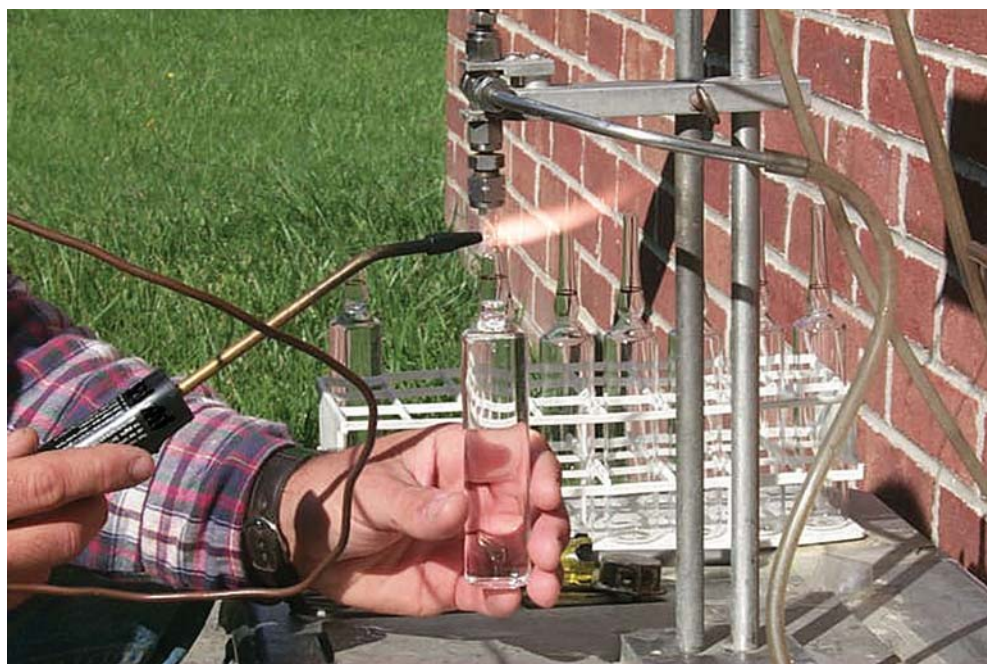


U.S. Department of the Interior
U.S. Geological Survey

Aquifer Susceptibility in Virginia, 1998-2000

Water-Resources Investigations Report 03-4278



Prepared in cooperation with:

Virginia Department of Health
Office of Drinking Water



Cover image: Collection of water sample for age dating ground water by chlorofluorocarbon technique.
Photograph by David L. Nelms, USGS.

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By David L. Nelms, George E. Harlow, Jr., L. Niel Plummer, and Eurybiades Busenberg

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Richmond, Virginia
2003

U.S. DEPARTMENT OF THE INTERIOR
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Acronyms and Abbreviations

A	^{14}C activity measured for the water sample
A_{nd}	adjusted ^{14}C activity in the observed water
A_0	initial ^{14}C activity
AP	Appalachian Plateaus regional aquifer system
Ar	argon
BP	before present
BR	Blue Ridge regional aquifer system
^{14}C	carbon-14
cc/L	cubic centimeters per liter
CCl_3F	chlorofluorocarbon-11 (trichlorofluoromethane)
CCl_2F_2	chlorofluorocarbon-12 (dichlorodifluoromethane)
$\text{C}_2\text{Cl}_3\text{F}_3$	chlorofluorocarbon-113 (trichlorotrifluoroethane)
CFC	chlorofluorocarbon
CFCs	chlorofluorocarbons
CFC-11	chlorofluorocarbon-11 (trichlorofluoromethane)
CFC-11/CFC-12	ratio of CFC-11 to CFC-12
CFC-12	chlorofluorocarbon-12 (dichlorodifluoromethane)
CFC-113	chlorofluorocarbon-113 (trichlorotrifluoroethane)
CFC-113/CFC-11	ratio of CFC-113 to CFC-11
CFC-113/CFC-12	ratio of CFC-113 to CFC-12
CO_2	carbon dioxide
CP	Coastal Plain
CP-D	Coastal Plain Deep regional aquifer system
CP-M	Coastal Plain Middle regional aquifer system
CP-S	Coastal Plain Shallow regional aquifer system
$\delta^{13}\text{C}$	isotopic ratio of carbon-13 to carbon-12
Δt	radiocarbon age of the water
Freon 11	chlorofluorocarbon-11 (trichlorofluoromethane)
Freon-12	chlorofluorocarbon-12 (dichlorodifluoromethane)
Freon-113	chlorofluorocarbon-113 (trichlorotrifluoroethane)
ft	feet
gal/min	gallon per minute
GC-ECD	gas chromatography with an electron capture detector
GIS	geographic information system
^3H	tritium
$^3\text{H}/^3\text{He}$	tritium/helium-3
Halon 1211	bromochlorodifluoromethane
$^3\text{He}_{trit}$	tritogenic ^3He
IAEA	International Atomic Energy Agency
Max	maximum
MCL	Maximum Contaminant Level
Med	median

Mgal/d	million gallons per day
mg/L	milligrams per liter
Min	minimum
MTBE	methyl <i>tert</i> -butyl ether
n	number of wells and springs sampled
N ₂	nitrogen
nd	not determined
Ne	neon
NO ₂ +NO ₃ -N	nitrite plus nitrate as nitrogen
NO ₃	nitrate
NP	not possible
PCE	tetrachloroethylene
PD	Piedmont regional aquifer system
‰	per mil
pg/kg	picogram per kilogram
pmc	percent modern carbon
ppb	parts per billion
SDWA	Safe Drinking Water Act
SNP	Shenandoah National Park
SWAP	Source Water Assessment Program
SF ₆	sulfur hexafluoride
T _{1/2}	half-life
TCA	1,1,1-trichloroethane
TCE	trichloroethylene
TU	tritium unit
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VAS	Virginia Aquifer Susceptibility
VBCH	Virginia Beach
VDH	Virginia Department of Health
VOCs	volatile organic compounds
VPDB	Vienna Peedee belemnite
VPI	Virginia Polytechnic and State University
VR-C	Valley and Ridge Carbonate regional aquifer system
VR-S	Valley and Ridge Siliciclastic regional aquifer system

CONVERSION FACTORS, DATUM, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
Length		
inch (in.)	25.4	millimeter
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
Area		
square mile (mi ²)	259.0	hectare
square mile (mi ²)	2.590	square kilometer
Volume		
gallon (gal)	3.785	liter
gallon (gal)	0.003785	cubic meter
Cubic inch	16.387	cubic centimeters
picrocurie per liter	37.04	becquerel per liter
picrocurie per liter	0.3135	tritium unit (TU)
ounce	28.35	gram
pound	0.4535	kilogram
picogram	1x10 ⁻¹²	gram
femtogram	1x10 ⁻¹⁵	gram

Water temperature is reported in degree Celsius (°C), which can be converted to degree Fahrenheit (°F) by the following equation: °F = 1.8 (°C) + 32

Stable isotope ratios are reported as δ values computed from the formula

$$\delta_x = \left(\frac{R_x}{R_{STD}} - 1 \right) 1,000$$

where R_x is the ratio of the isotopes measured in the sample and R_{STD} is the isotope ratio in the reference standard. The value of δ_x is in parts per thousand (per mil).

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29); horizontal coordinate information is referenced to the North American Datum of 1927 (NAD27).

Abbreviated water-quality units: Chemical concentration is reported in milligrams per liter (mg/L) or micrograms per liter (µg/L). Milligrams per liter is a unit expressing the concentration of chemical constituents in solution as weight (milligrams) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter. For concentrations less than 7,000 mg/L, the numerical value is the same as for concentrations in parts per million. Specific electrical conductance of water is reported in microsiemens per centimeter at 25 degrees Celsius (µS/cm).

Additional abbreviated units used in this report: L (liter), mL (milliliter), kg (kilogram), pg (picogram), fmol (femtomole), pptv (parts per trillion by volume), STP (standard temperature and pressure, 0 degrees Celsius and 1 atmosphere), cc/L (cubic centimeters per liter).

Aquifer Susceptibility in Virginia, 1998-2000

By David L. Nelms, George E. Harlow, Jr., L. Niel Plummer, and Eurybiades Busenberg

ABSTRACT

The U.S. Geological Survey (USGS), in cooperation with the Virginia Department of Health, sampled water from 171 wells and springs across the Commonwealth of Virginia between 1998 and 2000 as part of the Virginia Aquifer Susceptibility study. Most of the sites sampled are public water supplies that are part of the comprehensive Source Water Assessment Program for the Commonwealth. The fundamental premise of the study was that the identification of young waters (less than 50 years) by multiple environmental tracers could be used as a guide for classifying aquifers in terms of susceptibility to contamination from near-surface sources. Environmental tracers, including chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), tritium (^3H), and tritium/helium-3 ($^3\text{H}/^3\text{He}$), and carbon isotopes (^{14}C and $\delta^{13}\text{C}$) were used to determine the age of water discharging from wells and springs. Concentrations of CFCs greater than 5 picograms per kilogram and ^3H concentrations greater than 0.6 tritium unit were used as thresholds to indicate that parts of the aquifer sampled have a component of young water and are, therefore, susceptible to near-surface contamination.

Concentrations of CFCs exceeded the susceptibility threshold in 22 percent of the wells and in one spring sampled in the Coastal Plain regional aquifer systems. About 74 percent of the samples from wells with the top of the first water zone less than 100 feet below land surface exceeded the threshold values, and water supplies developed in the upper 100 feet of the Coastal Plain are considered to be susceptible to contamination from near-surface sources. The maximum depth to the top of the screened interval for wells that contained CFCs was less than 150 feet. Wells completed in the deep confined aquifers in the Coastal Plain generally contain water older than 1,000 years, as indicated by carbon-14 dating, and are not consid-

ered to be susceptible to contamination under natural conditions. All of the water samples from wells and springs in the fractured-rock terrains (the Appalachian Plateaus, Valley and Ridge, Blue Ridge, and Piedmont regional aquifer systems) contained concentrations of CFCs and ^3H greater than one or both of the thresholds. Because all of the water samples exceeded at least one of the threshold values, young water is present throughout most of these regional aquifer systems; therefore, water supplies developed in these systems are susceptible to contamination from near-surface sources. No relation between well depth and presence of CFCs is evident from samples in the fractured-rock terrains.

More than 95 percent of the samples for which the dating methods were applicable contained waters with apparent ages less than 35 years. About 5 percent of these samples, most of which were from the Blue Ridge and Piedmont regional aquifer systems, contained young waters with apparent ages of less than 5 years. Most of the samples from the Valley and Ridge Carbonate, Blue Ridge, and Piedmont regional aquifer systems had young water fractions of more than 50 percent, whereas samples from the Coastal Plain Shallow and Appalachian Plateaus regional aquifer systems contained less than 40 percent young waters.

Concentrations of CFCs in excess of air-water equilibrium, which can indicate that nonatmospheric sources (such as sewage effluent) have introduced CFCs into the ground-water system, were measured in 6 and 48 percent of the water samples from the Coastal Plain and fractured-rock regional aquifer systems, respectively. The nitrate (NO_3) concentrations greater than the USGS detection level of 0.05 milligrams per liter generally increase as the apparent age of the young water fraction decreases, with the highest NO_3 concentrations for samples in which one or more

of the CFCs are above modern atmospheric mixing ratios (commonly referred to as “contaminated” for ground-water dating purposes). Most of the samples in which NO_3 was detected were from the fractured-rock regional aquifer systems, especially the Valley and Ridge Carbonate regional aquifer system, where 90 percent of the samples had concentrations greater than the detection level. Numerous halogenated volatile organic compounds were detected at low concentrations (parts per quadrillion) in the samples from the regional aquifer systems in the fractured-rock terrains and the Coastal Plain Shallow regional aquifer system.

The ratio of the percentage and apparent age of the young fraction in binary mixtures of young and old (greater than 50 years) waters provides an indication of the relative degree of susceptibility. Large ratios are associated with samples in which the fraction of the young water is large (greater than 75 percent) and apparent age is extremely young (less than 5 years). Samples from the fractured-rock regional aquifer systems generally have the largest ratios. Analysis-of-variance tests indicate that the ratios in the samples from the Blue Ridge regional aquifer system are significantly higher ($p < 0.05$) than those in the other regional aquifer systems. Results from the multiple tracer approach indicate that shallow wells (less than 100 feet deep) and springs in the Coastal Plain and wells and springs in the fractured-rock terrains contain a component of young ground water and are, therefore, susceptible to contamination from near-surface sources.

INTRODUCTION

The U.S. Geological Survey (USGS), in cooperation with the Virginia Department of Health (VDH), conducted the Virginia Aquifer Susceptibility (VAS) study between 1998 and 2001 to determine the susceptibility to contamination from near-surface sources of the regional aquifer systems in Virginia that serve as public water supplies (Harlow and others, 1999). Water samples were collected from 165 wells and 6 springs in various hydrogeologic settings across Virginia (fig. 1). Multiple environmental tracers—chlorofluorocarbons

(CFCs), sulfur hexafluoride (SF_6), tritium (^3H), and tritium/helium-3 ($^3\text{H}/^3\text{He}$)—and carbon isotopes (^{14}C and $\delta^{13}\text{C}$) were used to determine the age of water discharging from wells and springs. Most of these wells and springs are regulated as public water supplies and are classified by the VDH as community, transient non-community, or non-transient non-community systems. Site and construction information for wells and springs sampled between 1998 and 2000 and the chemical and isotopic composition, recharge temperatures, and apparent ages of these water samples are presented in Nelms and Harlow (2003).

The Safe Drinking Water Act (SDWA) Amendments of 1996 require the Commonwealth of Virginia to develop and implement a comprehensive Source Water Assessment Program (SWAP). The VAS study is part of Virginia's SWAP (Virginia Department of Health, 1999), which is coordinated by the VDH, Division of Drinking Water. The fundamental premise of the VAS study was that the identification of young waters (less than 50 years) by multiple environmental tracers could be used as a guide for classifying aquifers in terms of susceptibility to contamination from near-surface sources. The information from the VAS study will be used by VDH (1) to determine which water supplies are sensitive to contamination from near-surface sources, and (2) to screen public ground-water supplies and identify those that require detailed source-water assessments.

Various methods have been used to determine the susceptibility and/or vulnerability of aquifers to near-surface contamination. DRASTIC, a ground-water vulnerability mapping method developed by Aller and others (1985), has been used throughout the world, including several counties in Virginia (Durnford and others, 1990; Hearne and others, 1992; Lynch and others, 1997; Melloul and Collin, 1998; Kim and Hamm, 1999). The DRASTIC method uses a subjective point-rating system that has been shown to have variable success when compared to actual ground-water-quality data (Barbash and Resek, 1996; Koterba and others, 1993; U.S. Environmental Protection Agency, 1993; Rupert, 1997, 2001). Ground-water vulnerability mapping in Great Britain has been done using a method that is similar to DRASTIC, but that includes detailed hydrogeologic variables (Daly and Warren, 1998; Palmer and Lewis, 1998).

Vowinkel and others (1994, 1996) and Storck and others (1997) developed numerical rating models to

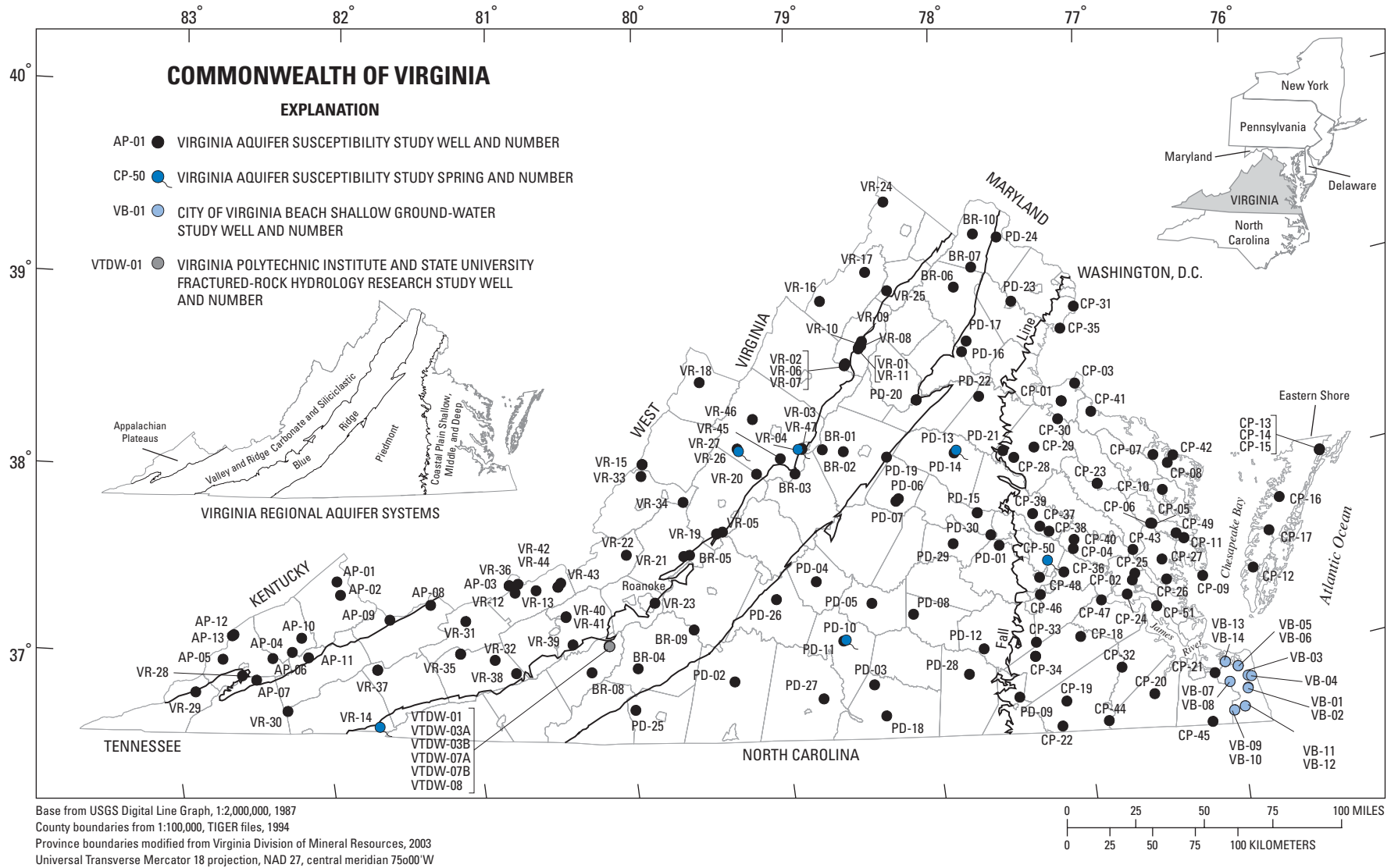


Figure 1. Regional aquifer systems and wells and springs sampled in Virginia, 1998-2000.

determine the vulnerability of public drinking-water supplies to pesticide contamination in New Jersey. These models used geospatial, soil, and well-construction characteristics in conjunction with intensity of pesticide use, and were tested with a geographic information system (GIS) by grouping sites in terms of vulnerability (high, medium, or low) by using measured concentrations in water samples. Recent studies have classified aquifer vulnerability in terms of probability of occurrence of selected chemical constituents by the use of logistic regression methods (Tesoriero and Voss, 1997; Nolan, 1998, 2001; Rupert, 1998; Squillace, Moran, Lapham, and others, 1999; Frans, 2000; Greene and others, 2002).

Detailed hydrogeologic information in Virginia is primarily limited to the aquifers in the Coastal Plain and Appalachian Plateaus Physiographic Provinces. The paucity of readily available hydrogeologic data makes it difficult to use numerical rating models and logistic regression methods to determine aquifer susceptibility on a statewide scale. However, previous investigations in Virginia used environmental tracers to identify young waters and, in some cases, indicated a correlation between apparent age and the occurrence of selected chemical constituents in ground water (Busenberg and Plummer, 1992; Dunkle and others, 1993; Nelms and Ahlin, 1993; Speiran, 1996; McFarland, 1997; Nelms and Brockman, 1997; Focazio and others, 1998; Plummer and others, 2001). The VAS study was designed to rely on measured concentrations of multiple environmental tracers in water samples collected from wells and springs that are representative of water supplies developed in the regional aquifer systems across Virginia (Harlow and others, 1999; Nelms and Harlow, 2000). The atmospheric origin of these environmental tracers increases their potential to be detected in ground water on a statewide scale. These tracers thus are more useful indicators of aquifer susceptibility than the occurrence and distribution of selected chemical constituents in ground water such as nutrients and synthetic organic compounds, which generally are related to near-surface point sources.

The term "apparent age," as defined by Plummer and Busenberg (2000), is used throughout this report because the model age from the environmental tracers approximates the time elapsed since a water sample was isolated from air in the unsaturated zone during recharge and is based on an analysis of measured concentrations of environmental tracers in ground water. Chemical (sorption and biodegradation) and physical

(mixing and matrix diffusion) processes can alter the concentrations of the tracers in ground water and thus the model ages (Plummer and Busenberg, 2000; Shapiro, 2001). The initial apparent age represents estimates based on an individual environmental tracer whereas the final apparent age assigned to a water sample is based on an evaluation of the ages based on multiple environmental tracers.

Purpose and Scope

The purpose of this report is to present determinations of aquifer susceptibility to contamination from near-surface sources for the regional aquifer systems that serve as public water supplies across the Commonwealth of Virginia. The report presents the findings of the VAS study, which was conducted from 1998 to 2001, and involved the use of multiple environmental tracers (CFCs, SF₆, ³H, and ³H/³He) and carbon isotopes (¹⁴C and δ¹³C) to classify aquifers in terms of susceptibility to contamination. Water samples were collected from 165 wells and 6 springs to determine susceptibility of the regional aquifer systems. The report (1) classifies regional aquifer systems in terms of susceptibility, and (2) evaluates the validity of the VAS study methodology by comparing the occurrence of selected chemical constituents to aquifer susceptibility, apparent ground-water ages, and percentage of young water.

Hydrogeologic Description of Regional Aquifer Systems in Virginia

The Commonwealth was subdivided into eight regional aquifer systems on the basis of (1) physiographic province (Fenneman, 1938), (2) geologic province, and (3) hydrogeologic characteristics, (4) major rock type (in the Valley and Ridge Province), and (5) depth of the top of the first screened interval (in the Coastal Plain Province). These regional aquifer systems are:

1. Appalachian Plateaus
2. Valley and Ridge Carbonate
3. Valley and Ridge Siliciclastic
4. Blue Ridge

5. Piedmont (including the Mesozoic Basins)
6. Coastal Plain Shallow (depths less than 200 ft below land surface)
7. Coastal Plain Middle (depths between 200 and 400 ft below land surface)
8. Coastal Plain Deep (depths greater than 400 ft below land surface).

The Appalachian Plateaus, Valley and Ridge Carbonate and Siliciclastic, Blue Ridge, and Piedmont regional aquifer systems are characterized by fractured-rock aquifers. The carbonate rocks (limestone and dolostone) in the Valley and Ridge regional aquifer systems have different hydrogeologic characteristics (karst topography, solution channels, and caves) than the fractured siliciclastic rocks (sandstone, shale, and siltstone). The Coastal Plain regional aquifer systems are primarily composed of unconsolidated sedimentary deposits (porous media). Because of the wedge-like geometry of the Coastal Plain deposits, a single aquifer may be assigned to/classified in multiple regional aquifer systems (fig. 2) on the basis of hydrogeologic setting (Nelms and Harlow, 2000). The distribution of sites sampled during the VAS study by aquifer within the regional aquifer systems is summarized in table 1. The aquifer designations in the fractured-rock terrains are based on geologic formation whereas the aquifer designations in the Coastal Plain are based on aquifer nomenclature from Meng and Harsh (1988) and Hamilton and Larson (1988). The following sections contain descriptions of the regional aquifer systems and the corresponding physiographic provinces (modified from Nelms and others, 1997).

Appalachian Plateaus Regional Aquifer System

The Appalachian Plateaus regional aquifer system is within the Appalachian Plateaus Physiographic Province. This province encompasses approximately 1,600 mi² and is characterized by a well-dissected mountainous landscape with dendritic drainage formed on almost flat-lying to gently folded Paleozoic sedimentary rocks (Trapp and Horn, 1997). Elevations range from about 1,000 ft to more than 4,000 ft above sea level on High Knob in Wise County. The eastern edge of the province is the Cumberland Escarpment, which coincides with the Appalachian structural front where the westernmost fault of the Valley and Ridge Province

reaches land surface. A thin mantle of weathered material (regolith) covers the bedrock, which is composed of relatively undeformed sedimentary rocks—sandstone, shale, and limestone (Powell and Larson, 1985). The most characteristic rock type is coal that occurs as beds and seams and is commonly fractured along joint systems (referred to as cleats) (Harlow and LeCain, 1991). Vertical stress-relief fractures are another prominent feature in this province (Wyrick and Borchers, 1981).

Ground water flows in (1) the regolith (unconsolidated alluvium, colluvium, and saprolite), and (2) along fractures and joints in the bedrock. Recharge to the fractured-rock aquifers is somewhat limited by the highly dissected, steep terrain and relatively impermeable bedrock. Ground water moves in a step-like manner along the more permeable vertical fractures and along cleats and fractures in the sub-horizontal coal and sandstone beds (Harlow and LeCain, 1991; Trapp and Horn, 1997). Downward movement of water along vertical fractures can be rapid and enhanced by pumpage.

Valley and Ridge Regional Aquifer Systems

The Valley and Ridge regional aquifer systems are within the Valley and Ridge Physiographic Province. This province encompasses approximately 10,600 mi² along the western part of Virginia and consists of a belt of northeast-southwest trending ridges and valleys formed by the differential erosion of a thick sequence of folded and faulted Paleozoic sedimentary rocks (Pet-tijohn, 1970). Elevations range from about 380 ft above sea level where the Shenandoah River flows from Virginia into Maryland to 4,604 ft above sea level in southwestern Virginia (Butts, 1940). North of the city of Roanoke, Va., the province is part of the central Appalachians and is separated into two subdivisions: (1) a southeastern valley area, commonly referred to as the Great Valley, underlain by Cambrian to Ordovician carbonate rocks and shale characterized by broad valleys with interspersed ridges or hills; and (2) a northwestern ridge area underlain by Silurian to Pennsylvanian sandstones and shale characterized by high ridges with interspersed narrow valleys (Hack, 1989). Another feature of the province north of Roanoke is a thick mantle of residuum, talus, and alluvial deposits that overlie the Cambrian carbonate rocks on the eastern slope of the valley at the foot of the Blue Ridge (King, 1950; Leonard, 1962; Hack, 1965, 1989).

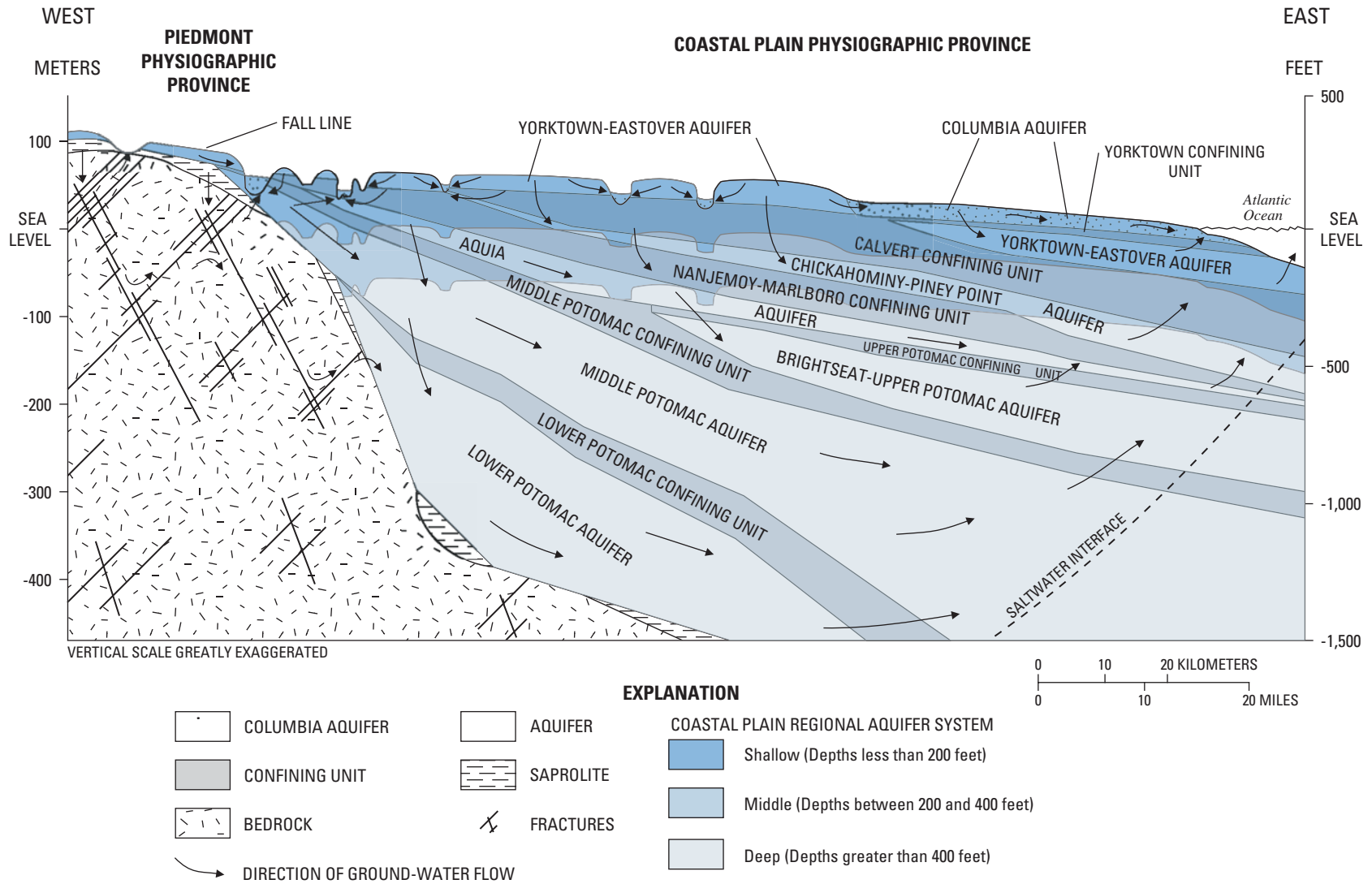


Figure 2. Generalized hydrogeologic section representing conceptualization of the Virginia Coastal Plain Province as layered aquifers and confining units (modified from McFarland, 1999). The regional aquifer system classification used during the Virginia Aquifer Susceptibility study is also shown.

