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Preliminary Estimates of Residence Times and Apparent Ages of Ground Water in the Chesapeake Bay Watershed, and Water-Quality Data From a Survey of Springs

Water-Resources Investigations Report 97-4225

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Richmond, Virginia
September 1998

U.S. Department of the Interior
Bruce Babbitt, Secretary

U.S. Geological Survey
Thomas J. Casadevall, Acting Director

United States Government Printing Office: 1998

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

Multiply	By	To obtain
inch (in.)	2.54	millimeter
inch per year (in/yr)	0.02540	meter per year
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
quart	0.001057	milliliter (mL)

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

Water-quality units: In this report, tritium concentration is expressed in picocuries per liter (pCi/L). Values of the isotope delta 15 nitrogen ($\delta^{15}N$) are expressed as per mil (parts per thousand). Specific electrical conductance of water is expressed in microsiemens per centimeter at 25 degrees Celsius (µS/cm). Chemical concentration in water is expressed in milligrams per liter (mg/L), and excess air is expressed in cubic centimeter per liter (cm^3/L). Temperature in degree Celsius (^oC) can be converted to degrees Fahrenheit (^oF) by use of the following equation:

$$^oF = 1.8 \times (^oC) + 32$$

Preliminary Estimates of Residence Times and Apparent Ages of Ground Water in the Chesapeake Bay Watershed, and Water-Quality Data From a Survey of Springs

By Michael J. Focazio, L. Niel Plummer, John Karl Böhlke, Eurybiades Busenberg, L. Joseph Bachman, *and* David S. Powars

Abstract

Knowledge of the residence times of the ground-water systems in Chesapeake Bay watershed helps resource managers anticipate potential delays between implementation of land-management practices and any improvements in river and estuary water quality. This report presents preliminary estimates of ground-water residence times and apparent ages of water in the shallow aquifers of the Chesapeake Bay watershed.

A simple reservoir model, published data, and analyses of spring water were used to estimate residence times and apparent ages of ground-water discharge. Ranges of aquifer hydraulic characteristics throughout the Bay watershed were derived from published literature and were used to estimate ground-water residence times on the basis of a simple reservoir model. Simple combinations of rock type and physiographic province were used to delineate hydrogeomorphic regions (HGMR's) for the study area. The HGMR's are used to facilitate organization and display of the data and analyses. Illustrations depicting the relation of aquifer characteristics and associated residence times as a continuum for each HGMR were developed. In this way, the natural variation of aquifer characteristics can be seen graphically by use of data from selected representative studies. Water samples collected in September and November 1996, from 46 springs throughout the watershed were analyzed for chlorofluorocarbons (CFC's) to estimate the apparent age of ground water. For comparison purposes, apparent ages of water from springs were calculated assuming piston flow. Additional data are given to estimate apparent ages assuming an exponential distribution of ages in spring discharge. Additionally, results from previous studies of CFC-dating of ground water from other springs and wells in the watershed were compiled. The CFC data, and the data on major ions, nutrients, and nitrogen isotopes in the water collected from the 46 springs are included in this report.

The apparent ages of water discharging from 30 of the 46 springs sampled were less than 20 years, including 5 that were "modern" (0-4 years). Four samples had apparent ages of 22 to 34 years, and two others from thermal springs were 40 years or greater. The remaining ten samples were contaminated with local sources of CFC and could not be dated.

Nitrate concentrations and nitrate delta 15 nitrogen ($\delta^{15}N$) values in water from many springs are similar to those in shallow ground water beneath fertilized fields, and some values are high enough to indicate a probable source from animal-waste components. The nitrogen data reported here highlight the significance of the springs sampled during this study as pathways for nutrient transport in the Chesapeake Bay watershed.

Ground-water samples were collected from springs during an unusually high flow period and thus may not be representative of low base-flow conditions. Residence times estimated from plausible ranges of aquifer properties and results of previous age-dating analyses generally corroborate the apparent-age analysis made in the current study and suggests that some residence times could be much longer. The shortest residence times tend to be in the Blue Ridge and northern carbonate areas; however, the data are preliminary and not

appropriate for statistical tests of significance or variance. Because the age distributions in the aquifer discharging to the springs are not known, and because the apparent ages of water from the springs are based on various combinations of CFC criteria, the apparent ages and calculated residence times are compared for illustrative purposes but are considered preliminary until further work is accomplished.

Introduction

The ecosystem of the Chesapeake Bay has been adversely affected by a combination of nutrient enrichment, toxic substances, sediment, and overharvesting of shellfish and finfish. Excessive nutrient inputs have caused eutrophication and periods of hypoxia (dissolved oxygen concentrations lower than 1.0 mg/L), which in turn have killed and stressed living resources in many areas of the Bay. The algal blooms resulting from high nutrient inputs and sediment loads also decrease water clarity, which is largely responsible for the decline of submerged aquatic vegetation. Submerged aquatic vegetation (SAV), one of the most important components of the ecosystem, provides critical habitat for shellfish and finfish and food for waterfowl.

In 1987, the Chesapeake Bay Program, a multi-agency restoration effort, established a goal to reduce controllable nutrient loads to the estuary by 40 percent by the year 2000. The goal was based on the results of a computer model that indicated a 40-percent reduction in nutrient loads would eliminate hypoxia in the mainstem of the Bay. The nutrient load reduction is expected to decrease the severity of algal blooms in tributaries, and encourage the regrowth of SAV. Resource managers, however, are concerned that the Bay and watershed will respond more slowly to the nutrient-reduction measures than was previously anticipated. Therefore, scientific information on lag times between nutrient inputs in the watershed, coupled with linkages between water quality and living-resource response, is needed to assess the effectiveness of nutrient-reduction strategies. Analysis of long-term biological, chemical, and hydrogeologic records, integrated with newly collected information, can help resource managers gain a perspective on the bounds of inherent variability of the ecosystem and their effect on restoration goals. The U.S. Geological Survey (USGS), through its Chesapeake Bay Ecosystem Program, collects and interprets appropriate scientific information to help resource managers determine the success of management strategies and the response of the ecosystem to nutrient reduction.

The primary objectives of the USGS Chesapeake Bay Ecosystem Program are to: (1) Determine the response of water quality and selected living resources of the Bay watershed and estuary to changes in nutrient and sediment inputs and climatic variability over several temporal scales--information from the recent past (1 to 15 years) encompasses the time frame for many management actions and the last several decades is the time frame needed to assess the impact of population increase; (2) further define and evaluate the natural and anthropogenic controls on water quality and selected living resources to changes in nutrient and sediment sources and climatic variability; and (3) provide resource managers with the management implications of the scientific findings and develop investigative tools so that they may evaluate the effectiveness of different nutrient-reduction strategies.

The USGS Chesapeake Bay Ecosystem Program, which began in May 1996, is a 5-year effort to provide relevant information on nutrient and sediment conditions and response times, on factors affecting nutrient and sediment dynamics, and on selected living resources for the re-evaluation of the nutrient-reduction strategy in 1997--and its final assessment in the year 2000. Existing nutrient and sediment data for the entire watershed will be used to document and further understand conditions in the watershed. Detailed investigations are designed to clarify the principal factors affecting nutrient and sediment transport and their relation to the changes in the sources of these constituents in selected hydrogeomorphic regions (HGMR's) of the watershed. HGMR's are areas of unique physiography and rock type that may have characteristic water quality and biologic responses to changes in nutrient inputs and natural variability. The USGS will relate surface and subsurface characteristics to water quality and living-resource response over several temporal scales through studies in selected sub-watersheds and in river and estuary reaches within the Bay watershed.

Purpose and Scope

This report presents preliminary estimates of ground-water residence times and apparent ages of water in shallow aquifers of Chesapeake Bay watershed. Water-quality, nitrogen-isotope, and chlorofluorocarbon (CFC) data for selected springs in the Bay watershed are compiled. Nitrogen-isotope chemistry is presented to highlight the relevance of the selected springs as sources of nutrients to surface waters of the watershed.

Published values of aquifer porosities, thicknesses, and recharge rates were used to estimate ground-water residence times by use of a simple reservoir model. Analysis of water from springs, and results from previous studies, were used to evaluate ground-water residence times. Major ions and nutrients, nitrogen-isotopes, and CFC’s in water issuing from 46 springs were collected and analyzed in September 1996. Selected springs were sampled again in November 1996. The water-quality data are tabulated in data tables. The CFC data are used to determine apparent ages of the water, and the nitrogen-isotope data are used to depict potential sources of nutrient contamination.

