is the lowest concentration that can reliably be quantitated using routine laboratory procedures. Sampling and analytical methods recently developed by the USGS allow for the quantitation of pesticides in water samples at concentrations relevant to risk-based GWQCs. Dieldrin was the only pesticide compound detected at concentrations greater than its established GWQC (table 6).

Five of these pesticides also have been assigned aquatic-life criteria by either the USEPA or the Canadian Council of Resource and Environment Ministers. An aquatic-life criterion is the estimated highest concentration of a chemical that aquatic organisms can be

exposed to for a 4-day period, once every 3 years, without deleterious effects. Aquatic-life criteria are included in table 6 because most of the base flow in streams in southern New Jersey is derived from ground-water discharge. Consequently, aquatic communities and surface-water resources are affected by the chemical quality of ground water. Dieldrin was detected at concentrations greater than its established aquatic-life criterion (table 6).

Cumulative distributions of total pesticide concentrations in samples from the three well networks are shown in figure 8. This figure was developed as described in the discussion of nitrate. For each sample, the total pesticide concentration was calculated by summing the concentrations of each pesticide detected. Samples in which no pesticides were detected were assigned a concentration of zero. No pesticide-concentration data suitable for comparison with those collected as part of this investigation were available for public-supply wells outside the Glassboro study area.

The median total pesticide concentration for samples from the shallow and moderate-depth monitoring and public-supply wells was 0.02, 0.026, and 0.035 µg/L, respectively; the median number of pesticides per sample was 2, 1, and 1, respectively; and the maximum number of pesticides per sample was 9, 5, and 7, respectively. Results of ANOVA on the rank-transformed number and total concentration of pesticides per sample indicate that the mean ranked number and mean ranked total concentration of pesticides per sample were statistically similar among all three well networks at a 95-percent confidence level. Nevertheless, detection frequencies for individual pesticide compounds differed substantially among the networks as a result of differences in their use and physical and chemical properties and in source-area and well-type characteristics.

Atrazine and simazine, both widely used herbicides, and the atrazine degradation byproduct deethylatrazine were detected in 24 to 50 percent of samples from the three well networks (fig. 9; app. 2). Reactions such as photolysis and hydrolysis do not account for a substantial loss of atrazine or simazine in the environment (table 5). Both compounds are moderately persistent in aerobic and anaerobic soils and have a low tendency to sorb to soil particles on both a mass basis and an organic-carbon-normalized basis and, thus, have high movement ratings (table 5). Atrazine, however, is more soluble than simazine (table 5), and the usage patterns of these compounds differ.

Atrazine is a restricted-use pesticide and, as such, may be purchased and used only by licensed applicators. Atrazine use by licensed applicators in New Jersey is almost exclusively for the control of weeds in agricultural settings, where it constitutes about 10 percent of total herbicide use (table 2). Atrazine was detected at concentrations greater than 0.01 µg/L more frequently in samples from public-supply wells than in samples from the monitoring-well networks (fig. 9), reflecting atrazine's primary use for agricultural purposes and the greater amount of agricultural land in areas contributing water to public-supply wells than in areas contributing water to the monitoring wells (table 1). Overall, however, detection frequencies for atrazine were greater in samples from the monitoring-well networks, which are located in urban and suburban areas. Some monitoring wells, however, are installed in areas that were previously agricultural. Also, prior to 1993, atrazine was approved for the control of weeds in non-cropland areas and may have been used to control weeds in rights-of-way (U. S. Environmental Protection Agency, 1998c). Minor amounts of atrazine use in New Jersey were reported for lawn maintenance in 1995 and right-of-way maintenance in 1992 (table 2). Atrazine also has been detected in samples of precipitation

from the Glassboro study area and, although detections were seasonal and associated with spring and early summer applications, concentrations were similar to those detected in shallow ground water (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.). Thus, the higher detection frequency for atrazine in monitoring wells, which are located in areas where there is little current reported atrazine use, may reflect relict land-use patterns, relict atrazine-use patterns, and (or) wet deposition.

Unlike atrazine, simazine is a general-use pesticide and, as such, its purchase and use is not restricted to licensed applicators. The use of simazine by non-licensed applicators was not documented for this report; use by licensed applicators in New Jersey is primarily for agricultural weed control, lawn maintenance, and the clearing of vegetation along urban rights-of-way (table 2). Simazine detection patterns were similar to those of atrazine; detection frequency was highest (46 percent) in the shallow monitoring wells, 33 percent in the moderate-depth monitoring wells, and 24 percent in the public-supply wells (fig. 9). Despite simazine's low solubility (table 5), the percentage of samples with detections greater than 0.01 µg/L was higher for simazine than for any other pesticide and highest in samples from the shallow monitoring wells (fig. 9). This result can be attributed to the dual use of simazine in suburban and urban as well as agricultural areas and its status as a general-use pesticide, which allows for its use by non-licensed applicators. Simazine also has been detected in samples of precipitation from the Glassboro study area during the spring and early summer months at concentrations similar to those detected in shallow ground water (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.); thus, precipitation also may be a diffuse, low-level source of simazine in the Kirkwood-Cohansey aquifer system.

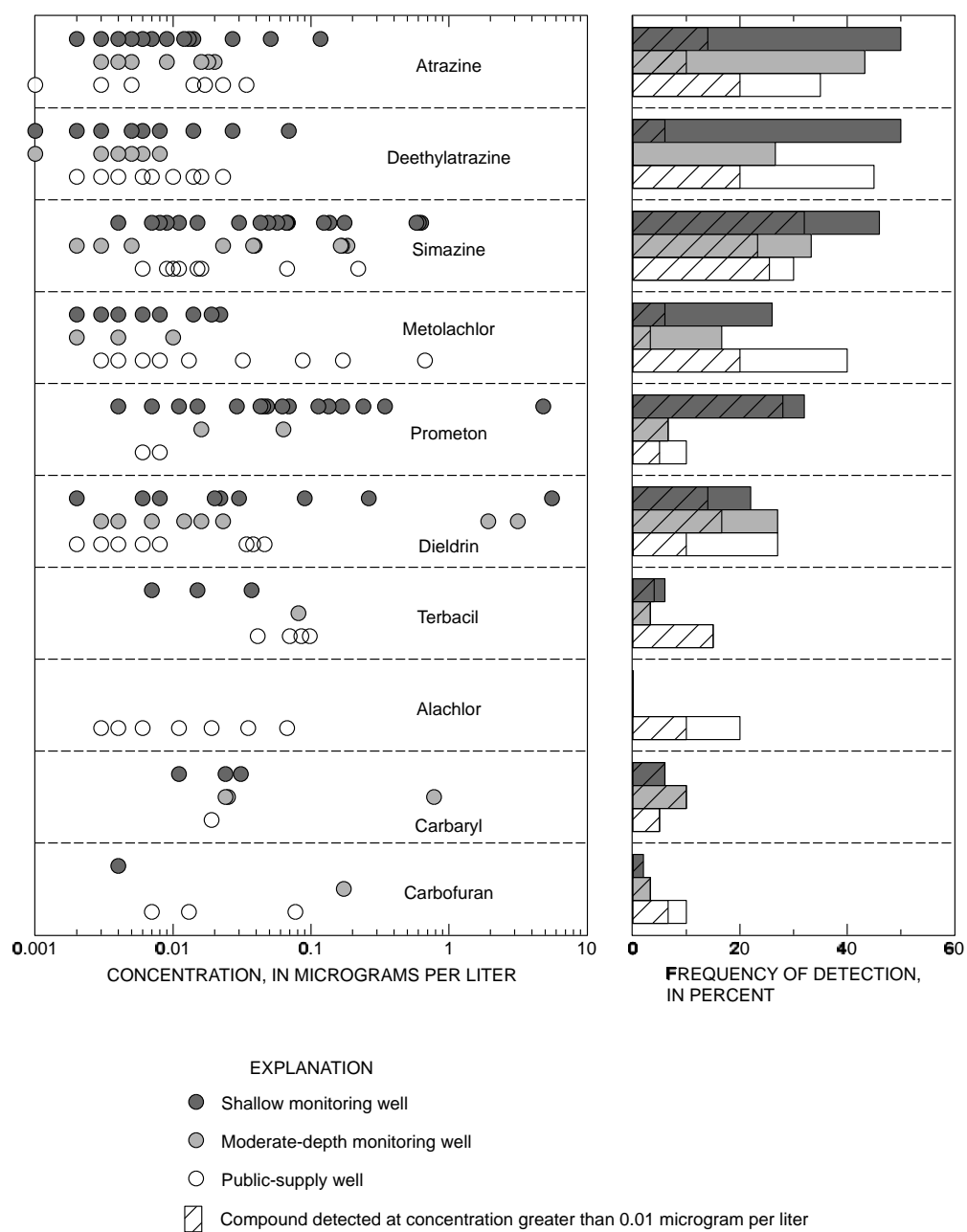


Figure 9. Concentration and frequency of detection of selected pesticides in water samples from all three well networks, Glassboro study area, N.J.

Prometon is a general-use, non-selective herbicide used in areas where total vegetation control is desired (for example, roadway, railway, and utility rights-of-way). Typical application rates for prometon are greater than those for the other frequently detected pesticides (table 5). Prometon is persistent in both aerobic and anaerobic soils and is poorly sorbed to soil particles; therefore, it has a very high movement rating (table 5). Prometon is also highly water-soluble and loss due to photolysis or hydrolysis reactions is not significant (table 5). A detailed discussion of the environmental occurrence and behavior of prometon is available in Capel and others (1999).

Non-licensed applications of prometon were not documented for this study. Use of prometon by licensed applicators in New Jersey is primarily for lawn maintenance and to control weed growth along rights-of-way and in non-cropland agricultural settings (table 2). Prometon also is mixed with or applied beneath asphalt to control the growth of weeds through asphalt surfaces. The amount of prometon applied in any given use category by registered applicators is, however, relatively small and constitutes less than 1 percent of total herbicide use (table 2). In addition, prometon was detected in only 1 of 34 samples of precipitation collected in the Glassboro study area, indicating that precipitation is an unlikely source of prometon detected in shallow ground water (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.).

Despite its limited use by licensed applicators and its infrequent detection in precipitation, prometon was one of the most frequently detected pesticides in samples from the shallow-monitoring wells and was second only to simazine with respect to the percentage of samples in which concentrations were greater than 0.01 µg/L (fig. 9; app. 2). The high

detection frequency and concentration per sample likely reflect both the use of prometon by non-licensed users and its solubility and mobility. Prometon's detection frequency in samples from the moderate-depth monitoring and public-supply wells, however, was 10 percent or less. The reason for this result is unclear but may be related to changes in usage patterns. For example, the most recently compiled pesticide-use data for lawn maintenance and the control of weeds along rights-of-way is for the early to mid-1990's (table 2). Samples from a subset of the shallow and moderate-depth monitoring wells had median apparent ages of 1.4 and 14 years, respectively, and results of ground-water flow simulation indicate that the public-supply wells withdraw water ranging in age from less than 3 to more than 180 years, with a median age of 19 years (fig. 5). Thus, if the use of prometon has increased substantially since the mid-1990's, this compound would most likely be detected more frequently in samples from the shallow monitoring wells than in those from the moderate-depth monitoring or public-supply wells. If prometon is detected most frequently in samples from the shallow monitoring wells as a result of changes in use, then detection frequencies in moderate-depth monitoring and public-supply wells will likely increase with time.