Table 1. Distribution of wells and springs sampled as part of the Virginia Aquifer Susceptibility study by regional aquifer system and aquifer, 1998-2000

[n, indicates number of wells and springs sampled]

APPALACHIAN PLATEAUS		VALLEY AND RIDGE			
		Carbonate		Siliciclastic	
Aquifer	n	Aquifer	n	Aquifer	n
Bluefield	1	Conococheague	7	Brallier	4
Lee	1	Elbrook	3	Chattanooga	1
New River	1	Knox	1	Chemung	2
Norton	7	Martinsburg	1	Devonian/Silurian	2
Pennington Gap	1	Middle Ordovician	1	Granite	1
Wise	2	Reedsville/Eggleston/Moccasin	1	Huntersville	1
Total	13	Rome	3	Millboro	4
		Shady	3	Millboro/Needmore	1
		Waynesboro	1	Missippian Fms. Undiv	1
		Total	21	Moccasin/Bays	1
				Reedsville/Eggleston/Moccasin	1
				Rome	4
				Rose Hill	1
				Waynesboro	1
				Total	25
BLUE RIDGE		PIEDMONT			
Aquifer	n	Aquifer	n		
Augen gneiss	6	Amphibolite and Amphibolite rich foliats	2		
Catoctin	1	Balls Bluff	3		
Elbrook	1	Biotite gneiss	2		
Granite	1	Everona	1		
Granite Gneiss	4	Fork Mountain	1		
Marshall	2	Garnet-biotite gneiss	1		
Metamorphosed Sedimentary Rocks	1	Granite	1		
Shady	1	Granite Gneiss	7		
Total	17	Jurassic System	1		
		Manassas	1		
		Metamorphosed Sedimentary Rocks	2		
		Metamorphosed Volcanic and Sedimentary Rocks	3		
		Mylonite	1		
		Newark	1		
		Ordovician System	1		
		Petersburg	1		
		Vinita	1		
		Total	30		
COASTAL PLAIN¹					
Shallow (depths less than 200 ft)		Middle (depths between 200 and 400 ft)		Deep (depths greater than 400 ft)	
Aquifer	n	Aquifer	n	Aquifer	n
Columbia	9	Chickahominy/Piney Point	7	Upper Potomac	2
Yorktown-Eastover	20	Aquia	1	Middle Potomac	8
Chickahominy/Piney Point	1	Upper Potomac	2	Lower Potomac	1
Virginia Beach	1	Middle Potomac	9	Total	11
Middle Potomac	2	Lower Potomac	1		
Granite Gneiss	1	Total	20		
Total	34				

¹ Depths are below land surface and aquifer system designation for a particular site sampled is based on the depth below land surface of the top of the first screened interval.

This belt of unconsolidated deposits, commonly referred to as the “Western Toe” of the Blue Ridge, can exceed 600 ft in thickness (T.M. Gathright, II, Virginia Division of Mineral Resources, oral commun., 1994). South of Roanoke, the province is part of the southern Appalachians and is characterized by ridges and narrow valleys, and the predominant style of deformation within the province changes from folding to thrust faulting (Hack, 1989).

For this study, the Valley and Ridge Province was subdivided into two regional aquifer systems based on major rock type—carbonate (limestone and dolostone) and siliciclastic (sandstone, siltstone, and shale). The carbonate rocks in the Valley and Ridge have unique hydrogeologic features (karst topography, solution channels, and caves) that are not characteristic of siliciclastic rocks. Ground water in the carbonate rocks of the Valley and Ridge flows (1) in the regolith (alluvium, colluvium, and residuum); (2) along fractures, joints, and bedding plane partings in the bedrock; and (3) in solution channels and cavities (caves) formed by the dissolution of carbonate minerals. Ground-water storage in the carbonate rocks can be in the regolith and in the solution channels and cavities in the bedrock. Large volumes of ground water can move at relatively high flow velocities along the dissolution features in areas with low hydraulic gradients.

Ground water in the siliciclastic rocks of the Valley and Ridge Province flows (1) in the regolith (primarily alluvium and colluvium); and (2) along fractures, joints, and bedding-plane partings in the bedrock. Hobba (1972) estimated that circulation depths of ground water are over 1,500 ft in the thermal spring areas of western Virginia. Ground-water storage in the siliciclastic rocks can be in the regolith and in the fractures, joints, and bedding-plane partings. Flow velocities and gradients can be high and ground-water storage is limited in the fractured siliciclastic rock aquifers.

Blue Ridge Regional Aquifer System

The Blue Ridge regional aquifer system is within the Blue Ridge Physiographic Province. This province encompasses approximately 3,000 mi² along a narrow northeast-trending belt between the Valley and Ridge and Piedmont Provinces and consists of a chain of mountains and highlands underlain by metamorphosed Proterozoic and Paleozoic rocks (Reed, 1970). Elevations range from about 220 ft above sea level along the

Potomac River at the Maryland/Virginia state line to 5,729 ft above sea level on Mount Rodgers. Generally, soils are thin and weathering profiles are shallow (Meyer and others, 1965). Hack (1982) separated the province into two sections because the origins of the topography differ. The section north of the Roanoke River, the Northern Blue Ridge Mountains, is characterized by a narrow range of high mountains underlain by Precambrian to Cambrian quartzite, phyllite, metabasalt, and granodiorite that form the northwest limb of an anticlinorium. The section south of the Roanoke River, the Southern Blue Ridge Province, is much broader and was separated by Hack (1982) into five subdivisions based on topography: (1) the Chilhowee-Walden Creek belt, underlain by Cambrian quartzite and faulted carbonate rocks and shale that form long, steep ridges separated by parallel valleys along the northwest margin; (2) the Mount Rodgers area, underlain by Precambrian volcanic and metasedimentary rocks that form a few high ridges just north of the North Carolina/Virginia border; (3) the Blue Ridge Highlands, underlain by massive Precambrian gneisses and amphibolites that form high mountains cut by deep valleys and basins; (4) the New River Plateau, which encompasses the headwaters of the New River in North Carolina, underlain by thinly layered schist and gneiss that form a broad plateau with a few low mountains; and (5) the Blue Ridge Escarpment, underlain by finely laminated gneiss that forms a narrow strip of land that drains southeastward to the Piedmont Province.

Ground water flows in (1) the regolith (unconsolidated alluvium, colluvium, and saprolite), and (2) along fractures and joints in the bedrock. Numerous springs discharge from the regolith and from the contacts between the regolith and bedrock. Flow velocities and gradients can be high and ground-water storage is limited in the fractured-rock aquifers in the Blue Ridge. Springs with source areas in the alluvium and colluvium on the mountain slopes can contain water with extremely short residence times, from 0 to 3 years (Plummer and others, 2001).

Piedmont Regional Aquifer System

The Piedmont regional aquifer system is within the Piedmont Physiographic Province. This province encompasses approximately 16,300 mi² along the east-central part of the study area and consists of a gently rolling plain underlain by polydeformed and meta-

morphosed Proterozoic and Paleozoic rocks (Fisher, 1970). A thick mantle of soil and weathered rock (saprolite, regolith, or residuum) that overlies the fractured crystalline bedrock is a characteristic feature of the province (Meyer and others, 1965; Conley, 1985; Swain and others, 1991). Generally, regolith developed on the crystalline rocks is thick under the hilltops and thin to absent in the stream valleys (Richardson, 1982; Pavich and others, 1989). Elevations range from about 200 ft above sea level along the eastern border to 1,000 ft above sea level along the western border of the province. Hack (1982) noted that the Piedmont Physiographic Province of Virginia consists of the Foothill zone on the west, the Piedmont Lowlands on the east, and the Northeastern Highlands on the north. The Foothill zone also encompasses the southeastern part of the Blue Ridge Physiographic Province. Resistant volcanic and metamorphic rocks that form chains of isolated hills and ridges underlie the region of the Foothill zone north of the Roanoke River. The region of the Foothill zone south of the Roanoke River is underlain by resistant rocks of the Smith River allochthon that forms an upland (Hack, 1982). The Piedmont Lowlands are underlain by feldspathic gneiss and schist intruded by granitic plutons with lesser amounts of metasedimentary and metavolcanic rocks that form low ridges or hills and ravines.

Down-faulted Mesozoic sedimentary basins, which encompass approximately 1,340 mi², are located within the Piedmont Physiographic Province. These basins are underlain by shale, siltstone, mudstone, sandstone, and basalt and are characterized by generally lower relief than the surrounding Piedmont (Hack, 1989, p. 461). Thin soils and shallow weathering profiles are characteristic features of the Mesozoic Basins (Froelich, 1985; Conley, 1985).

Ground water in the crystalline terrains flows (1) in the regolith (predominantly saprolite), and (2) along fractures and joints in the bedrock. Most of the ground-water storage in the crystalline terrains is in the saprolite. Ground water in the Mesozoic Basins predominantly flows along fractures, joints, and bedding-plane partings. Because of the thin mantle of saprolite, ground-water storage in the rocks of the Mesozoic Basins is predominantly in the fractures, joints, and bedding-plane partings. Flow velocities and gradients can be high near pumped wells.

Coastal Plain Regional Aquifer Systems

The Coastal Plain regional aquifer systems are within the Coastal Plain Physiographic Province. This province encompasses approximately 8,500 mi² in the eastern part of the study area and consists of an eastward-thickening wedge of sediments composed principally of unconsolidated gravels, sands, silts, and clays, with variable amounts of shells. These unconsolidated deposits directly overlie bedrock that slopes eastward and is commonly referred to as the "basement." The sediments attain a maximum thickness of more than 6,000 ft in the northeastern part of the Coastal Plain of Virginia. Onuschak (1972) states that the sediments are 6,186 ft thick beneath the Eastern Shore Peninsula at Temperanceville, Va. Coastal Plain sediments thin westward and effectively end at the Fall Line, the boundary with the Piedmont Province. Elevations range from sea level in the coastal areas to about 250 ft above sea level near the Fall Line.

The regional aquifer systems in the Coastal Plain are subdivided into a series of aquifers separated by intervening confining units consisting of silts and clays (Meng and Harsh, 1988). Generally, the Columbia aquifer and, in certain areas, the Yorktown-Eastover aquifer, are unconfined and the deeper aquifers are confined, except in areas near the Fall Line where these aquifers are exposed at the surface (McFarland, 1997). In the lower Chesapeake Bay, the structural and stratigraphic features created by the Chesapeake Bay impact crater have disrupted the "normal" aquifer system sequence and influenced the hydrogeology, ground-water-flow system, and water quality in a large part of the Coastal Plain. The impact crater was formed when a large comet or meteorite crashed into shallow shelf-depth waters of the western Atlantic Ocean approximately 35 million years ago. The crater is a 56-mile wide structure that penetrates the basement to a depth of at least 1.2 miles near the town of Cape Charles located in the southern part of the Eastern Shore of Virginia (Powars and Bruce, 1999; Powars, 2000).

The Coastal Plain was subdivided into the following three regional aquifer systems on the basis of the depth of the aquifer and screened interval below land surface: (1) shallow (depths less than 200 ft below land surface), (2) middle (depths between 200 and 400 ft below land surface), and (3) deep (depths greater than 400 ft below land surface). Because of the wedge-like geometry of the Coastal Plain deposits, a single aquifer

may be assigned to/classified in multiple regional aquifer systems on the basis of hydrogeologic setting (Nelms and Harlow, 2000). For example, near the Fall Line, the Middle Potomac aquifer is classified in the Coastal Plain Shallow system, but the regional aquifer system designation changes to the Coastal Plain Middle system and then to the Coastal Plain Deep system as the aquifer becomes deeper towards the east and is less connected to hydrologic and anthropogenic activities at the surface.

Ground water flows around and between sediment grains in the Coastal Plain. This tortuous path causes the residence times to be much longer than in the other provinces. Ground-water storage can be much larger in the Coastal Plain than in the other provinces. About 100 Mgal/d (million gallons per day) are removed from the Coastal Plain aquifers by major ground-water users (Hammond and Focazio, 1995). Flow in the shallow aquifer system generally is along local to subregional flow paths, whereas flow in the middle and deep aquifer systems is along subregional to regional flow paths.

Sampling Locations

Public water supplies, which are classified by the VDH as community, transient non-community, or non-transient non-community systems on the basis of water use and population, were the primary focus of the VAS study. Sampling locations were selected on the basis of (1) geographic position of the supply within Virginia and within the respective regional aquifer system, (2) availability of well-construction information, and (3) site accessibility (fig. 1). Some sites that are not classified as public water supplies were selected because of their unique characteristics. For example, the public water-supply data base maintained by the VDH did not contain any springs in the Coastal Plain of Virginia; therefore, spring CP-50 was selected for sampling to assess the susceptibility to contamination of springs in the Coastal Plain. The wells and springs that were sampled, which included wells for a shallow ground-water study for the city of Virginia Beach (Johnson, 1999) and wells for a Virginia Polytechnic Institute and State University fractured-rock hydrology study, were assigned VAS numbers (fig. 1). Site and construction information for wells and springs sampled between 1998 and 2000, and the chemical and isotopic composition, recharge temperatures, and apparent ages

of these water samples are presented in Nelms and Harlow (2003).

Methods

The sampling and analytical methods used during the VAS study are described in detail in Nelms and Harlow (2003). Ground-water apparent ages were estimated by a multiple tracer approach whereby the environmental tracers—chlorofluorocarbons (CFCs), sulfur hexafluoride (SF_6), tritium (^3H), and tritium/helium-3 ($^3\text{H}/^3\text{He}$)—are used to date young waters (less than 50 years), and naturally occurring carbon isotopes—carbon-14 (^{14}C) and carbon-13 ($\delta^{13}\text{C}$)—are used to date paleowaters (greater than 1,000 years).

Ground-water dating with CFCs (Busenberg and Plummer, 1992) is based on Henry's law of solubility, which is a function of the temperature during recharge and the salinity of the ground water. Concentrations of dissolved nitrogen (N_2) and argon (Ar) were used to estimate recharge temperatures and excess air in ground water (Heaton, 1981; Heaton and Vogel, 1981; Heaton and others, 1983; Busenberg and others, 1993). In shallow ground waters, salinity corrections are not necessary because these waters generally contain dilute salt concentrations (Plummer and Busenberg, 2000). The apparent CFC age of the water sample was determined by comparing the calculated partial pressures of CFCs in solubility equilibrium with the sample to the historical atmospheric CFC concentrations in North American air (fig. 3).

The SF_6 dating method (Busenberg and Plummer, 2000) is similar to the CFC dating method (fig. 3). However, unlike CFCs, SF_6 in ground water can be derived from anthropogenic and terrigenic sources, it is generally not affected by sorption and biodegradation processes, and it can be affected by excess air in ground water, which is attributed to air entrainment during recharge (Heaton and Vogel, 1981).

Tritium (^3H) is the radioactive isotope of hydrogen with a half-life of 12.43 years (International Atomic Energy Agency, 1981) and is an indicator of ground water recharged since 1952 (Clark and Fritz, 1997). Production of ^3H in the atmosphere naturally occurs by cosmic ray spallation, but the principal source since about 1952 has been the atmospheric testing of thermonuclear weapons (fig. 3). Because ^3H levels in water are not unique to a specific year, the ^3H method was

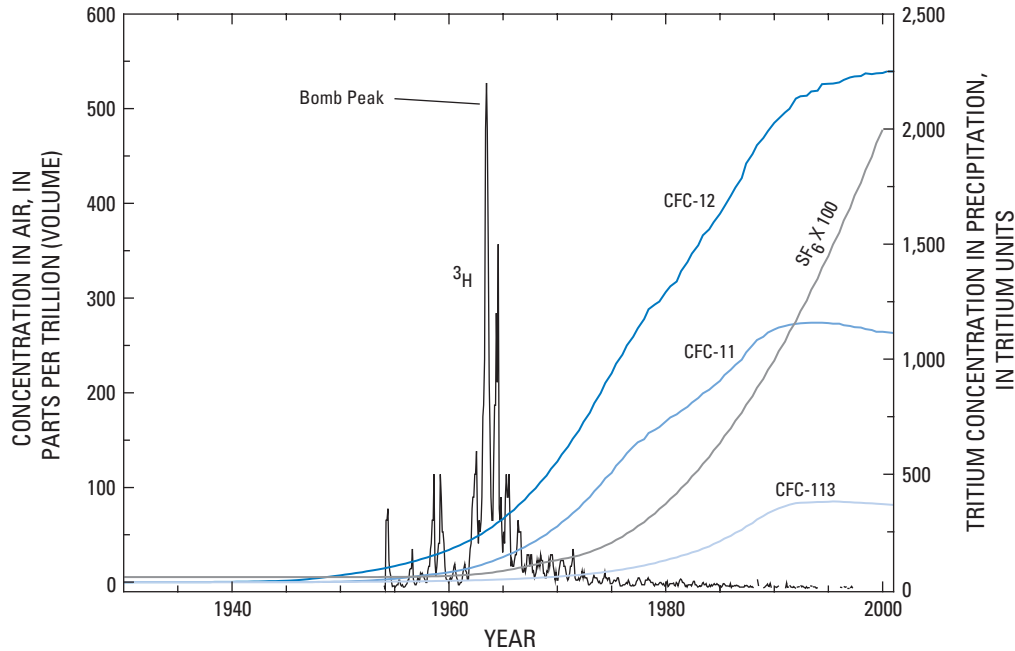


Figure 3. Atmospheric mixing ratios of chlorofluorocarbon-11 (CFC-11), chlorofluorocarbon-12 (CFC-12), chlorofluorocarbon-113 (CFC-113), and sulfur hexafluoride (SF₆) for North American air and estimated monthly concentration of tritium (³H) in precipitation for Virginia. Tritium data derived from estimation technique of Michel (1989) and are not corrected for radioactive decay. Modified from Plummer and Busenberg (2000).

used primarily to confirm the presence of young water. The ³H/³He method is based on the radioactive decay of ³H to ³He such that the helium isotope mass balance is used to determine the amount of tritiogenic ³He (³He_{trit}) derived from ³H (Schlosser and others, 1988, 1989). If the ³He_{trit} is confined in the aquifer, apparent ³H/³He ages of the water samples (τ) can be calculated from the following formula (Schlosser and others, 1988, 1989):

$$\tau = T_{1/2} / \ln 2 \times \left[1 + \frac{[{}^3\text{He}_{\text{trit}}]}{{}^3\text{H}} \right] \quad (1)$$

where T_{1/2} is the half-life of tritium. Neon (Ne) concentrations are used to correct ³He_{trit} for samples that contain terrigenous helium from crustal and mantle sources such as crystalline rocks.

Dating of paleowaters recharged over the past 30,000 years is based on the radioactive decay of ¹⁴C (Clark and Fritz, 1997). Radiocarbon dating is problematic for two reasons: (1) the initial ¹⁴C activity (A₀) at the time the water was isolated (recharged) from the

ambient ¹⁴C reservoir is not known, and (2) the ¹⁴C activity measured for the water sample (A) does not indicate the effects of chemical reactions that might have altered the initial ¹⁴C activity along a flow path (Wigley and others, 1978, 1979; Plummer and others, 1994). Adjustment models are applied to individual water samples to account for inorganic reactions that could have affected the inorganic carbon reservoir in the aquifers sampled (Plummer and others, 1994). Inorganic carbon adjustment models (Fontes and Garnier, 1979; Tamers, 1975; Ingerson and Pearson, 1964; Mook, 1972; and Eichinger, 1983) determine an adjusted ¹⁴C activity (A_{nd}) in the observed water with the assumption that radioactive decay of ¹⁴C has not occurred. The radiocarbon age of the water (Δt (years)) is determined by comparing the adjusted ¹⁴C activity to the measured ¹⁴C activity by means of the radioactive decay equation (Plummer and others, 1994).

$$\Delta t(\text{years}) = \frac{5,568}{\ln 2} \ln \left(\frac{A_{nd}}{A} \right) \quad (2)$$

The adjusted radiocarbon ages are based on the Libby half-life of 5,568 years, reported in radiocarbon years BP (before present, where present is AD 1950), and were not calibrated to calendar years. The adjustment models were accessed through the geochemical model NETPATH (Plummer and others, 1994), and the following initial conditions were assumed:

1. ^{14}C activity in carbonate minerals of 0 percent modern carbon (pmc),
2. ^{14}C activity in soil gas carbon dioxide (CO_2) of 100 pmc,
3. $\delta^{13}\text{C}$ in carbonate minerals of 0 ‰ (per mil) relative to the Vienna Pee Dee belemnite (VPDB) standard, and
4. $\delta^{13}\text{C}$ in soil gas CO_2 of -20 ‰ relative to VPDB.

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AQUIFER SUSCEPTIBILITY

The potential for an aquifer to be contaminated from near-surface sources is indicated by the presence of young waters. The VAS study used the CFC method (Busenberg and Plummer, 1992) as the principal indicator of the presence of young waters. Water samples from 171 wells and springs across Virginia were analyzed for concentrations of the CFC compounds trichlorofluoromethane (CCl_3F , CFC-11, Freon 11), dichlorodifluoromethane (CCl_2F_2 , CFC-12, Freon 12), and trichlorotrifluoroethane ($\text{C}_2\text{Cl}_3\text{F}_3$, CFC-113), and for concentrations of ^3H . The detection level for CFC-11 and CFC-12 was near 0.3 pg/kg (picogram per kilogram) and for CFC-113 was approximately 1.0 pg/kg (Plummer and others, 1998). These detection levels are equivalent to less than 1 part per quadrillion (Plummer and others, 1998) and are about five orders of magnitude less than detection levels for standard drinking-water samples. Sorption and biodegradation processes can reduce CFC concentrations in ground water; therefore, ^3H was used as a secondary indicator of the presence of young water. The detection level for ^3H was less than 0.3 ± 0.3 TU (tritium unit). The results of CFC and ^3H sampling of the 171 wells and springs were used to classify regional aquifer systems across Virginia as susceptible or not susceptible to contamination from near-surface sources. Apparent ages and the percentage of young water in the samples provided additional information on aquifer susceptibility. For samples that were indicative of binary mixtures of young and old (pre-CFC, or greater than 50 years) waters, CFC, SF_6 , and $^3\text{H}/^3\text{He}$ methods were used to estimate the apparent age of the young fraction. As a means of evaluating the validity of the VAS study methodology, the occurrence of selected chemical constituents in the water samples was compared to aquifer susceptibility determinations, apparent ground-water ages, and percentages of young water.

Determination of Susceptibility of Regional Aquifer Systems

Under the Commonwealth's SWAP, existing and potential threats to the quality of the public drinking water at each water system throughout Virginia are being evaluated by (1) delineating the source-water assessment area, (2) conducting a contaminant-source inventory, and (3) determining the susceptibility of the public water supply to contamination from the inventoried sources (Virginia Department of Health, 1999). Susceptibility determination is a three-step process (table 2). First, the findings from the VAS study will be used to determine if a ground-water source (community well or spring) is sensitive to land-use activities in the source-water assessment area. Second, the assessment area will be divided into two zones and land-use activities will be inventoried. A field inventory will be done in a 1,000-ft radius around the well (zone 1); in a 1-mi radius around the well (zone 2), potential sources of contamination will be identified from geographic information system (GIS) data layers from State and Federal regulatory authorities and other sources. Third, the SWAP susceptibility determination (very low, low, moderate, or high) will be assigned.

Table 2. Virginia Source Water Assessment Program (SWAP) susceptibility determinations for ground-water sources

[Modified from Virginia Department of Health, 1999]

Sensitive source ¹	Land-use activity present in source area	SWAP susceptibility
No	No	Very Low
No	Yes	Low
Yes	No	Moderate
Yes	Yes	High

¹The Virginia Department of Health will use the findings from the VAS study to determine if a ground-water source is sensitive to land-use activities in the source-water assessment area.

Results of the CFC and ³H analyses from the water samples from 171 wells and springs across Virginia were used to determine which regional aquifer systems are susceptible to contamination from near-surface sources. The VAS study used a threshold CFC concentration of 5 pg/kg as the principal indication of the presence of young waters (less than 50 years) in the

regional aquifers sampled. The threshold CFC concentration is greater than the detection levels for the CFC compounds and was established to avoid possible complications introduced by analytical precision at extremely low levels of detection. The threshold was considered to be exceeded if one of the CFC concentrations was greater than the threshold value. A threshold concentration for ³H of 0.6 TU was used for samples that met at least one of the following criteria: (1) the threshold was not exceeded for any of the CFCs measured, (2) dissolved oxygen concentrations were low, (3) methane and hydrogen sulfide were detected, and (4) the aquifer was known to contain abundant organic matter (for example, coal and peat deposits). Sorption of CFCs to sediments and organic matter and biodegradation of the CFCs can decrease the concentrations of CFCs in ground water, making the water sample "appear" older than it actually is (Busenberg and Plummer, 1992; Plummer and Busenberg, 2000). In some situations, these processes can completely remove the CFCs from the water. For ³H, analytical precision at the detection level is ±0.3 TU; similar to the CFCs, the threshold ³H concentration is greater than the detection level plus the precision error concentration.

Summary statistics for averaged values from the replicate analyses for the CFCs and individual analyses of ³H concentrations for samples from the regional aquifer systems are provided in table 3. Concentrations that exceed the CFC and ³H thresholds indicate the presence of young waters (shaded cells in table 3). The large maximum concentrations for the CFCs indicate that sources other than the atmosphere have introduced CFCs into the ground water; therefore, precise age dating of these samples is not possible. However, these samples still indicate the presence of young waters. Threshold concentrations of at least one CFC compound and of ³H frequently were exceeded in the regional aquifer systems in the fractured-rock terrains and in the shallow parts of the Coastal Plain (fig. 4).