This report provides information on ground-water ages and residence times, and a companion report on ground-water volume and load is planned for publication soon. These two reports will provide the Chesapeake Bay Program with information on the amount of ground water entering the Bay, the amount of associated nitrogen load, and the estimates of ground-water ages and residence times. The information and interpretations on ground-water ages and residence times in this report are based on results from the first year of study and include analyses of water collected from springs in September and November 1996. Refinements and modifications will likely be made in subsequent reports as the study progresses. For example, the springs that were sampled for ground-water age determinations are subject to refinement when they are sampled again during different hydrologic conditions and re-interpreted as new information and data on springs in the different HGMR’s are obtained. Accordingly, the ages and estimates of residencetimes reported here are considered preliminary.

Description of Study Area

The Chesapeake Bay watershed is approximately 64,000 mi^2 and contains more than 150,000 stream miles in the District of Columbia and parts of New York, Pennsylvania, Maryland, Virginia, West Virginia, and Delaware (fig. 1). The climate is humid continental and precipitation averaged 44 in/yr at selected National Atmospheric and Oceanic Administration (NOAA) stations from 1930-61 (Langland and others, 1995). Large spatial and temporal variations in precipitation, however, are common in the watershed because of its size, orographic effects, and the proximity to the Atlantic Ocean. The watershed consists of six major physiographic provinces that include the Appalachian Plateau, the Valley and Ridge, the Blue Ridge, New England (Reading Prong Section), the Piedmont, and the Coastal Plain Physiographic Provinces (fig. 1). For purposes of this report, four major rock types based on similar lithologic and geologic characteristics--carbonate, crystalline, siliciclastic, and unconsolidated sedimentary rocks--are delineated.

Acknowledgments

The authors would like to thank the many landowners who provided access to privately owned springs, and the resource managers, planners, and town officials who provided access to, and information on, public springs.

Study Methods

The methods of study for this report are divided into the following categories: (1) delineation of hydrogeomorphic regions, (2) chlorofluorocarbon analysis, (3) nitrogen isotope analysis, (4) major ion and nutrient analysis, and (5) estimation of residence time by a simple reservoir model.

Delineation of Hydrogeomorphic Regions

A simplified hydrogeomorphic classification system based on rock type and physiographic province was developed to aid in the interpretation of ground-water residence time estimation and apparent age analyses. Rock type maps were digitized from paper copies of intermediate-scale

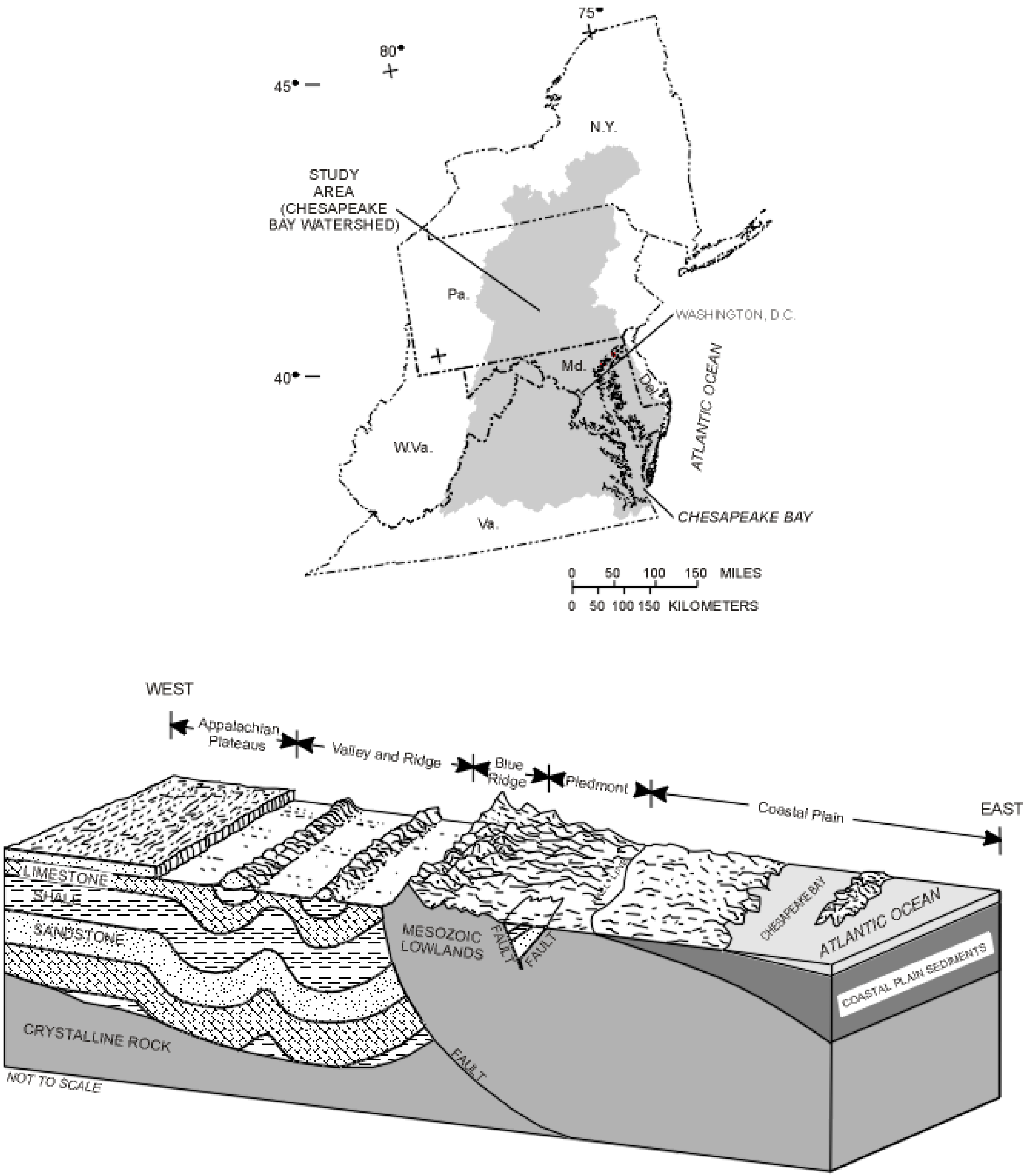

Figure 1. Chesapeake Bay watershed study area and representative geologic section (modified from Trapp and Horn, 1997).

(1:250,000 to 1:500,000) published State and USGS geologic maps of New York, Pennsylvania, Maryland, Virginia, and West Virginia. The physiographic province maps were generalized from the geologic and published physiographic maps. A description of the preparation of the digital maps is given in Langland and others (1995). The published source maps were generalized into four rock types: crystalline, siliciclastic, carbonate, and unconsolidated. The following physiographic provinces also were part of the generalization: Coastal Plain, Piedmont, Mesozoic Lowland, Blue Ridge, Valley and Ridge, and Appalachian Plateau.

In delineating the hydrogeomorphic regions (HGMR's), not every possible combination of rock type and physiographic province was included. Some combinations may occur; for example, unconsolidated alluvial deposits and glacial deposits are found in the Valley and Ridge and Appalachian Plateau Physiographic Provinces but, due to the scale of the source maps, these occurrences were not mapped, or they were inappropriate for this study. The four major rock types in the Chesapeake Bay watershed and physiographic provinces were combined (fig. 2) using a geographic-information system, resulting in the following HGMR's: Coastal Plain, Piedmont crystalline, Piedmont carbonate, Mesozoic Lowland, Blue Ridge, Valley and Ridge siliciclastic, Valley and Ridge carbonate, Appalachian Plateau siliciclastic, and Appalachian Plateau carbonate. Analyses of residence time were not developed for the Appalachian Plateau carbonate HGMR and, therefore, it is not discussed further in this report.

Chlorofluorocarbon Analysis

Busenberg and Plummer (1992) describe a sampling method for collecting CFC compounds in ground water, and a method for interpreting the concentrations in terms of the time elapsed since the water was isolated from the atmosphere (recharged to the water table). The method is based on the assumption that water is in equilibrium with tropospheric air at recharge and moves through the aquifer without gas loss, degradation, diffusion, or dispersion. All water samples were analyzed for CFC concentrations (including CFC-11, 12, and 113) at the USGS laboratory in Reston, Va., using purge and trap, gas chromatographic procedures with electron-capture detector (Bullister, 1984; Bullister and Weiss, 1988; Busenberg and Plummer, 1992). The analytical detection limit for CFC-12, CFC-11 and CFC-113 in water is approximately 0.3 picograms per kg (pg/kg) of water, corresponding to water recharged in approximately 1941, 1947, and 1955, respectively. In some cases, the ground water has been contaminated with CFC compounds from local sources and, therefore, these water samples were not analyzed for recharge dates. However, samples that are contaminated by local sources of CFC can be useful indicators of ground-water systems that are generally vulnerable to contamination by other potential contaminants and also indicate that the water probably is composed of at least some modern water (water recharged within the past 4 years).