Metolachlor is a general-use herbicide that is widely used to control the growth of weeds in agricultural settings and, to a smaller extent, in lawn maintenance and to control weed growth along rights-of-way. Although metolachlor is only moderately persistent in soils, it does not sorb strongly to soil particles and, thus, has a high movement rating (table 5). Metolachlor is also highly water-soluble and loss due to hydrolysis or photolysis reactions is not substantial (table 5).

Non-licensed applications of metolachlor were not documented for this study. Use of

metolachlor by licensed applicators in New Jersey is primarily for agricultural purposes. Agricultural use nearly doubled from the mid-1980's to the early 1990's; currently (mid-1990's) it accounts for more than 25 percent of total agricultural herbicide use (table 2). The detection frequency and percentage of samples with concentrations greater than 0.01 µg/L were greatest for the public-supply wells (fig. 9; app. 2), reflecting metolachlor's primary use for agricultural purposes and the greater amount of agricultural land in areas contributing water to the public-supply wells than in areas contributing water to the monitoring wells (table 1). Metolachlor also was detected frequently in samples from the monitoring wells, however, reflecting its secondary use for lawn and golf-course maintenance and its status as a general-use herbicide, which allows for its use by non-licensed applicators. The detection of metolachlor in some monitoring wells also may reflect relict agricultural land use. Finally, metolachlor was detected in 50 percent of samples of precipitation collected in the Glassboro study area at concentrations similar to those detected in shallow ground water (unpublished data on file at the U.S. Geological Survey office in West Trenton, N.J.). Precipitation, therefore, is a potential nonpoint source of metolachlor in the shallow Kirkwood-Cohansey aquifer system.

Dieldrin is an organochlorine insecticide used historically to control termites in residential and commercial settings and, to a smaller extent, to control insects in agricultural settings. Aldrin, an insecticide that is closely related to dieldrin chemically and that readily degrades to dieldrin in the environment, was used historically for similar purposes. Agricultural uses of aldrin and dieldrin were banned by the USEPA between 1975 and 1980 because of cancer risks, and use of these compounds as termiticides was banned in 1984 (Ware, 1989). Neither dieldrin nor aldrin is

currently manufactured in, or imported into, the United States. Accordingly, no use of dieldrin by licensed applicators in New Jersey has been reported since the mid-1980's (table 2). Although dieldrin has a relatively long aerobic soil half-life, it is strongly sorbed to soil particles and, thus, has an extremely low movement rating (table 5). Dieldrin is also practically insoluble in water (table 5) but, once dissolved, it is highly persistent, as demonstrated by its consistent detection frequency and the relatively high percentage of samples in which concentrations were greater than 0.01 µg/L (fig. 9; app. 2) nearly 15 years after all uses of dieldrin and aldrin were banned. Dieldrin was detected in 22, 27, and 27 percent of samples from the shallow and moderate-depth monitoring and public-supply wells, respectively, and three of the six highest pesticide concentrations reported among the three well networks were for dieldrin (fig. 9). This high detection frequency seemingly contradicts dieldrin's extremely low movement rating and illustrates the variation in movement potential that can result from variations in persistence and sorption due to soil, climate, and other site-specific conditions. For example, dieldrin sorbs most strongly to organic matter in soils. Soils in the study area generally contain little organic matter; the 25th-, 50th-, and 75th-percentile organic-matter contents are 0.42, 0.47, and 0.63 percent by weight, respectively (U. S. Department of Agriculture, 1995). Because the ability of dieldrin to sorb to soils in the study area may be overestimated, its actual movement potential may be greater than that indicated by its movement rating.

In all samples in which dieldrin was detected, concentrations were at or above the GWQC of 0.002 µg/L, yet most (67 percent) were less than the PQL of 0.03 µg/L. This result demonstrates the usefulness of improved sampling and analytical methods recently developed by the USGS in refining measurements of the occurrence and

distribution of pesticides in the environment and in providing data needed to evaluate the risks posed by the occurrence of selected pesticides. Although an MCL currently does not exist for dieldrin, a known human carcinogen, concentrations in more than 18 percent of the samples in which dieldrin was detected were above the aquatic-life standard (table 6).

Alachlor is a restricted-use herbicide used to control the growth of weeds in agricultural settings. Although reported use of alachlor by licensed applicators in New Jersey is exclusively for agricultural purposes, use of this compound declined 50 percent from the mid-1980's to the early 1990's (table 2). Alachlor does not sorb strongly to soil particles but is not persistent in soils; therefore, it has a moderate movement rating (table 5). Alachlor is water-soluble (table 5). It was detected exclusively in samples from the public-supply wells, reflecting its restricted-use status as an agricultural herbicide and its widespread historical use. Areas that contribute water to public-supply wells contain more agricultural land than areas that contribute water to monitoring wells (table 1). In addition, public-supply wells intercept water flowing along longer paths associated with longer residence times (fig. 5), which therefore is more likely to contain pesticides such as alachlor that were used in greater quantities in the past. Alachlor was detected in 8 (23.5 percent) of 34 samples of precipitation collected in the Glassboro study area; however, its absence from samples of shallow ground water indicates that precipitation is not a likely source of alachlor in ground water.

Terbacil is a general-use herbicide used primarily to control weeds in agricultural settings. The use of terbacil by non-licensed applicators was not documented for this report. All reported use of terbacil by licensed applicators in New Jersey was for agricultural

purposes; however, the use of terbacil by licensed applicators has declined steadily since the late 1980's (table 2). Terbacil has a long aerobic soil half-life and does not sorb strongly to soil particles; therefore its movement rating is very high (table 5). Terbacil also is highly water-soluble (table 5). Terbacil was detected most frequently and at the highest concentrations in samples from the public-supply wells, reflecting (1) its primary use for agricultural purposes; (2) the greater amount of agricultural land in areas contributing water to public-supply wells than in areas contributing water to the monitoring wells (table 1); (3) the larger component of older ground water withdrawn from public-supply wells (fig. 5), which recharged the aquifer system when terbacil use was more prevalent than it is currently; and (4) its persistence and mobility. Detection of terbacil in water from the monitoring-well networks likely reflects relict agricultural land use and (or) this compound's status as a general-use herbicide, which allows for its use by non-licensed applicators. Terbacil was not detected in any of the 34 samples of precipitation collected in the Glassboro study area; therefore, precipitation is not a likely source of terbacil in shallow ground water in the study area.

Carbaryl is a general-use insecticide used to control insects in agricultural settings; in forest, lawn, and golf-course maintenance; and on poultry, livestock, and pets. Use of carbaryl by non-licensed applicators was not documented for this report. Reported use of carbaryl by licensed applicators in New Jersey was for agricultural purposes and lawn and golf-course maintenance (table 2). Carbaryl has a low persistence in soil and is moderately to strongly sorbed to soil particles; therefore, it has a low movement rating (table 5). Nonetheless, carbaryl was detected in samples from the shallow and moderate-depth monitoring wells at a frequency of 10 and 6 percent, respectively, and also was detected,

although less frequently, in samples from the public-supply wells (fig. 9; app. 2). Detection of carbaryl in water from the three well networks at low frequencies reflects its dual use for agricultural and non-agricultural purposes and its low movement rating. Carbaryl was detected in 11 (32 percent) of the 34 samples of precipitation collected in the Glassboro study area, at concentrations similar to those detected in shallow ground water. Thus, precipitation may be an additional source of carbaryl in shallow ground water in the study area.

Carbofuran is a restricted-use insecticide used to control insects in agriculture and forest management. Reported use of carbofuran by licensed applicators in New Jersey was exclusively for agricultural purposes; however, the amount applied has declined steadily since the mid-1980's (table 2). Carbofuran is moderately persistent in soils and does not sorb strongly to soil particles; therefore, it has a very high movement rating (table 5). Carbofuran also is highly soluble in water (table 5). Carbofuran was detected most frequently in samples from the public-supply wells, demonstrating its persistence and mobility, its primary use for agricultural purposes (table 2), and the greater amount of agricultural land in areas contributing water to the public-supply wells than in areas contributing water to the monitoring wells (table 1). The infrequent detection of carbofuran in water from the monitoring wells reflects the general absence of agricultural land in areas contributing water to the monitoring wells and the declining use of this pesticide over the last 15 years. Carbofuran was detected in only 1 of the 34 samples of precipitation; therefore, precipitation is not a likely source of carbofuran in shallow ground water in the Glassboro study area.

Volatile Organic Compounds

VOCs are a class of organic compounds that have a multitude of uses. VOCs are

present in fuels and the exhaust from their combustion, and in common household products, such as air fresheners, bathroom deodorants, cleaning and polishing products, paints, solvents, and adhesives. They also are widely used in industrial applications as solvent degreasers and refrigerants, in the dry-cleaning industry, in the manufacture of pharmaceutical products and plastics, and in agricultural applications as active and inactive components of pesticides and fumigants (Bloemen and Burn, 1993; Smith and others, 1988; Verschueren, 1983). Amounts of selected VOCs produced within the United States, as reported to the U. S. International Trade Commission (USITC), for selected years from 1930 to 1994 are listed in table 7. Because producers report data on organic chemicals to the USITC only for those compounds whose production or sales exceed established minimum thresholds, the data are not available for each compound for each year. In addition, the USITC does not publish statistics on production values for individual compounds if doing so might disclose the operations of individual producers. Although values listed in table 7 are for overall production amounts within the United States and do not take into account the potential import and (or) export of individual compounds, they provide a general indication of both historical trends in the production and use of selected VOCs and of the quantities of these compounds currently being produced.