Appalachian Plateaus Regional Aquifer System

The threshold CFC concentration was exceeded in 11 of the 13 wells (85 percent) sampled to represent the Appalachian Plateaus regional aquifer system (fig. 4). CFC concentrations ranged from less than 0.3 to 4,113 pg/kg with median concentrations of 15.8, 13.4, and less than 1.0 pg/kg for CFC-11, CFC-12, and CFC-113, respectively (table 3). The threshold ³H con-

Table 3. Summary statistics for average chlorofluorocarbon and tritium concentrations by regional aquifer system

[Shaded cells indicate values that exceeded chlorofluorocarbon (CFC) and tritium thresholds of 5 picograms per kilogram (pg/kg) and 0.6 tritium unit (TU), respectively. Min, minimum; Max, maximum; Med, median; AP, Appalachian Plateaus; VR-C, Valley and Ridge Carbonate; VR-S, Valley and Ridge Siliciclastic; BR, Blue Ridge; PD, Piedmont; CP-S, Coastal Plain Shallow (depths less than 200 feet); CP-M, Coastal Plain Middle (depths between 200 and 400 feet); CP-D, Coastal Plain Deep (depths greater than 400 feet); <, less than]

Aquifer system	CFC-11 (pg/kg)			CFC-12 (pg/kg)			CFC-113 (pg/kg)			Tritium (TU)		
	Min	Max	Med	Min	Max	Med	Min	Max	Med	Min	Max	Med
AP	1.1	4,113.4	15.8	<0.3	3,244.6	13.4	<1.0	151.5	<1.0	5.9	8.9	7.4
VR-C	5.7	1,197.0	310.8	<.3	1,832.8	192.1	2	129,128.4	136.9	0.02	12.3	4.7
VR-S	1.3	846.9	87.3	3.1	5,349.9	65.8	<1.0	907.9	26.4	0.6	10.2	5.6
BR	9.4	9,853.1	134.7	69.1	98,347.9	299.8	<1.0	4,031.8	88.3	2.5	12.6	9
PD	2.7	19,410.5	253.7	8.1	9,472.1	232.3	<1.0	776.3	53.1	<.3	12.8	7.6
CP-S	<.3	1,620.3	0.8	<.3	644.7	1.3	<1.0	634.3	<1.0	0.01	15.4	<.3
CP-M	<.3	4.4	<.3	<.3	1.9	<.3	<1.0	0.4	<1.0	0.01	0.7	<.3
CP-D	<.3	3.1	<.3	<.3	2.4	<.3	<1.0	<1.0	<1.0	<.3	0.6	<.3

centration was exceeded in all of the samples (fig. 4). The ³H concentrations ranged from 5.9 to 8.9 TU with a median concentration of 7.4 TU (table 3). Although the CFC concentrations in samples from wells AP-07 and AP-11 were slightly less than the CFC threshold, the ³H concentrations from these two wells (7.3±0.1 and 8.3±0.6 TU, respectively) were considerably greater than the ³H threshold. Because all of the water samples exceeded at least one of the threshold values, it is concluded that young water is present throughout most of the Appalachian Plateaus regional aquifer system. Water supplies developed in this aquifer system, therefore, are considered susceptible to contamination from near-surface sources (fig. 4).

Valley and Ridge Carbonate Regional Aquifer System

The threshold CFC concentration was exceeded in all of the 19 wells and 2 springs sampled to represent the Valley and Ridge Carbonate regional aquifer system (fig. 4). CFC concentrations ranged from less than 0.3 to 129,128 pg/kg with median concentrations of 311, 192, and 137 pg/kg for CFC-11, CFC-12, and CFC-113, respectively (table 3). The threshold ³H concentration was exceeded in all but one of the samples. The ³H concentrations ranged from 0.02 to 12.3 TU with a median concentration of 4.7 TU (table 3). Well VR-01, which is on the border between the Valley and Ridge and Blue Ridge Provinces, had a measured ³H

concentration of 0.02±0.04 TU. This well is 632-ft deep with 500 ft of casing, which was grouted to 100 ft below land surface. Water enters this well from three zones between 526 and 578 ft, and the depth to bedrock is 494 ft. Although the CFC-11 concentration of 5.7 pg/kg indicates that young water enters this well, the thick overburden and/or the manner in which the well is constructed may be limiting susceptibility to contamination from near-surface sources. Because all of the water samples exceeded at least one of the threshold values, it is concluded that young water is present throughout most of the Valley and Ridge Carbonate regional aquifer system. Water supplies developed in this aquifer system, therefore, are considered susceptible to contamination from near-surface sources (fig. 4).

Valley and Ridge Siliciclastic Regional Aquifer System

The threshold CFC concentration was exceeded in 23 of the 24 wells and in the only spring (96 percent) sampled to represent the Valley and Ridge Siliciclastic regional aquifer system (fig. 4). CFC concentrations ranged from less than 1.0 to 5,350 pg/kg with median concentrations of 87.3, 65.8, and 26.4 pg/kg for CFC-11, CFC-12, and CFC-113, respectively (table 3). The threshold ³H concentration was met or exceeded in 23 wells and 1 spring. The ³H concentrations ranged from 0.6 to 10.2 TU with a median concentration of 5.6 TU (table 3). The concentrations of all three CFCs were below the thresholds in the sample from well

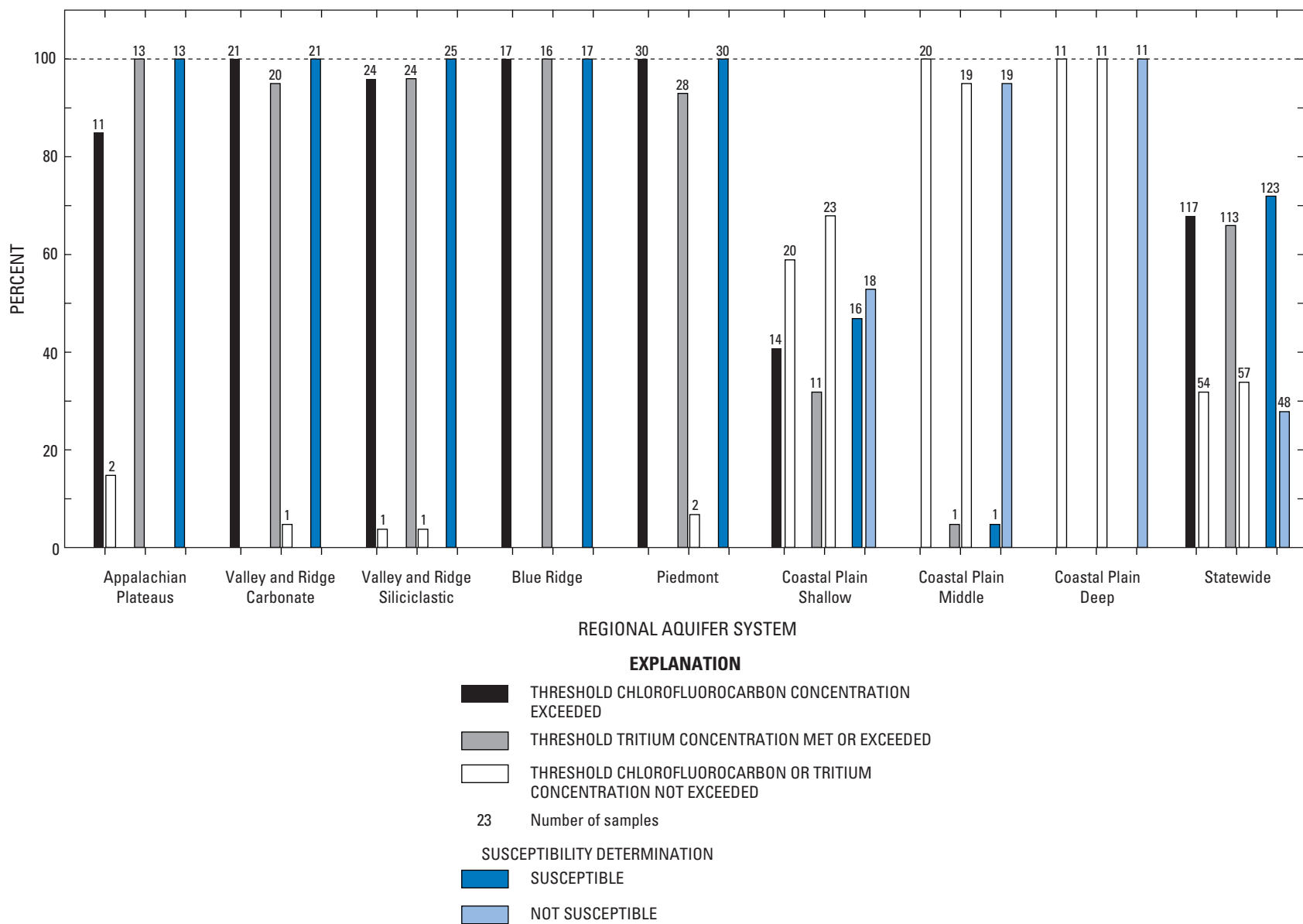


Figure 4. Exceedance of threshold chlorofluorocarbon and tritium concentrations and susceptibility determinations by regional aquifer system, Virginia.

VR-35, which was drilled to 130 ft, cased and grouted to 60 ft, and encountered bedrock at 30 ft. This well produces water from three zones between 88 ft and the bottom of the well. A ^3H concentration of 6.1 ± 0.1 TU and a dissolved oxygen concentration of 0.5 mg/L were measured in well VR-35. Sorption and biodegradation processes possibly have reduced the CFC concentrations. The concentration of ^3H (0.6 ± 0.1) was slightly below the threshold value for the sample from well VR-11, which is downhill from well VR-01 and produces water from 7 zones between 333 and 490 ft. Well VR-11 was drilled to 490 ft, cased to 316 ft, grouted to 100 ft, and encountered bedrock at 293 ft. The CFC-113 concentration (14.9 pg/kg) in the sample from well VR-11 indicates that young water is present. Review of the results from VR-01 and VR-11 suggests that the applicable age ranges of the various methods for age dating young ground water could be exceeded in hydrologic settings characterized by thick overburden (for example, the "Western Toe"). Despite the thick overburden and the manner of well construction, young waters were detected at the depth ranges for wells VR-01 and VR-11. Because all of the water samples exceeded at least one of the threshold values, it is concluded that young water is present throughout most of the Valley and Ridge Siliciclastic regional aquifer system. Water supplies developed in this aquifer system, therefore, are considered susceptible to contamination from near-surface sources (fig. 4).

Blue Ridge Regional Aquifer System

The threshold values for CFC and ^3H concentrations were exceeded in all of the wells sampled to represent the Blue Ridge regional aquifer system (fig. 4). CFC concentrations ranged from less than 1.0 to 98,348 pg/kg with median concentrations of 135, 300, and 88.3 pg/kg for CFC-11, CFC-12, and CFC-113, respectively (table 3). The ^3H concentrations ranged from 2.5 to 12.6 TU with a median concentration of 9.0 TU (table 3). Because all of the water samples exceeded at least one of the threshold values, it is concluded that young water is present throughout most of the Blue Ridge regional aquifer system. Water supplies developed in this aquifer system, therefore, are considered susceptible to contamination from near-surface sources (fig. 4).

Piedmont Regional Aquifer System

The threshold CFC concentration was exceeded in all of the 28 wells and 2 springs sampled to represent the Piedmont regional aquifer system (fig. 4). CFC concentrations ranged from less than 1.0 to 19,410 pg/kg with median concentrations of 254, 232, and 53 pg/kg for CFC-11, CFC-12, and CFC-113, respectively (table 3). The threshold ^3H concentration was met or exceeded in 26 wells and 2 springs (93 percent). The ^3H concentrations ranged from 0.3 to 12.8 TU with a median concentration of 7.6 TU (table 3). The ^3H concentrations in the samples from wells PD-01 and PD-17 (0.3 ± 0.03 and 0.6 ± 0.3 TU, respectively) were below the threshold value. Well PD-01 was drilled as an irrigation well to a depth of 950 ft, cased to 101 ft, grouted to 21 ft, and encountered bedrock at 90 ft. The well produces water from three zones between 200 and 950 ft. The driller reported that the lower water zone (940 to 950 ft) yields 200 gal/min (Robert Royall, Royall Pump and Well Co., Inc., written commun., 1999). The presence of CFCs in well PD-01 may be the result of natural ground-water flow or an artifact of the air-rotary drilling method because the well was completed less than a year prior to the date of sample collection. Recent research involving the addition of Halon 1211 (bromochlorodifluoromethane) into the drilling air indicates that the effects of the drilling were still evident in water samples collected 6 months after the date of well completion (L.N. Plummer, U.S. Geological Survey, written commun., 2002). The ^3H concentration in the water sample from well PD-17 was slightly below the threshold value, but this concentration could have been the result of analytical or sampling error, dilution of the young water with old (pre-CFC) waters, or matrix diffusion (Shapiro, 2001). Because all of the water samples exceeded at least one of the threshold values, it is concluded that young water is present throughout most of the Piedmont regional aquifer system. Water supplies developed in this aquifer system, therefore, are considered susceptible to contamination from near-surface sources (fig. 4).

Coastal Plain Shallow Regional Aquifer System

The threshold CFC concentration was exceeded in 13 of the 33 wells and in the only spring (41 percent) sampled to represent the Coastal Plain Shallow

regional aquifer system (fig. 4). CFC concentrations ranged from less than 0.3 to 1,620 pg/kg with median concentrations of 0.8, 1.3, and less than 1.0 pg/kg for CFC-11, CFC-12, and CFC-113, respectively (table 3). The threshold ^3H concentration was exceeded in 10 wells and 1 spring (32 percent). The ^3H concentrations ranged from 0.01 to 15.4 TU with a median concentration of less than 0.3 TU (table 3). The CFC and ^3H concentrations measured in the samples from wells VB-07 and VB-11 are thought to be an artifact of well drilling or the result of contamination during sample collection. Wells VB-07 and VB-11 are finished in very fine-grained sediments mapped as confining units by Smith and Harlow (2002). During sample collection, the yields of these wells were low (less than 1 gal/min) and the water levels were lowered to the pump setting, which was above the top of the screened interval. Samples were collected on the following day because of slow water-level recovery.

About 74 percent of the samples with the top of the first water zone less than 100 ft below land surface exceeded the susceptibility threshold values. The maximum depth to the top of the first water zone for which the threshold values were exceeded was 143 ft below land surface at well VB-09. These depths are similar to the depths at which young waters were detected by Nelms and others (2001) in a local study area in the Coastal Plain of Virginia. Young water was consistently detected in the first 100 ft of the Coastal Plain Shallow regional aquifer system. Consequently, the probability of water supplies being affected by near-surface sources of contamination is greatest in the upper 100 ft of the Coastal Plain Shallow regional aquifer system. Water supplies developed in the upper 100 ft of this aquifer system, therefore, are considered susceptible to contamination from near-surface sources. The analyses of the sample from spring CP-50 and results from previous studies of springs in the Coastal Plain of Virginia (Focazio and others, 1998; Nelms and others, 2001) indicate that springs in this regional aquifer system contain young water, and, therefore, are considered susceptible to contamination from near-surface sources.

Coastal Plain Middle Regional Aquifer System

The threshold CFC concentration was not equaled or exceeded in any of the 20 wells sampled to represent the Coastal Plain Middle regional aquifer system

(fig. 4). CFC concentrations ranged from less than 0.3 to 4.4 pg/kg with median concentrations of less than 0.3 pg/kg for CFC-11 and CFC-12, and less than 1.0 pg/kg for CFC-113 (table 3). The threshold ^3H concentration was exceeded in only one well (5 percent). The ^3H concentrations ranged from 0.01 to 0.7 TU with a median concentration of less than 0.3 TU (table 3). The low concentrations of CFCs and ^3H may be the result of analytical or sampling error, or transient leakage from the well casing or wellbore. Because the threshold CFC concentration was not exceeded in any sample and a large percentage (95 percent) of the samples did not exceed the threshold ^3H value, it is concluded that young water is generally not present throughout most of the Coastal Plain Middle regional aquifer system. Water supplies developed in this aquifer system, therefore, are considered not susceptible to contamination from near-surface sources (fig. 4).

Coastal Plain Deep Regional Aquifer System

The threshold concentrations for CFCs and ^3H were not equaled or exceeded in any of the 10 wells sampled to represent the Coastal Plain Deep regional aquifer system (fig. 4). CFC concentrations ranged from less than 0.3 to 3.1 pg/kg with median concentrations of less than 0.3 pg/kg for CFC-11 and CFC-12, and less than 1.0 pg/kg for CFC-113 (table 3). The ^3H concentrations ranged from less than 0.3 to 0.6 TU with a median concentration of less than 0.3 TU (table 3). Similar to the samples from the Coastal Plain Middle regional aquifer system, the low concentrations of CFCs and ^3H may be the result of analytical or sampling error, or transient leakage from the well casing or wellbore. Because none of the water samples exceeded the threshold values, it is concluded that young water is not present throughout most of the Coastal Plain Deep regional aquifer system. Water supplies developed in this aquifer system, therefore, are considered not susceptible to contamination from near-surface sources (fig. 4).

Relation between Aquifer Susceptibility and Apparent Ground-Water Age

The multiple tracer approach allows for the determination of the apparent age of the sample and of whether the sample is a mixture of waters of different

ages. Previous studies with multiple tracers (Plummer and others, 1999; Plummer and others, 2001) indicate that the analytical results from the CFC method can be interpreted using binary mixing models. The CFC data provide an indication of whether the sample represents a binary mixture from which the relative proportions of old (which is assumed to be pre-CFC) and young waters can be estimated. The apparent age of the young water fraction can be estimated from CFC ratios (CFC-11/CFC-12, CFC-113/CFC-11, and CFC-113/CFC-12) and/or from $^3\text{H}/^3\text{He}$ and SF_6 dating methods. For example, the water sample from well PD-22 indicates that the apparent piston-flow ages, which assumes that the tracer (the CFC compound) is transported as a plug through the aquifer with no dispersive mixing in the direction of flow (Busenberg and Plummer, 1992), from CFC-11, CFC-12, and CFC-113 are 22, 23, and 17 years, respectively (fig. 5). The apparent ages from CFC-113/CFC-12, CFC-113/CFC-11, and SF_6 are 13, 14, and 15 years, respectively. The CFC ratios indicate that the percentage of the young fraction (15 years) in a binary mixture with old waters is between 64 and 72 percent (fig. 5). In most cases, the assumption that the old fraction represents pre-CFC waters is valid based on an evaluation of where the sample from well PD-22 plots in relation to the apparent ages of the young fraction from the CFC ratios, SF_6 , and $^3\text{H}/^3\text{He}$ (fig. 5). Various mixing models such as binary mixtures of only young waters or exponential models can be used to interpret the analytical results. These models also would indicate that the regional aquifer systems are susceptible, similar to the findings of the VAS study, although the degree of susceptibility may vary.

Young Waters

The apparent ages and percentages of young water, given the assumption of binary mixtures, are summarized in tables 5 and 6 (at end of report). The apparent ages of young water fractions statewide ranged from less than 1 to 48 years with a median apparent age of 18 years (fig. 6). It is evident that the regional aquifer systems in the fractured-rock terrains and in the Coastal Plain Shallow system contain young water and therefore are susceptible to contamination from near-surface sources. The three samples containing young water from the Coastal Plain Middle and Deep regional aquifer systems probably represent analytical or sampling error or transient leakage from the well

casing or wellbore. The dating methods for young waters were not applicable in 53 of the 171 samples because of (1) contamination of CFCs from sources other than the atmosphere, (2) sorption and degradation of CFCs, (3) contamination of SF_6 and ^3He from terrigenous sources, or (4) presence of paleowaters that do not contain the environmental tracers used to date young waters. More than 95 percent of the 118 samples for which the dating methods were applicable contained waters with apparent ages less than 35 years. About 5 percent of these samples contained young waters with apparent ages of less than 5 years, most of which were samples from the Blue Ridge and Piedmont regional aquifer systems. A relatively small percentage of the samples from the Valley and Ridge Carbonate regional aquifer system had apparent ages of less than 5 years.

Dye tracer studies are a common method for determining areas contributing recharge to springs and wells in carbonate terrains where travel times generally are on the order of days, weeks, or months. The multiple tracer approach and the assumption of binary mixtures of young and pre-CFC waters do not allow for dating waters with such rapid travel times. The apparent ages determined by the VAS study probably represent maximum ages of the young fractions because processes such as dilution and matrix diffusion (Shapiro, 2001) can alter the original tracer concentrations as the ground water moves through the flow system. The actual ages of the young fractions, therefore, may be younger than the apparent ages presented in this report and the regional aquifer systems may be more susceptible, especially in the fractured-rock terrains, than is indicated by this study.

In addition to apparent age, the amount of the young water fraction, assuming binary mixtures with old (pre-CFC) waters, provides information about aquifer susceptibility. The distribution of percent young water fractions from the binary mixture model is shown on figure 7. Most of the samples from the Valley and Ridge Carbonate, Blue Ridge, and Piedmont regional aquifer systems had greater than 50 percent young water fractions. Hydrogeologic characteristics, such as the karst features in the Valley and Ridge Carbonate and the steep hydraulic gradients, limited ground-water storage, and short flow paths (Stone and others, 1986) of the Blue Ridge and the Piedmont regional aquifer systems, may explain the abundance of young waters detected in these systems. Porous media flow,

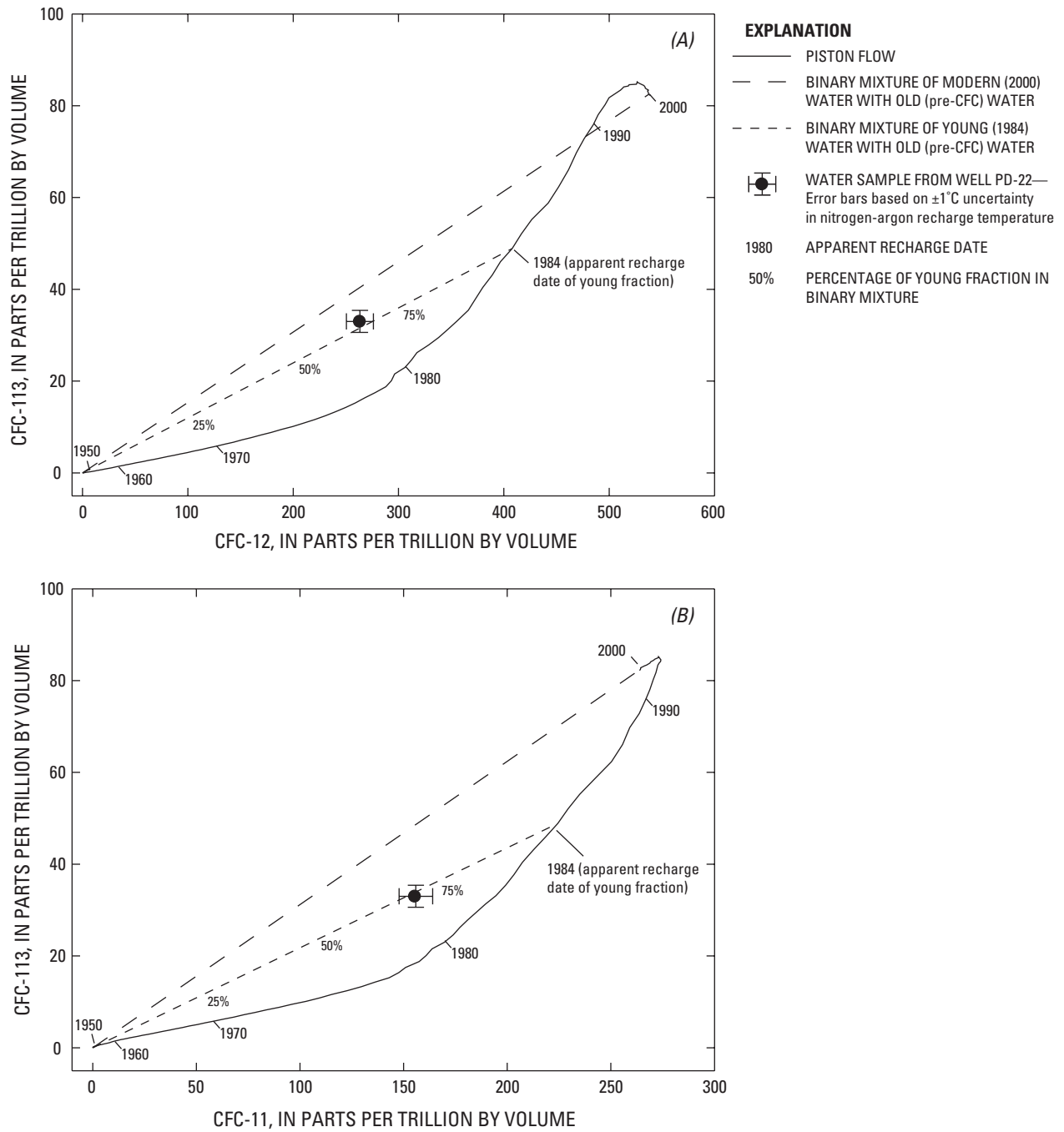


Figure 5. Mixing ratios of chlorofluorocarbon-113 (CFC-113) and chlorofluorocarbon-12 (CFC-12) (A) and CFC-113 and chlorofluorocarbon CFC-11 (B) for water from well PD-22, Lake Wilderness, Virginia, October 1999. The sample is compared to three hypothetical mixing models. The apparent recharge date of 1984 was determined by sulfur hexafluoride (SF_6).

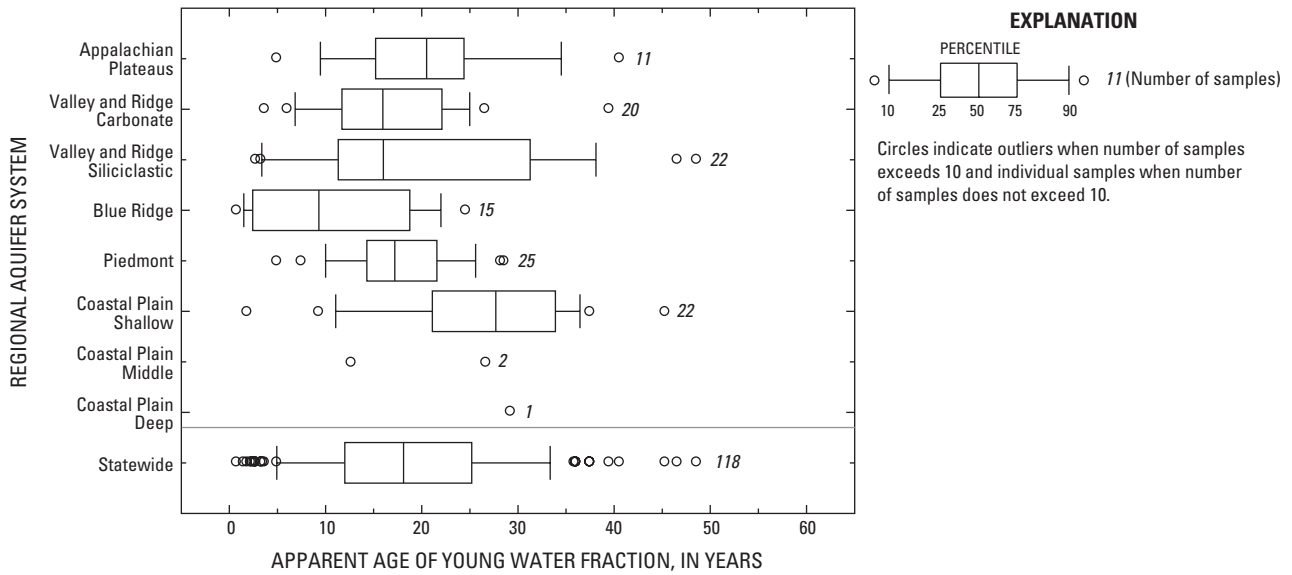


Figure 6. Distribution of apparent age of young water fraction in binary mixtures with old (pre-chlorofluorocarbon) waters by regional aquifer system, Virginia.

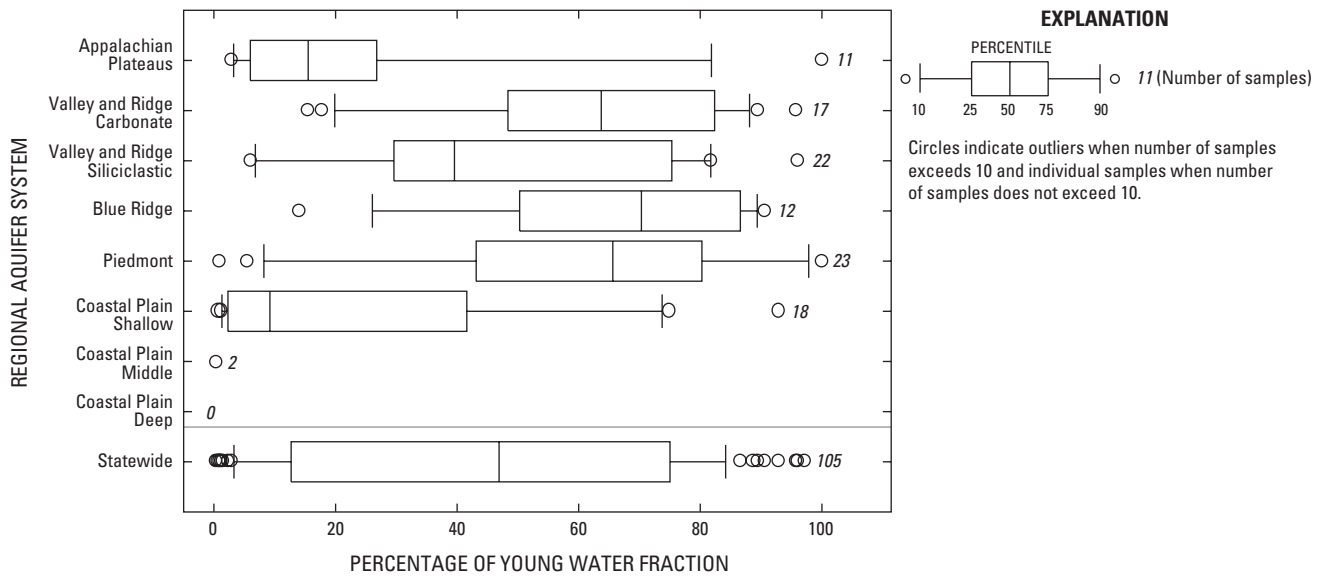


Figure 7. Distribution of young water fraction in binary mixtures with old (pre-chlorofluorocarbon) waters by regional aquifer system, Virginia.

ground-water storage, and low hydraulic gradients in the Coastal Plain Shallow aquifer and low permeability of the rocks in the Appalachian Plateaus (Harlow and LeCain, 1991) are possible explanations for a majority of the water samples from these regional aquifer systems containing less than 40 percent young waters.