Although concentrations of CFC's can be measured precisely in water samples, assignment of age is based on an interpretation of flow conditions, and the assumption that no other processes have altered CFC concentrations beyond those established by air-water equilibrium during recharge. Because these processes are not always understood or recognized for a particular water sample, age is usually referred to as "apparent" age. The presence of CFC's in a ground-water sample indicates that the water contains at least a fraction of post-1940's water, because CFC's were not produced prior to this time. As a first approximation, and for purposes of comparison, preliminary apparent age is based on the assumption of piston flow. The assumption of piston flow has been shown appropriate for interpretation of apparent age of water samples collected from wells and piezometers open to relatively narrow intervals of an aquifer (Dunkle and others, 1993; Ekwurzel and others, 1994; Reilly and others, 1994; Katz and others, 1995; Cook and others, 1995; Szabo and others, 1996). In contrast, ground-water discharge from springs may represent a collection of a wide range of flow lines and water ages, and thus, mixed ages. The nature of mixing of flow lines in discharge from springs depends on the hydrogeology of the catchment area for the spring. Ground-water samples for CFC analysis can be collected from a well (or piezometers) and (or) a spring, as long as they are

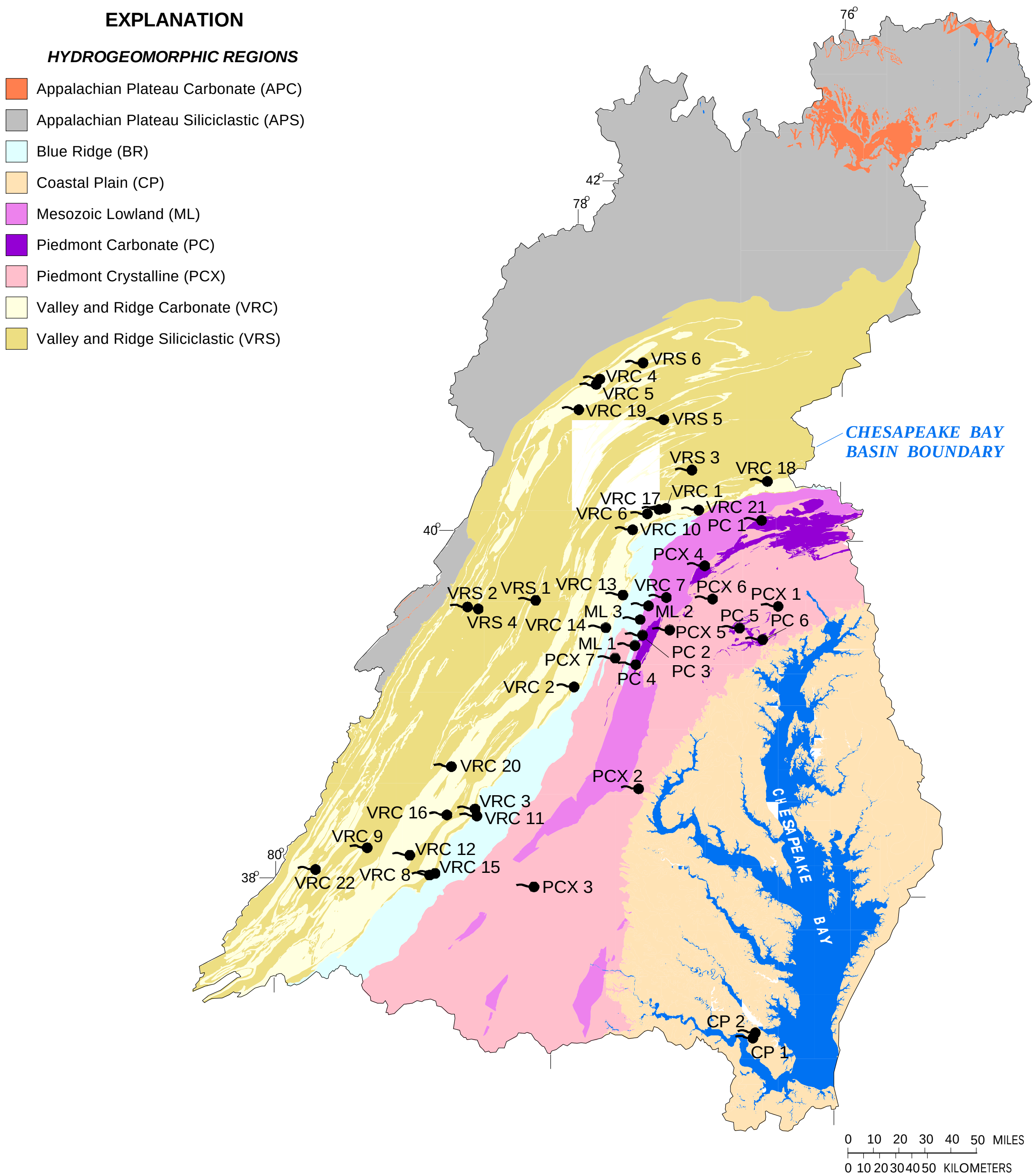

Figure 2. Locations of springs in the Chesapeake Bay watershed sampled in September and November 1996.

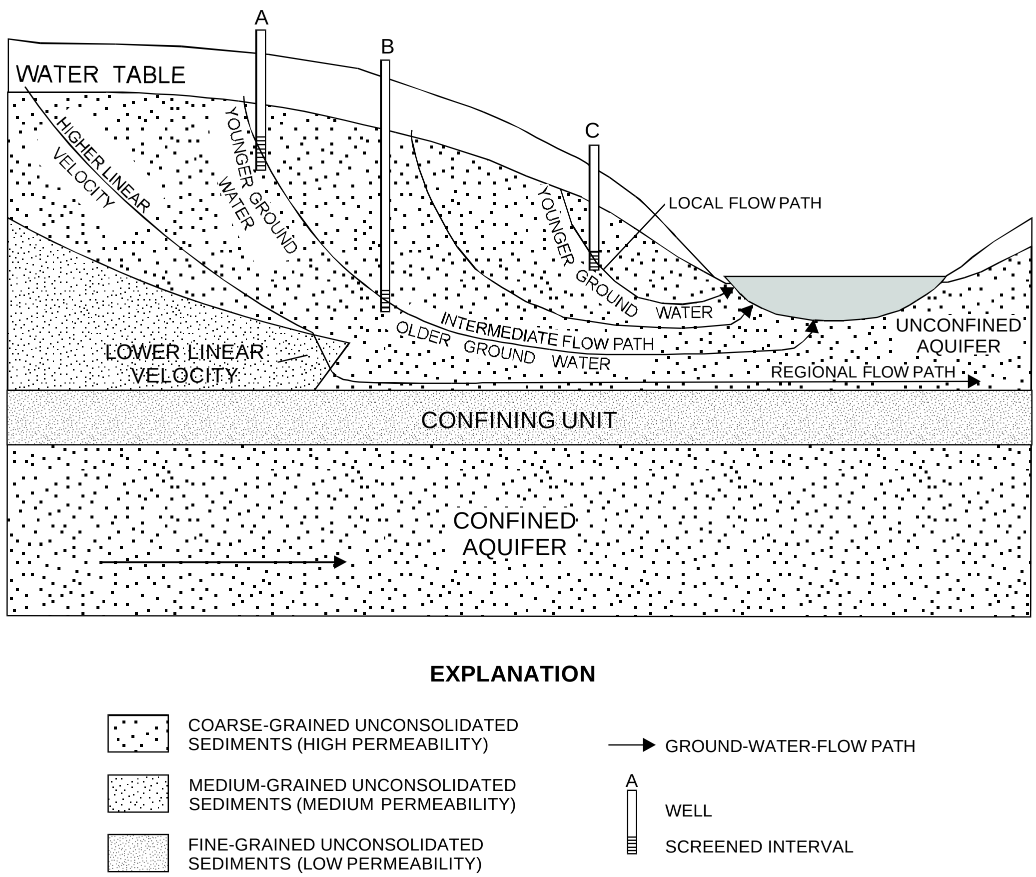

Figure 3. Generalized ground-water-flow path through a shallow Coastal Plain aquifer.