Concentrations of 87 VOCs in samples from the three well networks were measured to determine the occurrence, distribution, and concentration of VOCs in the Kirkwood-Cohansey aquifer system in the Glassboro study area (table 8). VOCs were selected for analysis because they (1) are found on one or more regulatory lists (for example, Safe Drinking Water Act, Clean Water Act), (2) are associated with effects on human health and (or) that of aquatic communities, (3) may

Table 7. Production amounts of selected volatile organic compounds for selected years from 1930 to 1994, as reported to the U.S. International Trade Commission
[Data from U.S. International Trade Commission (1930-94); values in million pounds per reported year; values are rounded; --: no data; NP: separate statistics not published to avoid disclosure of individual company operations]

Compound	1930	1940	1950	1960	1965	1970	1975	1980	1985	1986	1987	1988	1989	1991	1992	1993	1994
Chloroform	2.5	3.1	20.3	76.4	153	240	262	353	275	422	462	524	588	505	NP	476	¹ 480
Tetrachloroethene	--	--	--	209	429	707	679	765	678	414	473	498	481	240	245	¹ 292	247
1,1,1-Trichloroethane	--	--	--	--	--	366	459	692	869	652	694	724	783	644	692	452	¹ 366
Trichloroethene	--	--	--	353	435	611	293	266	--	--	--	--	--	² 320	NP	NP	NP
Methyl tert-butyl ether	--	--	--	--	--	--	--	706	1,891	3,375	3,514	5,680	8,229	8,503	8,945	11,839	11,033
1,4-Dichlorobenzene	5.5	15.1	49.1	64	65.8	69.6	45.7	75.0	--	81.5	103	--	--	--	NP	72	79
1,2-Dichlorobenzene	--	5.8	17.4	24.7	41.1	66.2	54.6	48.7	--	41.0	--	--	--	43.3	34.0	35	34
Trichlorofluoromethane	--	--	--	72.4	170	244	270	158	176	202	198	249	193	99	278	72	¹ 16
Carbon tetrachloride	34.3	101	217	372	594	1,012	906	710	646	627	672	761	--	315	NP	NP	NP
Benzene	--	--	--	2,266	5,203	7,675	7,019	14,322	8,251	8,860	10,588	11,627	11,938	11,486	11,268	12,232	14,222
Chlorobenzene	2.9	4.9	383	605	546	485	306	283	--	223	246	271	295	210	232	195	219
1,2-Dibromoethane	--	--	--	--	--	297	275	--	--	--	--	--	--	--	--	--	--
Chloromethane	--	3.0	27.0	84.1	188	423	366	362	1,174	605	373	597	461	916	966	1,053	999
Carbon disulfide	--	--	426	523	756	721	479	377	--	--	--	--	--	--	³ 207	NP	NP

¹ Sales amount

² U.S. Environmental Agency, 1998f

³ U.S. Environmental Agency, 1994b

Table 8. Volatile organic compounds analyzed for in samples from all three well networks, Glassboro study area, N.J.

[CAS, Chemical abstract service number; MRL, minimum reporting level; µg/L, micrograms per liter]

Compound	CAS	MRL (µg/L)	Compound	CAS	MRL (µg/L)
1,1,1,2-Tetrachloroethane	630-20-6	0.044	4-Chlorotoluene	106-43-4	.056
1,1,1-Trichloroethane	71-55-6	.032	4-Isopropyl-1-methylbenzene	99-87-6	.11
1,1,2,2-Tetrachloroethane	79-34-5	.132	4-Methyl-2-pentanone	108-01-1	.374
1,1,2-Trichloroethane	79-00-5	.064	Acetone	67-64-1	4.9
1,1,2-Trichlorotrifluoroethane	76-13-1	.092	Acrolein	107-02-8	1.43
1,1-Dichloroethane	75-34-3	.066	Acrylonitrile	107-13-1	1.23
1,1-Dichloroethylene	75-35-4	.044	Benzene	71-43-2	.032
1,1-Dichloropropene	563-58-6	.026	Bromobenzene	108-86-1	.036
1,2,3,4-Tetramethylbenzene	488-23-3	.23	Bromochloromethane	74-97-5	.044
1,2,3,5-Tetramethylbenzene	527-53-7	.24	Bromodichloromethane	75-27-4	.048
1,2,3-Trichlorobenzene	87-61-6	.266	Bromoform	75-25-2	.104
1,2,3-Trichloropropane	96-18-4	.07	Bromomethane	74-83-9	.148
1,2,3-Trimethylbenzene	526-73-8	.124	Butylbenzene	104-51-8	.186
1,2,4-Trichlorobenzene	120-82-1	.188	Carbon disulfide	75-15-0	.08
1,2,4-Trimethylbenzene	95-63-6	.056	Chlorobenzene	108-90-7	.028
1,2-Dibromo-3-chloropropane	96-12-8	.214	Chloroethane	75-00-3	.12
1,2-Dibromoethane	106-93-4	.036	Chloroform	67-66-3	.052
1,2-Dichlorobenzene	95-50-1	.048	Chloromethane	74-87-3	.254
1,2-Dichloroethane	107-06-2	.134	Dibromochloromethane	124-48-1	.182
1,2-Dichloropropane	78-87-5	.068	Dibromomethane	74-95-3	.05
1,3,5-Trimethylbenzene	108-67-8	.044	Dichlorodifluoromethane	75-71-8	.096
1,3-Dichlorobenzene	541-73-1	.054	Dichloromethane	75-09-2	.382
1,3-Dichloropropane	142-28-9	.116	Diethyl ether	60-29-7	.17
1,4-Dichlorobenzene	106-46-7	.05	Diisopropyl ether	108-20-3	.098
2,2-Dichloropropane	594-20-7	.078	Ethyl methacrylate	97-63-2	.278
2-Butanone	78-93-3	1.65	Ethyl tert-butyl ether	637-92-3	.054
2-Chlorotoluene	95-49-8	.042	Ethylbenzene	100-41-4	.03
2-Hexanone	591-78-6	.746	Hexachlorobutadiene	87-68-3	.142
3-Chloropropene	107-05-1	.196	Hexachloroethane	67-72-1	.362

Table 8. Volatile organic compounds analyzed for in samples from all three well networks, Glassboro study area, N.J.--Continued

Compound	CAS	MRL (µg/L)
Isopropylbenzene	98-82-8	0.032
Methyl acrylate	96-33-3	.612
Methyl acrylonitrile	126-98-7	.570
Methyl iodide	74-88-4	.076
Methyl methacrylate	80-62-6	.350
Naphthalene	91-20-3	.250
Propylbenzene	103-65-1	.042
Styrene	100-42-5	.042
Tetrachloroethylene	127-18-4	.038
Tetrachloromethane	56-23-5	.088
Tetrahydrofuran	109-99-9	1.150
Toluene	108-88-3	.038
Trichloroethylene	79-01-6	.038
Trichlorofluoromethane	75-69-4	.032
Vinyl bromide	593-60-2	.100
Vinyl chloride	75-01-4	.112
cis-1,2-Dichloroethylene	156-59-2	.038
cis-1,3-Dichloropropene	10061-01-5	.092
m- and p-Xylene	jdjdj	.064
o-Ethyl toluene	611-14-3	.100
o-Xylene	95-47-6	.064
sec-Butylbenzene	135-98-8	.048
tert-Butyl methyl ether	1634-04-4	.112
tert-Butylbenzene	98-06-6	.096
tert-Pentyl methyl ether	994-05-8	.112
trans-1,2-Dichloroethylene	156-60-5	.032
trans-1,3-Dichloropropene	10061-02-6	.134
trans-1,4-Dichloro-2-butene	110-57-6	.692

promote ozone depletion and (or) be subject to aquatic bioaccumulation, and (or) (4) are used as fuel oxygenates (Bender and others, 1999). In addition, these compounds are amenable to determination with purge-and-trap gas-chromatography/mass- spectrometry analytical methods.

Unlike nitrate and pesticides, VOCs typically are introduced to aquifer systems from point sources such as leaking storage tanks, leachate from landfills, accidental spills, and improper disposal of products containing VOCs. Potential nonpoint sources of VOCs include the atmosphere and urban stormwater runoff, but these sources are considered to be less prevalent than point sources. As a result of their volatility, VOCs can evaporate readily and thus be introduced to the atmosphere, where they are dispersed and diluted by wind. Once in the atmosphere VOCs can partition to rain and subsequently be reintroduced to land surface through precipitation. Infiltration of precipitation to the subsurface represents a potential widespread (nonpoint) source of VOCs to shallow ground water. The atmosphere as a potential nonpoint source of low-level concentrations of VOCs in shallow ground water in the Glassboro study area was evaluated by Baehr and others (1999a). Their findings indicate that, except for MTBE, concentrations of VOCs detected in the atmosphere were insufficient to account for their occurrence in shallow ground water and, therefore, their occurrence in ground water must be attributed to other point and (or) nonpoint sources.

Delzer and others (1996) evaluated urban stormwater runoff as a potential nonpoint source of VOCs in shallow ground water across the Nation. Their findings indicate that urban stormwater runoff frequently contains VOCs, especially those associated with fuels, and that it is therefore a potential nonpoint

source of VOCs in shallow ground water underlying urban areas.

The potential for VOCs to contaminate ground water, like that for pesticides, depends not only on their use and release into the environment but also on their physical and chemical characteristics, their susceptibility to biodegradation, and the characteristics of the soil and aquifer material they penetrate. Physical and chemical properties that may partly determine the likelihood that a VOC will contaminate ground water are listed in table 9 for VOCs detected in more than 10 percent of samples from at least one of the well networks. Values of these properties, like those given earlier for pesticides, are considered to be approximations and may vary greatly as a result of variations in soils, climate, and other site-specific characteristics; nonetheless, they can be used to distinguish those VOCs most likely to persist within the subsurface from those least likely to persist. VOCs that are highly water-soluble, poorly sorbed, and most recalcitrant pose the greatest risk of contaminating and persisting in ground water.

One or more VOCs were detected in more than 90 percent of samples from each of the three well networks. Concentrations, however, generally were low (less than 1 µg/L). Detection frequencies were high, in part, as a result of the sensitive analytical methods recently developed by the USGS, which allow for the determination of VOCs at concentrations of 0.1 µg/L and less (Connor and others, 1998). Nineteen VOCs were detected in more than 10 percent of samples from at least one of the well networks (table 10). Eight of these VOCs are classified by the USEPA as known, probable, or possible human carcinogens, and 14 have been assigned MCLs by the USEPA (table 10). In addition, the NJDEP has established MCLs for nine of these compounds that are more stringent than the Federal regulations (table 10).

Tetrachloroethene, trichloroethene, cis-1,2-dichloroethene, and 1,2-dibromoethane were detected in one or more samples at concentrations exceeding an established Federal and (or) State MCL. Although enforceable Federal or State drinking-water regulations in the form of MCLs do not currently exist for methyl tert-butyl ether (MTBE), 1,1-dichloroethane, trichlorofluoromethane, or carbon disulfide, HALs have been established or proposed for three of these compounds (table 10). Chloroform is regulated on the basis of the sum of the concentration of itself and three other trihalomethanes: bromodichloromethane, chlorodibromomethane, and tribromomethane. The sum of these constituent concentrations cannot exceed 100 µg/L (U.S. Environmental Protection Agency, 1996). Only MTBE was detected at a concentration that exceeded the lower limit of a proposed HAL. Fourteen of these VOCs have been assigned GWQCs by the NJDEP, and three (tetrachloroethene, cis-1,2-dichloroethene, and benzene) were detected in one or more samples at concentrations exceeding the GWQC. Finally, of the nine compounds that have been assigned aquatic-life criteria by the Canadian Council of Resource and Environment Ministers (table 10), only chloroform was detected at a concentration that exceeded the criteria.