The percentage of the young water fraction, given the assumption of binary mixtures, generally decreases as the apparent age increases, as shown by the LOW-ESS (Helsel and Hirsch, 1992) line (fig. 8) for the water samples collected in this study. This relation is important because processes that reduce contaminant concentrations, such as biodegradation of organic compounds and denitrification of nitrate, can take place for a longer time in older waters. Additionally, contaminant concentrations can be reduced by dilution when small fractions of young waters containing contaminants mix with older, contaminant-free waters. Thus, ground waters with a large fraction (greater than 90 percent) of extremely young water (less than 5 years) are highly susceptible to land-use activities within the area contributing recharge. Comparisons of the percentage of the young water fraction to factors other than apparent age, including casing and grout depth, depth to bedrock in the fractured-rock terrains, and age of well, produced random distributions and no significant relations.

The regional aquifer systems can be used as a surrogate for geology in comparisons to apparent ground-water age and percentage of the young water fraction. Other than the general conclusions mentioned previously, no significant relations could be determined between geology and apparent age or percentage of young fraction (fig. 8). This is to be expected for water supplies developed in fractured-rock aquifers where the frequency, geometry, and interconnectedness of the fractures control the movement of ground water and may be more important than the lithology. Limited ground-water storage in these aquifers can cause hydraulic gradients to be steep when the aquifers are stressed by pumpage.

A group of samples from the Coastal Plain Shallow regional aquifer system has apparent ages that range from 20 to 40 years with generally less than 20 percent young water fractions (fig. 8). Most of these samples are from shallow confined aquifers overlain by one or two confining units. For samples from wells screened below a confining unit, the apparent age is at least 25 years (fig. 9). Many of the samples from the shallow confined aquifers did not exceed the susceptibility

threshold values, but these samples still could be dated by the multiple tracer approach (fig. 9). The presence of young waters beneath 30 to 60 ft of confining units is consistent with the concept of leaky or breached confining units (Powell and others, 1990; Brockman and others, 1997; Nelms and others, 2001). Under stressed conditions, the head in the shallow confined aquifer may be lowered and cause the downward gradient to increase, which can induce flow from the overlying unconfined (water table) aquifer.

About 32 percent of the samples contained CFCs in excess of modern air (1998 to 2000) equilibrium. These large CFC mixing ratios indicate that the local air is enriched with CFCs or that a nonatmospheric source has contributed to CFCs measured in the water samples. Szabo and others (1996) estimated that local air in a southern New Jersey study area was enriched with CFCs by about 10 to 30 percent. In contrast, the CFCs measured during the VAS study generally were orders of magnitude greater than modern air mixing ratios, suggesting that sources other than the atmosphere (for example, sewage) have introduced CFCs into the ground water. The presence of CFC contamination (where "contamination" refers to an effect on ground-water dating, not to exceedance of water-quality standards) is another means of assessing the validity of the VAS methodology for determining aquifer susceptibility to near-surface contamination.

One or more of the CFCs were the result of contamination in 48 percent of the water samples from the fractured-rock terrains and in 6 percent of the samples from the Coastal Plain regional aquifer systems, all of which were from the Coastal Plain Shallow regional aquifer system (fig. 10). None of the samples from the Coastal Plain Middle and Deep regional aquifer systems contained CFC contamination, and CFCs were not detected in a majority of the samples. The high percentage of samples with measured CFC contamination in the fractured-rock terrains indicates that supplies developed in these regional aquifer systems are susceptible. The absence of either CFCs or CFC contamination in the samples from the Coastal Plain Middle and Deep regional aquifer systems illustrates the lack of connection and the long period of time it takes water to flow to these aquifers from near land surface under natural conditions.

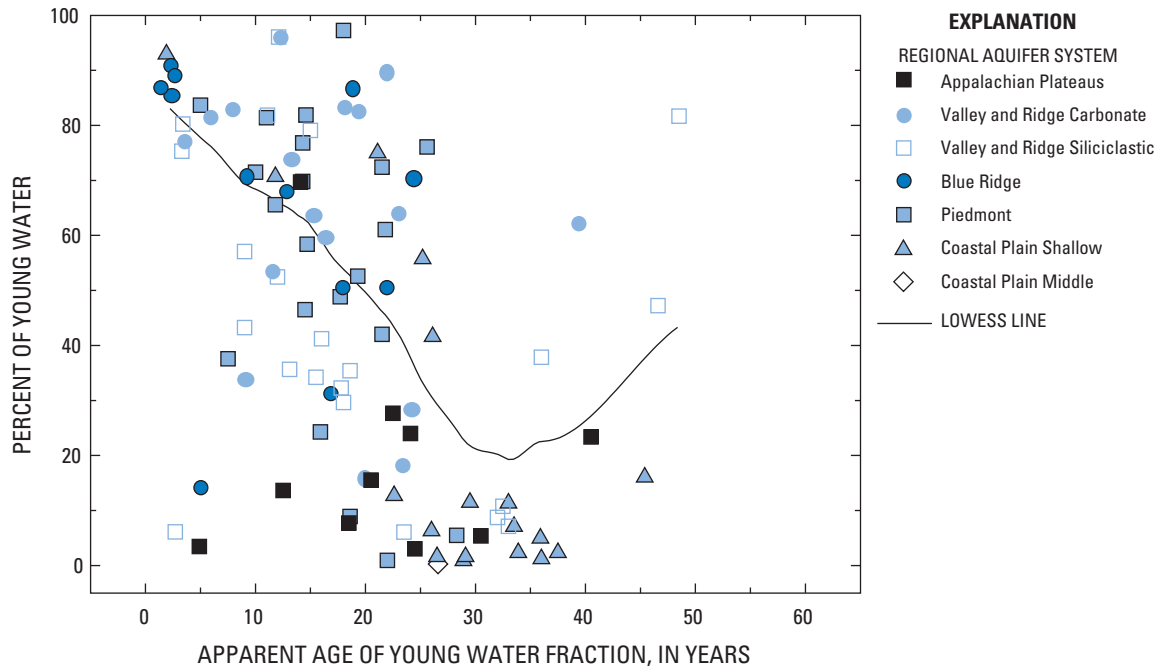


Figure 8. Percentage of young water in relation to apparent age of young water fraction in binary mixtures with old (pre-chlorofluorocarbon) waters by regional aquifer system, Virginia.

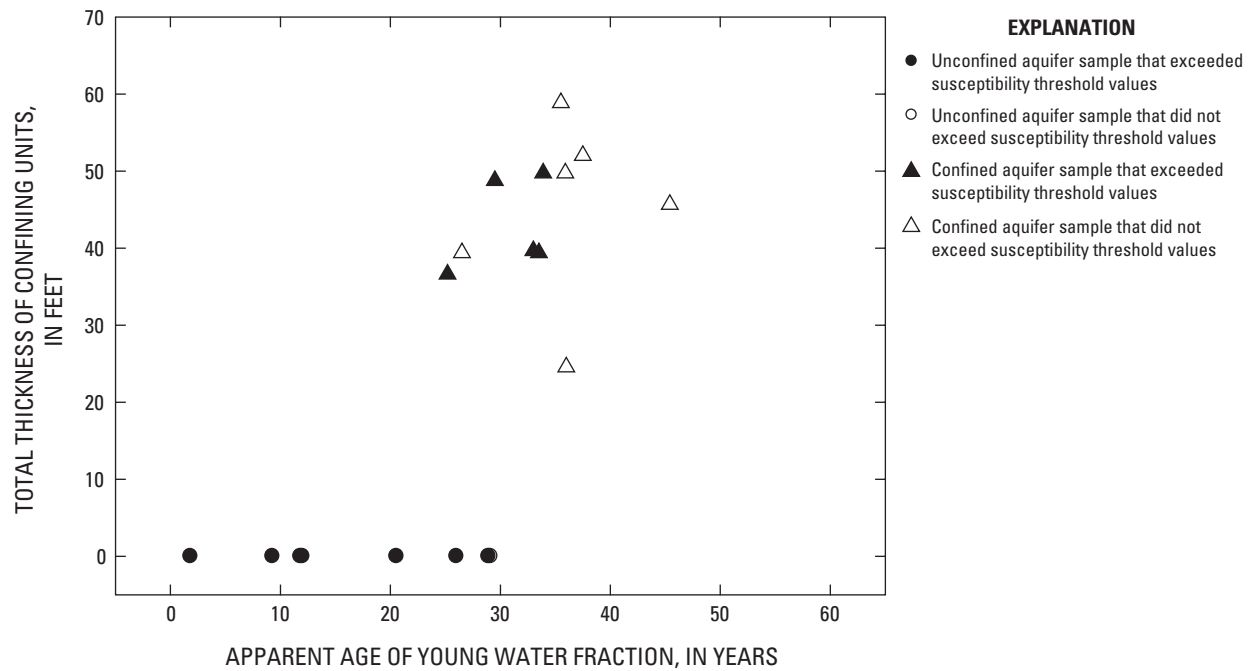


Figure 9. Total thickness of the confining units in relation to apparent age of young water fraction in binary mixtures with old (pre-chlorofluorocarbon) waters for samples from the Coastal Plain Shallow regional aquifer system, Virginia.

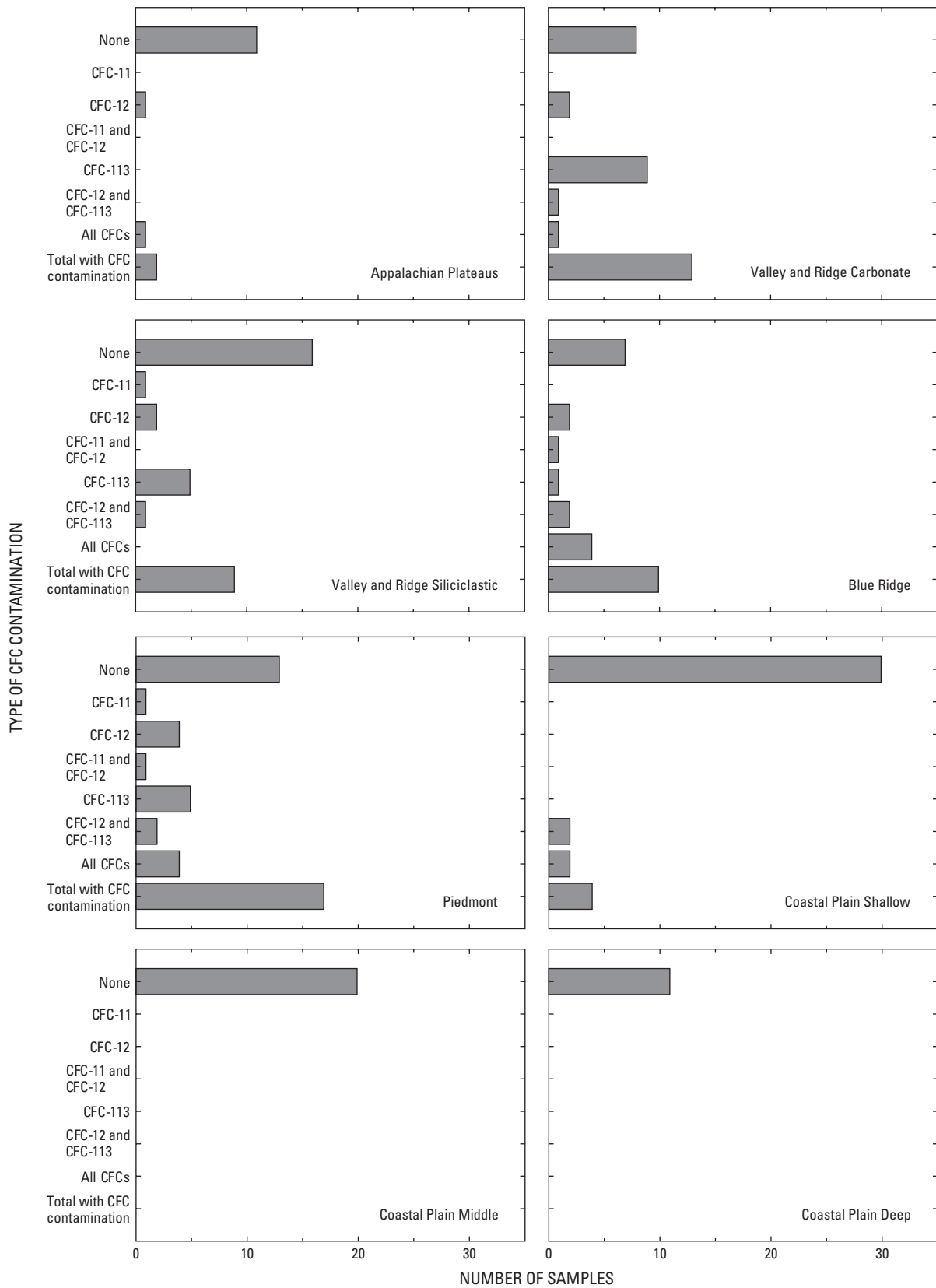


Figure 10. Distribution of chlorofluorocarbon (CFC) contamination by regional aquifer system, Virginia.

Old Waters or Paleowaters

The presence of old waters (pre-CFC or greater than 50 years) or paleowaters (greater than 1,000 years) in water samples was used as an indication that these regional aquifer systems probably are not affected by near-surface activities and, therefore, are not susceptible to contamination under natural conditions. Radiocarbon (carbon-14 or ^{14}C) dating (Plummer and others, 1994; Clark and Fritz, 1997; Kalin, 2000) was conducted on 34 water samples containing old or paleowaters from the Coastal Plain regional aquifer systems. The radiocarbon ages summarized in table 5 are adjusted radiocarbon ages based on the Fontes and Garnier (1979) model. The uncertainties in the radiocarbon age estimates were determined by varying by $\pm 5\%$ the $\delta^{13}\text{C}$ in soil gas CO_2 input for the Fontes and Garnier (1979) model. The distribution of adjusted radiocarbon ages for water samples from the Coastal Plain regional aquifer systems is summarized in table 4. The negative value for the minimum adjusted radiocarbon age in the Coastal Plain Shallow regional aquifer system is explained by the presence of young water for which the initial ^{14}C activity was greater than 100 pmc as a result of atmospheric thermonuclear weapons testing and nuclear power plant releases (Clark and Fritz, 1997). Radiocarbon dating is therefore not viable and was not done for samples containing young waters, which included samples from the fractured-rock terrains and some samples from the Coastal Plain Shallow regional aquifer system.

Table 4. Summary statistics for adjusted Fontes-Garnier radiocarbon ages (Fontes and Garnier, 1979) in the Coastal Plain regional aquifer systems

[Adjusted radiocarbon ages are in radiocarbon years BP (before present where present is AD 1950) based on the Libby half-life of 5,568 years and have not been calibrated to calendar years]

Statistic	Coastal Plain regional aquifer system		
	Shallow	Middle	Deep
Minimum	-1,200	9,090	27,900
Median	2,400	24,200	33,600
Maximum	10,100	36,900	39,700
Number of samples	4	20	10

The presence of paleowaters in the Coastal Plain regional aquifer systems is consistent with conceptual and flow-simulation models of this region (Harsh and Lacznia, 1990; Lacznia and Meng, 1988; Hamilton and Larson, 1988; McFarland, 1998). In these models, ground-water recharge occurs along the Fall Line, and water flows towards the Atlantic Ocean along deep regional flow paths. Adjusted radiocarbon ages of water samples increase as distance from the Fall Line increases (fig. 11); the samples from wells CP-11 and CP-21 in the Coastal Plain Shallow regional aquifer system, however, represent relatively local recharge and flow along local or subregional flow paths where there is potential for encountering young water (Nelms and others, 2001).

The relation between increasing adjusted radiocarbon ages and distance from the Fall Line for samples from the Cretaceous aquifers (upper, middle, and lower Potomac aquifers) appears to differ with regard to orientation of a given site with respect to the James River. Samples from north of the James River become older over a shorter distance from the Fall Line than those samples from south of the James River (fig. 11). This apparent relation is more prevalent in the samples from the middle Potomac aquifer, except for wells CP-24, CP-27, and CP-51. Samples from these three wells also have measured concentrations of sodium and chloride that are large relative to the other samples from the Coastal Plain aquifers. These wells are located in the hydrogeochemical feature that Cederstrom (1943, 1946a, 1946b) referred to as the "inland saltwater wedge." This difference in the progression of adjusted radiocarbon ages in the Cretaceous aquifers may result from the bifurcation of flow, as proposed by Cederstrom (1943, 1946a, 1946b), around what is now known to be the Chesapeake Bay impact crater (Powars and Bruce, 1999; Powars, 2000).

The adjusted radiocarbon ages also increase as the total thickness of the overlying confining units increase (fig. 12). It is also true that as the distance from the Fall Line increases, the thickness of the aquifers and confining units increases. The degree of confinement from near-surface activities is greater in the Coastal Plain Middle and Deep regional aquifer systems, where confining units are buried under a greater accumulation of sediments than in the Coastal Plain Shallow regional aquifer system (fig. 9). Conjointly, the relations between adjusted radiocarbon ages and (1) distance from the Fall Line and (2) thickness of the overlying confining units indicate that the combination of long

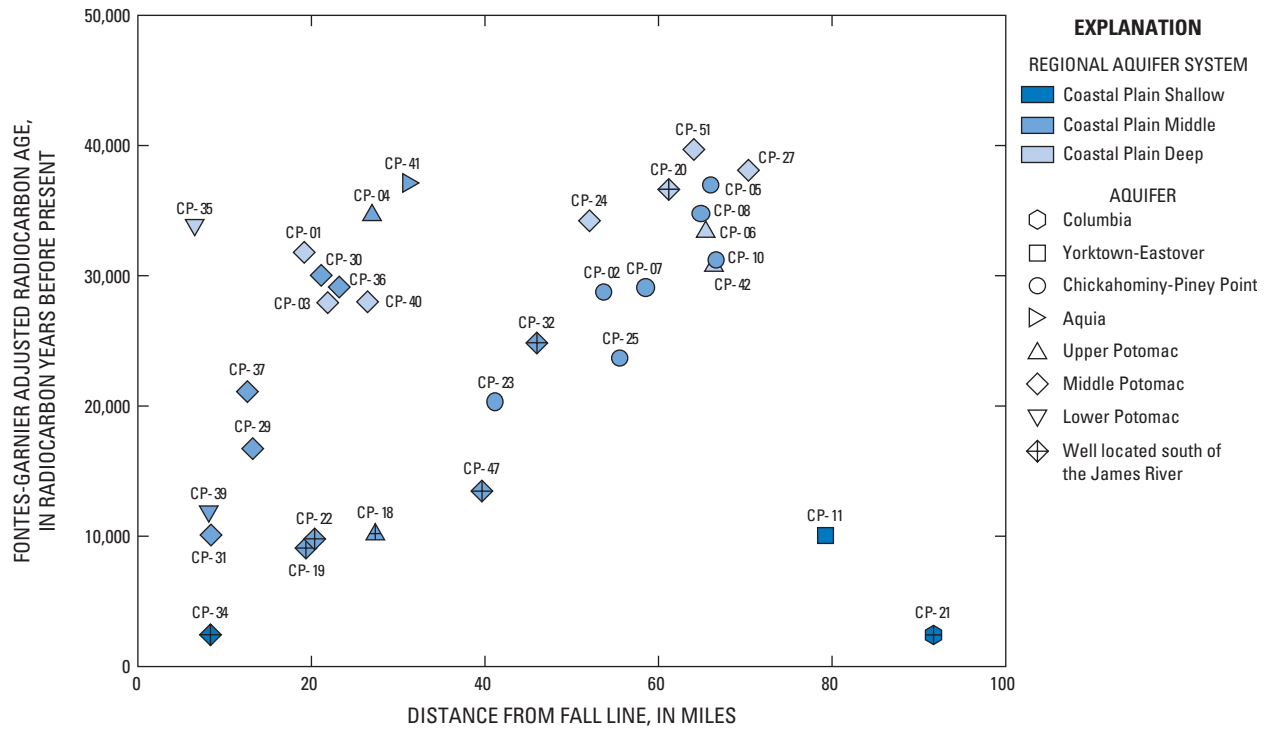


Figure 11. Relation between Fontes-Garnier adjusted radiocarbon age (Fontes and Garnier, 1979) and distance from the Fall Line by Coastal Plain regional aquifer system and aquifer. See figure 1 for location of Fall Line in Virginia.

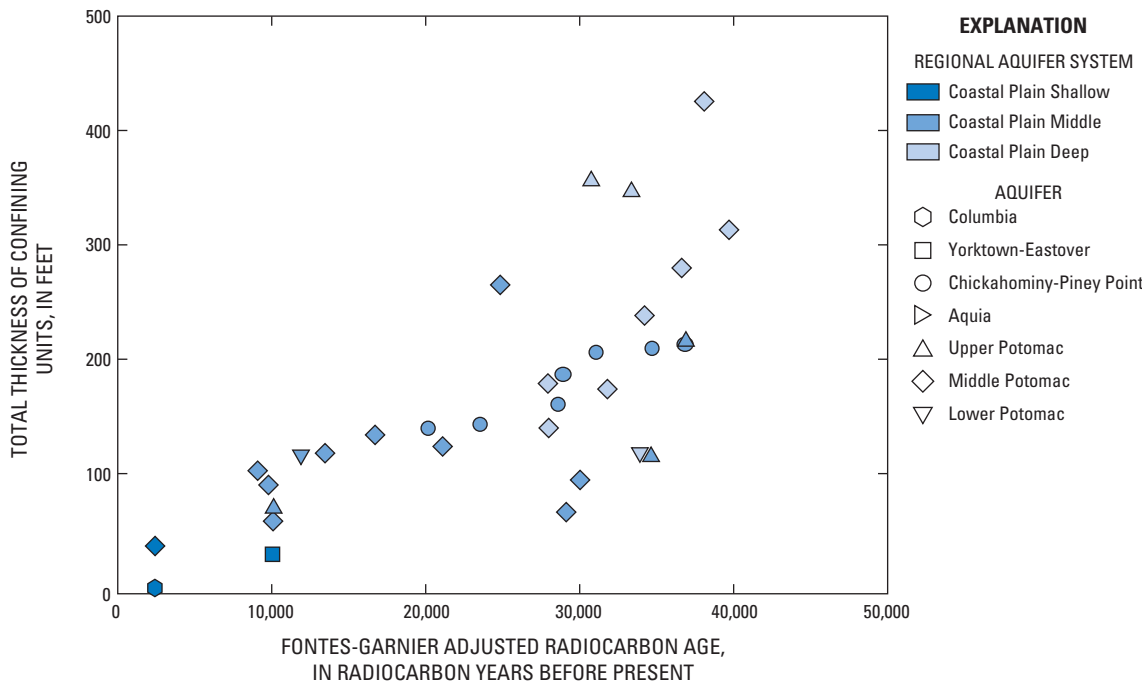


Figure 12. Relation between total thickness of confining units and Fontes-Garnier adjusted radiocarbon age by Coastal Plain regional aquifer system and aquifer, Virginia.

flow paths and slow flow through low-permeability confining units results in long ground-water residence times. This is the first quantification of a common conceptual model for the Coastal Plain aquifer systems in Virginia.

Relation between Aquifer Susceptibility and Selected Chemical Constituents

Comparison of susceptibility and apparent age determinations to the occurrence of selected chemical constituents in ground water is an additional means of evaluating the validity of the VAS study methodology. Nitrite plus nitrate as nitrogen ($\text{NO}_2 + \text{NO}_3\text{-N}$), which is essentially nitrate because of low nitrite concentrations, is introduced into ground-water systems from commercial fertilizers, manure, and sewage effluent. Volatile organic compounds (VOCs) have been produced in considerable quantities and have widespread use in the United States (Squillace, Moran, Lapham, and others, 1999). Because of these factors, VOCs are eventually released into the environment and are frequently detected in ground water (Westrick and others, 1984; U.S. Environmental Protection Agency, 1997; Squillace, Moran, Lapham, and others, 1999; Clawges and others, 2001; Grady and Casey, 2001; Moran and others, 2001; Stackelberg and others, 2001; Shapiro and others, 2003). The occurrence and distribution of nitrate and VOCs are indicators of contamination from near-surface sources and, thus, of aquifer susceptibility and vulnerability to contamination (Rupert, 1998; Shelton and others, 2001).

Nitrate

Nitrate (NO_3) concentrations were measured in water samples from 171 wells and springs during the VAS study between 1998 and 2000 (Nelms and Harlow, 2003). The NO_3 concentrations did not exceed the U.S. Environmental Protection Agency's Maximum Contaminant Level (MCL) of 10 mg/L in any samples and ranged from less than the USGS detection levels (0.005 mg/L and 0.05 mg/L) to 9.92 mg/L. Nitrate concentrations measured in the samples increase as the CFC mixing ratios increase, which means that NO_3 concentrations are higher in younger waters (fig. 13). Generally, the highest NO_3 concentrations are in waters with CFC mixing ratios that were greater than ratios in

equilibrium with modern air for the year 2000, which is considered contaminated for dating purposes. There are three possible explanations for the small NO_3 concentrations (equal to or slightly greater than the USGS detection levels) associated with CFC contamination: (1) the NO_3 in ground water has been removed by denitrification processes; (2) the NO_3 concentration has been reduced by dilution; or (3) a source for NO_3 was not within the area contributing recharge to the well or spring sampled. These three scenarios illustrate the limitations of aquifer susceptibility methods based on the occurrence and distribution of NO_3 in ground water. In terms of apparent age of the young water fraction, the number of samples with NO_3 concentrations greater than the USGS detection levels generally increases as apparent age of the young fraction decreases (fig. 14a). Nitrate concentrations were equal to or slightly greater than the USGS detection levels for samples that contained only old or paleowaters (fig. 14b).

On the basis of the NO_3 concentrations in the old or paleowaters, the aquifer susceptibility determinations were evaluated by comparing the NO_3 concentrations to the USGS detection level of 0.05 mg/L. About 43 percent of the samples were greater than the detection level (fig. 15). Most of these samples were from the fractured-rock terrains, especially the Valley and Ridge Carbonate regional aquifer system, where 90 percent of the samples had greater than 0.05 mg/L of NO_3 . The reporting limit was exceeded in 57 and 65 percent of the samples from the Piedmont and Blue Ridge regional aquifer systems, respectively. Although the evaluation of NO_3 concentrations and the multiple tracer approach yielded somewhat consistent results in terms of aquifer susceptibility, the viability of NO_3 concentrations as an indicator of aquifer susceptibility in the Appalachian Plateaus, Valley and Ridge Siliciclastic, and Coastal Plain Shallow regional aquifer systems can be limited by processes such as dilution and methanogenesis, and by proximity to near-surface sources.