kept isolated from the atmosphere. Apparent ages of water collected from wells should be interpreted differently than those collected from springs. Although no wells were sampled for the present study, results from previous studies are presented in this report. Therefore, a discussion of sampling wells in contrast to sampling springs is warranted. The flow paths that contribute water to the screened or open interval of a well (fig. 3) can be significantly different than the converging flow paths that contribute water to a natural ground-water discharge area, such as a spring (fig. 4). In these two conceptual models, the age of water sampled from a well would be more indicative of a point in the flow field along a single flow path and the age of water sampled from a spring would more likely be the result of a mixture of water from various flow paths and associated ages. In this way, as the number of wells of varying depths in a flow field increases and includes most of the flow paths in the aquifer, the average age of water from those wells approaches a representative, or average, residence time for water in the aquifer. Similarly, as the number of converging flow paths contributing to a spring increases and includes most of the flow paths in the aquifer, the age of water from a single sample collected from the spring approaches a representative, or average, residence time for water in the aquifer. These two conceptual models are presented as general indicators of the assumptions and limitations of analyzing the age of water collected from wells in

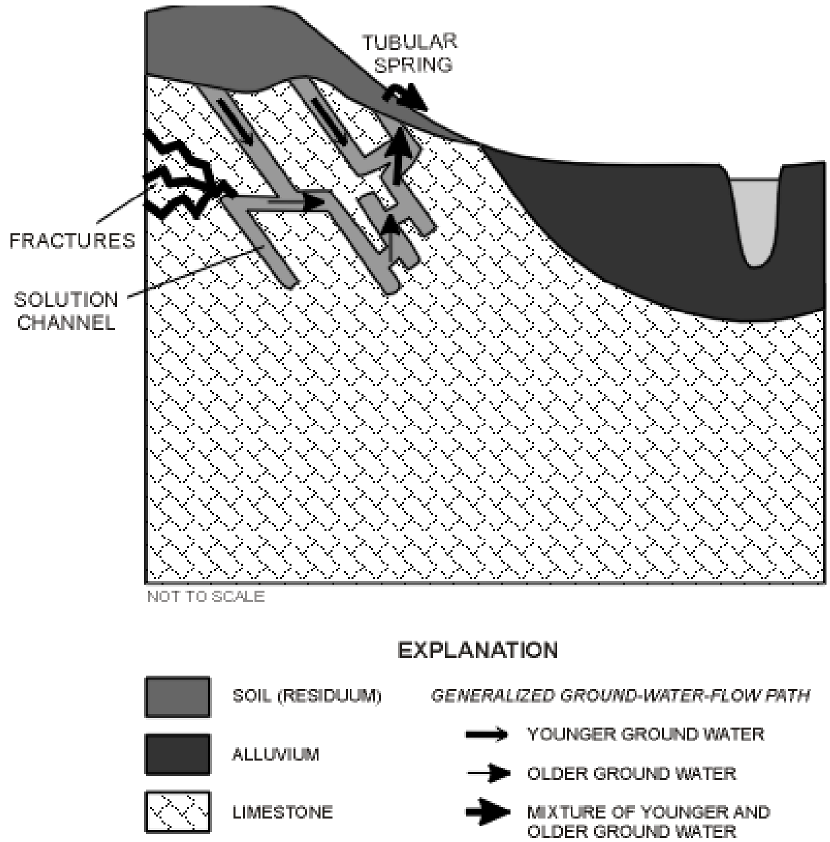

Figure 4. Possible ground-water-flow path associated with a tubular spring in carbonate rock (modified from Brahana and others, 1986).

contrast to springs, and are not intended to account for all possible differences.

Nitrogen Isotope Analysis

Samples for nitrogen isotope analysis were filtered into plastic bottles and refrigerated. Analytical techniques are described by Böhlke and Denver (1995) and Böhlke and Coplen (1995). Nitrogen isotope ratios are expressed as $\delta^{15}N$ values, defined by $\delta^{15}N = 1{,}000[(^{15}N/^{14}N_{sample})/(^{15}N/^{14}N_{air}) - 1]$, and normalized to values of +0.4 per mil for IAEA-N1 and +180.0 per mil for USGS-32 (Böhlke and Coplen, 1995), with analytical uncertainties of around plus or minus 0.1 per mil.

Major Ion and Nutrient Analyses

Water samples were analyzed for determination of major ions and nutrients using standard procedures at the USGS Water-Quality Laboratory in Reston, Va. The chemical constituents analyzed in the laboratory include calcium, magnesium, silica, sodium, potassium, iron, manganese, aluminum, chloride, sulfate, nitrate, and alkalinity. Specific conductance, pH, dissolved oxygen, and water temperature were measured in the field.

Estimation of Residence Time by Application of a Simple Reservoir Model

The specific discharge (also known as the darcian velocity) is the discharge per unit area of an aquifer, and it is defined as the velocity at which water would move through an aquifer if the aquifer were an open conduit (Fetter, 1994):

$$v = \frac{q}{a} \quad , \tag{1}$$

where

v = specific discharge (L/T),
q = volumetric discharge (L^3/T), and
a = cross-sectional area of flow (L^2).

Flow through the aquifer, however, is limited by the pore space between grains of aquifer material. The seepage velocity (also called linear velocity) (fig. 3) is equal to the specific discharge divided by the porosity, and it is defined as the average rate at which water moves between two points in the aquifer:

$$v_x = \frac{v}{n} \quad , \tag{2}$$

where

v_x = seepage velocity (L/T),
v = specific discharge (L/T), and
n = porosity (unitless).

Porosity is defined as the ratio of the volume of open space, or interstices, to the total volume of aquifer material (Todd, 1980). Part of the pore space in an aquifer, however, contains stagnant water. The part of pore space through which flow actually occurs is defined as the effective porosity (also called connected porosity or secondary porosity). Therefore, the amount of time that ground water spends in an aquifer is controlled by the seepage velocity and is a function of the hydraulic gradient, the cross sectional area of flow, the permeability, and the porosity. If all other aquifer characteristics are equal, water in an aquifer with high seepage velocities (and, similarly small porosities) will have shorter residence times than water in an aquifer with low seepage velocities (large effective porosities).

Many aquifers in the Chesapeake Bay watershed are composed of consolidated material, or hard rock. Water flows through these aquifers because of primary and secondary porosity and permeability. The primary porosity is associated with the rock matrix itself and is a function of the original formational processes of the rock. The secondary porosity (usually the effective or connected porosity) is a function of the fractures and other void spaces that have developed since the rock was formed. A hard-rock aquifer with an extensive fracture system typically will have higher permeabilities, higher rates of flow, and therefore shorter residence times than one with fewer, smaller fractures. Similarly, some aquifer material is easily dissolved and, therefore, these aquifers develop large conduits, or solution openings, through which significant amounts of water can flow. On the other hand, aquifers with larger porosities can have longer average ground-water residence times in comparison to other aquifers having similar recharge rates and aquifer geometry.

Porosity also can be defined as the sum of the specific yield and the specific retention (Fetter, 1994). Specific yield is a measure of the water-yielding capacity of a rock or soil, and the specific retention is a measure of the water-retaining capacity of a rock or soil. In fine-grained soils such as clay, the porosity is high but the water-yielding capabilities are low because the porosity is dominated by specific retention, not specific yield. On the other hand, porosity is dominated by secondary controls in the hard-rock aquifers, the specific retention is low, and therefore specific yield is sometimes used as a reasonable first approximation to porosity (Johnson, A.I., 1967; Gburek and others, 1994).

An approximation of the average residence time of water in a water table aquifer can be estimated by assuming that steady-state flow conditions exist on an inter-annual basis, and recharge rates and other aquifer properties are constant. In this way, the annual recharge is equal to the annual discharge and the average ground-water residence time is proportional to the volume of void space in the aquifer. As applied in this study, the simple reservoir model assumes near-steady-state flow conditions at a resolution of a year or more over time scales of years to decades; thus, it is used only in situations where the aquifer volume is at least several times the annual ground-water flux. The residence time can then be defined as the ratio of the volume of aquifer void space to the volumetric rate of water moved through the aquifer:

$$\text{aquifer void volume } (L^3) = bnA_a, \qquad (3)$$

where

b = aquifer thickness (L),
n = aquifer porosity (dimensionless),
A_a = areal extent of aquifer (L^2), and

$$\text{recharge to a watershed } (L^3/T) = rA_w \qquad (4)$$

where

r = recharge rate per unit watershed area (L/T),
A_w = watershed area (L^2), and

$$T = \frac{bnA_a}{rA_w}, \qquad (5)$$

if

$A_a = A_w$, then

$$T = \frac{bn}{r}, \qquad (6)$$

where

T = residence time (T),
b = aquifer thickness (L),
n = porosity (unitless), and
r = annual recharge (or discharge) rate (L/T).

In this way, water in an aquifer having a small void volume [small porosity and (or) thickness] and a high recharge rate will have to move through the aquifer faster (have a shorter residence time) than an aquifer with larger void volume and smaller recharge rates. Therefore, with other aquifer characteristics constant, a higher porosity, a larger thickness, and a smaller recharge rate are all independently associated with a longer residence time.