The cumulative distribution of total VOC concentrations in samples from the three well networks is shown in figure 10. This figure was developed as described in the discussion of nitrate. For each sample, the total VOC concentration was calculated by summing the concentrations of all detected VOCs. Samples in which no VOCs were detected were assigned a total concentration of zero. Figure 10 also shows the cumulative distribution of available VOC concentrations in water from 26 public-supply wells throughout the Kirkwood-Cohansey outcrop area. These data are included to compare the total VOC concentrations in

Table 9. Physical and chemical properties of selected volatile organic compounds

[Pa m³/g mol, Pascals cubic meter per gram mole; °C, degrees Celsius; mm Hg, millimeters of mercury; mg/L, milligrams per liter; log Kow, logarithm of the octanol-water partition coefficient; Koc, soil-sorption coefficient; --, no data; <, less than]

Compound	Henry's law constant ¹ (Pa m ³ /g mol, 25 °C)	Vapor pressure (mm Hg, 20-30 °C)	Log Kow	Solubility (mg/L, 20-25 °C)	Koc
Chloroform	--	159	1.97	--	--
Tetrachloroethene	1,790	18.5	3.40	150	210-238
1,1,1-Trichloroethane	1,700	100	2.49	4,400	81-89
Trichloroethene	979	57.8	2.29	1,100	100
1,1-Dichloroethene	2,650	591	1.32	2,500	150
cis-1,2-Dichloroethene	420	273	-1.86	3,500	36-49
Methyl tert-butyl ether	64.3	245	1.24	51,000	12.3
1,1-Dichloroethane	560	64	1.48	<1,000	
1,4-Dichlorobenzene	279	10 at 54.8° C	3.37	65,300	409-1514
1,2-Dichlorobenzene	183	1.47	3.38	140	280-320
Trichlorofluoromethane	8,830	--	--	--	--
Carbon tetrachloride	--	91.3	2.64	<1,000	--
Benzene	557	--	2.13	1,800	98
Chlorobenzene	358	11.8	2.18-2.84	450	126
1,2-Dibromoethane	65.9	11.2	1.35	40,000	14-160
trans-1,2-Dichloroethene	809	395	-2.06	6,300	36-49
1,3-Dichlorobenzene	278	5	--	<1,000	--
Chloromethane	901	3,800	.91	--	--
Carbon disulfide	--	260	2.16	2,300	54

¹ Rathbun (1998)

Table 10. Concentrations and detection frequencies of volatile organic compounds detected in more than 10 percent of samples from at least one of the well networks, Glassboro study area, N.J.
 [µg/L, micrograms per liter; <, less than; MRL, minimum reporting level; A, known human carcinogen; B2, probable human carcinogen; C, possible human carcinogen; D, not classifiable as to human carcinogenicity; --, no data]

Compound	MRL (µg/L)	Percentage of wells in which compound was detected	Median detected concentration (µg/L)	Maximum concentration (µg/L)	Carcinogenic potential	Human health advisory (µg/L)	Ground- water- quality criterion (µg/L)	Aquatic- life criterion ¹ (µg/L)
Chloroform	0.05	90	0.098	5.6	B2	280-100	6	2
Tetrachloroethene	.05	50	.03	71	--	³ ₁ , ⁴ ₅	0.4	110
1,1,1-Trichloroethane	.05	47	.028	1.13	--	³ ₂₆ , ⁴ ₂₀₀	30	--
Trichloroethene	.05	24	.137	8.74	--	³ ₁ , ⁴ ₅	--	20
1,1-Dichloroethene	.1	23	.026	.722	C	³ ₂ , ⁴ ₇	1	--
cis-1,2-Dichloroethene	.05	15	.213	12.1	D	³ ₁₀ , ⁴ ₇₀	10	--
Methyl tert-butyl ether	.1	46	.2	43.8	--	220-200	--	--
1,1-Dichloroethane	.05	19	.037	5.6	C	--	70	--
1,4-Dichlorobenzene	.05	15	.044	.457	C	⁴ ₇₅	75	4
1,2-Dichlorobenzene	.05	13	.021	.729	--	⁴ ₆₀₀	600	2.5
Trichlorofluoromethane	.1	14	.146	17	--	⁵ ₂₀₀₀	--	--
Carbon tetrachloride	.05	4	.014	.031	B2	³ ₂ , ⁴ ₅	.4	13
Benzene	.05	7	.066	.333	A	³ ₁ , ⁴ ₅	.2	300
Chlorobenzene	.05	7	.013	.128	D	³ ₄ , ⁴ ₁₀₀	4	15
1,2-Dibromoethane	.1	4	.026	.066	B2	⁴ _{.05}	--	--
trans-1,2-Dichloroethene	.05	4	.061	.18	D	³ ₁₀ , ⁴ ₁₀₀	100	--
1,3-Dichlorobenzene	.05	7	.022	.104	--	⁴ ₆₀₀	600	2.5
Chloromethane	.02	11	.015	1.9	C	⁴ ₃	30	--
Carbon disulfide	.05	28	.013	.17	--	--	--	--

¹Canadian Council of Resource and Environment Ministers (1996)

²Proposed lifetime health advisory (U. S. Environmental Protection Agency, 1996)

³NJDEP maximum contaminant level (Shelton, 1994)

⁴Maximum contaminant level (U. S. Environmental Protection Agency, 1996)

⁵Lifetime health advisory (U. S. Environmental Protection Agency, 1996)

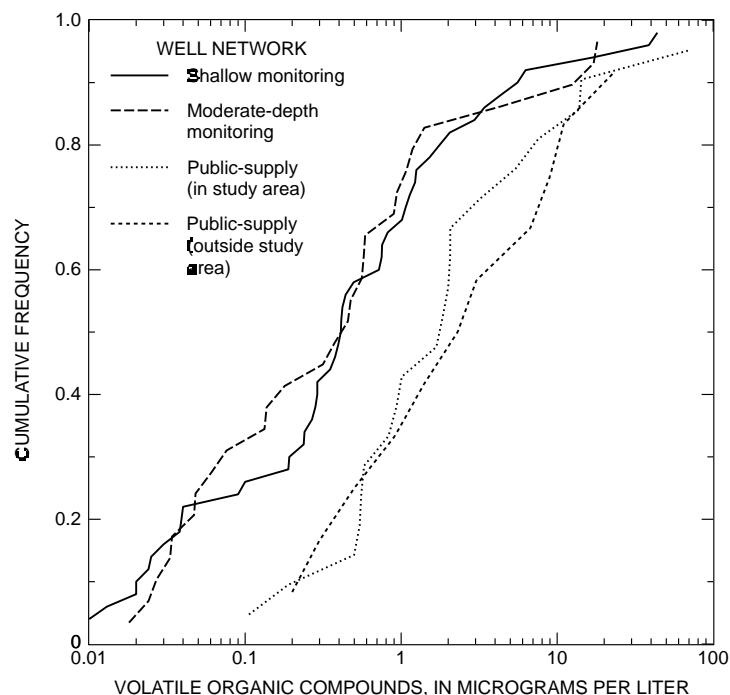


Figure 10. Cumulative frequency of total volatile organic compound concentrations in water samples from four well networks within and outside the Glassboro study area, N.J.

samples from public-supply wells in the Glassboro study area to available total VOC concentration data from other public-supply wells in the Kirkwood-Cohansey aquifer system. VOC data were considered appropriate for comparison if (1) the public-supply well from which the sample was collected was screened in an unconfined part of the aquifer system, (2) the sample had been analyzed after 1987, and (3) one or more VOCs were detected in the sample. Inclusion of samples in which no VOCs were detected and a statistical comparison of total VOC concentrations per sample for public-supply wells in the Glassboro study area with those for public-supply wells throughout the Kirkwood-Cohansey aquifer system were not appropriate for the following reasons: Each sample from public-supply wells in the Glassboro study area was analyzed for 87 VOCs, whereas samples from public-supply wells outside the Glassboro study area were analyzed for no more than 40

VOCs. Also, MRLs for VOC analysis of samples from public-supply wells outside the Glassboro study area were 0.2 $\mu\text{g/L}$ or greater, whereas most of the VOCs detected in samples from public-supply wells in the Glassboro study area are reported at concentrations of 0.1 $\mu\text{g/L}$ or less. Consequently, the proportion of samples with non-detectable concentrations of VOCs was greater for public-supply wells outside the Glassboro study area than for those in the Glassboro study area. Where VOCs were detected in public-supply wells outside the Glassboro study area, however, their total concentrations were similar to those reported for public-supply wells in the Glassboro study area and greater than those reported for either monitoring-well network (fig. 10).

The median total VOC concentration in samples from the shallow and moderate-depth monitoring and public-supply wells was 0.40, 0.34, and 1.5 $\mu\text{g/L}$, respectively; the median number of VOCs per sample was 4, 3, and 7.5, respectively; and the maximum number of VOCs detected per sample was 14, 18, and 20, respectively. Results of ANOVA and multiple-comparison tests on the ranked-transformed number of VOCs and total VOC concentration per sample (Helsel and Hirsch, 1992) indicate that samples from public-supply wells contained a significantly greater number of VOCs per sample ($p=0.0004$) and a greater total VOC concentration per sample ($p=0.0019$) than samples from the two monitoring-well networks. Differences in detection frequency patterns among the three well networks for individual VOCs result from differences in their (1) mode of introduction into the environment (point or nonpoint), (2) chemical and physical properties, (3) current

and historical use, and (4) source-area characteristics. These differences are illustrated below.

Unlike other VOCs, chloroform and MTBE generally were detected frequently in samples from all three well networks, indicating widespread (nonpoint) sources. Chloroform was detected in more than 80 percent of samples from each well network (fig. 11). Chloroform is both manmade and naturally occurring, although human activity is thought to be responsible for most of the chloroform found in the environment (Agency for Toxic Substances and Disease Registry, 1989). Chloroform is used primarily in the production of fluorocarbon-22; however, it was used historically as an extraction solvent in the manufacture of pharmaceuticals, as a dry-cleaning agent, in fire extinguishers, and as a fumigant and anesthetic (U. S. Department of Health and Human Services, 1999). Commercial production of chloroform for these purposes began in the 1920's and has exceeded 400 million pounds per year since the mid-1980's (table 7). Chloroform also is a common byproduct of the chlorination of public drinking-water supplies. During chlorination, chlorine can react with naturally occurring humic substances to form chloroform in the treated water. Public-supply water can provide widespread (nonpoint-source) recharge to surficial aquifer systems underlying urban areas through a variety of mechanisms, including lawn sprinklers, swimming pools, leaking water and sewer lines, septic systems, and recharge basins. Finally, chloroform has been shown to form naturally in some soil environments (Hoekstra and others, 1998); this source also may contribute to the widespread (nonpoint-source), frequent occurrence of chloroform in all three well networks. Chloroform introduced to the aquifer system from point sources associated with the compound's various commercial and industrial uses may augment that derived from nonpoint

sources and may explain the higher proportion of chloroform detections greater than 0.1 µg/L in samples from the public-supply wells than in samples from the monitoring wells (fig. 11); because public-supply wells have larger contributing areas, they are more likely to intercept water flowing from point sources of chloroform and other VOCs.