Volatile Organic Compounds

VOCs are synthetic organic chemicals that are used in adhesives, dry cleaning, paints, plastics, solvents, and petroleum products. Many VOCs are mobile, persistent, and toxic compounds that are frequently detected in ground water (Squillace, Moran, Lapham, and others, 1999; Clawges and others, 2001; Grady and

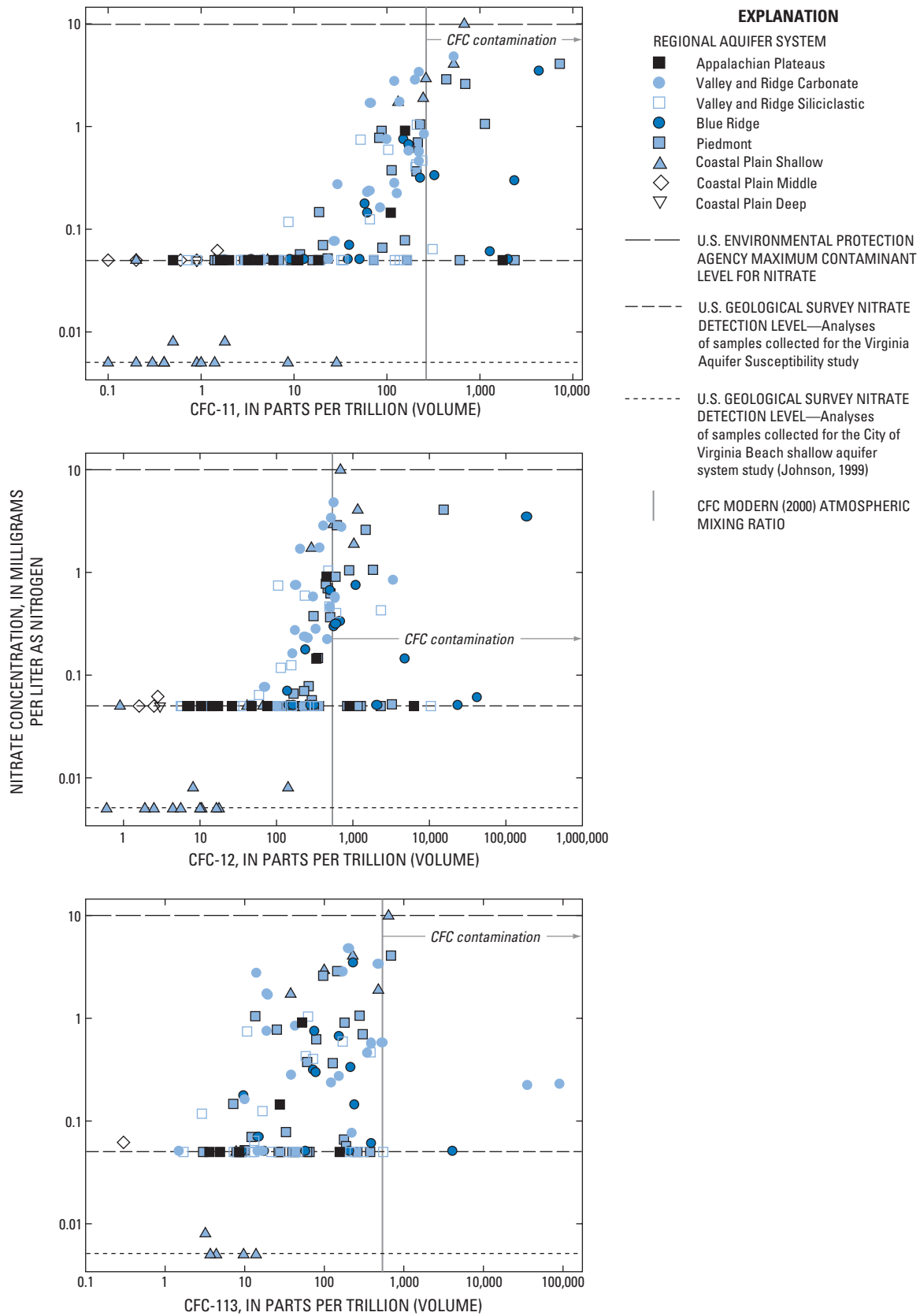


Figure 13. Nitrate concentrations in relation to chlorofluorocarbon (CFC) mixing ratios in samples from 171 wells and springs in Virginia.

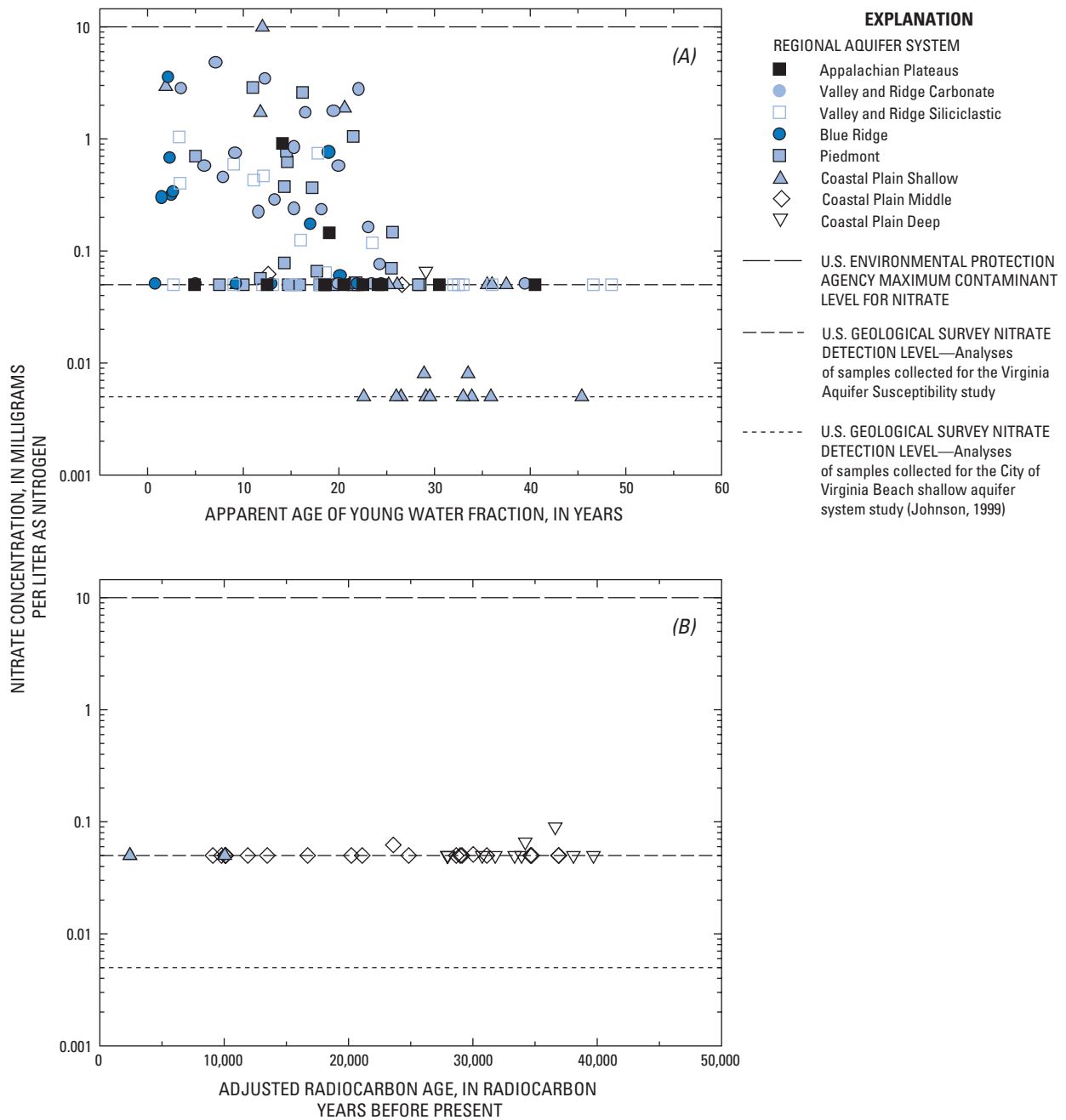


Figure 14. Nitrate concentrations in relation to apparent ages of young water fractions in binary mixtures with old (pre-chlorofluorocarbon) waters (A) and to Fontes-Garnier adjusted radiocarbon ages (B), Virginia.

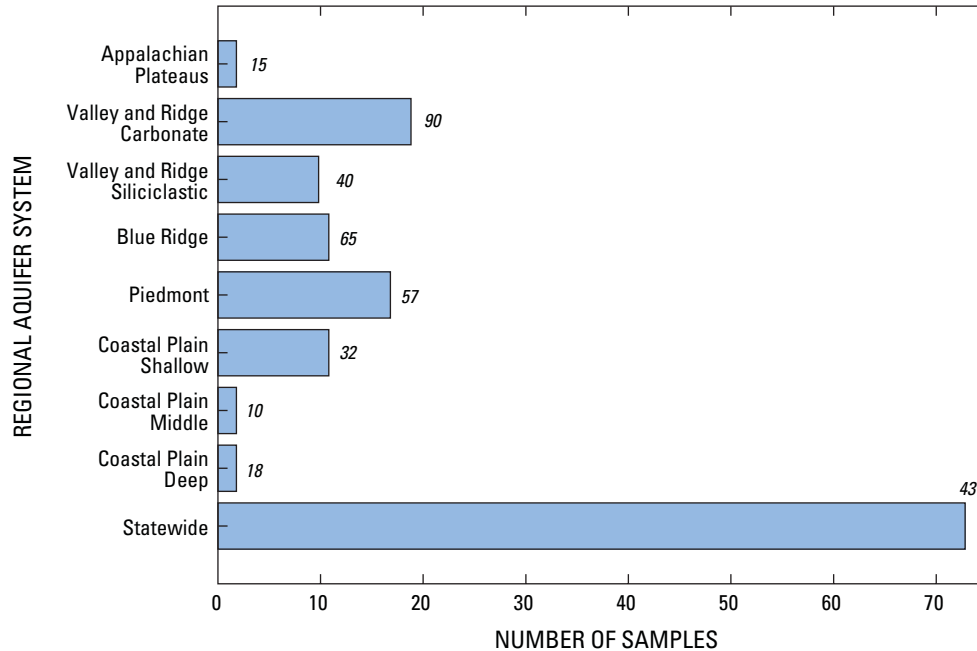


Figure 15. Distribution by regional aquifer system (in Virginia) of nitrate concentrations greater than the U.S. Geological Survey (USGS) detection level of 0.05 milligrams per liter. Numbers in italics indicate percentage of wells that exceeded the USGS detection level.

Casey, 2001; Moran and others, 2001; Stackelberg and others, 2001). The production of these compounds in the United States increased by an order of magnitude between 1945 and 1985 (Ashford and Miller, 1998). The fuel oxygenate methyl *tert*-butyl ether (MTBE) was the 39th-highest organic chemical produced in 1970, and by 1998 was 4th-highest in the United States (Squillace, Moran, and Clawges, 1999; Johnson and others, 2000). The atmospheric increase of the environmental tracers used during the VAS study coincides and to some degree mimics the use and production of VOCs in the United States. Shapiro and others (2003) used archived chromatograms and water samples collected between 1989 and 2000 from more than 2,600 sites throughout the United States to assess low-level (parts per quadrillion) detections of halogenated VOCs. These samples were originally analyzed by gas chromatography with an electron capture detector (GC-ECD) in the USGS CFC laboratory in Reston, Va., for the purpose of ground-water dating. About 6 percent of these analyses were from water samples collected for the VAS study.

The run times on the GC-ECD are sufficient to detect halogenated VOCs other than CFCs in water samples. The identification of the VOCs is only qualitative because quantitative analysis to determine actual

concentrations is not possible with GC-ECD. However, Shapiro and others (2003) state that low-level detections of VOCs by GC-ECD can be used to indicate aquifer susceptibility and provide early warning of potential contamination of ground-water sources. Comparison of GC-ECD chromatograms for water samples from the different regional aquifer systems is another means of validating the VAS study methodology. For example, the chromatogram shows that water from well CP-08 produces paleowater (about 34,000 radiocarbon years) that has not been affected by VOCs (fig. 16), and thus probably is not affected by anthropogenic activities. The chromatogram for spring SNP-028 indicates that this water is young and contains CFCs and VOCs that are probably of atmospheric origin. Contamination from near-surface sources is illustrated by the chromatograms for wells CP-15 and VR-23, which contain several VOC peaks with large peak areas (fig. 16). Furthermore, these two wells illustrate the disparity with relation to depth of contaminant migration between supplies developed in the unconsolidated deposits of the Coastal Plain and in the fractured-rock terrains where contaminants can readily migrate to relatively deep depths.

One or more VOC peaks were frequently identified from the GC-ECD chromatograms for the samples

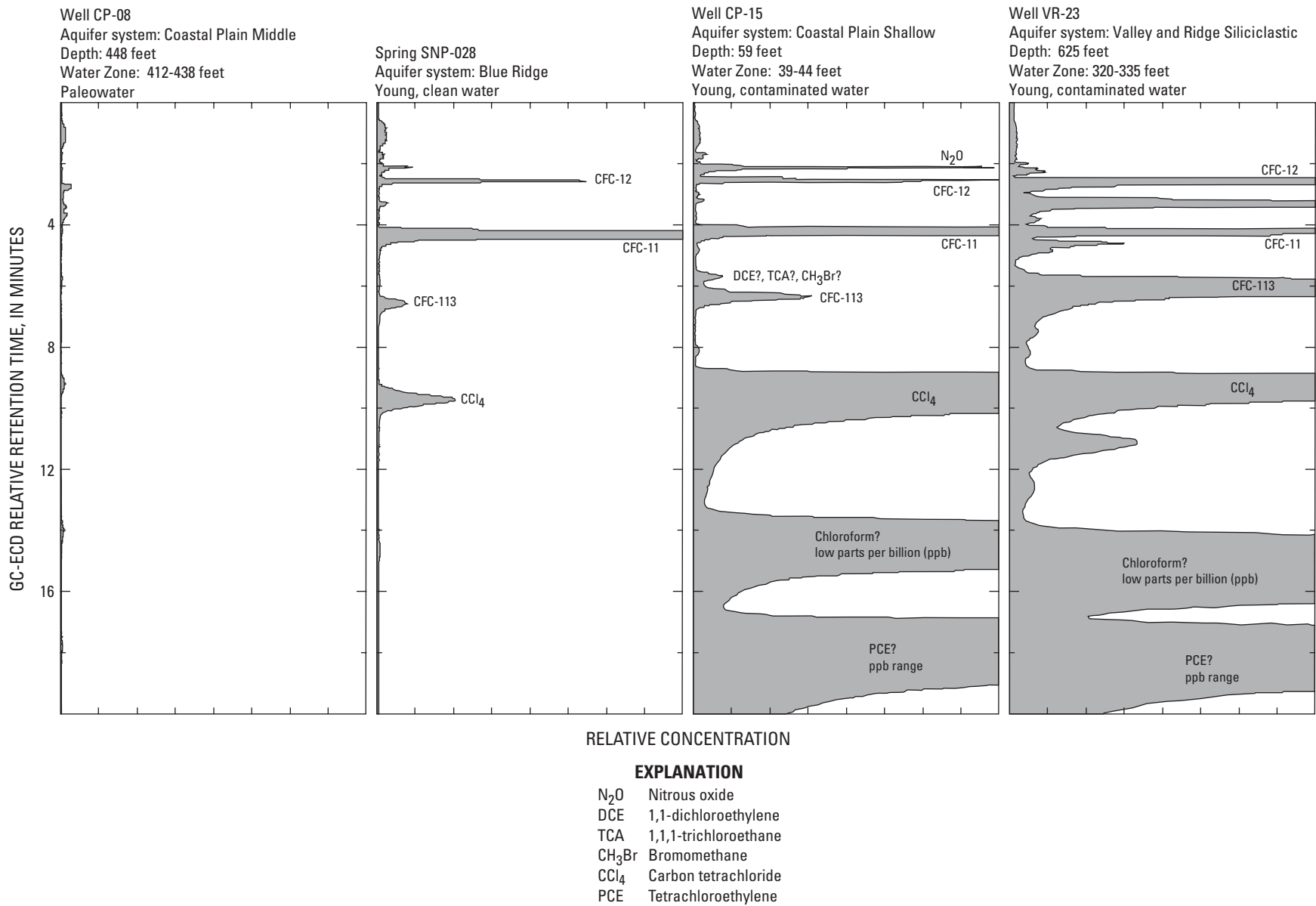


Figure 16. Chromatograms for selected wells and a spring in Virginia from gas chromatography with an electron capture detector (GC-ECD) for chlorofluorocarbon (CFC) dating. Spring SNP-028 from Plummer and others (2001).

from the regional aquifer systems in the fractured-rock terrains and the shallow parts of the Coastal Plain (fig. 17). Shapiro and others (2003) classified the VOC peak areas into three groups based on the number of counts recorded by the detector: small (100,000 to 499,000 counts), medium (500,000 to 999,999 counts), and large (greater than 1,000,000 counts). The range in peak area counts approximately corresponds to VOC concentrations from parts per quadrillion to parts per billion (Shapiro and others, 2003). Numerous VOCs with small to large peak areas were detected in the samples from the regional aquifer systems in the fractured-rock terrains and the Coastal Plain Shallow regional aquifer system (fig. 17a). The presence of VOCs in these samples is to be expected because the susceptibility threshold concentrations were exceeded and the regional aquifer systems are classified as susceptible to contamination from near-surface activities. The frequent detections of carbon tetrachloride and chloroform are in response to the high sensitivity of the GC-ECD to these compounds (Shapiro and others, 2003). The detection of 1,1,1-trichloroethane (TCA), trichloroethylene (TCE), and tetrachloroethylene (PCE) in the water samples is consistent with the widespread and abundant use of these compounds (Harte and others, 1991); TCE and PCE detections are of concern because these compounds are known carcinogens and eventually degrade to vinyl chloride, which is a more toxic compound (Harte and others, 1991).

The identification of VOC peaks in the samples from the Coastal Plain Middle and Deep regional aquifer systems is problematic (fig. 17b). Generally, the VOC peaks identified in the samples from the Coastal Plain Middle and Deep regional aquifer systems are classified as small peak areas and usually correspond to the retention times for carbon tetrachloride (fig. 17b). The samples with medium to large peak areas for carbon tetrachloride typically had low detections of ^3H (0.4 to 0.6 TU) and were from wells that were drilled prior to 1973. The combination of these factors suggests that transient leakage from the well casing or wellbore is allowing young water to enter the well. Another possibility is that the VOCs are remnants from well-construction or pump-maintenance activities.

Comparison of the number of VOCs detected and the major land-use category within 1,000 ft of the well or spring suggests that the occurrence of VOCs is only slightly greater in the developed areas than in forested and agricultural areas (fig. 18). However, most of the

samples were collected from public supplies located in or near developed areas. The occurrence of VOCs is probably related to the proximity of the well or spring to specific local anthropogenic activities, not the major land-use activity within 1,000 ft of the well. Furthermore, Franke and others (1998) show that the area contributing recharge to a well does not have to include the location of the well or the area encompassing a specified distance from the well.

Statewide Assessment of Aquifer Susceptibility

Susceptibility of the regional aquifers in Virginia to contamination from near-surface sources depends on a complex array of natural and anthropogenic factors. The multiple tracer approach was used during the VAS study to measure the relation between these factors, and the results of the study can be summarized in terms of the type and relative degree of susceptibility of the regional aquifer systems (fig. 19). There are two types of regional aquifer systems: porous media (unconsolidated deposits) aquifers in the Coastal Plain regional aquifer systems, and fractured-rock and karst aquifers in the Appalachian Plateaus, Valley and Ridge, Blue Ridge, and Piedmont regional aquifer systems. The relative degree of susceptibility is determined on the basis of the amount and apparent age of the young water fraction in binary mixtures.

In the Coastal Plain, aquifer susceptibility depends upon the depth and degree of confinement of the aquifers and the type of flow paths intercepted. Most of the water samples from the Coastal Plain regional aquifer systems did not exceed the susceptibility threshold concentrations for CFCs and ^3H (fig. 19). The frequency of NO_3 detections in the water samples from the Coastal Plain Shallow regional aquifer system was greater than in those from the Coastal Plain Middle and Deep regional aquifer systems. Although the frequency of detection of VOCs in the samples from the Coastal Plain Middle and Deep regional aquifer systems was high, these detections are thought to be the result of analytical or sampling error, transient leakage from the well casing or wellbore, or remnants of well-construction or pump maintenance activities (fig. 19). Young water was consistently detected in the samples from the water table and shallow confined aquifers in the upper 100 ft of the Coastal Plain Shallow regional aquifer system (fig. 20). Although the connection to near-sur-

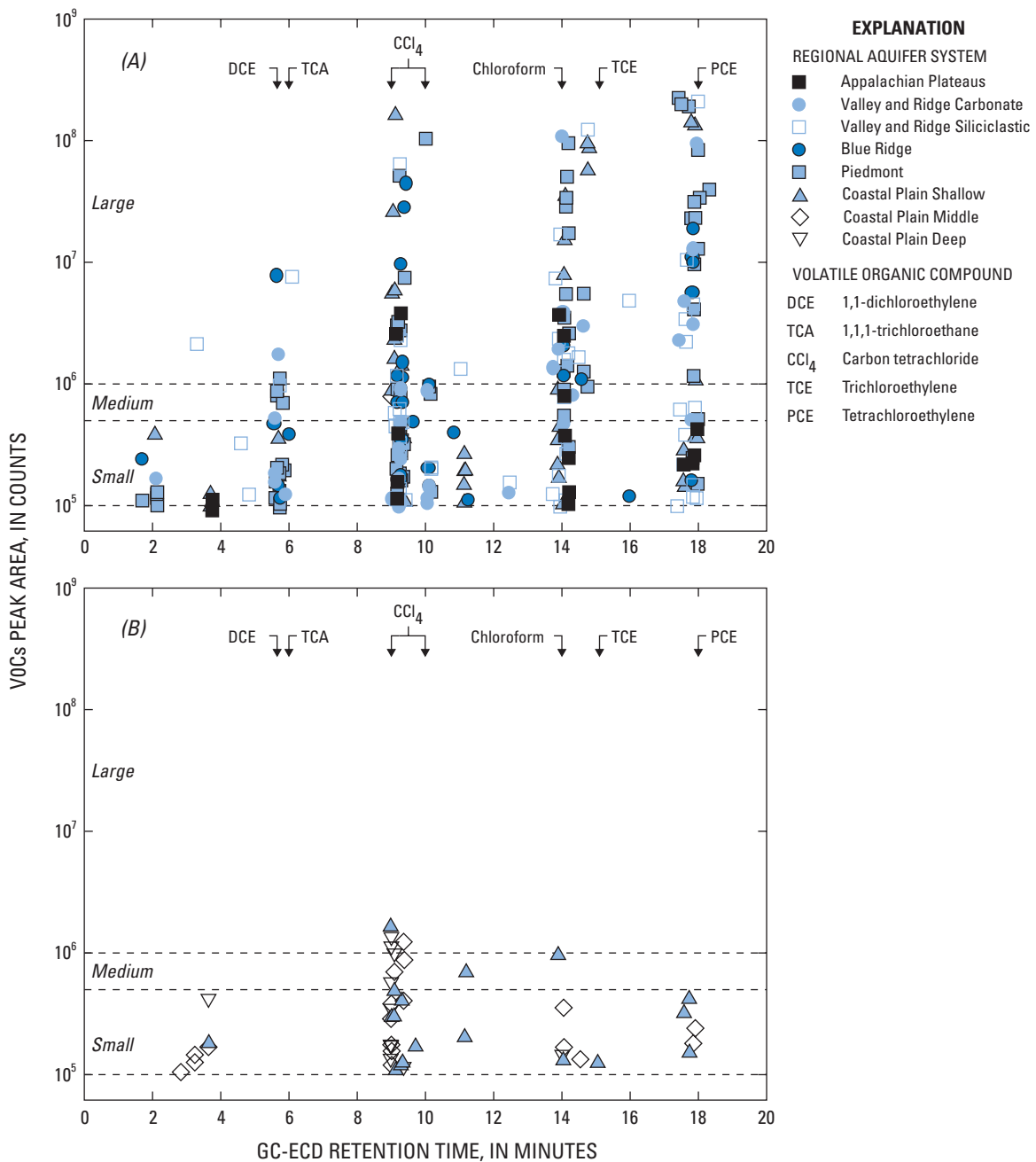


Figure 17. Peak areas in relation to retention times for volatile organic compounds (VOCs) from gas chromatography with an electron capture detector (GC-ECD) analysis for samples that exceeded susceptibility threshold concentrations (A) and for samples that did not exceed susceptibility threshold concentrations (B). Data from Shapiro and others (2003).

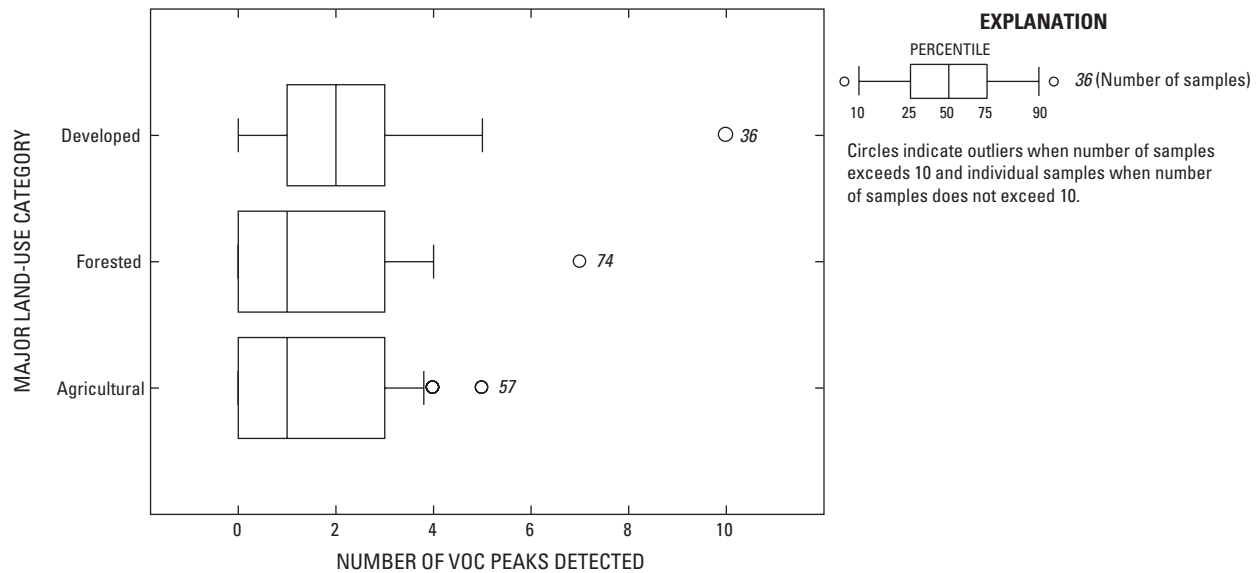


Figure 18. Distribution of volatile organic compounds (VOCs) detected in water samples by major land-use category within 1,000 feet of the well or spring, Virginia.

face sources is limited for the shallow confined aquifers, the presence of young waters is facilitated by the thin and leaky nature of the overlying confining units and mixtures of waters that flow along local to subregional flowpaths. The confined aquifers of the Coastal Plain Middle and Deep regional aquifer systems are overlain by a series of relatively thick confining units and contain old (pre-CFC) or paleowaters from subregional to regional flow paths. The water samples from these aquifer systems rarely exceed the susceptibility thresholds (fig. 20), which indicates that the susceptibility of these aquifers under natural conditions is negligible because the radiocarbon ages of these waters are usually greater than 1,000 years. However, the potential of introducing young waters from well integrity problems exists, as evidenced by the VOC detections in some of the water samples from these regional aquifer systems.

The fractured-rock and karst aquifers of the Appalachian Plateaus, Valley and Ridge, Blue Ridge, and Piedmont regional aquifer systems are susceptible to contamination from near-surface sources for the depth ranges investigated during the VAS study (fig. 19). All of the water samples from the fractured-rock terrains are classified as susceptible, and no relation exists between susceptibility and depth of the top of the first water zone or well depth (fig. 20). Ground-water movement along fractures, joints, and solution features can be rapid, especially under stressed conditions that can

result from pumpage. The geometry of these features can allow young ground water to circulate to substantial depths in these regional aquifer systems, and the depth at which the water enters the well (water zone) is more important than the total depth of the well (fig. 20). Previous investigations have identified the presence of young waters in these aquifer systems (Nelms and Ahlin, 1993; Nelms and Brockman, 1997; Focazio and others, 1998; Nelms and others, 1999; Kozar and others, 2001; Plummer and others, 2001). Similar findings from environmental tracer studies in South Carolina have also identified the presence of young waters in the Piedmont and Blue Ridge (Stone and others, 1986; Stone and others, 1989; Stone and others, 1992; Stone and others, 1997; Stone and Devlin, 1999a, 1999b). The frequent detections of NO_3 and VOCs, and CFC concentrations in excess of air-water equilibrium in water samples further support the classification of these aquifer systems as susceptible. Numerous investigations have documented the frequent occurrence of ambient flow within open boreholes in fractured-rock terrains (Williams and others, 2002; Johnson and others, 2002; Heisig, 2002). This mechanism in conjunction with rapid movement along fractures, joints, and solution features may be responsible for the ubiquitous occurrence of some fraction of young waters at depth in the fractured-rock regional aquifer systems.