Water-Quality Data and General Nitrogen Chemistry of Spring Water From Selected Hydrogeomorphic Regions

Samples of water from selected springs were analyzed for major nutrients and ions and nitrogen isotopes (fig. 2; appendix D). Water samples were collected in September and November 1996 at the same time the CFC samples were collected. The data are presented in this report without interpretation except for nitrogen chemistry, which highlights the relevance of the selected springs for nutrient contamination to the surface waters of the Chesapeake Bay watershed.

The $\delta^{15}N$ values of nitrate dissolved in water can be indicative of the source of nitrogen. The values in spring waters ranged from about +3 to +11 per mil (fig. 5; appendix D). Representative concentrations and $\delta^{15}N$ values are indicated in figure 5 for nitrate in atmospheric deposition, allowing for some concentration by evapotranspiration (Heaton, 1986; Garten, 1992; National Atmospheric Deposition Program, 1987-91; J.K. Böhlke, unpub. data, 1996), and for nitrate in oxic ground water recharging beneath crops receiving nitrogen fertilizers (limited data for some areas of the Chesapeake Bay watershed from Böhlke and Denver, 1995; J.K. Böhlke and M.E. O’Connell, U.S. Geological Survey, unpub. data). The $\delta^{15}N$ values of samples collected from springs are generally higher than those of atmospheric deposition; many are similar to those of shallow ground waters recharged beneath fertilized fields; whereas some are high enough to indicate probable animal waste source components. Arrows on figure 5 qualitatively indicate the effects of adding nitrate derived from nitrification of manure and other animal wastes (Kreitler, 1975) and of denitrification (microbial reduction of nitrate to nitrogen gas; Marriotti and others, 1988).

Detailed investigation of the relation of water chemistry to land use is beyond the scope of this report but is proposed to be addressed as the study progresses. Most of the springs that were sampled in September and November had similar $\delta^{15}N$ values both times.

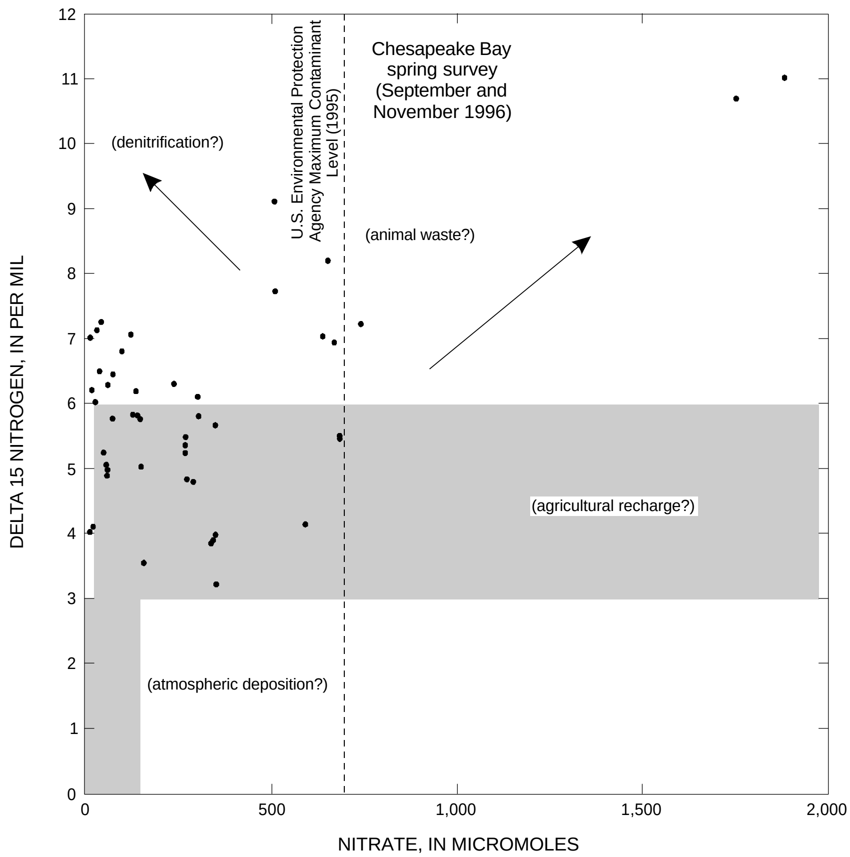

Figure 5. Relation of nitrate and delta 15 nitrogen in water collected from springs in the Chesapeake Bay watershed in September and November 1996.

Preliminary Estimates of Residence Times and Apparent Ages of Ground Water in the Chesapeake Bay Watershed

Water that discharges from a shallow aquifer can have varied age distributions depending on the distribution and magnitude of recharge and the configuration and hydraulic properties of the aquifer. One of the simplest models for estimating the average residence time (also referred to as turnover time) of water in a homogeneous aquifer receiving areally distributed recharge has an exponential age distribution in discharge (Zuber, 1986). The formulation of an exponential model is equivalent to a single-stage steady-state reservoir flux model (also referred to as a mixing-cell model), but it also can be applied to discharge from certain types of aquifers in which the water flow remains stratified (does not mix within the aquifer) (Vogel, 1967). The exponential model yields at best a gross approximation of the relative contributions of discharge of different ages, but it likely is more nearly correct than other simple reservoir models, such as those that assume all discharge to be the same age.

The apparent age of ground water determined by CFC analysis refers to the amount of time elapsed between the recharge date and the collection date. An apparent age derived from a single analysis of discharge, however, would equal the estimated residence time only in the limiting case of piston flow. For most other types of flow systems, including those that can be approximated by the simple reservoir model, an apparent age of ground-water discharge may be different from the average residence time because the relation between CFC concentration and age is nonlinear.

This concept is depicted graphically in fig. 6. Figure 6 shows concentrations of CFC's in

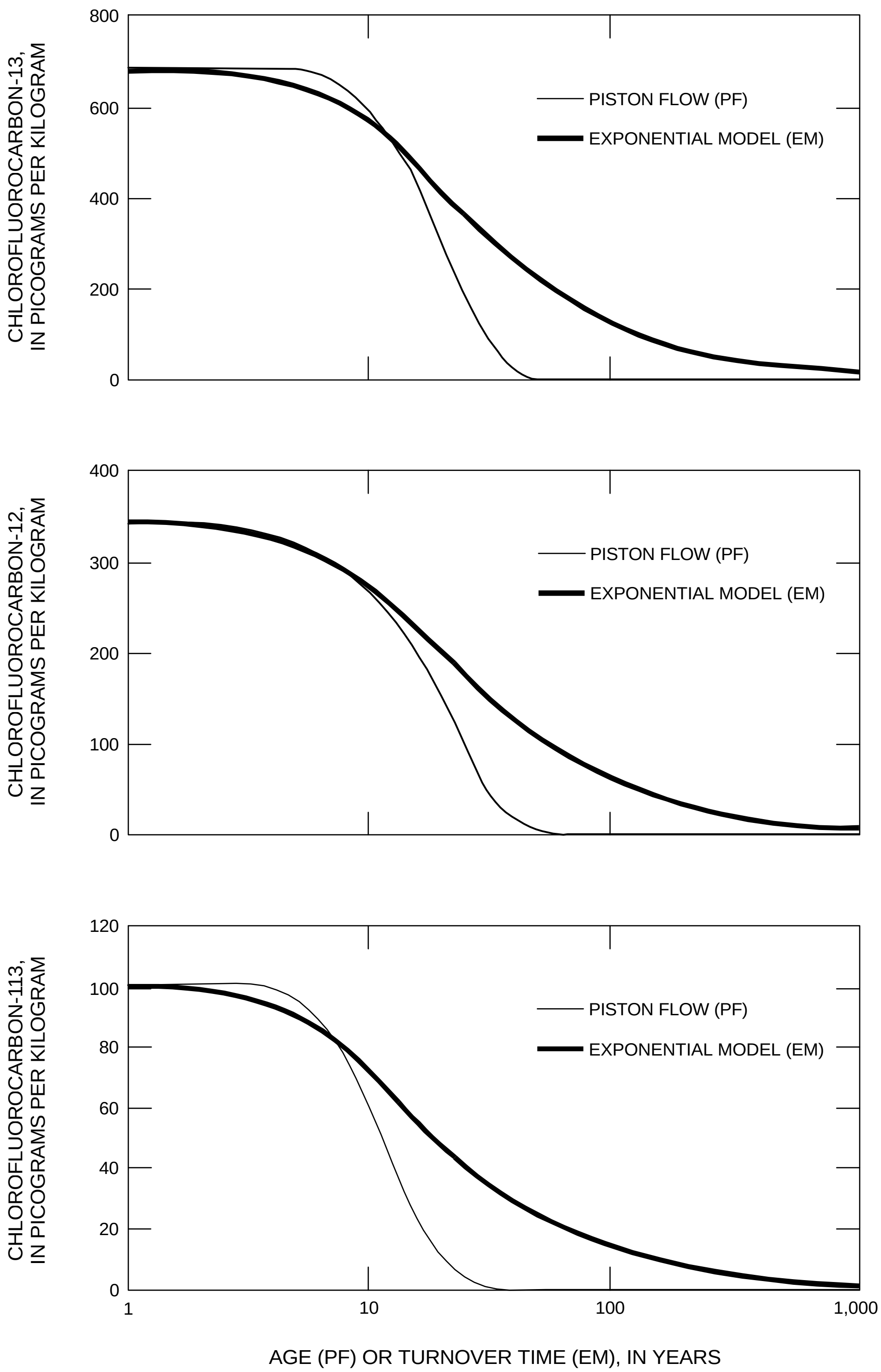

Figure 6. Relation of concentration of chlorofluorocarbon to ground-water residence time.