MTBE was detected frequently and in nearly equal proportions in samples from the shallow monitoring and public-supply wells but less frequently in samples from the moderate-depth monitoring wells (fig. 11). This result indicates that public-supply wells in the Glassboro study area intercept relatively short flow paths with associated short residence times, and further illustrates the vulnerability of public-supply wells in this region to contamination introduced at or near land surface.

MTBE was first used in gasoline in the late 1970's to enhance octane levels (Zogorski and others, 1997). The production and use of MTBE and the amount of MTBE added to gasoline increased significantly in the early 1990's when it became the most commonly used fuel oxygenate in many parts of the Nation, including the study area. The use of oxygenated fuels was mandated under the Clean Air Act amendments of 1990 to reduce atmospheric concentrations of carbon monoxide (Zogorski and others, 1997). Production of MTBE exceeded 700 million pounds in 1980 and has continued to increase since then, to more than 11 billion pounds in 1993 and 1994 (table 7) and more than 17.5 billion pounds in 1995 (Zogorski and others, 1997). MTBE is highly water-soluble and has a low soil-sorption (*K_{oc}*) coefficient (table 9); therefore, it can move readily through soils and leach to ground water. It is also resistant to physical, chemical, and microbial degradation (Zogorski and others, 1997) and is, therefore, likely to persist in the subsurface. MTBE also

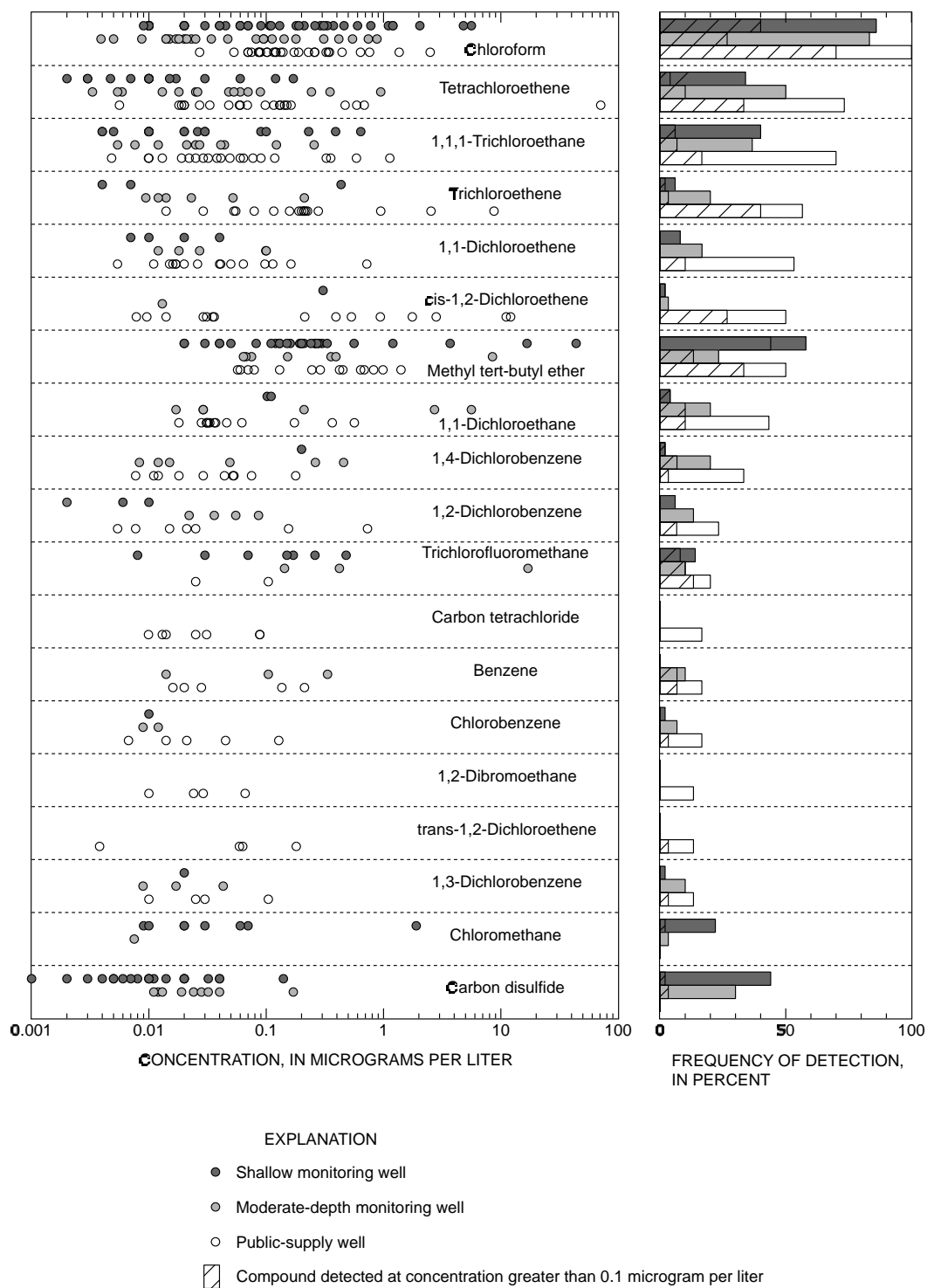


Figure 11. Concentration and frequency of detection of selected volatile organic compounds in water samples from all three well networks, Glassboro study area, N.J.

has a high vapor pressure and readily evaporates to the atmosphere. Direct emissions from automobile exhaust further contribute to the atmospheric load of MTBE. Atmospheric concentrations of MTBE in the Glassboro study area are sufficient to be a widespread (nonpoint) source of frequently detected low-level concentrations in shallow ground water (Baehr and others, 1999a). MTBE was the second most frequently detected VOC in samples from a network of 78 shallow monitoring wells in the Glassboro study area (Stackelberg and others, 1997), but concentrations generally were less than 1 µg/L. Aqueous equivalent concentrations of MTBE in 24-hour composite air samples collected every 12 days from November 1996 to February 1998 in the Glassboro study area were similar to concentrations measured in samples from the 78 shallow monitoring wells (Baehr and others, 1999a); thus, the atmosphere is a potential source of the widespread presence of MTBE at low-level concentrations in shallow ground water.

Urban stormwater runoff from roadways and parking lots is another potential widespread source of MTBE in shallow ground water underlying urban areas (Delzer and others, 1996). These widespread (nonpoint) sources (the atmosphere and urban stormwater runoff) may account for the frequent and nearly equal detections of MTBE in samples from the shallow monitoring and public-supply wells. Introductions of MTBE to the aquifer system from point sources associated with the use and storage of gasoline at private, commercial, and industrial facilities may augment those associated with nonpoint sources and may be responsible for the presence of MTBE at concentrations greater than about 1 µg/L in ground water in the study area (fig. 11).

MTBE was detected least frequently in samples from the moderate-depth monitoring wells, probably because of the recent increase

in its use. Whereas environmental tracers and results of ground-water flow simulations indicate that the median age of samples from the shallow monitoring wells is 1.4 years and that some water withdrawn from public-supply wells is young (less than 5 years old), the median age of samples from the moderate-depth monitoring wells is 14 years (fig. 5). Therefore, detection of MTBE in samples from the moderate-depth monitoring wells would be expected to be less frequent because use of the compound has increased only recently. As a result of its mobility and persistence, however, detection frequencies in moderate-depth monitoring wells likely will increase as MTBE is transported deeper into the aquifer system.

Tetrachloroethene (PCE), 1,1,1-trichloroethane (TCA), and trichloroethene (TCE) were the most frequently detected chlorinated organic compounds in samples from all three well networks (fig. 11). These compounds are also the most widely produced chlorinated organic compounds (table 7) and have a wide variety of industrial and commercial uses as metal degreasers, industrial solvents, and ingredients in aerosols, adhesives, and protective coatings. PCE is also widely used as a dry-cleaning solvent and in the manufacture of textiles (Harte and others, 1991). Each of these compounds has been produced in large quantities since the 1960's, with maximum production amounts exceeding 700, 800, and 600 million pounds per year for PCE, TCA, and TCE, respectively (table 7). More recently, production of these compounds has decreased as their uses have become more restricted (table 7). Their vapor pressures and Henry's law coefficients (table 9) indicate that they readily evaporate to the atmosphere. Direct atmosphere emissions from commercial and industrial sites account for most of the environmental releases of these compounds (Harte and others, 1991) and further contribute to the atmospheric load. The atmosphere is not a likely source of these and other chlorinated

organic compounds in shallow ground water in the Glassboro study area, however, because atmospheric concentrations are insufficient (Baehr and others, 1999a).

TCA and TCE are highly water-soluble and have low soil-sorption coefficients (table 9) and, therefore, are likely to leach to ground water once introduced to the subsurface. Degradation rates for these compounds are expected to be low and, thus, they are likely to be persistent. PCE is less soluble and more likely to sorb to organic matter in the soil zone than TCA and TCE (table 9); therefore, it is considered to be less mobile in the subsurface. In addition, PCE biodegrades under anaerobic conditions. Despite these characteristics, PCE was the most frequently detected chlorinated organic compound (fig. 11), which may reflect its overall high production rate (table 7) and diverse uses, including commercial applications such as dry cleaning in addition to various industrial applications. As a result of concerns about ozone depletion, the USEPA has mandated reductions in the amount of TCA manufactured and used within the United States (U.S. Environmental Protection Agency, 1994a). Reported production of TCA was 644 million pounds in 1991 but was expected to be less than 50 million pounds per year after 1995 (U.S. Environmental Protection Agency, 1994a). TCA was detected infrequently in samples from the shallow-monitoring wells, possibly reflecting the USEPA-mandated reduction in its use and the fact that the water sampled in this network is young. Higher detection frequencies for TCA in moderate-depth monitoring and public-supply wells likely reflect (1) historical use patterns, (2) older water sampled in these networks, and (3) larger contributing areas (for the public-supply wells) which integrate water from multiple sources. Higher detection frequencies in the moderate-depth and public-supply wells also

demonstrate the mobility and persistence of

these compounds.

Several other chlorinated organic compounds, including 1,1-dichloroethene, cis-1,2-dichloroethene, 1,1-dichloroethane, and trans-1,2-dichloroethene, were detected primarily in samples from the public-supply wells (fig. 11). Although these compounds are used in industrial and commercial applications similar to those of PCE, TCA, and TCE, they are produced in much smaller quantities. Production data for 1,1-dichloroethane, cis-1,2-dichloroethene, and trans-1,2-dichloroethene were not available from the USITC; however, an estimated 200 million pounds of 1,1-dichloroethene was produced in the United States during the early 1980's (U.S. Environmental Protection Agency, 1998a). The moderate to high vapor pressures and low Henry's law coefficients of these compounds (table 9) indicate that they readily evaporate to the atmosphere; however, the atmosphere is unlikely to be a widespread source of these compounds in the Glassboro study area because atmospheric concentrations are insufficient (Baehr and others, 1999a). The compound's moderate to high water solubilities and low soil-sorption coefficients (table 9) indicate that they likely will leach to ground water once introduced to the subsurface. Moreover, their degradation rates are expected to be low and, therefore, they are likely to persist. In addition to minor industrial and commercial sources, these compounds may result from the degradation of the more widely used chlorinated organic compounds PCE and TCE (U.S. Environmental Protection Agency, 1998b). The occurrence of these compounds almost exclusively in samples from public-supply wells may indicate that parent compounds are degrading along extended flow paths and (or) that large contributing areas are required to integrate water from a sufficient number of sources of these compounds to result in their detection.