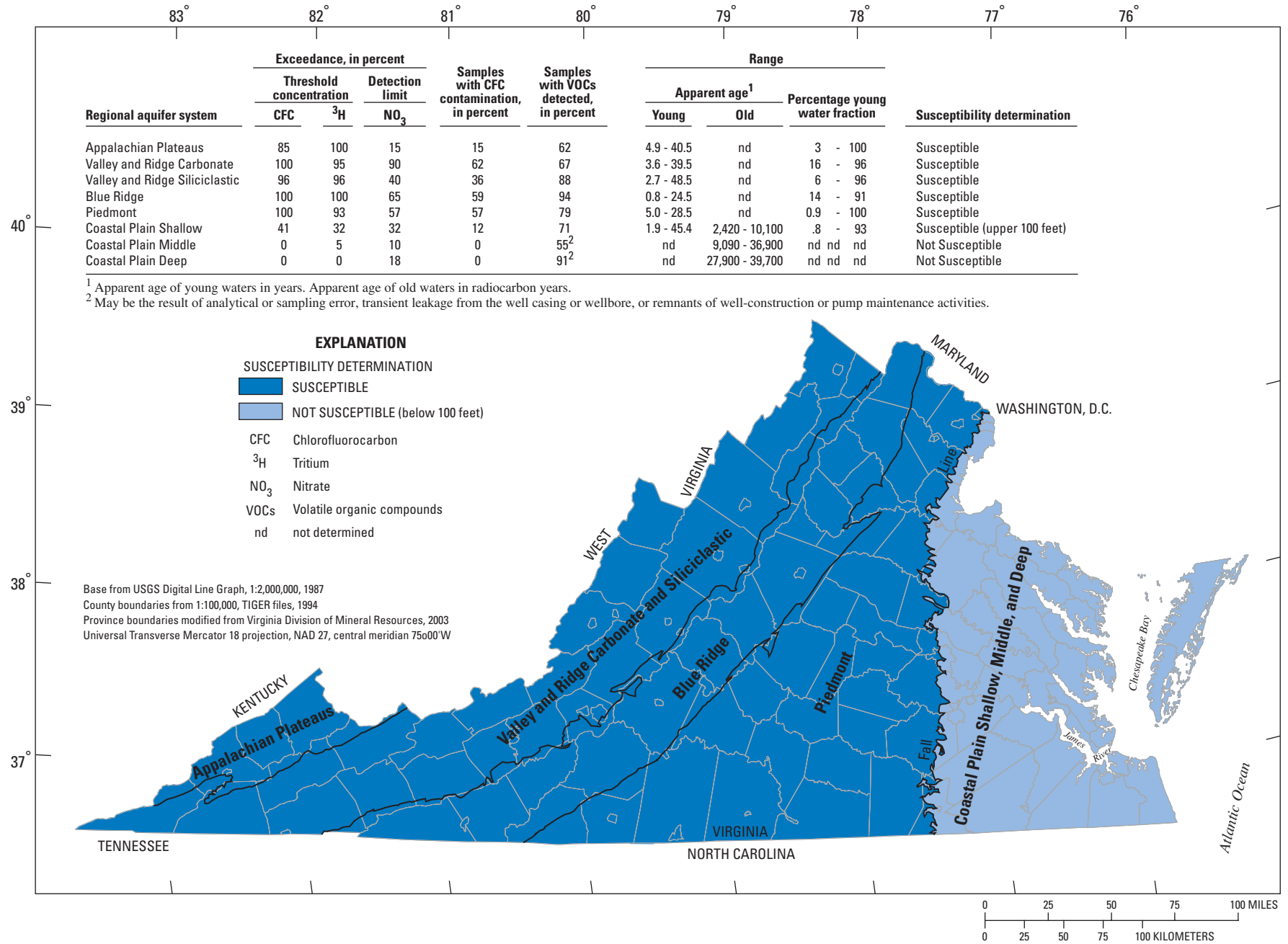


Figure 19. Susceptibility to contamination from near-surface sources of the regional aquifer systems in Virginia, 1998-2000.

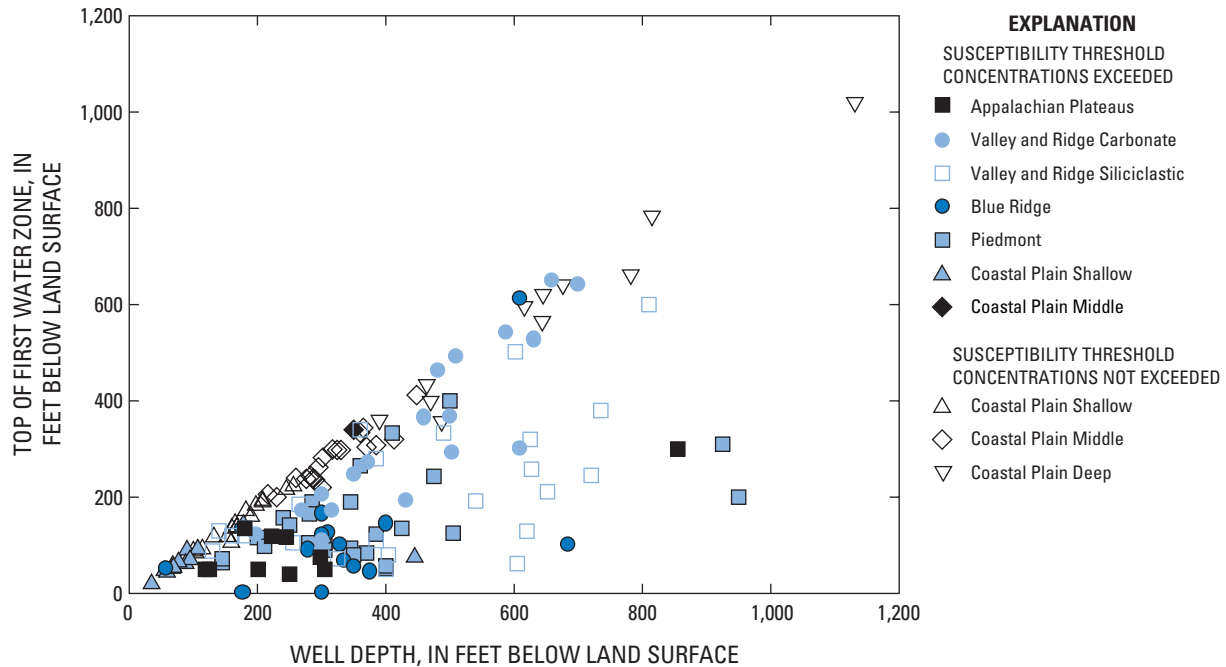


Figure 20. Depth to top of first water zone and well depth in relation to exceedance and nonexceedance of susceptibility threshold concentrations by regional aquifer system, Virginia.

The multiple tracer approach used during the VAS study provided a consistent means to identify the presence of young waters in the regional aquifer systems across Virginia. The low-level detections of the environmental tracers not only identified the presence of young waters, but also allowed for the determination of small fractions of young waters in binary mixtures with older (pre-CFC) waters. The ratio of the percentage and apparent age of the young fraction in binary mixtures provides an indication of the relative degree of susceptibility. The large ratios (greater than 10) depicted on figure 21 are associated with samples in which the fraction of the young water is large (greater than 75 percent) and apparent age is extremely young (less than 5 years). Samples from the fractured-rock regional aquifer systems generally have the largest ratios. The abundance of large ratios in the Blue Ridge regional aquifer system is consistent with the findings from Plummer and others (2001), in which apparent ages for springs and wells in Shenandoah National Park ranged from 0 to 3 and 0 to 25 years, respectively, and the percentage of young water fraction was generally greater than 50 percent. Analysis-of-variance tests indicate that the ratios in the samples from the Blue Ridge regional aquifer system are significantly larger ($p < 0.05$) than

those in the other regional aquifer systems, whereas the ratios of the other regional aquifer systems could not be statistically separated.

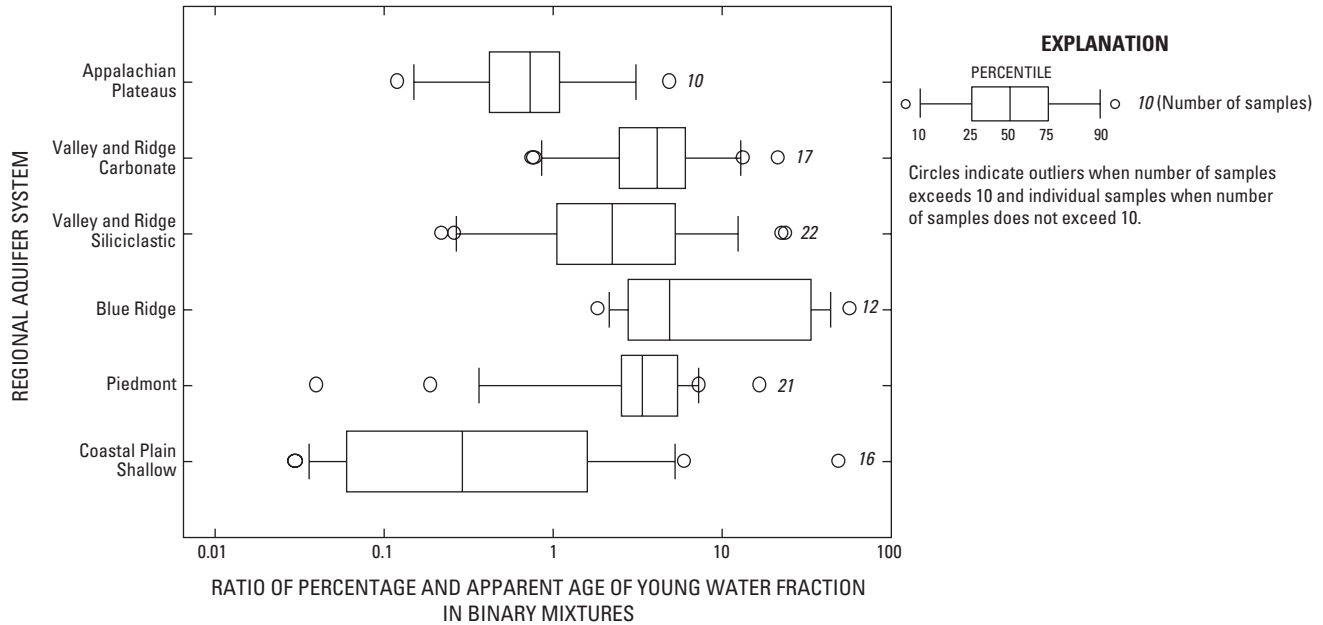


Figure 21. Distribution of the ratio of the percentage and apparent age of the young water fraction in binary mixtures with old (pre-chlorofluorocarbon) waters by regional aquifer system, Virginia.

SUMMARY AND CONCLUSIONS

The U.S. Geological Survey (USGS), in cooperation with the Virginia Department of Health, sampled water from 171 wells and springs across the Commonwealth of Virginia between 1998 and 2000 as part of the Virginia Aquifer Susceptibility (VAS) study. Most of the sites sampled are public water supplies that are part of the comprehensive Source Water Assessment Program for the Commonwealth. This report presents determinations of aquifer susceptibility to contamination from near-surface sources for the regional aquifers that serve as public water supplies and compares aquifer susceptibility determinations to apparent ground-water ages and to the occurrence of selected chemical constituents in ground water. The Commonwealth was subdivided into eight regional aquifer systems on the basis of (1) physiographic province, (2) geologic province, (3) hydrogeologic characteristics, (4) major rock type (in the Valley and Ridge Province), and (5) depth of the top of the first screened interval (in the Coastal Plain Province). These regional aquifer systems are:

1. Appalachian Plateaus
2. Valley and Ridge Carbonate
3. Valley and Ridge Siliciclastic
4. Blue Ridge
5. Piedmont (including the Mesozoic Basins)
6. Coastal Plain Shallow (depths less than 200 ft below land surface)
7. Coastal Plain Middle (depths between 200 and 400 ft below land surface)
8. Coastal Plain Deep (depths greater than 400 ft below land surface).

The fundamental premise of the study was that the identification of young waters (less than 50 years) by multiple environmental tracers could be used as a guide for classifying aquifers in terms of susceptibility to contamination from near-surface sources. Multiple environmental tracers—chlorofluorocarbons (CFCs), sulfur hexafluoride (SF₆), tritium (³H), and tritium/helium-3 (³H/³He)—and carbon isotopes (¹⁴C and ^δ¹³C) were used to determine the age of water discharging from wells and springs. Concentrations of CFCs greater than 5 pg/kg and ³H concentrations greater than 0.6 TU were used as thresholds to indicate that parts of the aquifer sampled have a component of

young water and are, therefore, susceptible to near-surface contamination.

Concentrations of CFCs exceeded the susceptibility threshold in 22 percent of the wells and in one spring sampled in the Coastal Plain regional aquifer systems. About 74 percent of the samples from wells with the top of the first water zone less than 100 ft below land surface exceeded the threshold values, and water supplies developed in the upper 100 ft of the Coastal Plain are considered to be susceptible to contamination from near surface sources. The maximum depth to the top of the screened interval for wells that contained CFCs was less than 150 ft. The probability of water supplies being affected by near-surface sources of contamination is greatest in the upper 100 ft of the Coastal Plain Shallow regional aquifer system. The analyses of the sample from one spring and results from previous studies of springs in the Coastal Plain of Virginia indicate that springs in this shallow regional aquifer system contain young water, and, therefore, are susceptible to contamination from near-surface sources.

Wells completed in the deep confined aquifers in the Coastal Plain generally contain water older than 1,000 years, as indicated by radiocarbon dating, and ranged from 9,090 to 39,700 radiocarbon years BP (before present where present is AD 1950). These regional aquifer systems are not considered to be susceptible to contamination under natural conditions. The low concentrations of CFCs and ^3H detected in some of samples from the Coastal Plain Middle and Deep regional aquifer systems may be the result of analytical or sampling error, or transient leakage from the well casing or wellbore. The presence of paleowaters in the Coastal Plain regional aquifer systems is consistent with conceptual and flow-simulation models of this region, where ground-water recharge occurs along the Fall Line, and water flows towards the Atlantic Ocean along deep regional flow paths. The relation between increasing adjusted radiocarbon ages and distance from the Fall Line for samples from the Cretaceous aquifers (upper, middle, and lower Potomac aquifers) appears to differ with regard to a site's orientation to the James River. Samples from north of the James River become older over a shorter distance from the Fall Line than those samples from south of the James River, which may be the result of possible bifurcation of flow around what is now known to be the Chesapeake Bay impact crater.

All of the water samples from wells and springs in the fractured-rock terrains (the Appalachian Plateaus, Valley and Ridge, Blue Ridge, and Piedmont regional aquifer systems) contained concentrations of CFCs and ^3H greater than one or both of the thresholds. Because all of the water samples exceeded at least one of the threshold values, young water is present throughout most of these regional aquifer systems; therefore, water supplies developed in these systems are susceptible to contamination from near-surface sources. No relation between well depth and presence of CFCs is evident from samples in the fractured-rock terrains.

More than 95 percent of the samples for which the dating methods were applicable contained waters with apparent ages less than 35 years. About 5 percent of these samples, most of which were from the Blue Ridge and Piedmont regional aquifer systems, contained young waters with apparent ages of less than 5 years. Most of the samples from the Valley and Ridge Carbonate, Blue Ridge, and Piedmont regional aquifer systems had young water fractions of more than 50 percent, whereas samples from the Coastal Plain Shallow and Appalachian Plateaus regional aquifer systems contained less than 40 percent young waters. The apparent ages determined by the VAS study probably represent maximum ages of the young fractions because processes such as dilution and matrix diffusion can alter the original tracer concentrations as the ground water moves through the flow system. The actual ages of the young fractions, therefore, may be younger than the apparent ages presented in this report and the regional aquifer systems may be more susceptible, especially in the fractured-rock terrains, than is indicated by the findings of this study.

Concentrations of CFCs in excess of air-water equilibrium, which can indicate that nonatmospheric sources (such as sewage effluent) have introduced CFCs into the ground-water system, were measured in 6 and 48 percent of the water samples from the Coastal Plain and fractured-rock regional aquifer systems, respectively. The presence of CFC contamination is another means of assessing the validity of the VAS methodology for determining aquifer susceptibility to near-surface contamination. None of the samples from the Coastal Plain Middle and Deep regional aquifer systems contained CFC contamination, and CFCs were not detected in a majority of the samples. The high percentage of samples with measured CFC contamination in the fractured-rock terrains indicates that supplies

developed in these regional aquifer systems are susceptible. The absence of either CFCs or CFC contamination in the samples from the Coastal Plain Middle and Deep regional aquifer systems illustrates the lack of connection and the long period of time it takes water to flow to these aquifers from near land surface under natural conditions.

The nitrate (NO_3) concentrations greater than the USGS detection level of 0.05 mg/L generally increase as the apparent age of the young water fraction decreases, with the highest NO_3 concentrations for samples in which one or more of the CFCs are above modern atmospheric mixing ratios (commonly referred to as “contaminated” for ground-water dating purposes). Most of the samples in which NO_3 was detected were from the fractured-rock regional aquifer systems, especially the Valley and Ridge Carbonate regional aquifer system, where 90 percent of the samples had concentrations greater than the detection level. Nitrate concentrations were equal to or slightly greater than the USGS detection levels for samples that contained only old or paleowaters. Although the evaluation of NO_3 concentrations and the multiple tracer approach yielded somewhat consistent results in terms of aquifer susceptibility, the viability of NO_3 concentrations as an indicator of aquifer susceptibility in the Appalachian Plateaus, Valley and Ridge Siliciclastic, and Coastal Plain Shallow regional aquifer systems can be limited by processes such as dilution and methanogenesis and by proximity of sampling sites to near-surface sources.

Numerous halogenated volatile organic compounds were detected at low concentrations (parts per quadrillion) in the samples from the regional aquifer systems in the fractured-rock terrains and the Coastal Plain Shallow regional aquifer system. The presence of VOCs in these samples is to be expected because the susceptibility threshold concentrations were exceeded and the regional aquifer systems are classified as susceptible to contamination from near-surface activities. The identification of the VOCs is only qualitative because quantitative analysis to determine actual concentrations is not possible with gas chromatography with an electron capture detector (GC-ECD). However, low-level detections of VOCs by GC-ECD can be used to indicate aquifer susceptibility and provide early warning of potential contamination of ground-water sources. The identification of VOC peaks in the samples from the Coastal Plain Middle and Deep regional aquifer systems is problematic and suggests that tran-

sient leakage from the well casing or wellbore is allowing young water to enter the well or that the VOCs are remnants from well-construction or pump-maintenance activities. Comparison of the number of VOCs detected and the major land-use category within 1,000 ft of the well or spring suggests that the occurrence of VOCs is only slightly greater in the developed areas than in forested and agricultural areas. The area contributing recharge to a well does not have to include the actual location of the well or the area encompassing a specified distance from the well.

The relative degree of susceptibility can be indicated by the ratio of the percentage and apparent age of the young fraction in binary mixtures of young and old waters. Large ratios are associated with samples in which the fraction of the young water is large (greater than 75 percent) and apparent age is extremely young (less than 5 years). Samples from the fractured-rock regional aquifer systems generally have the largest ratios. Analysis-of-variance tests indicate that the ratios in the samples from the Blue Ridge regional aquifer system are significantly higher ($p < 0.05$) than those in the other regional aquifer systems.

Results from this study indicate that shallow wells (less than 100 ft deep) and springs in the Coastal Plain Shallow regional aquifer system and wells and springs in the fractured-rock terrains contain a component of young ground water and are, therefore, susceptible to contamination from near-surface sources.

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Tables 5-6

Table 5. Apparent ages from chlorofluorocarbons, tritium/helium-3, and sulfur hexafluoride dating methods, and adjusted radiocarbon ages for water samples from wells and springs in Virginia, 1998-2000

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded CFC and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC₁₃); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); ³H/³He, tritium/helium-3; SF₆, sulfur hexafluoride; ¹⁴C Adj. age, adjusted radiocarbon age in radiocarbon years BP (present is AD 1950); nd, not determined. All ¹⁴C ages are based on the Libby half-life of 5,568 years and have not been calibrated to calendar years; NP, not possible; >, older than age denoted; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system ²	Susc. cat.	Date	Apparent age and uncertainty ³ , in years								¹⁴ C Adj. age ⁴ (years)	Final age ⁵		
						CFC-11	CFC-12	CFC-113	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	³ H/ ³ He	SF ₆		Young	Old	Tracer used
AP-01	VAS	Well	AP	Y	7/10/2000	C	C	C	nd	nd	nd	nd	36.0 ± 1.8	nd	nd	nd	nd
AP-02	VAS	Well	AP	Y	7/10/2000	40.5 ± 1.8	45.5 ± 1.8	>45.5 ± 0.0	nd	nd	nd	4.9 ± 0.8	36.0 ± 1.5	nd	4.9	nd	³ H/ ³ He
AP-03	VAS	Well	AP	Y	7/20/2000	22.6 ± 1.3	12.6 ± 1.5	14.1 ± 0.5	NP	NP	nd	nd	C	nd	14.1	nd	CFC-113
AP-04	VAS	Well	AP	Y	7/11/2000	48.0 ± 1.8	49.0 ± 3.3	>45.5 ± 0	47	nd	nd	nd	40.5 ± 2.5	nd	40.5	nd	SF ₆
AP-05	VAS	Well	AP	Y	7/12/2000	45.5 ± 0.5	38.5 ± 1.5	34.0 ± 1.8	NP	20.5	nd	nd	18.0 ± 1.0	nd	20.5	nd	CFC-113/CFC-12
AP-06	VAS	Well	AP	Y	7/13/2000	44.0 ± 0.5	35.0 ± 0.3	32.0 ± 1.8	NP	22.5	nd	nd	16.0 ± 0.8	nd	22.5	nd	CFC-113/CFC-12
AP-07	VAS	Well	AP	Y	7/13/2000	47.5 ± 1.0	>60.5 ± 0	>45.5 ± 0	nd	nd	nd	24.1 ± 0.3	36.0 ± 0.5	nd	24.1	nd	³ H/ ³ He
AP-08	VAS	Well	AP	Y	7/10/2000	26.0 ± 0.5	19.0 ± 1.8	19.5 ± 0.8	NP	NP	12.5	nd	18.0 ± 0.8	nd	19	nd	CFC-12, CFC-113 (piston)
AP-09	VAS	Well	AP	Y	7/10/2000	37.5 ± 1.0	43.0 ± 0.8	>45.5 ± 0	nd	nd	nd	nd	18.5 ± 1.3	nd	18.5	nd	SF ₆
AP-10	VAS	Well	AP	Y	7/11/2000	51.0 ± 1.5	50.5 ± 1.3	>45.5 ± 0	NP	nd	nd	nd	24.5 ± 1.0	nd	24.5	nd	SF ₆
AP-11	VAS	Well	AP	Y	7/11/2000	48.0 ± 0.8	47.0 ± 1.0	>45.5 ± 0	NP	nd	nd	nd	30.0 ± 1.3	nd	nd	nd	nd
AP-12	VAS	Well	AP	Y	7/12/2000	40.5 ± 0.5	C	28.0 ± 0.8	nd	nd	nd	nd	12.5 ± 1.3	nd	12.5	nd	SF ₆
AP-13	VAS	Well	AP	Y	7/12/2000	46.0 ± 0.3	51.0 ± 1.8	>45.5 ± 0	30.5	nd	nd	nd	41.0 ± 1.8	nd	30.5	nd	CFC-11/CFC-12
BR-01	VAS	Well	BR	Y	7/19/1999	30.0 ± 1.8	23.5 ± 0.5	26.0 ± 0.5	NP	nd	17	nd	C	nd	17	nd	CFC-113/CFC-11
BR-02	VAS	Well	BR	Y	7/19/1999	13.5 ± 1.3	C	10.5 ± 0.8	nd	nd	2.5	nd	C	nd	2.5	nd	CFC-113/CFC-11
BR-03	VAS	Well	BR	Y	7/20/1999	C	C	9.1 ± 1.0	nd	nd	nd	1.5 ± 0.2	5.1 ± 1.3	nd	1.5	nd	³ H/ ³ He
BR-04	VAS	Well	BR	Y	7/20/1999	45.1 ± 1.0	21.6 ± 0.8	>44.6 ± 0	NP	nd	nd	nd	13.1 ± 0.8	nd	13	nd	SF ₆
BR-05	VAS	Well	BR	Y	8/25/1999	C	C	C	nd	nd	nd	20.2 ± 2.1	20.2 ± 2.5	nd	20.2	nd	³ H/ ³ He, SF ₆
BR-06	VAS	Well	BR	Y	9/13/1999	32.7 ± 1.3	C	C	nd	nd	nd	5.1 ± 0.2	C	nd	5.1	nd	³ H/ ³ He
BR-07	VAS	Well	BR	Y	9/14/1999	29.7 ± 0.5	C	C	nd	nd	nd	nd	C	nd	nd	nd	nd
BR-08	VAS	Well	BR	Y	9/16/1999	C	C	C	nd	nd	nd	2.2 ± 0.1	2.2 ± 1.8	nd	2.2	nd	³ H/ ³ He, SF ₆
BR-09	VAS	Well	BR	Y	10/18/1999	40.8 ± 1.0	19.3 ± 1.0	12.8 ± 0.5	NP	nd	nd	nd	9.3	nd	9.3	nd	SF ₆
BR-10	VAS	Well	BR	Y	10/26/1999	C	C	C	nd	nd	nd	nd	0.8	nd	0.8	nd	SF ₆
CP-01	VAS	Well	CP-D	N	6/23/1998	>53.5 ± 0	>58.5 ± 0	>43.5 ± 0	nd	nd	nd	nd	18.0 ± 1.0	31,800 ± 2,300	nd	31,800	¹⁴ C
CP-02	VAS	Well	CP-M	N	6/24/1998	>53.5 ± 0	>58.5 ± 0	>43.5 ± 0	nd	nd	nd	nd	27.5 ± 1.0	28,700 ± 1,900	nd	28,700	¹⁴ C
CP-03	VAS	Well	CP-D	N	6/25/1998	>53.5 ± 0	>58.5 ± 0	>43.5 ± 0	nd	nd	nd	nd	34.5 ± 0.8	27,900 ± 1,900	nd	27,900	¹⁴ C
CP-04	VAS	Well	CP-M	N	7/1/1998	>53.5 ± 0	>58.5 ± 0	>43.5 ± 0	nd	nd	nd	nd	31.5 ± 0.5	34,600 ± 1,900	nd	34,600	¹⁴ C

Table 5. Apparent ages from chlorofluorocarbons, tritium/helium-3, and sulfur hexafluoride dating methods, and adjusted radiocarbon ages for water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded CFC and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC₁₁); CFC-12, (dichlorodifluoromethane, CFC₁₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); ³H/³He, tritium/helium-3; SF₆, sulfur hexafluoride; ¹⁴C Adj. age, adjusted radiocarbon age in radiocarbon years BP (present is AD 1950); nd, not determined. All ¹⁴C ages are based on the Libby half-life of 5,568 years and have not been calibrated to calendar years; NP, not possible; >, older than age denoted; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system ²	Susc. cat.	Date	Apparent age and uncertainty ³ , in years							¹⁴ C Adj. age ⁴ (years)	Final age ⁵			
						CFC-11	CFC-12	CFC-113	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	³ H/ ³ He		SF ₆	Young	Old	Tracer used
CP-05	VAS	Well	CP-M	N	7/6/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	26.0 ± .5	36,900 ± 1,900	nd	36,900	¹⁴ C
CP-06	VAS	Well	CP-D	N	7/6/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	26.5 ± .8	33,400 ± 1,900	nd	33,400	¹⁴ C
CP-07	VAS	Well	CP-M	N	7/7/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	35.0 ± .5	29,000 ± 2,600	nd	29,000	¹⁴ C
CP-08	VAS	Well	CP-M	N	7/7/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	28.5 ± 1.0	34,700 ± 1,900	nd	34,700	¹⁴ C
CP-09	VAS	Well	CP-S	N	7/8/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	30.0 ± .8	nd	nd	nd	nd
CP-10	VAS	Well	CP-M	N	7/8/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	30.0 ± .8	31,100 ± 1,900	nd	31,100	¹⁴ C
CP-11	VAS	Well	CP-S	N	7/9/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	33.0 ± .5	10,100 ± 2,800	nd	10,100	¹⁴ C
CP-12	VAS	Well	CP-S	N	7/14/1998	46.5 ± 2.0	55.5 ± 3.3	>43.5 ± .0	nd	nd	nd	nd	37.5 ± 1.0	nd	37.5	nd	SF ₆
CP-13	VAS	Well	CP-S	N	7/15/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	>46.5 ± .0	nd	nd	nd	nd
CP-14	VAS	Well	CP-S	Y	7/15/1998	11.0 ± 1.0	C	C	nd	nd	nd	20.6 ± .4	15.5 ± 1.0	nd	20.6	nd	³ H/ ³ He
CP-15	VAS	Well	CP-S	N	7/15/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	26.5 ± .8	nd	nd	nd	nd
CP-16	VAS	Well	CP-S	N	7/16/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	35.5 ± .8	nd	35.5	nd	SF ₆
CP-17	VAS	Well	CP-S	N	7/16/1998	>53.5 ± .0	>58.5 ± .0	>43.5 ± .0	nd	nd	nd	nd	21.0 ± .8	nd	nd	nd	nd
CP-18	VAS	Well	CP-M	N	7/27/1998	47.6 ± 1.3	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	24.6 ± .5	10,100 ± 2,800	nd	10,100	¹⁴ C
CP-19	VAS	Well	CP-M	N	7/27/1998	50.6 ± .5	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	26.6 ± .8	9,790 ± 2,500	26.6	9,790	¹⁴ C/SF ₆
CP-20	VAS	Well	CP-D	N	7/28/1998	>53.6 ± 0.0	>58.6 ± 0.0	>43.6 ± 0.0	nd	nd	nd	nd	31.1 ± 0.8	36,600 ± 1,900	nd	36,600	¹⁴ C
CP-21	VAS	Well	CP-S	Y	7/29/1998	>53.6 ± .0	34.1 ± .3	>43.6 ± .0	NP	nd	nd	34.5 ± 1.0	26.1 ± .8	2,420 ± 2,800	26.1	2,420	SF ₆
CP-22	VAS	Well	CP-M	N	7/30/1998	>53.6 ± .0	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	>46.6 ± 2.3	9,090 ± 3,000	nd	9,090	¹⁴ C
CP-23	VAS	Well	CP-M	N	8/3/1998	>53.6 ± .0	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	>46.6 ± .0	20,200 ± 2,600	nd	20,200	¹⁴ C
CP-24	VAS	Well	CP-D	N	8/4/1998	>53.6 ± .0	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	29.1 ± .8	34,200 ± 1,900	29.1	34,200	¹⁴ C/SF ₆
CP-25	VAS	Well	CP-M	N	8/4/1998	46.6 ± 1.0	52.1 ± .8	43.6 ± 1.3	21.6	12.6	12.6	nd	25.6 ± .8	23,600 ± 1,900	12.6	23,600	¹⁴ C,CFC-113/CFC-12
CP-26	VAS	Well	CP-S	Y	8/5/1998	C	C	C	nd	nd	nd	12.0 ± .2	10.1 ± 1.3	nd	12	nd	³ H/ ³ He
CP-27	VAS	Well	CP-D	N	8/6/1998	>53.6 ± .0	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	30.6 ± .8	38,100 ± 1,900	nd	38,100	¹⁴ C
CP-28	VAS	Well	CP-S	Y	8/17/1998	>53.6 ± .0	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	21.1 ± 1.0	nd	21.1	nd	SF ₆
CP-29	VAS	Well	CP-M	N	8/17/1998	>53.6 ± .0	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	34.1 ± .5	16,700 ± 3,100	nd	16,700	¹⁴ C
CP-30	VAS	Well	CP-M	N	8/18/1998	>53.6 ± .0	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	>46.6 ± .0	30,000 ± 2,300	nd	30,000	¹⁴ C
CP-31	VAS	Well	CP-M	N	8/19/1998	>53.6 ± .0	>58.6 ± .0	>43.6 ± .0	nd	nd	nd	nd	34.1 ± .5	10,100 ± 2,900	nd	10,100	¹⁴ C