discharge corresponding to apparent ages (from the piston-flow assumption) and turnover times (or average residence times from the exponential model). Data are plotted for recharge at 10 °C at 600-ft elevation (roughly the averages for the springs), and discharge in mid-1996 (near the first sampling episode). The piston-flow assumption corresponds to plug flow in a single flow tube without diffusion, or dispersion. The exponential model could correspond to either complete mixing within the aquifer or mixing of stratified ground waters at discharge (Vogel, 1967; Zuber, 1986). For apparent ages less than about 10 years, the apparent age and exponential model turnover time are not significantly different for CFC-12, but the turnover time is slightly less than the apparent age for CFC-11 and CFC-113. For apparent ages more than about 10-15 years, the exponential model turnover times are significantly larger than the apparent ages for all 3 compounds. Because the age distributions in the aquifer discharging to the springs are not known, and because the apparent ages of water from the springs are based on various combinations of CFC criteria, the apparent ages and calculated residence times (eq. 6) are compared for illustrative purposes but are considered preliminary until further work is accomplished.

Though much of the Chesapeake Bay watershed is represented, the spatial variability of apparent ages within and between HGMR's is large (fig. 7), and not enough data were collected to permit statistical tests of the variance of apparent ages of spring water. Generally, the apparent ages of water from most of the springs are less than 20 years (fig. 8), with a few between 21 and 32 years, and several that have modern water (0-4 years). Samples collected from two geothermal springs have the oldest apparent ages (greater than 40 years). Several samples were contaminated by local sources of CFC (fig. 7) and could not be dated.

Michel (1992) calculated residence times for water in seven river basins in the United States by analysis of long-term tritium records. The Potomac River Basin at Point of Rocks, Md., one of the two basins studied in the Chesapeake Bay watershed, had the longest residence time (20 years) of all seven basins. In comparison, the residence time for the Susquehanna River above Harrisburg, Pa., was 10 years. Michel (1992) also determined the percentage of annual runoff attributed to "within-year runoff" and the percentage from "long-term reservoirs." The Potomac River has a low percentage of within-year runoff (46 percent) and a correspondingly high percentage of long-term reservoirs (54 percent) when compared to other eastern rivers. The Susquehanna, on the other hand, had 80 percent within-year runoff and only 20 percent from long-term reservoirs.

Additional calculations were made to test the sensitivity of Michel's (1992) reservoir-model results for tritium data from the Susquehanna and Potomac Rivers, and an additional site, not modeled by Michel (1992), on the Delaware River at Philadelphia, Pa. A two-box model (after Michel, 1992) was assumed where stream water is a mixture of two reservoirs, a short residence-time reservoir (within 1 year), and a longer residence-time water (values of 2, 5, 10, and 20 years assumed). The modeling exercise attempted to determine best-fit values of the fraction of young water (1-year reservoir), n, and the residence time of water in the long-term reservoir by comparing model results to actual yearly average stream tritium concentrations.

The tritium-precipitation records used by Michel (1992) were no longer available. Tritium in precipitation was reconstructed monthly for each location as in Michel (1989) by interpolation between stations on the USGS tritium network. Monthly precipitation data were obtained from records maintained by the Carbon Dioxide Information Analysis Center, Oak Ridge, Tenn. (accessed 8/25/98 at http://cdiac.esd.ornl.gov). The sites selected for precipitation records were the ones closest to the tritium sampling sites: Harrisburg, Pa. (site number 363699), Lincoln, Va. (site number 444909), and Moorestown, N.J. (site number 285728). Monthly-weighted tritium-in-precipitation records were constructed for each site and used as input to the reservoir models.

The tritium activity in river water was modeled monthly by adding the fraction of output from the short-term box (1-yr reservoir) to the fraction from the long-term box. The fractions, n, and residence time of water in the long-term reservoir were varied generating a series of plots of tritium levels over time. The measured data were compared

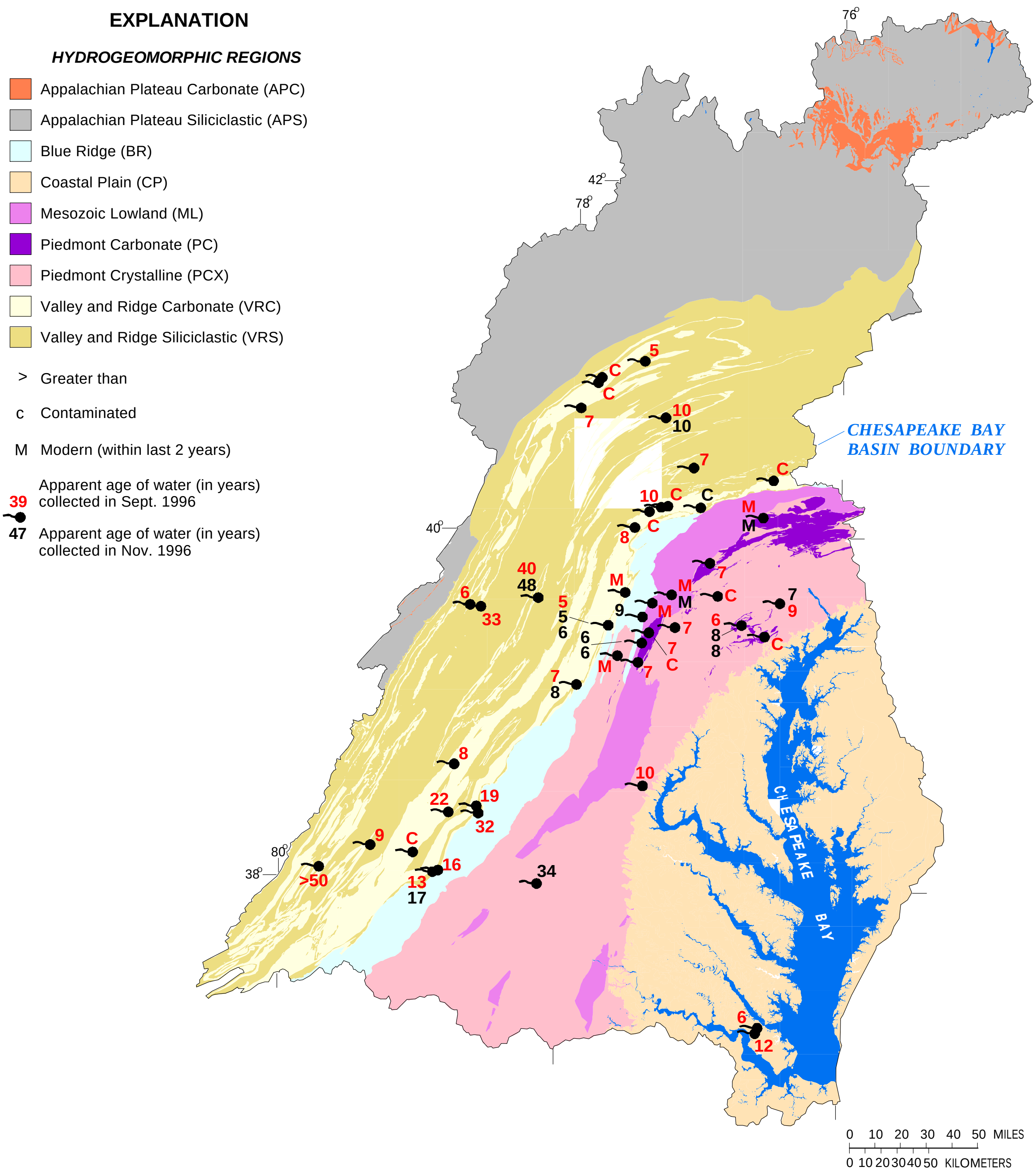

Figure 7. Apparent ages of water collected from springs in the Chesapeake Bay watershed in September and November 1996.