Two other chlorinated organic compounds, carbon tetrachloride and 1,2-dibromoethane, were detected exclusively in samples from the public-supply wells; however, unlike 1,1-dichloroethene, cis-1,2-dichloroethene, 1,1-dichloroethane, and trans-1,2-dichloroethene, they probably are not derived from the degradation of other VOCs. Carbon tetrachloride is used primarily as a chemical intermediate in the production of the chlorofluorocarbons CFC-11 and CFC-12, as a general solvent in industrial degreasing operations, and as a grain fumigant (U. S. Department of Health and Human Services, 1999). Production of carbon tetrachloride on a large scale in the United States began around 1907 and, by 1930, more than 34 million pounds were produced in the United States annually (table 7). Production continued to increase and peaked between 1970 and 1975, when more than 900 million pounds were produced annually (table 7). As a result of concerns about ozone depletion, however, the production of CFC-11 and CFC-12 is declining rapidly, and the use of carbon tetrachloride as a grain fumigant was banned by the USEPA in 1985 (U. S. Department of Health and Human Services, 1999), leading to a decline in its manufacture and use as well (table 7). 1,2-dibromoethane is used primarily as an additive to leaded gasoline, a soil fumigant in agricultural applications, and a turf fumigant in the maintenance of golf courses (U. S. Environmental Protection Agency, 1998d). Production of 1,2-dibromoethane approached 300 million pounds per year during the early 1970's, but has decreased with the decline in the use of leaded gasoline (table 7). In addition, the use of 1,2-dibromoethane as an agricultural and turf fumigant was banned by the USEPA in 1984 (U. S. Environmental Protection Agency, 1998e). Thus, the occurrence of carbon tetrachloride and 1,2-dibromoethane exclusively in samples from the public-supply wells likely reflects historical use patterns and the fact that the public-supply wells intercept

longer flow paths than those intercepted by the shallow and moderate-depth monitoring wells. Water flowing along longer paths is more likely to contain VOCs such as carbon tetrachloride and 1,2-dibromoethane that were used in greater quantities in the past.

Transferability of water-quality results

As discussed in the sections on nitrate and VOCs, water-quality data from public-supply wells sampled during this study are comparable to available water-quality data from public-supply wells in the Kirkwood-Cohansey aquifer system outside the Glassboro study area. In addition, the general characteristics of the public-supply wells, as well as land-use, soil, and aquifer characteristics, in the Glassboro study area are comparable to those elsewhere in the Kirkwood-Cohansey aquifer system. Therefore, results of this study are considered to be transferable to the entire extent of the Kirkwood-Cohansey aquifer system.

General characteristics of the 30 public-supply wells sampled during this study were compared to those of more than 180 public-supply wells screened in the Kirkwood-Cohansey aquifer system throughout southern New Jersey. The 25th-, 50th-, and 75th-percentile depths below land surface of the 30 public-supply wells in the Glassboro study area and 183 public-supply wells outside the study area were 101, 144, and 162 ft, and 91, 146, and 182 ft, respectively (fig. 12). The 25th-, 50th-, and 75th-percentile screen lengths of the public-supply wells in the Glassboro study area and 166 public-supply wells outside the study area were 25, 30, and 33 ft, and 20, 25, and 35 ft, respectively (fig. 12). The 25th-, 50th-, and 75th-percentile average annual pumping rates for 1992-96 for the Glassboro study area public-supply wells and the 183 public-supply

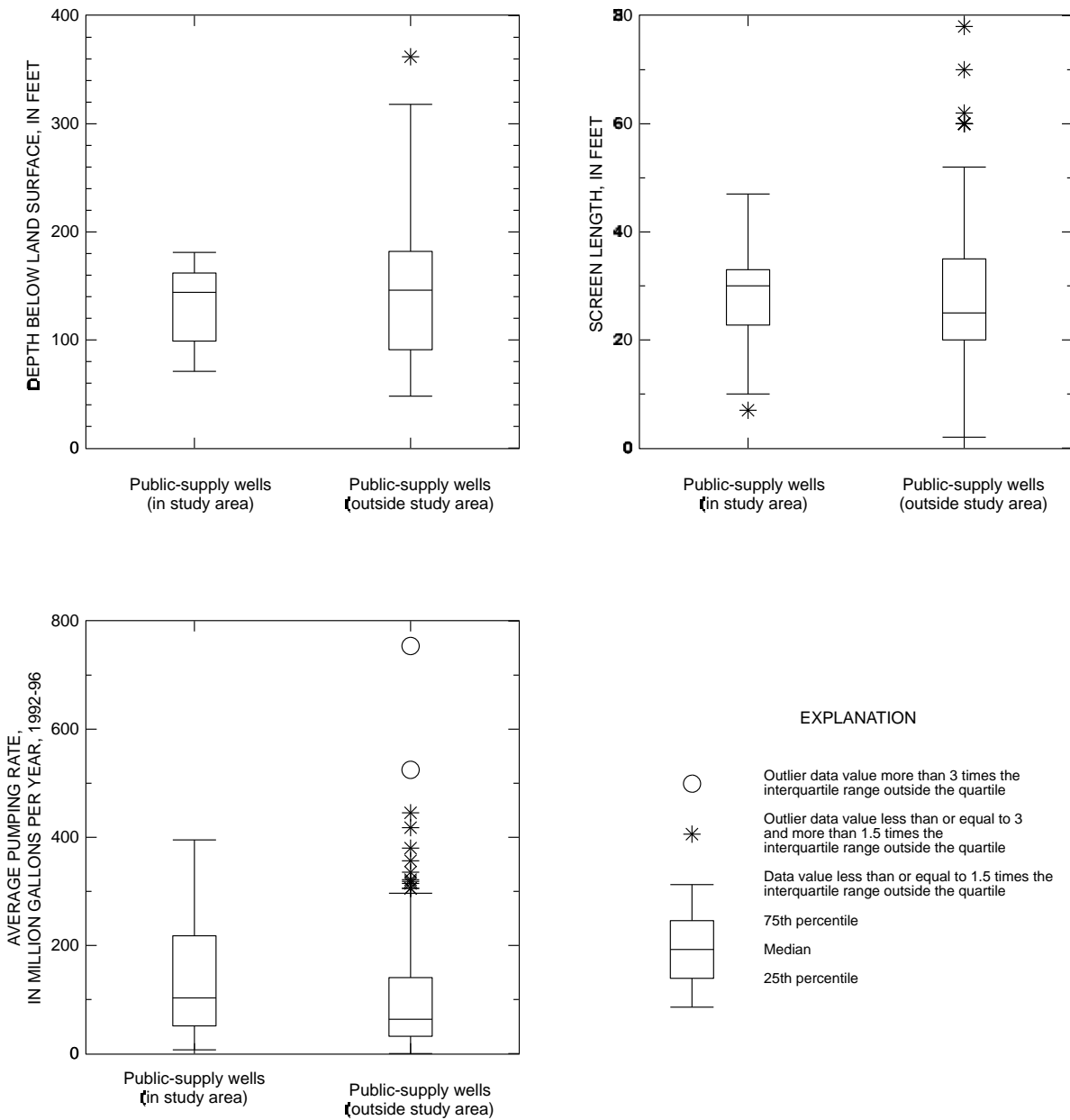


Figure 12. Distribution of values of general characteristics of public-supply wells within and outside the Glassboro study area, N.J.

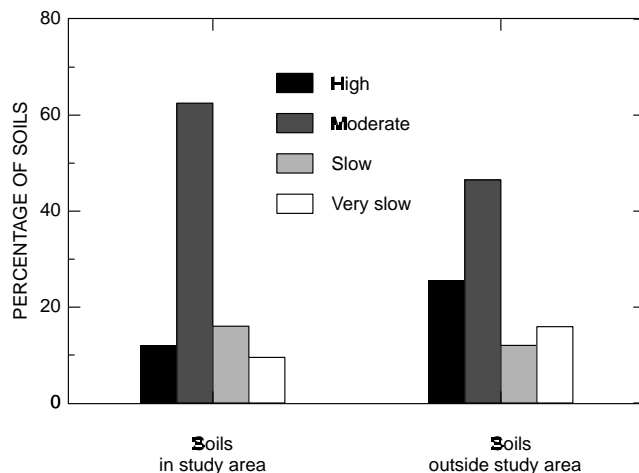


Figure 13. Infiltration rate of soils within and outside the Glassboro study area, N.J.

wells outside the study area were 52, 103, and 205 Mgal/yr, and 32, 63, and 140 Mgal/yr, respectively (fig. 12). Results of ANOVA on the rank-transformed depth below land surface, screen length, and average annual pumping rate indicate that mean ranked values of each of these characteristics are statistically similar between the 30 public-supply wells in the study area and those outside the study area at a 95-percent confidence level.

The land-use composition of the Glassboro study area was compared to that of the entire outcrop area of the Kirkwood-Cohansey aquifer system. The Glassboro study area is composed of urban (21 percent), agricultural (26 percent), and undeveloped (39 percent) land (New Jersey Department of Environmental Protection, 1996). Miscellaneous land-use categories such as surface-water bodies and wetlands comprise the remaining 14 percent. The outcrop area of the Kirkwood-Cohansey aquifer system as a whole is composed of urban (22 percent), agricultural (19 percent), and undeveloped (39 percent) land (New Jersey Department of Environmental Protection, 1996). Miscellaneous land-use categories comprise the remaining 20 percent.

Soil characteristics in the Glassboro study area were compared to those in the entire outcrop area of the Kirkwood-Cohansey aquifer system. Soils both within and outside the study area are composed predominantly of sandy loams with moderate infiltration rates (U. S. Department of Agriculture, 1995) (fig. 13). A higher percentage of soils outside the study area have high infiltration rates, as a result, in part, of the presence of highly permeable beach deposits that form the State's barrier islands.

Aquifer characteristics were determined from results of aquifer tests in the Kirkwood-Cohansey aquifer system at 12 sites--6 within and 6 outside the study area--across southern New Jersey (Martin, 1998). Values of transmissivity in the study area ranged from 4,000 to 20,000 ft²/d with an average of about 9,000 ft²/d. Outside the study area, transmissivity values ranged from 3,600 to 20,000 ft²/d with an average of about 10,000 ft²/d. Hydraulic-conductivity values in the study area ranged from 90 to 250 ft/d with an average of 156 ft/d. Outside the study area, hydraulic-conductivity values ranged from 53 to 140 ft/d with an average of 114 ft/d.