Table 5. Apparent ages from chlorofluorocarbons, tritium/helium-3, and sulfur hexafluoride dating methods, and adjusted radiocarbon ages for water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded CFC and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC₁₁); CFC-12, (dichlorodifluoromethane, CFC₁₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); ³H/³He, tritium/helium-3; SF₆, sulfur hexafluoride; ¹⁴C Adj. age, adjusted radiocarbon age in radiocarbon years BP (present is AD 1950); nd, not determined. All ¹⁴C ages are based on the Libby half-life of 5,568 years and have not been calibrated to calendar years; NP, not possible; >, older than age denoted; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system ²	Susc. cat.	Date	Apparent age and uncertainty ³ , in years							¹⁴ C Adj. age ⁴ (years)	Final age ⁵				
						CFC-11	CFC-12	CFC-113	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	³ H/ ³ He		SF ₆	Young	Old	Tracer used	
CP-32	VAS	Well	CP-M	Y	8/31/1998	>53.7 ± .0	>58.7 ± .0	>43.7 ± .0	nd	nd	nd	nd	>46.7 ± .0	24,800 ± 2,900	nd	24,800	¹⁴ C	
CP-33	VAS	Well	CP-S	N	8/31/1998	>53.7 ± .0	>58.7 ± .0	>43.7 ± .0	nd	nd	nd	nd	38.2 ± 1.3	nd	nd	nd	nd	
CP-34	VAS	Well	CP-S	Y	8/31/1998	42.7 ± .5	37.7 ± .8	26.7 ± 3.3	NP	nd	nd	nd	25.2 ± 3.3	2,430 ± 2,800	25.2	nd	SF ₆	
CP-35	VAS	Well	CP-D	N	9/1/1998	>53.7 ± .0	>58.7 ± .0	>43.7 ± .0	nd	nd	nd	nd	33.2 ± .5	33,900 ± 2,800	nd	33,900	¹⁴ C	
CP-36	VAS	Well	CP-M	N	9/1/1998	48.7 ± .5	52.2 ± 2.4	>43.7 ± .0	43.2	nd	nd	nd	34.7 ± 1.8	29,100 ± 1,900	nd	29,100	¹⁴ C	
CP-37	VAS	Well	CP-M	N	9/2/1998	>53.7 ± .0	>58.7 ± .0	>43.7 ± .0	nd	nd	nd	nd	33.2 ± .8	21,100 ± 3,100	nd	21,100	¹⁴ C	
CP-38	VAS	Well	CP-D	N	9/2/1998	>53.7 ± .0	>58.7 ± .0	>43.7 ± .0	nd	nd	nd	nd	30.7 ± .5	nd	nd	nd	nd	
CP-39	VAS	Well	CP-M	N	9/2/1998	>53.7 ± .0	>58.7 ± .0	>43.7 ± .0	nd	nd	nd	nd	38.7 ± 1.8	11,900 ± 3,100	nd	11,900	¹⁴ C	
CP-40	VAS	Well	CP-D	N	9/3/1998	47.7 ± .8	52.2 ± .3	>43.7 ± .0	41.2	nd	nd	nd	40.2 ± 2.3	28,000 ± 2,200	nd	28,000	¹⁴ C	
CP-41	VAS	Well	CP-M	N	9/10/1998	>53.7 ± .0	>58.7 ± .0	>43.7 ± .0	nd	nd	nd	nd	31.7 ± .5	36,900 ± 1,900	nd	36,900	¹⁴ C	
CP-42	VAS	Well	CP-D	N	9/10/1998	>53.7 ± .0	>58.7 ± .0	>43.7 ± .0	nd	nd	nd	nd	34.2 ± 1.3	30,800 ± 1,900	nd	30,800	¹⁴ C	
CP-43	VAS	Well	CP-S	N	10/1/1998	>53.8 ± .0	>58.8 ± .0	>43.8 ± .0	nd	nd	nd	nd	36.8 ± 1.0	nd	nd	nd	nd	
CP-44	VAS	Well	CP-S	N	10/5/1998	50.8 ± 2.1	>58.8 ± .0	>43.8 ± .0	nd	nd	nd	nd	30.8 ± .5	nd	nd	nd	nd	
CP-45	VAS	Well	CP-S	Y	10/5/1998	>53.8 ± .0	22.8 ± .8	>43.8 ± .0	NP	nd	nd	20.3 ± .5	9.3 ± .8	nd	9.3	nd	SF ₆	
CP-46	VAS	Well	CP-S	Y	10/6/1998	22.8 ± .8	20.8 ± 1.8	14.8 ± .8	NP	11.8	8.8	23.2 ± .4	19.3 ± .8	nd	11.8	nd	CFC-113/CFC-12	
CP-47	VAS	Well	CP-M	N	10/6/1998	51.8 ± 1.8	53.8 ± 3.6	>43.8 ± .0	48.8	nd	nd	nd	35.8 ± .8	13,500 ± 2,500	nd	13,500	¹⁴ C	
CP-48	VAS	Well	CP-S	Y	10/7/1998	C	C	C	nd	nd	nd	nd	C	nd	nd	nd	nd	
CP-49	VAS	Well	CP-S	N	10/27/1998	50.8 ± .5	>58.8 ± .0	>43.8 ± .0	nd	nd	nd	nd	36.3 ± 2.0	nd	36	nd	SF ₆	
CP-50	VAS	Spring	CP-S	Y	10/28/1998	9.8 ± 2.9	C	C	nd	nd	nd	1.9 ± .2	4.3 ± 1.5	nd	1.9	nd	³ H/ ³ He	
CP-51	VAS	Well	CP-D	N	11/4/1998	>53.8 ± .0	>58.8 ± .0	>43.8 ± .0	nd	nd	nd	nd	34.3 ± .8	39,700 ± 1,900	nd	39,700	¹⁴ C	
PD-01	VAS	Well	PD	Y	6/28/1999	C	19.5 ± 1.8	18.0 ± .8	nd	nd	nd	42.6 ± 9.2	C	nd	18	nd	CFC-113	
PD-02	VAS	Well	PD	Y	6/29/1999	45.5 ± 1.0	26.5 ± .8	34.5 ± 1.3	NP	nd	nd	nd	40.6 ± .8	7.5 ± 1.3	nd	7.5	nd	SF ₆
PD-03	VAS	Well	PD	Y	6/30/1999	36.5 ± .8	17.0 ± 2.5	28.0 ± .3	NP	nd	nd	nd	25.6 ± .4	17.5 ± .8	nd	25.6	nd	³ H/ ³ He
PD-04	VAS	Well	PD	Y	6/30/1999	35.5 ± .5	C	26.0 ± .5	nd	nd	nd	nd	21.8 ± .5	C	nd	21.8	nd	³ H/ ³ He
PD-05	VAS	Well	PD	Y	7/1/1999	C	C	27.0 ± 2.5	nd	nd	nd	nd	15.9 ± .5	C	nd	15.9	nd	³ H/ ³ He
PD-06	VAS	Well	PD	Y	8/23/1999	28.6 ± .5	C	C	nd	nd	nd	nd	10.0 ± .3	14.1 ± 1.0	nd	10	nd	³ H/ ³ He
PD-07	VAS	Well	PD	Y	8/23/1999	37.6 ± .5	16.6 ± 1.0	C	NP	nd	nd	nd	31.5 ± 1.3	18.6	nd	18.6	nd	SF ₆

Table 5. Apparent ages from chlorofluorocarbons, tritium/helium-3, and sulfur hexafluoride dating methods, and adjusted radiocarbon ages for water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded CFC and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC₁₁); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); ³H/³He, tritium/helium-3; SF₆, sulfur hexafluoride; ¹⁴C Adj. age, adjusted radiocarbon age in radiocarbon years BP (present is AD 1950); nd, not determined. All ¹⁴C ages are based on the Libby half-life of 5,568 years and have not been calibrated to calendar years; NP, not possible; >, older than age denoted; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system ²	Susc. cat.	Date	Apparent age and uncertainty ³ , in years								¹⁴ C Adj. age ⁴ (years)	Final age ⁵		
						CFC-11	CFC-12	CFC-113	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	³ H/ ³ He	SF ₆		Young	Old	Tracer used
PD-08	VAS	Well	PD	Y	8/30/1999	14.7 ±1.0	11.2 ±1.3	C	NP	nd	nd	nd	C	nd	nd	nd	nd
PD-09	VAS	Well	PD	Y	8/31/1999	40.7 ±.8	29.2 ±.3	12.2 ±1.0	NP	nd	nd	nd	10.2 ±2.5	nd	nd	nd	nd
PD-10	VAS	Spring	PD	Y	9/1/1999	C	C	C	nd	nd	nd	11.0 ±.2	13.7 ±1.5	nd	11	nd	³ H/ ³ He
PD-11	VAS	Well	PD	Y	9/1/1999	C	C	C	nd	nd	nd	16.2 ±.2	C	nd	16.2	nd	³ H/ ³ He
PD-12	VAS	Well	PD	Y	9/1/1999	47.2 ±.5	24.7 ±.5	14.7 ±1.5	NP	nd	nd	nd	C	nd	14.7	nd	CFC-113
PD-13	VAS	Spring	PD	Y	9/2/1999	15.2 ±1.3	8.2 ±2.8	C	NP	nd	nd	17.2 ±0.2	13.7 ±0.8	nd	17.2	nd	³ H/ ³ He
PD-14	VAS	Well	PD	Y	9/2/1999	19.2 ±1.0	8.2 ±3.6	9.2 ±1.5	NP	NP	nd	14.6 ±.2	10.7 ±.8	nd	14.6	nd	³ H/ ³ He
PD-15	VAS	Well	PD	Y	9/2/1999	36.7 ±.3	23.7 ±.5	11.7 ±.8	NP	nd	nd	24.0 ±.2	C	nd	nd	nd	nd
PD-16	VAS	Well	PD	Y	9/13/1999	27.2 ±.5	C	C	nd	nd	nd	nd	C	nd	nd	nd	nd
PD-17	VAS	Well	PD	Y	9/13/1999	27.2 ±1.5	27.7 ±.5	C	24.2	nd	nd	nd	17.7 ±1.0	nd	17.7	nd	SF ₆
PD-18	VAS	Well	PD	Y	10/18/1999	39.3 ±.5	21.3 ±1.0	C	NP	nd	nd	nd	11.8 ±1.5	nd	11.8	nd	SF ₆
PD-19	VAS	Well	PD	Y	10/19/1999	25.3 ±.5	20.3 ±1.3	12.3 ±.5	NP	nd	nd	19.3 ±.3	14.3 ±.8	nd	14.3	nd	SF ₆
PD-20	VAS	Well	PD	Y	10/19/1999	42.3 ±.5	C	15.8 ±1.0	nd	nd	nd	17.0 ±.2	19.3 ±1.8	nd	19.3	nd	SF ₆
PD-21	VAS	Well	PD	Y	10/25/1999	47.8 ±.5	46.3 ±.3	18.8 ±1.8	NP	nd	nd	nd	28.3 ±1.0	nd	28.3	nd	SF ₆
PD-22	VAS	Well	PD	Y	10/25/1999	21.8 ±1.0	22.8 ±.5	17.3 ±.5	nd	13.3	14.3	nd	14.8 ±1.0	nd	14.3	nd	CFC-113/CFC-12, SF ₆
PD-23	VAS	Well	PD	Y	10/25/1999	C	C	C	nd	nd	nd	nd	C	nd	nd	nd	nd
PD-24	VAS	Well	PD	Y	10/26/1999	C	C	C	nd	nd	nd	nd	C	nd	nd	nd	nd
PD-25	VAS	Well	PD	Y	6/27/2000	14.5 ±1.0	C	24.5 ±.5	nd	nd	nd	26.5 ±.2	21.5 ±.5	nd	21.5	nd	SF ₆
PD-26	VAS	Well	PD	Y	6/27/2000	28.5 ±.5	13.5 ±1.5	20.0 ±.5	NP	NP	8.5	nd	C	nd	14.5	nd	CFC-113/CFC-11
PD-27	VAS	Well	PD	Y	6/28/2000	37.0 ±.3	25.5 ±1.8	25.5 ±3.5	NP	NP	nd	nd	C	nd	25.5	nd	CFC-12,CFC-113(Piston)
PD-28	VAS	Well	PD	Y	6/28/2000	21.0 ±2.3	27.5 ±1.0	28.5 ±.5	nd	nd	nd	nd	1	nd	28.5	nd	CFC-12,CFC-113(Piston)
PD-29	VAS	Well	PD	Y	6/29/2000	48.5 ±1.3	C	>45.5 ±.0	nd	nd	nd	21.6 ±.3	22.0 ±4.6	nd	22	nd	SF ₆
PD-30	VAS	Well	PD	Y	6/29/2000	40.5 ±.3	32.5 ±.5	27.5 ±.5	NP	18.5	nd	21.5 ±1.3	22.0 ±.5	nd	21.5	nd	³ H/ ³ He
VB-01	VBCH	Well	CP-S	N	5/13/1999	48.4 ±.0	52.9 ±.3	>44.4 ±.0	35.9	nd	nd	nd	>47.4 ±.0	nd	35.9	nd	CFC-11/CFC-12
VB-02	VBCH	Well	CP-S	Y	5/14/1999	48.4 ±2.3	57.9 ±2.3	>44.4 ±.0	nd	nd	nd	nd	33.9 ±1.0	nd	33.9	nd	SF ₆
VB-03	VBCH	Well	CP-S	Y	5/10/1999	49.9 ±1.0	28.9 ±1.0	>44.4 ±.0	NP	nd	nd	nd	33.4 ±.5	nd	28.9	nd	CFC-12
VB-04	VBCH	Well	CP-S	N	5/12/1999	50.4 ±.3	53.9 ±3.4	>44.4 ±.0	45.4	nd	nd	nd	>47.4 ±2.0	nd	45.4	nd	CFC-11/CFC-12

Table 5. Apparent ages from chlorofluorocarbons, tritium/helium-3, and sulfur hexafluoride dating methods, and adjusted radiocarbon ages for water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded CFC and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC₁₃); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); ³H/³He, tritium/helium-3; SF₆, sulfur hexafluoride; ¹⁴C Adj. age, adjusted radiocarbon age in radiocarbon years BP (present is AD 1950); nd, not determined. All ¹⁴C ages are based on the Libby half-life of 5,568 years and have not been calibrated to calendar years; NP, not possible; >, older than age denoted; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system ²	Susc. cat.	Date	Apparent age and uncertainty ³ , in years							¹⁴ C Adj. age ⁴ (years)	Final age ⁵			
						CFC-11	CFC-12	CFC-113	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	³ H/ ³ He		SF ₆	Young	Old	Tracer used
VB-05	VBCH	Well	CP-S	N	8/14/2000	53.6 ± 2.0	>60.6 ± .0	>45.6 ± .0	nd	nd	nd	nd	32.6 ± 2.0	nd	nd	nd	
VB-06	VBCH	Well	CP-S	N	8/11/2000	52.6 ± .5	52.6 ± .8	>45.6 ± .0	NP	nd	nd	nd	29.1 ± 1.5	nd	29.1	nd	SF ₆
VB-07	VBCH	Well	CP-S	Y	8/10/2000	35.6 ± .8	45.6 ± 1.5	24.6 ± 1.0	nd	nd	nd	nd	22.6 ± .5	nd	nd	nd	
VB-08	VBCH	Well	CP-S	Y	8/9/2000	>55.6 ± .0	49.1 ± .8	32.6 ± 1.5	NP	nd	nd	nd	33.1 ± .5	nd	33	nd	SF ₆
VB-09	VBCH	Well	CP-S	Y	8/16/2000	48.1 ± 5.5	50.1 ± 2.0	35.1 ± 1.3	45.6	nd	nd	nd	33.6 ± .8	nd	33.5	nd	SF ₆
VB-10	VBCH	Well	CP-S	N	8/17/2000	51.6 ± 2.8	52.1 ± 2.0	>45.6 ± .0	51.1	nd	nd	nd	26.6 ± .5	nd	26.5	nd	SF ₆
VB-11	VBCH	Well	CP-S	Y	8/16/2000	42.1 ± 6.7	49.1 ± 3.0	34.1 ± 5.6	nd	nd	nd	nd	26.1 ± 1.0	nd	nd	nd	
VB-12	VBCH	Well	CP-S	Y	8/15/2000	52.1 ± 1.0	46.1 ± .5	27.1 ± .5	NP	nd	nd	nd	29.6 ± 1.0	nd	29.5	nd	SF ₆
VB-13	VBCH	Well	CP-S	N	8/8/2000	48.6 ± .5	>60.6 ± .0	>45.6 ± .0	nd	nd	nd	nd	C	nd	nd	nd	
VB-14	VBCH	Well	CP-S	N	8/7/2000	>55.6 ± .0	>60.6 ± .0	>45.6 ± .0	nd	nd	nd	nd	C	nd	nd	nd	
VR-01	VAS	Well	VR-C	Y	7/6/1999	47.0 ± 1.5	>59.5 ± .0	39.5 ± 5.5	nd	nd	nd	nd	13.5 ± .8	nd	39.5	nd	CFC-113
VR-02	VAS	Well	VR-C	Y	7/6/1999	26.0 ± .3	26.5 ± 1.8	21.0 ± 2.0	22.5	15	15.5	9.2 ± .3	-0.5	nd	9.2	nd	³ H/ ³ He
VR-03	VAS	Well	VR-C	Y	7/7/1999	14.0 ± 1.0	8.0 ± 3.3	C	NP	nd	nd	19.1 ± .9	C	nd	8	nd	CFC-12
VR-04	VAS	Spring	VR-C	Y	7/7/1999	19.5 ± 1.0	20.0 ± 1.3	C	NP	nd	nd	nd	C	nd	20	nd	CFC-11,CFC-12
VR-05	VAS	Well	VR-C	Y	7/8/1999	14.0 ± 1.0	C	C	nd	nd	nd	6.0 ± .2	C	nd	6	nd	³ H/ ³ He
VR-06	VAS	Well	VR-C	Y	7/8/1999	24.0 ± .8	11.0 ± 1.5	C	NP	nd	nd	11.7 ± .4	C	nd	11.7	nd	³ H/ ³ He
VR-07	VAS	Well	VR-C	Y	7/8/1999	29.5 ± .3	22.5 ± 1.0	C	NP	nd	nd	18.2 ± 1.1	2.0 ± 1.0	nd	18.2	nd	³ H/ ³ He
VR-08	VAS	Well	VR-C	Y	7/9/1999	34.0 ± .5	27.0 ± .3	C	NP	nd	nd	43.0 ± 2.1	2.5 ± 1.5	nd	nd	nd	nd
VR-09	VAS	Well	VR-C	Y	7/9/1999	29.0 ± .3	25.5 ± 1.3	21.0 ± .5	NP	16.5	9	29.7 ± .7	1.0 ± 1.5	nd	16.5	nd	CFC-113/CFC-12
VR-10	VAS	Well	VR-C	Y	7/9/1999	23.0 ± .8	15.5 ± 1.0	21.0 ± .5	NP	NP	19.5	16.1 ± 1.1	C	nd	19.5	nd	CFC-113/CFC-11
VR-11	VAS	Well	VR-S	Y	7/9/1999	49.0 ± .3	50.0 ± 3.5	24.5 ± 1.3	48.5	nd	nd	nd	15.0 ± .8	nd	48.5	nd	CFC-11/CFC-12
VR-12	VAS	Well	VR-C	Y	7/21/1999	24.6 ± .3	C	23.6 ± .5	nd	nd	22.1	nd	C	nd	22.1	nd	CFC-113/CFC-11
VR-13	VAS	Well	VR-C	Y	7/21/1999	C	C	C	nd	nd	nd	7.2 ± .2	7.1 ± 1.3	nd	7.2	nd	³ H/ ³ He, SF ₆
VR-14	VAS	Spring	VR-C	Y	7/22/1999	34.6 ± .5	34.6 ± .8	C	NP	nd	nd	24.3 ± .5	1.1 ± 1.0	nd	24.3	nd	³ H/ ³ He
VR-15	VAS	Well	VR-S	Y	8/10/1999	48.6 ± .8	50.6 ± 1.3	C	46.6	nd	nd	nd	36.6 ± 0.5	nd	46.6	nd	CFC-11/CFC-12
VR-16	VAS	Well	VR-S	Y	8/11/1999	45.6 ± .3	41.1 ± .3	C	NP	nd	nd	nd	22.6 ± .5	nd	nd	nd	nd
VR-17	VAS	Well	VR-C	Y	8/11/1999	13.6 ± 1.0	3.1 ± 4.2	C	NP	nd	nd	12.4 ± 0.3	C	nd	12.4	nd	³ H/ ³ He

Table 5. Apparent ages from chlorofluorocarbons, tritium/helium-3, and sulfur hexafluoride dating methods, and adjusted radiocarbon ages for water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded CFC and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC₁₃); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); ³H/³He, tritium/helium-3; SF₆, sulfur hexafluoride; ¹⁴C Adj. age, adjusted radiocarbon age in radiocarbon years BP (present is AD 1950); nd, not determined. All ¹⁴C ages are based on the Libby half-life of 5,568 years and have not been calibrated to calendar years; NP, not possible; >, older than age denoted; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system ²	Susc. cat.	Date	Apparent age and uncertainty ³ , in years								¹⁴ C Adj. age ⁴ (years)	Final age ⁵		
						CFC-11	CFC-12	CFC-113	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	³ H/ ³ He	SF ₆		Young	Old	Tracer used
VR-18	VAS	Well	VR-S	Y	8/12/1999	42.1 ± .5	32.6 ± .5	C	NP	nd	nd	nd	41.1	nd	nd	nd	nd
VR-19	VAS	Well	BR	Y	8/24/1999	22.1 ±1.3	C	9.6 ±1.3	nd	nd	nd	26.6 ± .3	19.2 ±1.0	nd	19	nd	SF ₆
VR-20	VAS	Well	VR-C	Y	8/24/1999	16.1 ±1.3	13.1 ±1.0	C	NP	nd	nd	3.6 ± .2	4.7 ±1.5	nd	3.6	nd	³ H/ ³ He
VR-21	VAS	Well	VR-C	Y	8/25/1999	29.1 ± .5	24.1 ±1.0	C	NP	nd	nd	15.4 ± .4	C	nd	15.4	nd	³ H/ ³ He
VR-22	VAS	Well	VR-S	Y	8/26/1999	25.7 ± .5	24.2 ± .5	C	NP	nd	nd	15.7 ± .3	9.2 ±1.3	nd	9	nd	SF ₆
VR-23	VAS	Well	VR-S	Y	8/26/1999	24.7 ± .3	C	C	nd	nd	nd	nd	C	nd	nd	nd	nd
VR-24	VAS	Well	VR-S	Y	10/27/1999	47.3 ±2.3	49.8 ± .5	28.3 ±1.8	44.3	nd	nd	nd	33.3 ±1.5	nd	33	nd	SF ₆
VR-25	VAS	Well	VR-C	Y	10/27/1999	44.3 ± .5	37.8 ± .5	23.3 ±1.3	NP	nd	nd	nd	19.8 ± .5	nd	20	nd	SF ₆
VR-26	VAS	Spring	VR-S	Y	10/28/1999	20.3 ±1.0	17.3 ±1.0	14.3 ± .5	NP	12.3	10.3	15.0 ± .3	15.3 ± .8	nd	15	nd	³ H/ ³ He, SF ₆
VR-27	VAS	Well	VR-S	Y	10/28/1999	23.3 ± .5	18.8 ±1.0	15.3 ± .5	NP	12.3	4.8	nd	8.8 ± .8	nd	9	nd	SF ₆
VR-28	VAS	Well	VR-S	Y	7/12/2000	46.0 ± .3	41.0 ± .3	39.5 ±1.5	NP	26.5	nd	2.7 ± .3	23.0 ± .5	nd	2.7	nd	³ H/ ³ He
VR-29	VAS	Well	VR-S	Y	7/13/2000	46.5 ± .3	48.0 ± .8	>45.5 ± .0	45.5	nd	nd	nd	32.0 ± .8	nd	32	nd	SF ₆
VR-30	VAS	Well	VR-S	Y	7/13/2000	34.5 ± .3	31.5 ± .5	25.0 ± .8	NP	15.5	nd	nd	23.0 ± .8	nd	15.5	nd	CFC-113/CFC-12
VR-31	VAS	Well	VR-S	Y	7/17/2000	45.0 ± .5	48.5 ±1.8	>45.5 ± .0	36.5	nd	nd	nd	32.5 ± .5	nd	32.5	nd	SF ₆
VR-32	VAS	Well	VR-S	Y	7/17/2000	42.0 ± .8	31.5 ± .5	35.5 ±2.5	NP	nd	nd	23.5 ±1.0	25.5 ± .5	nd	23.5	nd	³ H/ ³ He
VR-33	VAS	Well	VR-S	Y	7/18/2000	17.0 ±1.3	C	11.5 ±1.5	nd	nd	nd	3.4 ± .2	C	nd	3.4	nd	³ H/ ³ He
VR-34	VAS	Well	VR-S	Y	7/18/2000	34.5 ± .5	25.0 ±1.0	17.5 ±1.0	NP	12	nd	nd	7.6 ±1.3	nd	12	nd	CFC-113/CFC-12
VR-35	VAS	Well	VR-S	Y	7/19/2000	51.1 ± .8	52.1 ±2.5	>45.6 ± .0	50.1	nd	nd	13.3 ± .5	36.1 ± .8	nd	36	nd	SF ₆
VR-36	VAS	Well	VR-S	Y	7/20/2000	16.1 ±1.0	11.6 ±2.0	12.6 ± .5	NP	NP	9.6	3.3 ± .4	8.1 ±1.5	nd	3.3	nd	³ H/ ³ He
VR-37	VAS	Well	VR-S	Y	7/17/2000	30.0 ± .5	29.0 ± .5	23.0 ±1.3	NP	16	12.5	23.8 ± .3	10.0 ±1.0	nd	16	nd	CFC-113/CFC-12
VR-38	VAS	Well	VR-C	Y	7/18/2000	25.5 ± .5	19.5 ± .8	16.5 ± .8	NP	15	3.5	13.4 ± .3	C	nd	13.4	nd	³ H/ ³ He
VR-39	VAS	Well	VR-S	Y	7/18/2000	31.5 ± .5	32.5 ± .8	26.5 ± .5	28.5	16.5	15.5	17.8 ± .3	23.6 ± .5	nd	17.8	nd	³ H/ ³ He
VR-40	VAS	Well	VR-S	Y	7/19/2000	C	36.6 ± .5	25.1 ± .5	nd	nd	nd	18.6 ± .3	26.1 ±1.0	nd	18.6	nd	³ H/ ³ He
VR-41	VAS	Well	VR-C	Y	7/19/2000	36.6 ± .3	38.1 ± .5	23.1 ± .5	30.1	nd	nd	nd	23.6 ± .5	nd	23.5	nd	SF ₆
VR-42	VAS	Well	VR-S	Y	7/20/2000	16.6 ±1.0	C	13.6 ± .5	nd	nd	11.1	nd	C	nd	11.1	nd	CFC-113/CFC-11
VR-43	VAS	Well	VR-S	Y	7/20/2000	37.6 ± .5	32.6 ± .5	27.6 ±1.0	NP	18.1	nd	19.0 ± .3	16.6 ±1.8	nd	18	nd	CFC-113/CFC-12
VR-44	VAS	Well	VR-C	Y	7/20/2000	12.6 ±1.5	C	15.6 ± .5	nd	nd	NP	15.3 ± .2	C	nd	15.3	nd	³ H/ ³ He