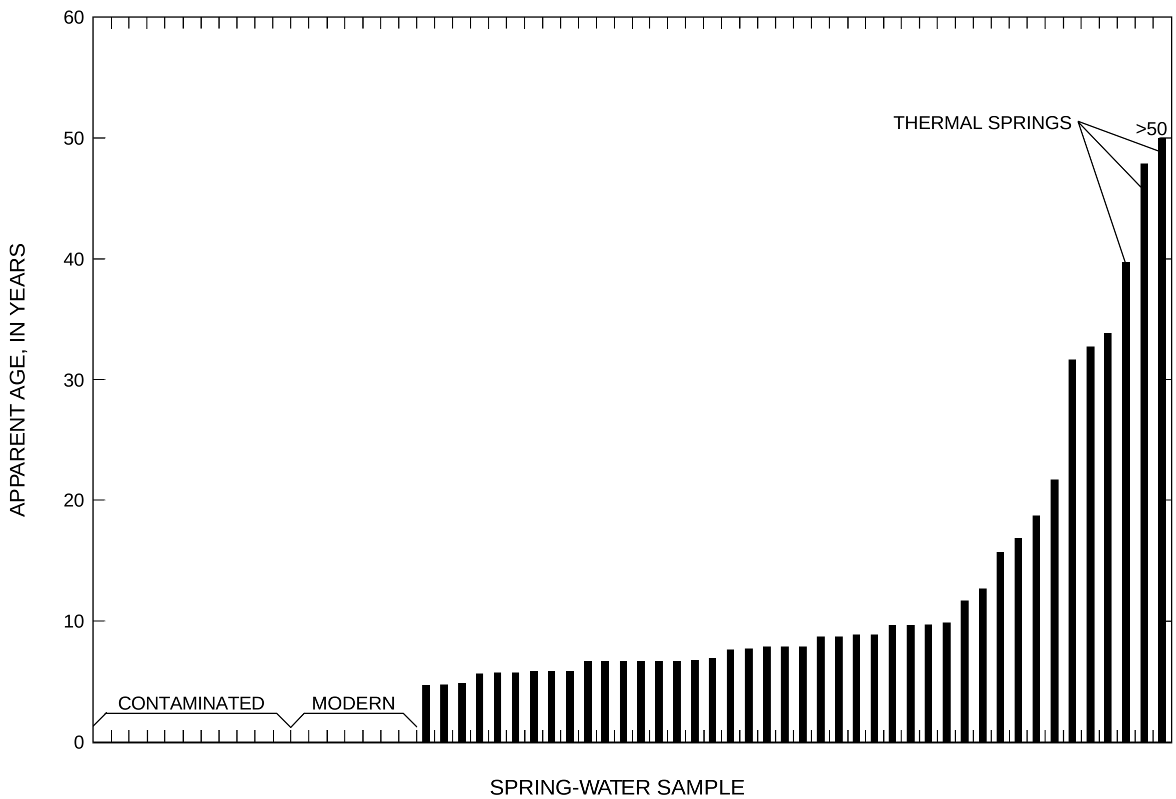

Figure 8. Apparent ages of water collected from springs in the Chesapeake Bay watershed in September and November 1996.

with the curves of each residence time and value of *n*, and a visual judgement was made on the likelihood of a particular fraction and residence curve appropriately modeling the river tritium record.

Results for the Susquehanna River at Harrisburg, Pa., suggest $n = 0.5$ and residence time of approximately 10-20 yrs. Michel (1992) found $n = 0.8$ and residence time of 10 years. Michel did not present results for differing values of *n* and residence time. Michel's result of $n = 0.8$ and residence time of 10 years closely models most of the data, but multiple residence times fit the data with a scaling factor of $n = 0.8$. The mid-1960's tritium peak is much higher, however, than any measured stream tritium values with $n = 0.8$. The values $n = 0.5$ (a more restrictive scaling factor for this data) and residence times of 10-20 years appear to model the peak river tritium values better.

During the period 1970-80, the modeled 2-year residence time for the Susquehanna drops below modeled results for larger residence times and actually fits the river data better than any other residence time. One possible cause is the inappropriateness of the model. Better fits could be obtained if more reservoirs were considered. Furthermore, the assumption of steady-state behavior of the reservoirs may not be appropriate. The latter could result from increased runoff of younger water, such as from increased land development, or increased recharge forcing younger water from the long-term reservoir. The period of poorer fit between model and observed seems to coincide with a period of increased precipitation in the 1970's.

It was not possible to find a two-box model that adequately fit the tritium records for the Potomac River at Point of Rocks, Md. Consequently is was not possible to reproduce Michel's (1992) results of $n = 0.46$ and residence time of 20 years. It is possible that Michel (1992) used different tritium and precipitation input functions than our calculations. If the river basin covered multiple grid areas, Michel (Michel, oral commun., 1996) defined the input function as fractions of the various grids computed from Michel (1989). Only a single station near the site of the tritium record was used in the present study. It is also possible that different sources of precipitation data were used. However, preliminary calculations suggest that such variations should not have a great effect on the results. Using Michel's (1992) result, the fit between model and observed is adequate to about 1967, but poor afterwards. Also, some peak values seem to fall too low. The best fits after about 1970 were obtained from the condition, $n = 1$ (discharge 100 percent of the 1-year residence time).

Model calculations were also made for the Delaware River at Franklin Bridge in Philadelphia, Pa. The data are described in Wyerman and others (1970). The data best fit values of $n = 0.4$ and residence time of about 20 years. Michel (1992) did not model this site, so no further comparisons could be made. Although this site is not within the Chesapeake Bay watershed, it is nearby and may be representative of some river basins in the Bay watershed.

The tritium reservoir model approach puts some limitations on residence times of water discharging to rivers. Although the approach integrates large areas, the results are unfortunately not precise. The tritium reservoir model approach shows that most rivers must have significant fractions of young water in order to explain observed tritium, but that they also contain almost equal amounts of older water. The best fit values for the Susquehanna and Delaware Rivers suggest that values of n in the range of 0.4 to 0.5, and residence times of 10-20 years are the most reasonable.

There are presently no independent measures of n to directly corroborate the latter observations; however, base-flow indexes were calculated for the Susquehanna River at Harrisburg, Pa., and the Potomac River at Point of Rocks, Md., with data from 1972 through 1996 (Bachman and others, 1998). The base-flow index is defined as the total volume of annual base flow (determined by hydrograph separation) divided by the total volume of annual streamflow. The average base-flow index for the period of record was 0.57 for the Susquehanna River and 0.53 for the Potomac River indicating that: (1) there is not much difference between the two basins, and (2) there is approximately an equal volume of stormflow and base flow discharging from these basins on an annual basis. Therefore, to the extent that storm-flows are associated with the shorter residence-time reservoirs and base flows are associated with the longer time reservoirs, values of n near 0.5 are reasonable for both basins.

The tritium reservoir model approach assumes steady state in n and residence time of the older fraction. This may not be valid. It also assumes that the river discharge can be modeled by only 2 reservoirs. This is possibly an over simplification. The critical data needed to resolve reservoir models are stream tritium measurements from the mid-1960's and the following 10-yr period. Such records are known for only a few rivers in the United States (Michel, 1992). It is unlikely that we will be able to resolve much more information by looking at recent stream tritium values, because all model results converge and there is often no unique solution in more recent years.

Hydrologic Conditions During Sampling

The springs were sampled in September 1996, which was an unusually wet month. Surface-water flow to Chesapeake Bay was 342 percent above average for the month of September and 82 percent above average for the month of August, and the surface-water flow to the Bay for the 1996 calendar year was the highest on record (J.J. Manning, U.S. Geological Survey, oral commun., 1997). These extreme hydrologic conditions are illustrated for a surface-water site and a ground-water site near a spring (VRC2) sampled in the Valley and Ridge carbonates of Virginia (fig. 9). Similar conditions existed throughout the Chesapeake Bay watershed during this study period.