Fate and significance of nitrate, pesticides, and VOCs in the Kirkwood-Cohansey aquifer system

Nitrate concentrations in samples from 80 percent of the moderate-depth monitoring wells and from more than 90 percent of the public-supply wells were greater than 1.0 mg/L; median concentrations were 2.45 and 3.5 mg/L, respectively. One or more pesticide compounds were detected in 75 to 80 percent of samples from the moderate-depth monitoring and public-supply wells, and one or more VOCs were detected in 80 percent of samples from the moderate-depth monitoring and in 100 percent

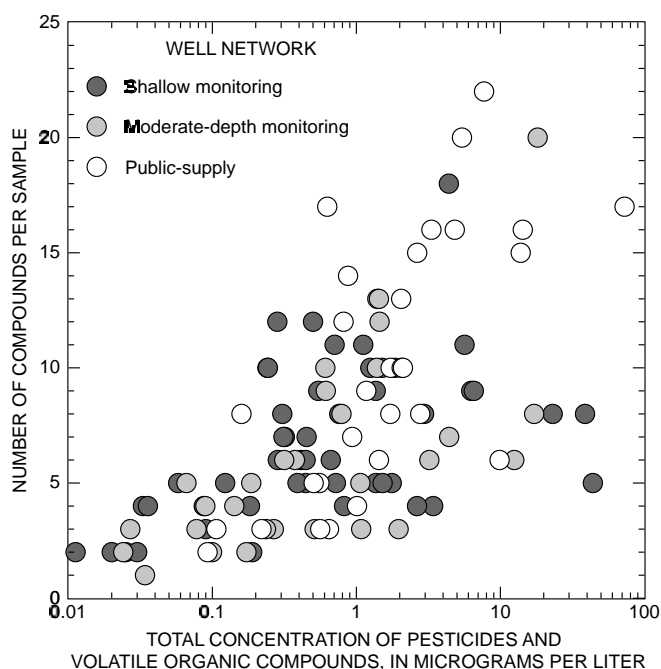


Figure 14. Total concentration and number of pesticides and volatile organic compounds per sample in water samples from all three well networks, Glassboro study area, N.J.

of samples from the public-supply wells. Concentrations of these constituents, however, rarely exceeded established Federal or State MCLs or HALs. The frequent detection of pesticides and VOCs results, in part, from the use of sensitive analytical methods recently developed by the USGS, which allow for the detection of pesticides at concentrations of 0.01 µg/L and less and the detection of VOCs at concentrations of 0.1 µg/L and less (Zaugg and others, 1995; Conner and others, 1998).

Although concentrations generally were low, these results indicate that most of the samples from public-supply wells and monitoring wells screened in parts of the aquifer system used for domestic supply in the Glassboro study area contained nitrate at concentrations greater than expected background levels and organic compounds that are introduced to the environment by human activities. These findings indicate that human activities have affected the chemical quality of ground water throughout the Kirkwood-Cohansey aquifer system underlying the

Glassboro study area and that supply wells screened in this aquifer system in the study area are vulnerable to contaminants introduced at or near land surface. Furthermore, pesticides and VOCs detected most frequently in samples from the shallow monitoring wells also were detected most frequently in samples from the moderate-depth monitoring and public-supply wells, indicating that (1) rates of processes such as degradation and sorption/dispersion that may be occurring within the aquifer system are insufficient to prevent the occurrence of these compounds in parts of the aquifer system used for domestic and public supply, and (2) contaminants detected in samples of recently recharged ground water collected at or near the water table are likely to persist within the aquifer system and eventually discharge to supply wells or surface-water bodies.

Established drinking-water regulations were rarely exceeded in ground-water samples collected during this study. Four pesticide and VOC compounds that were detected in 10 percent or more of samples, however, have not been assigned drinking-water regulations by the USEPA or NJDEP (tables 6 and 10). Also, drinking-water regulations are currently (1999) based on the concentrations of individual compounds and do not account for possible cumulative health effects of the presence of more than one compound in the same well (Barbash and Resek, 1996). The total number and cumulative concentration of all pesticides and VOCs in each sample are illustrated in figure 14. Seventy-five percent of the samples from the three well networks contained four or more pesticides and (or) VOCs per sample (fig. 14). The presence of multiple pesticides and (or) VOCs increases the total concentration of organic compounds in a given sample. The possibility that the presence of multiple organic compounds, even at low concentrations, may have a synergistic adverse health consequence

is an area of current research (Biradar and Rayburn, 1995; Marinovich and others, 1996). Thus, although constituent concentrations generally were less than established drinking-water regulations, some human-health issues remain unresolved.

Of the 47 pesticide compounds analyzed for in samples from the three well networks, only 4 were pesticide-degradation byproducts. Because many pesticides are unstable in soil and the unsaturated zone, they degrade to other compounds that can be equally harmful to human health. Results of previous investigations indicate that degradation byproducts account for most of the pesticide load in ground water (Kolpin and others, 1995; 1996). In fact, deethylatrazine, a degradation byproduct of the pesticide atrazine, was the second most frequently detected pesticide compound in this study. In addition, some pesticides with significant use as reported to the Pesticide Control Program of the NJDEP by licensed applicators were not analyzed for in samples from all three well networks (table 4). Therefore, the total pesticide load determined in samples analyzed for this study is likely biased low. Further investigation is needed to document the presence and concentration of these high-use parent compounds and pesticide-degradation byproducts in ground water in order to determine the full effect of pesticide use in the Glassboro study area.

SUMMARY AND CONCLUSIONS

Samples from public-supply wells in the Glassboro study area of southern New Jersey contained a significantly greater number and greater total concentration of VOCs per sample than samples from the shallow and moderate-depth monitoring wells. VOCs commonly originate from point sources. Because public-supply wells withdraw larger volumes of water than monitoring wells their contributing areas

are larger and, therefore, the wells may intercept water flowing from more VOC point sources. Furthermore, results of ground-water flow simulations and particle tracking indicate that public-supply wells in the Glassboro study area intercept relatively young water flowing along short paths, making them vulnerable to contamination by the VOCs that are frequently detected in recently recharged ground water. Public-supply wells, however, also intercept water flowing along longer paths associated with longer residence times. This water is more likely than water from monitoring wells to contain VOCs derived from the degradation of parent compounds or VOCs that had significant historical use that has recently been reduced or phased out. Samples from monitoring wells, therefore, generally underrepresent the occurrence and concentration of VOCs in samples from public-supply wells in the study area. Chloroform and MTBE, which appear to originate in part from diffuse (nonpoint) sources in urban environments, are notable exceptions. These compounds were detected with nearly equal frequency in samples from the shallow monitoring and public-supply wells. MTBE was detected less frequently in samples from the moderate-depth monitoring wells because the median age of samples from these wells predates the recent increase in the use of MTBE as a fuel oxygenate. Because MTBE is recalcitrant and persistent, however, the frequency of occurrence of MTBE in samples from moderate-depth monitoring wells and, therefore, domestic wells, is likely to increase with time.

In contrast, nitrate concentrations and the number and total concentration of pesticides per sample were statistically similar among the three well networks, indicating that these compounds are introduced from diffuse (nonpoint) sources at relatively consistent concentrations. These results also indicate that samples from the shallow monitoring wells generally are indicative of the occurrence and

concentration of nonpoint-source contaminants in regional drinking-water supplies. Notable exceptions occur for individual compounds as a result of differences in their physical and chemical properties, current and historical use patterns, and source-area characteristics. For instance, metolachlor, terbacil, and alachlor were detected more frequently in samples from the public-supply wells than in those from either monitoring-well network. These herbicides are used primarily for agricultural purposes; however, metolachlor is currently one of the most commonly used agricultural herbicides, whereas the use of terbacil and alachlor has decreased significantly since the 1980's. Because public-supply wells have larger contributing areas than monitoring wells, they are more likely to contain greater amounts of agricultural land, and are more likely to yield water contaminated with agricultural herbicides. In addition, the public-supply wells intercept water flowing along longer flow paths, which is more likely to contain pesticides such as terbacil and alachlor, whose historical use is significant but whose recent use has declined.

REFERENCES CITED

- Agency for Toxic Substances and Disease Registry, 1989, Public health statement--Chloroform: (Accessed June 1, 1999, on the World Wide Web at URL <http://atsdr1.atsdr.cdc.gov:8080/ToxProfiles/phs8809.html>).
- Baehr, A.L., Stackelberg, P.E., and Baker, R.J., 1999a, Evaluation of the atmosphere as a source of volatile organic compounds in shallow ground water: *Water Resources Research*, v. 35, no. 1, p. 127-136.
- Baehr, A.L., Kauffman, L.J., Charles, E.G., Baker, R.J., Stackelberg, P.E., Ayers, M.A., and Zapecza, O.S., 1999b, 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.
- Barbash, J.E., and Resek, E.A., 1996, Pesticides in ground water: Distribution, trends, and governing factors: Chelsea, Mich., Ann Arbor Press, Inc., 588 p.
- Barringer, T., Dunn, D., Battaglin, W., and Vowinkel, E., 1990, Problems and methods involved in relating land use to ground-water quality: *Water Resources Bulletin*, v. 26, no. 1, p. 1-9.
- Bender, D.A., Zogorski, J.S., Halde, M.J., and Rowe, B.L., 1999, Selection procedure and salient information for volatile organic compounds emphasized in the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 99-182, 32 p.
- Biradar, D.P., and Rayburn, A.L., 1995, Chromosomal damage induced by herbicide contamination at concentrations observed in public water supplies: *Journal of Environmental Quality*, v. 24, p. 1222-1225.
- Bloemen, H.J.Th., and Burn, J., eds., 1993, Chemistry and analysis of volatile organic compounds in the environment: Glasgow, U.K., Blackie Academic and Professional, 290 p.
- Canadian Council of Resource and Environment Ministers, 1997, Canadian water quality guidelines: Ottawa, Ontario, Canada, Water Quality Branch, Inland Waters Division, Environment Canada.
- Capel, P.D., Spexet, A.H., and Larson, S.J., 1999, Occurrence and behavior of the herbicide prometon in the hydrologic system: *Environmental Science and Technology*, v. 33, no. 5, p. 674-680.