Table 5. Apparent ages from chlorofluorocarbons, tritium/helium-3, and sulfur hexafluoride dating methods, and adjusted radiocarbon ages for water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded CFC and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC₁₁); CFC-12, (dichlorodifluoromethane, CFC₁₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); ³H/³He, tritium/helium-3; SF₆, sulfur hexafluoride; ¹⁴C Adj. age, adjusted radiocarbon age in radiocarbon years BP (present is AD 1950); nd, not determined. All ¹⁴C ages are based on the Libby half-life of 5,568 years and have not been calibrated to calendar years; NP, not possible; >, older than age denoted; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system ²	Susc. cat.	Date	Apparent age and uncertainty ³ , in years								¹⁴ C Adj. age ⁴ (years)	Final age ⁵		
						CFC-11	CFC-12	CFC-113	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11	³ H/ ³ He	SF ₆		Young	Old	Tracer used
VR-45	VAS	Well	VR-C	Y	7/25/2000	28.1 ± .5	28.6 ± .5	26.6 ± .3	26.6	23.1	22.6	29.9 ± .4	C	nd	23.1	nd	CFC-113/CFC-12
VR-46	VAS	Well	VR-S	Y	7/25/2000	29.6 ± .5	29.1 ± .5	21.1 ± .8	NP	13.1	9.6	nd	11.1 ± 2.0	nd	13.1	nd	CFC-113/CFC-12
VR-47	VAS	Well	VR-S	Y	7/26/2000	13.6 ± 1.0	10.1 ± 2.0	C	NP	nd	nd	12.1 ± .3	C	nd	12.1	nd	³ H/ ³ He
VTDW-01	VPI	Well	BR	Y	9/16/1999	19.7 ± 5.0	8.7 ± 2.8	C	NP	nd	nd	2.4 ± .2	4.7 ± 1.8	nd	2.4	nd	³ H/ ³ He
VTDW-03A	VPI	Well	BR	Y	7/15/2000	31.5 ± 1.5	29.5 ± 1.3	22.5 ± 1.8	NP	14.5	nd	18.2 ± .3	22.0 ± .8	nd	22	nd	SF ₆
VTDW-03B	VPI	Well	BR	Y	7/15/2000	30.5 ± 1.0	28.0 ± 1.0	21.5 ± 1.0	NP	14.5	nd	20.4 ± .4	18.0 ± 1.0	nd	18	nd	SF ₆
VTDW-07A	VPI	Well	BR	Y	7/14/2000	39.5 ± .5	28.5 ± .5	27.5 ± 1.5	NP	24.5	nd	26.4 ± .3	20.0 ± 1.0	nd	24.5	nd	CFC-113/CFC-12
VTDW-07B	VPI	Well	BR	Y	7/14/2000	33.0 ± .3	30.0 ± .5	24.0 ± 1.0	NP	16	nd	nd	C	nd	nd	nd	nd
VTDW-08	VPI	Well	BR	Y	9/16/1999	C	C	C	nd	nd	nd	2.7 ± .2	4.7 ± 1.5	nd	2.7	nd	³ H/ ³ He

¹ Project designation: VAS, Virginia Aquifer Susceptibility study; VBCH, Virginia Beach shallow ground water study (Johnson, 1999); VPI, Virginia Polytechnic and State University fractured-rock hydrology study

² VAS Aquifer System designation: AP, Appalachian Plateaus; BR, Blue Ridge; CP-D, Coastal Plain Deep system (depths greater than 400 feet); CP-M, Coastal Plain Middle system (depths between 200 and 400 feet); CP-S, Coastal Plain Shallow system (depths less than 200 feet); PD, Piedmont; VR-C, Valley and Ridge Carbonate; VR-S, Valley and Ridge Siliciclastic

³ Apparent CFC age uncertainties are based on changes in age resulting from uncertainty in nitrogen-argon recharge temperature of ±1°C. Apparent SF₆ age uncertainties are based on changes in age resulting from uncertainty in nitrogen-argon excess air concentrations of recharge temperature of ±1 cc/L.

⁴ Radiocarbon age uncertainties are based on ±5‰ variation in the δ¹³C in soil gas carbon dioxide input for the Fontes and Garnier (1979) model.

⁵ Young water is defined as less than 50 years and old water is defined as pre-CFC.

Table 6. Percentage of young fraction in water samples from wells and springs in Virginia, 1998-2000

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded chlorofluorocarbon (CFC) and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC1₃); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); SF₆, sulfur hexafluoride; NP, not possible; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system	Susc. cat.	Date	Percentage of young fraction							Tracer used	
						CFC-11	CFC-12	CFC-113	SF ₆	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11		Average
AP-01	VAS	Well	AP	Y	7/10/2000	nd	nd	nd	nd	nd	nd	nd	nd	nd
AP-02	VAS	Well	AP	Y	7/10/2000	3.9	3.3	0	3.2	nd	nd	nd	3.4	CFC-11,CFC-12,SF ₆
AP-03	VAS	Well	AP	Y	7/20/2000	69.7	110.9	107.8	426.9	NP	NP	nd	69.7	CFC-11
AP-04	VAS	Well	AP	Y	7/11/2000	16.4	30.3	0	102.6	76.8	nd	nd	23.4	CFC-11,CFC-12
AP-05	VAS	Well	AP	Y	7/12/2000	2.4	15.4	15.7	140.2	NP	15.7	nd	15.7	CFC-113/CFC-12
AP-06	VAS	Well	AP	Y	7/13/2000	4	27.4	28	222.8	NP	27.8	nd	27.8	CFC-113/CFC-12
AP-07	VAS	Well	AP	Y	7/13/2000	1.5	0	0	24	nd	nd	nd	24	SF ₆
AP-08	VAS	Well	AP	Y	7/10/2000	60.9	101.2	99.5	118.5	NP	NP	44.5	nd	nd
AP-09	VAS	Well	AP	Y	7/10/2000	9.8	7.7	0	100.9	nd	nd	nd	7.7	CFC-12
AP-10	VAS	Well	AP	Y	7/11/2000	0.4	3	0	102	NP	nd	nd	3	CFC-12
AP-11	VAS	Well	AP	Y	7/11/2000	nd	nd	nd	nd	NP	nd	nd	nd	nd
AP-12	VAS	Well	AP	Y	7/12/2000	4.4	1,393.0	13.6	100.1	nd	nd	nd	13.6	CFC-113
AP-13	VAS	Well	AP	Y	7/12/2000	5.4	5.3	0	27.9	5.3	nd	nd	5.3	CFC-11/CFC-12
BR-01	VAS	Well	BR	Y	7/19/1999	30.8	69.7	31.6	2,763.9	NP	nd	31.5	31.5	CFC-113/CFC-11
BR-02	VAS	Well	BR	Y	7/19/1999	84.8	113.1	85.8	nd	nd	nd	85.7	85.7	CFC-113/CFC-11
BR-03	VAS	Well	BR	Y	7/20/1999	877.5	107.1	94.3	79.2	nd	nd	nd	86.7	CFC-113,SF ₆
BR-04	VAS	Well	BR	Y	7/20/1999	1.5	67.8	0	100	NP	nd	nd	67.8	CFC-12
BR-05	VAS	Well	BR	Y	8/25/1999	809.7	14,289.1	1,965.3	111.7	nd	nd	nd	nd	nd
BR-06	VAS	Well	BR	Y	9/13/1999	14.1	396	248.6	0	nd	nd	nd	14.1	CFC-11
BR-07	VAS	Well	BR	Y	9/14/1999	nd	nd	nd	nd	nd	nd	nd	nd	nd
BR-08	VAS	Well	BR	Y	9/16/1999	1,636.5	35,447.6	275.7	101.6	nd	nd	nd	nd	nd
BR-09	VAS	Well	BR	Y	10/18/1999	3.4	64.8	76.2	104.9	NP	nd	nd	70.5	CFC-12,CFC-113
BR-10	VAS	Well	BR	Y	10/26/1999	764.5	4,375.8	4,910.3	102.9	nd	nd	nd	nd	nd
CP-01	VAS	Well	CP-D	N	6/23/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-02	VAS	Well	CP-M	N	6/24/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-03	VAS	Well	CP-D	N	6/25/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-04	VAS	Well	CP-M	N	7/1/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-05	VAS	Well	CP-M	N	7/6/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-06	VAS	Well	CP-D	N	7/6/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd

Table 6. Percentage of young fraction in water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded chlorofluorocarbon (CFC) and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC1₃); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); SF₆, sulfur hexafluoride; NP, not possible; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system	Susc. cat.	Date	Percentage of young fraction							Tracer used	
						CFC-11	CFC-12	CFC-113	SF ₆	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11		Average
CP-36	VAS	Well	CP-M	N	9/1/1998	nd	nd	nd	nd	13.9	nd	nd	nd	nd
CP-37	VAS	Well	CP-M	N	9/2/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-38	VAS	Well	CP-D	N	9/2/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-39	VAS	Well	CP-M	N	9/2/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-40	VAS	Well	CP-D	N	9/3/1998	nd	nd	nd	nd	12.4	nd	nd	nd	nd
CP-41	VAS	Well	CP-M	N	9/10/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-42	VAS	Well	CP-D	N	9/10/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-43	VAS	Well	CP-S	N	10/1/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-44	VAS	Well	CP-S	N	10/5/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-45	VAS	Well	CP-S	Y	10/5/1998	0	51.4	0	104.7	NP	nd	nd	nd	nd
CP-46	VAS	Well	CP-S	Y	10/6/1998	57.4	68.7	72.6	46.5	NP	68.5	49.9	68.5	CFC-113/ CFC-12
CP-47	VAS	Well	CP-M	N	10/6/1998	nd	nd	nd	nd	23	nd	nd	nd	nd
CP-48	VAS	Well	CP-S	Y	10/7/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
CP-49	VAS	Well	CP-S	N	10/27/1998	1.2	0	0	102.7	nd	nd	nd	1.2	CFC-11
CP-50	VAS	Spring	CP-S	Y	10/28/1998	96.9	104.7	117.7	89	nd	nd	nd	93	CFC-11,SF ₆
CP-51	VAS	Well	CP-D	N	11/4/1998	nd	nd	nd	nd	nd	nd	nd	nd	nd
PD-01	VAS	Well	PD	Y	6/28/1999	343.5	97.3	106.9	3,844.1	nd	nd	nd	97.3	CFC-12
PD-02	VAS	Well	PD	Y	6/29/1999	1.1	37.6	3.7	107.6	NP	nd	nd	37.6	CFC-12
PD-03	VAS	Well	PD	Y	6/30/1999	19.4	185.1	76.1	330	NP	nd	nd	76.1	CFC-113
PD-04	VAS	Well	PD	Y	6/30/1999	15.6	1,203.8	61	4,938.1	nd	nd	nd	61	CFC-113
PD-05	VAS	Well	PD	Y	7/1/1999	1,186.8	314.8	24.3	835.7	nd	nd	nd	24.3	CFC-113
PD-06	VAS	Well	PD	Y	8/23/1999	27.4	266.5	518.5	71.5	nd	nd	nd	71.5	SF ₆
PD-07	VAS	Well	PD	Y	8/23/1999	8.9	113.3	995.1	104.4	NP	nd	nd	8.9	CFC-11
PD-08	VAS	Well	PD	Y	8/30/1999	78.6	88.8	359	124,138.9	NP	nd	nd	83.7	CFC-11,CFC-12
PD-09	VAS	Well	PD	Y	8/31/1999	nd	nd	nd	nd	NP	nd	nd	nd	nd
PD-10	VAS	Spring	PD	Y	9/1/1999	170	133.5	220.7	81.4	nd	nd	nd	81.4	SF ₆
PD-11	VAS	Well	PD	Y	9/1/1999	357.8	413.3	293	nd	nd	nd	nd	nd	nd
PD-12	VAS	Well	PD	Y	9/1/1999	0.8	58.4	106.9	765.9	NP	nd	nd	58.4	CFC-12
PD-13	VAS	Spring	PD	Y	9/2/1999	112.2	148.8	434.4	155.6	NP	nd	nd	nd	nd

Table 6. Percentage of young fraction in water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded chlorofluorocarbon (CFC) and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC1₃); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); SF₆, sulfur hexafluoride; NP, not possible; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system	Susc. cat.	Date	Percentage of young fraction							Tracer used	
						CFC-11	CFC-12	CFC-113	SF ₆	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11		Average
PD-14	VAS	Well	PD	Y	9/2/1999	81.9	130.7	183.9	147	NP	NP	nd	81.9	CFC-11
PD-15	VAS	Well	PD	Y	9/2/1999	nd	nd	nd	nd	NP	nd	nd	nd	nd
PD-16	VAS	Well	PD	Y	9/13/1999	nd	nd	nd	nd	nd	nd	nd	nd	nd
PD-17	VAS	Well	PD	Y	9/13/1999	48.3	49.4	598.5	101.7	72.4	nd	nd	72.4	CFC-11/CFC-12
PD-18	VAS	Well	PD	Y	10/18/1999	4.8	65.6	320.1	108.6	NP	nd	nd	65.6	CFC-12
PD-19	VAS	Well	PD	Y	10/19/1999	51.3	76.8	132.8	105	NP	nd	nd	76.8	CFC-12
PD-20	VAS	Well	PD	Y	10/19/1999	4	740.1	161.4	101.2	nd	nd	nd	4	CFC-11
PD-21	VAS	Well	PD	Y	10/25/1999	2.1	8.9	371.7	101.1	NP	nd	nd	5.5	CFC-11,CFC-12
PD-22	VAS	Well	PD	Y	10/25/1999	71.3	66.4	71.7	97.9	nd	63.5	71.8	67.6	CFC-113/CFC-12,CFC-113/CFC-11
PD-23	VAS	Well	PD	Y	10/25/1999	nd	nd	nd	nd	nd	nd	nd	nd	nd
PD-24	VAS	Well	PD	Y	10/26/1999	nd	nd	nd	nd	nd	nd	nd	nd	nd
PD-25	VAS	Well	PD	Y	6/27/2000	144.4	310	72.4	111.5	nd	nd	nd	72.4	CFC-113
PD-26	VAS	Well	PD	Y	6/27/2000	37.8	111.3	55.2	0	NP	NP	30.4	30.4	CFC-113/CFC-11
PD-27	VAS	Well	PD	Y	6/28/2000	18.7	109.3	112.4	1,492.3	NP	NP	nd	nd	nd
PD-28	VAS	Well	PD	Y	6/28/2000	224.6	121.9	110	1,757.5	nd	nd	nd	nd	nd
PD-29	VAS	Well	PD	Y	6/29/2000	0.9	302.9	0	107.3	nd	nd	nd	0.9	CFC-11
PD-30	VAS	Well	PD	Y	6/29/2000	7	35.6	48.5	103	NP	30.7	nd	30.7	CFC-113/CFC-12
VB-01	VBCH	Well	CP-S	N	5/13/1999	5	4.9	0	42	4.6	nd	nd	4.6	CFC-11/CFC-12
VB-02	VBCH	Well	CP-S	Y	5/14/1999	3.8	0.9	0	115	nd	nd	nd	2.3	CFC-11,CFC-12
VB-03	VBCH	Well	CP-S	Y	5/10/1999	0.8	111.5	0	62.3	NP	nd	nd	0.8	CFC-11
VB-04	VBCH	Well	CP-S	N	5/12/1999	17.9	14.2	0	93.9	12.9	nd	nd	12.9	CFC-11/CFC-12
VB-05	VBCH	Well	CP-S	N	8/14/2000	nd	nd	nd	nd	nd	nd	nd	nd	nd
VB-06	VBCH	Well	CP-S	N	8/11/2000	0.3	2.9	0	100.4	NP	nd	nd	1.6	CFC-11,CFC-12
VB-07	VBCH	Well	CP-S	Y	8/10/2000	19	6.4	79.4	103.3	nd	nd	nd	nd	nd
VB-08	VBCH	Well	CP-S	Y	8/9/2000	0	11.3	106.6	103.3	NP	nd	nd	11.3	CFC-12
VB-09	VBCH	Well	CP-S	Y	8/16/2000	4.9	9.3	83.3	104.8	47.9	nd	nd	47.9	CFC-11/CFC-12
VB-10	VBCH	Well	CP-S	N	8/17/2000	0.4	2.8	0	106.7	87.1	nd	nd	87.1	CFC-11/CFC-12
VB-11	VBCH	Well	CP-S	Y	8/16/2000	7.8	4.8	34.1	100.1	nd	nd	nd	nd	nd
VB-12	VBCH	Well	CP-S	Y	8/15/2000	0.4	11.5	145	103.9	NP	nd	nd	11.5	CFC-12

Table 6. Percentage of young fraction in water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded chlorofluorocarbon (CFC) and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC1₃); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); SF₆, sulfur hexafluoride; NP, not possible; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system	Susc. cat.	Date	Percentage of young fraction							Tracer used	
						CFC-11	CFC-12	CFC-113	SF ₆	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11		Average
VB-13	VBCH	Well	CP-S	N	8/8/2000	nd	nd	nd	nd	nd	nd	nd	nd	nd
VB-14	VBCH	Well	CP-S	N	8/7/2000	nd	nd	nd	nd	nd	nd	nd	nd	nd
VR-01	VAS	Well	VR-C	Y	7/6/1999	17.4	0	106.4	2,543	nd	nd	nd	17.4	CFC-11
VR-02	VAS	Well	VR-C	Y	7/6/1999	38.1	37.2	25.3	204.8	69.6	47.6	51	56.1	CFC-11/CFC-12,CFC-113/CFC-12,CFC-113/CFC-11
VR-03	VAS	Well	VR-C	Y	7/7/1999	82.5	100.9	434	479.7	NP	nd	nd	82.5	CFC-11
VR-04	VAS	Spring	VR-C	Y	7/7/1999	104.9	103	2,511.7	721.5	NP	nd	nd	nd	nd
VR-05	VAS	Well	VR-C	Y	7/8/1999	81.1	113.5	467.1	240.1	nd	nd	nd	81.1	CFC-11
VR-06	VAS	Well	VR-C	Y	7/8/1999	53.3	104.9	61,127.2	0	NP	nd	nd	53.3	CFC-11
VR-07	VAS	Well	VR-C	Y	7/8/1999	35.1	82.9	355,348.5	444.2	NP	nd	nd	82.9	CFC-12
VR-08	VAS	Well	VR-C	Y	7/9/1999	nd	nd	nd	nd	NP	nd	nd	nd	nd
VR-09	VAS	Well	VR-C	Y	7/9/1999	34.5	59	59.7	372.9	NP	59.8	25.4	59.8	CFC-113/CFC-12
VR-10	VAS	Well	VR-C	Y	7/9/1999	80.7	122	83.9	nd	NP	NP	84	84	CFC-113/CFC-11
VR-11	VAS	Well	VR-S	Y	7/9/1999	81.5	81.9	3,956.3	2,683.3	81.4	nd	nd	81.4	CFC-11/CFC-12
VR-12	VAS	Well	VR-C	Y	7/21/1999	85.8	279.1	93	1,031.5	nd	nd	86.5	86.5	CFC-113/CFC-11
VR-13	VAS	Well	VR-C	Y	7/21/1999	193.5	113	245.7	107.3	nd	nd	nd	nd	nd
VR-14	VAS	Spring	VR-C	Y	7/22/1999	23.8	32.3	1,918.9	1,062.1	NP	nd	nd	28.1	CFC-11,CFC-12
VR-15	VAS	Well	VR-S	Y	8/10/1999	47.7	46.8	121,244.4	172.1	46.4	nd	nd	46.4	CFC-11/CFC-12
VR-16	VAS	Well	VR-S	Y	8/11/1999	nd	nd	nd	nd	NP	nd	nd	nd	nd
VR-17	VAS	Well	VR-C	Y	8/11/1999	95.8	124.7	870.6	775.8	NP	nd	nd	95.8	CFC-11
VR-18	VAS	Well	VR-S	Y	8/12/1999	nd	nd	nd	nd	NP	nd	nd	nd	nd
VR-19	VAS	Well	BR	Y	8/24/1999	86.5	348.4	313.1	104.2	nd	nd	nd	86.5	CFC-11
VR-20	VAS	Well	VR-C	Y	8/24/1999	74.2	79.6	203.8	94.7	NP	nd	nd	76.9	CFC-11,CFC-12
VR-21	VAS	Well	VR-C	Y	8/25/1999	32.1	63.5	331.5	87,708.2	NP	nd	nd	63.5	CFC-12
VR-22	VAS	Well	VR-S	Y	8/26/1999	38.5	48	218.2	100.1	NP	nd	nd	43.3	CFC-11,CFC-12
VR-23	VAS	Well	VR-S	Y	8/26/1999	nd	nd	nd	nd	nd	nd	nd	nd	nd
VR-24	VAS	Well	VR-S	Y	10/27/1999	5.3	9	203.4	106.4	40.3	nd	nd	40.3	CFC-11/CFC-12
VR-25	VAS	Well	VR-C	Y	10/27/1999	2.8	15.6	68.3	109.8	NP	nd	nd	15.6	CFC-12
VR-26	VAS	Spring	VR-S	Y	10/28/1999	79.1	91.9	115.3	104	NP	79.2	64	71.6	CFC-113/CFC-12,CFC-113/CFC-11
VR-27	VAS	Well	VR-S	Y	10/28/1999	51	65.5	54.7	108.2	NP	72.6	50.3	61.4	CFC-113/CFC-12,CFC-113/CFC-11

Table 6. Percentage of young fraction in water samples from wells and springs in Virginia, 1998-2000—Continued

[VAS, Virginia Aquifer Susceptibility study; Susc. Cat., Susceptibility category where "Y" indicates water sample exceeded chlorofluorocarbon (CFC) and tritium threshold values of 5 picograms per kilograms (pg/kg) and 0.6 tritium units (TU), respectively and "N" indicates water sample did not exceed threshold values. CFC-11, (trichlorofluoromethane, CFC₁₃); CFC-12, (dichlorodifluoromethane, CF₂Cl₂); CFC-113, (trichlorotrifluoroethane, C₂F₃Cl₃); SF₆, sulfur hexafluoride; NP, not possible; nd, not determined. See figure 1 for location of wells and springs]

VAS no.	Project ¹	Site type	Regional aquifer system	Susc. cat.	Date	Percentage of young fraction							Tracer used	
						CFC-11	CFC-12	CFC-113	SF ₆	CFC-11/ CFC-12	CFC-113/ CFC-12	CFC-113/ CFC-11		Average
VR-28	VAS	Well	VR-S	Y	7/12/2000	1.2	6.4	2	14.8	NP	17.1	nd	15.9	CFC-113/CFC-12,SF ₆
VR-29	VAS	Well	VR-S	Y	7/13/2000	5.8	11.7	0	104.6	72.6	nd	nd	72.6	CFC-11/CFC-12
VR-30	VAS	Well	VR-S	Y	7/13/2000	15.9	29.5	30.6	42.6	NP	30.7	nd	36.6	CFC-113/CFC-12,SF ₆
VR-31	VAS	Well	VR-S	Y	7/17/2000	10.2	11.4	0	102.9	19.5	nd	nd	19.5	CFC-11/CFC-12
VR-32	VAS	Well	VR-S	Y	7/17/2000	6.1	44.1	19	80.4	NP	nd	nd	6.1	CFC-11
VR-33	VAS	Well	VR-S	Y	7/18/2000	74.9	112.9	85.5	nd	nd	nd	nd	80.2	CFC-11,CFC-113
VR-34	VAS	Well	VR-S	Y	7/18/2000	12.6	51.6	53.3	145.2	NP	53.2	nd	53.2	CFC-113/CFC-12
VR-35	VAS	Well	VR-S	Y	7/19/2000	2.1	9	0	102.5	70.8	nd	nd	70.8	CFC-11/CFC-12
VR-36	VAS	Well	VR-S	Y	7/20/2000	77.6	89.3	74.2	74.1	NP	NP	78	76	CFC-113/CFC-11,SF ₆
VR-37	VAS	Well	VR-S	Y	7/17/2000	31.6	41.1	41.3	181.1	NP	41.4	26.8	41.4	CFC-113/CFC-12
VR-38	VAS	Well	VR-C	Y	7/18/2000	51.8	76.8	70.2	0	NP	84.4	46	84.4	CFC-113/CFC-12
VR-39	VAS	Well	VR-S	Y	7/18/2000	27.4	30.3	34.2	51.2	65.6	28.5	24.9	42.5	CFC-11/CFC-12,CFC-113/CFC-12,CFC-113/CFC-11,SF ₆
VR-40	VAS	Well	VR-S	Y	7/19/2000	171.3	18	47.4	40.8	nd	nd	nd	44.1	CFC-113,SF ₆
VR-41	VAS	Well	VR-C	Y	7/19/2000	16.5	19.1	109.4	100.7	36.8	nd	nd	36.8	CFC-11/CFC-12
VR-42	VAS	Well	VR-S	Y	7/20/2000	80	495.2	83.7	469.7	nd	nd	80.2	80.2	CFC-113/CFC-11
VR-43	VAS	Well	VR-S	Y	7/20/2000	10.1	29.6	29.7	124	NP	29.7	nd	29.7	CFC-113/CFC-12
VR-44	VAS	Well	VR-C	Y	7/20/2000	119.7	871.6	101.8	541.8	nd	nd	NP	nd	nd
VR-45	VAS	Well	VR-C	Y	7/25/2000	60.1	64.1	66.8	1,061.4	83.2	62.2	58.2	67.9	CFC-11/CFC-12,CFC-113/CFC-12,CFC-113-CFC-11
VR-46	VAS	Well	VR-S	Y	7/25/2000	30.7	37.2	39.1	129.1	NP	36.7	26.9	31.8	CFC-113/CFC-12,CFC-113/CFC-11
VR-47	VAS	Well	VR-S	Y	7/26/2000	96.1	108.8	611.2	762.3	NP	nd	nd	96.1	CFC-11
VTDW-01	VPI	Well	BR	Y	9/16/1999	63.6	93.6	185.4	87.9	NP	nd	nd	90.7	CFC-12,SF ₆
VTDW-03A	VPI	Well	BR	Y	7/15/2000	32.2	50.2	95.8	101.7	NP	36.7	nd	36.7	CFC-113/CFC-12
VTDW-03B	VPI	Well	BR	Y	7/15/2000	32.5	50.4	68.7	104.7	NP	44	nd	44	CFC-113/CFC-12
VTDW-07A	VPI	Well	BR	Y	7/14/2000	10.1	69.6	70.6	190.1	NP	70.5	nd	70.5	CFC-113/CFC-12
VTDW-07B	VPI	Well	BR	Y	7/14/2000	nd	nd	nd	nd	NP	nd	nd	nd	nd
VTDW-08	VPI	Well	BR	Y	9/16/1999	121.8	127.3	255.6	88.8	nd	nd	nd	88.8	SF ₆

¹ Project designation: VAS, Virginia Aquifer Susceptibility study; VBCH, Virginia Beach shallow ground water study (Johnson, 1999); VPI, Virginia Polytechnic and State University fractured-rock hydrology study

² VAS Aquifer System designation: AP, Appalachian Plateaus; BR, Blue Ridge; CP-D, Coastal Plain Deep system (depths greater than 400 feet); CP-M, Coastal Plain Middle system (depths between 200 and 400 feet); CP-S, Coastal Plain Shallow system (depths less than 200 feet); PD, Piedmont; VR-C, Valley and Ridge Carbonate; VR-S, Valley and Ridge Siliciclastic