- Connor, B.F., Rose, D.L., Noriega, M.C., Murtagh, L.K., and Abney, S.R., 1998, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory--Determination of 86 volatile organic compounds in water by gas chromatography/mass spectrometry, including detections less than reporting limits: U.S. Geological Survey Open-File Report 97-829, 78 p.
- Cook, P.G., and Solomon, D.K., 1997, Recent advances in dating young groundwater: Chlorofluorocarbons, $^3\text{H}/^3\text{He}$, and ^{85}Kr : Journal of Hydrology, v. 191, p. 245-265.
- Delzer, G.C., Zogorski, J.S., Lopes, T.J., and Bosshart, R.L., 1996, Occurrence of the gasoline oxygenate MTBE and BTEX compounds in urban stormwater in the United States, 1991-95: U.S. Geological Survey Water-Resources Investigations Report 96-4145, 6 p.
- Ekwurzel, B., Schlosser, P., Smethie, W.M., Plummer, L.N., Busenberg, E., Michel, R.L., Weppernig, R., and Stute, M., 1994, Dating of shallow groundwater: Comparison of the transient tracers $^3\text{H}/^3\text{He}$, chlorofluorocarbons, and ^{85}Kr : Water Resources Research, v. 30, no. 6, p. 1693-1708.
- Franke, O.L., Reilly, T.E., Pollock, D.W., and LaBaugh, J.W., 1998, Estimating areas contributing recharge to wells--Lessons from previous studies: U.S. Geological Survey Circular 1174, 14 p.
- Hamilton, G.C., and Meyer, R., 1994, A nine-year comparison of pesticide use in New Jersey, in Weigman, D.L., ed., New directions in pesticide research, management, and policy: Blacksburg, Virginia, Virginia Water Resources Research Center, November 1-3, 1993, p. 335-365.
- Harte, J., Holdren, C., Schneider, R., and Shirley, C., 1991, Toxics A to Z--A guide to everyday pollution hazards: Berkeley and Los Angeles, Calif., University of California Press, 479 p.
- Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier, 522 p.
- Hoekstra, E.J., De Leer, E.W.B., and Brinkman, U.A.Th., 1998, Natural formation of chloroform and brominated trihalomethanes in soil: Environmental Science and Technology, v. 32, no. 23, p. 3724-3729.
- Kauffman, L.J., Stackelberg, P.E., and Ayers, M.A., 1998, Simulation of advective transport of nonpoint source contaminants in an unconfined aquifer: EOS, Transactions of the American Geophysical Union, v. 79, no. 45, 1998 Fall Meeting Abstract Supplement, Dec. 6-10, 1998, San Francisco, Calif., p. F314.
- Kolpin, D.W., Goolsby, D.A., and Thurman, E.M., 1995, Pesticides in near-surface aquifers--An assessment using highly sensitive analytical methods and tritium: Journal of Environmental Quality, v. 24, p. 1125-1132.
- Kolpin, D.W., Nations, B.K., Goolsby, D.A., and Thurman, E.M., 1996, Acetochlor in the hydrologic system in the midwestern United States, 1994: Environmental Science and Technology, v. 30, no. 5, p. 1459-1464.
- Koterba, M.T., Franceska, W.D., and Lapham, W.W., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment program: Collection and documentation of water-quality samples and related data: U.S. Geological Survey Open-File Report 95-399, 113 p.
- Lapham, W.W., Franceska, D.W., and Koterba, M.T., 1995, Ground-water data-collection protocols and procedures for the National Water-Quality Assessment program: Selection, installation, and documentation of wells, and collection of related data:

- U.S. Geological Survey Open-File Report 95-398, 69 p.
- Mabey, W.R., Smith, J.H., Podoll, R.T., Johnson, H.L., Mill, T., Chou, T.W., Gates, I., Partridge, W., Jaber, H., and Vandenberg, D., 1982, Aquatic fate process data for organic priority pollutants: U.S. Environmental Protection Agency, EPA Report No. 440/4-81-014, 432 p.
- Majewski, M.S., and Capel, P.D., 1995, Pesticides in the hydrologic system, v. 1: Pesticides in the atmosphere: Chelsea, Mich., Ann Arbor Press, Inc., 214 p.
- Marinovich, M.R., Ghilard, F., and Gucci, C.L., 1996, Effect of pesticide mixtures on in-vitro nervous cells: Toxicology, v. 108, p. 201-206.
- Martin, M., 1998, Ground-water flow in the New Jersey Coastal Plain, U.S. Geological Survey Professional Paper 1404-H, 146 p.
- McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 6, chap. A1, 586 p.
- New Jersey Department of Environmental Protection, 1993, New Jersey 1992 State water quality inventory report, chapter IV: Trenton, N.J., N.J. Department of Environmental Protection, 44 p.
- New Jersey Department of Environmental Protection, 1996, New Jersey geographic information system CD-ROM series 1, v. 2: Trenton, N.J., N.J. Department of Environmental Protection.
- New Jersey Department of Environmental Protection, 1999, Ground water quality standards: N.J. Administrative Code 7:9-6 (Accessed June 1, 1999, on the World Wide Web at URL <http://www.state.nj.us/dep/srp/regs/gwqs>).
- Plummer, L.N., Michel, R.L., Thurman, E.M., and Glynn, P.D., 1993, Environmental tracers for age dating young ground water, in Alley, W.M., ed., Regional ground-water quality: New York, Van Nostrand Reinhold, 634 p.
- Pollock, D.W., 1989, Documentation of computer programs to compute and display pathlines using results from the U.S. Geological Survey modular three-dimensional finite-difference ground-water flow model. U.S. Geological Survey Open-File Report 89-381, 188 p.
- Rathbun, R.E., 1998, Transport, behavior, and fate of volatile organic compounds in streams: U.S. Geological Survey Professional Paper 1589, 151 p.
- Scott, J.C., 1990, Computerized stratified random site-selection approaches for design of a ground-water-quality sampling network: U.S. Geological Survey Water-Resources Investigations Report 90-4101, 109 p.
- Shelton, L.R., 1994, Field guide for collecting and processing stream-water samples for the National Water-Quality Assessment program: U.S. Geological Survey Open-File Report 94-455, 42 p.
- Smith, J.A., Witkowski, P.J., and Fusillo, T.V., 1988, Manmade organic compounds in the surface waters of the United States--A review of current understanding. U.S. Geological Survey Circular 1007, 92 p.
- Squillace, P.J., and Price, C.V., 1996, Urban land-use study plan for the National Water-Quality Assessment Program: U.S. Geological Survey Open-File Report 96-217, 30 p.
- 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.
- Szabo, Z., Rice, D.E., Plummer, L.N., Busenberg, E., Drenkard, S., and Schlosser, P., 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.
- U.S. Department of Agriculture, 1995a, State Soil Geographic (STATSGO) Data Base: Fort Worth, Texas, NRCS National Cartography and Geographic Information System Center, CD-ROM.
- U.S. Department of Agriculture, 1995b, Agricultural research services--Pesticide properties: (Accessed June 15, 1999, on the World Wide Web at URL <http://wizard.arsusda.gov/rsml/textfiles/>).
- U.S. Department of Health and Human Services, 1999, Eighth report on carcinogens--1998 Summary: (Accessed June 1, 1999, on the World Wide Web at URL <http://ehis.niehs.nih.gov/roc/eighth/chemicals/>).
- U.S. Environmental Protection Agency, 1994a, Chemical summary for methylchloroform: prepared by Office of Pollution Prevention and Toxics, EPA 749-F-94-014a, 11 p.
- U.S. Environmental Protection Agency, 1994b, Chemical summary for carbon disulfide: prepared by Office of Pollution Prevention and Toxics, EPA 749-F-94-008 (Accessed June 15, 1999, on the World Wide Web at URL <http://www.epa.gov/opptintr/chemfact/>).
- U.S. Environmental Protection Agency, 1996, Drinking water regulations and health advisories: Washington, D.C., Office of Water, EPA 82208096-002, 16 p.
- U.S. Environmental Protection Agency, 1998a, National primary drinking water regulations--Technical factsheet on 1,1-dichloroethylene: Office of Ground Water and Drinking Water (Accessed June 1, 1999, on the World Wide Web at URL <http://www.epa.gov/OGWDW/dwh/t-soc>).
- U.S. Environmental Protection Agency, 1998b, National primary drinking water regulations--Technical factsheet on 1,2-dichloroethylene: Office of Ground Water and Drinking Water (Accessed June 1, 1999, on the World Wide Web at URL <http://www.epa.gov/OGWDW/dwh/t-soc>).
- U.S. Environmental Protection Agency, 1998c, National primary drinking water regulations--Technical factsheet on atrazine: Office of Ground Water and Drinking Water (Accessed June 1, 1999, on the World Wide Web at URL <http://www.epa.gov/OGWDW/dwh/t-soc>).
- U.S. Environmental Protection Agency, 1998d, Carbon tetrachloride: (Accessed June 15, 1999, on the World Wide Web at URL <http://www.epa.gov/ttn/uatw/hlthef/carbonte.html>).
- U.S. Environmental Protection Agency, 1998e, Ethylene dibromide: (Accessed June 15, 1999, on the World Wide Web at URL <http://www.epa.gov/ttn/uatw/hlthef/ethyl-di.html>).
- U.S. Environmental Protection Agency, 1998f, National primary drinking water regulations--Technical factsheet on 1,1,1-trichloroethane: Office of Ground Water and Drinking Water (Accessed June 15, 1999, on the World Wide Web at URL <http://www.epa.gov/OGWDW/dwh/t-voc>).
- U.S. Geological Survey, 1999, Pesticides analyzed in NAWQA samples--Use, chemical analyses, and water-quality criteria: (Accessed August 15, 1999, on the World Wide Web at URL <http://water.wr.usgs.gov/pnsp/anstrat/>).
- U.S. International Trade Commission, 1930-94, Synthetic organic compounds--U.S. production and sales (published annually): Washington, D.C.
- Verschuere, K., 1983, Handbook of environmental data on organic chemicals: New York, Van Nostrand Reinhold Company, Inc., 1310 p.
- Vogue, P.A., Kerle, E.A., and Jenkins, J.J., 1994, OSU Extension Pesticide Properties Database (Accessed June 15, 1999, on the World Wide Web at URL <http://ace.orst.edu/info/nptn/ppdmove.html>).

- Ward, M.H., Mark, S.D., Cantor, K.P., Weisenburger, D.D., Correa-Villasenor, A., and Zahm, S.H., 1996, *Epidemiology*, v. 7, p. 465-471.
- Ware, G.W., 1989, *The pesticide book*: New York, W.H. Freeman and Company, 386 p.
- Zapeczka, O.S., 1989, Hydrogeologic framework of the New Jersey Coastal Plain: U.S. Geological Survey Professional Paper 1404-B, 49 p., 24 pl.
- Zaugg, S.D., Sandstrom, M.W., Smith, S.G., and Fehlberg, K.M., 1995, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory--Determination of pesticides in water by C-18 solid-phase extraction and capillary-column gas chromatography/mass spectrometry with selected-ion monitoring: U.S. Geological Survey Open-File Report 95-181, 49 p.
- Zogorski, J.S., Morduchowitz, A., Baehr, A.L., Bauman, B.J., Conrad, D.L., Drew, R.T., Korte, N.E., Lapham, W.W., Pankow, J.F., and Washington, E.R., 1997, Fuel oxygenates and water quality, *in* Interagency assessment of oxygenated fuels: Washington, D.C., Office of Science and Technology Policy, Executive Office of the President, chap. 2, p. 2-1 - 2-80.