The apparent ages estimated from the September 1996 sampling possibly are biased with

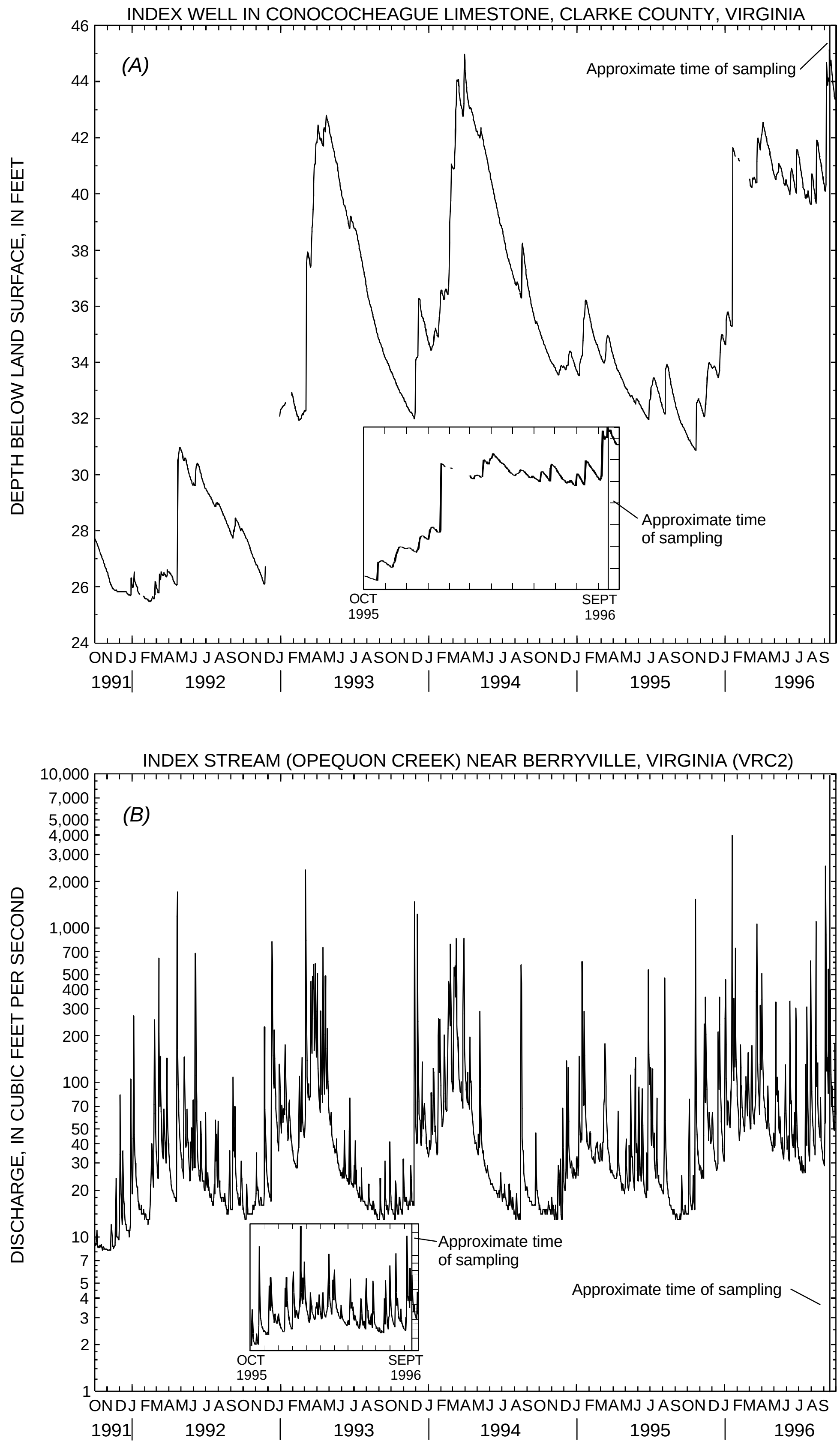

Figure 9. Hydrographs of (A) ground water and surface water (B) index sites in the study area.

respect to normal late summer conditions. Additional preliminary data were collected in November 1996 (during lower flow conditions as compared to September) to be compared with the September data (table 1). Spring water collected in November had approximately the same apparent ages (plus or minus 2 years) as those collected in September. Samples from two springs were substantially older in November than September. The occurrence of older water in two springs in November could be consistent with the hypothesis that lower flow conditions are associated with older water; however, this hypothesis has not been thoroughly tested. Additionally, the specific conductance and dissolved oxygen decreased between September and November for many of the springs possibly because near-surface components (presumably the younger water) have higher dissolved solids and oxygen than older ground-water components. Usually, ground water associated with deeper, older systems has higher specific conductance (and dissolved solids) than shallower, younger water because of the longer flow paths and contact times. If there is a near-surface source of contamination, however, or if the shorter flow paths are in contact with minerals that are more readily dissolved than those in the deeper systems, it is plausible that the younger water would have higher specific conductances than the older water. This hypothesis also has not been tested and warrants further investigation when additional samples are collected and analyzed during different hydrologic conditions. The November sampling also took place during an unusually high flow (November flow to the Bay was 118 percent above average; J.J. Manning, oral commun., 1997). Additional data are needed to adequately test the hypotheses concerning the mixture of water during different hydrologic conditions.

Coastal Plain Hydrogeomorphic Region

The Coastal Plain aquifer system consists of a series of aquifers and associated confining units that range from Cretaceous to Holocene age. The aquifers and confining units are composed of unconsolidated sands, silts, and clays. The surficial unconfined (water-table) aquifer is the dominant source of water discharging to streams and rivers (fig. 3). Principal controls on the ground-water residence times in the unconsolidated deposits of the surficial aquifer include widely varied permeabilities (and associated recharge) and aquifer thicknesses. The bottom of the water-table aquifer is the top of the first underlying confining unit.

More published work on ground-water residence times and ages has been done in the Coastal Plain HGMR than in the other HGMR’s. Therefore, the Coastal Plain HGMR section includes a more detailed discussion of the comparison of apparent ages and estimated residence times with corresponding published information than is presented for the other HGMR’s.

Speiran (1996) used CFC analysis to determine apparent ages and age distributions of ground water within a section of the water-table aquifer on the Eastern Shore of Virginia (fig. 10). The average apparent age in water from 10 wells of varying depths was about 18 years. The average recharge rate at this study site was about 0.2 ft/yr (Speiran, 1996). Given a representative aquifer thickness of 20 ft, and a porosity of 0.3, the estimated residence time of this aquifer is 30 years (eq. 6). If there is an exponential age distribution, the average age of water should occur at a depth of 0.632 times the aquifer thickness as assumed by the reservoir model (Vogel, 1967). The 30-year contour (fig. 10) is consistent with this characteristic of aquifers with an exponential age distribution; however, the average apparent ages of water from CFC analyses are not. This could be caused by a number of reasons including insufficient CFC-age data and (or) invalid model assumptions. Similar results were obtained using equation 6 for two other sites (Speiran, 1996) having thicknesses of 30 and 35 ft and recharge rates of 0.45 and 0.75 ft/yr (not shown).

McFarland (1995) found ground-water residence time to be about 10 years by use of a flow model within a section of the water-table aquifer in the Patuxent River Basin, Md. The average apparent age of water from four wells was 5 years. The representative thickness of the aquifer is approximately 20 ft, the recharge rate is about 0.66 ft/yr, and the porosity is about 0.3; thus, the estimated residence time is about 9 years (eq. 6). The 9-year contour is toward the middle of this aquifer (not shown).

Table 1. *Field parameters and apparent ages of water collected from selected springs in the Chesapeake Bay watershed during September and November 1996*

[(1), sample collected in September 1996; (2), sample collected in November 1996; C, contaminated; M, modern; C, degrees Celsius; mg/L, milligrams per liter; µS/cm, microsiemens per centimeter at 25 degrees Celsius; --, no data; do., ditto]

Spring name	Spring no.	Water temperature (C)	Dissolved oxygen (mg/L)	pH	Specific conductance (µS/cm)	Apparent age (year)
4-H Camp						
(1)	PCx1	13.0	8.04	5.23	46	9
(2)	do.	11.7	6.53	5.07	36	7
Arthur Weiss						
(1)	VRC2	13.9	8.50	6.79	602	7
(2)	do.	11.8	4.93	7.32	445	8
Berkeley Spring						
(1)	VRS1	22.6	3.68	6.77	303	40
(2)	do.	22.0	3.40	6.77	286	48
Black Rock Spring						
(1)	VRC7	13.1	4.35	6.79	420	M
(2)	do.	12.2	4.73	6.87	313	M
Coyner Spring						
(1)	VRC8	12.7	9.4	7.69	197	13
(2)	do.	11.7	6.94	8.16	143	17
Donegal Spring						
(1)	PC1	12.3	4.88	6.76	676	M
(2)	do.	10.1	5.03	7.67	686	M
Hanover Spring						
(1)	PCx4	12.2	8.62	5.66	36	7
(2)	do.	11.1	8.37	6.36	37	9
McAllisterville Spring						
(1)	VRS5	12.3	7.82	4.65	27	10
(2)	do.	9.9	8.44	5.39	24	10
Oregon Ridge Spring						
(1)	PC5	13.0	2.53	7.02	424	6
(2)	do.	12.7	3.25	7.22	301	8
Trout Spring						
(1)	VRC21	12.4	7.24	7.39	545	C
(2)	do.	11.1	7.55	--	552	C

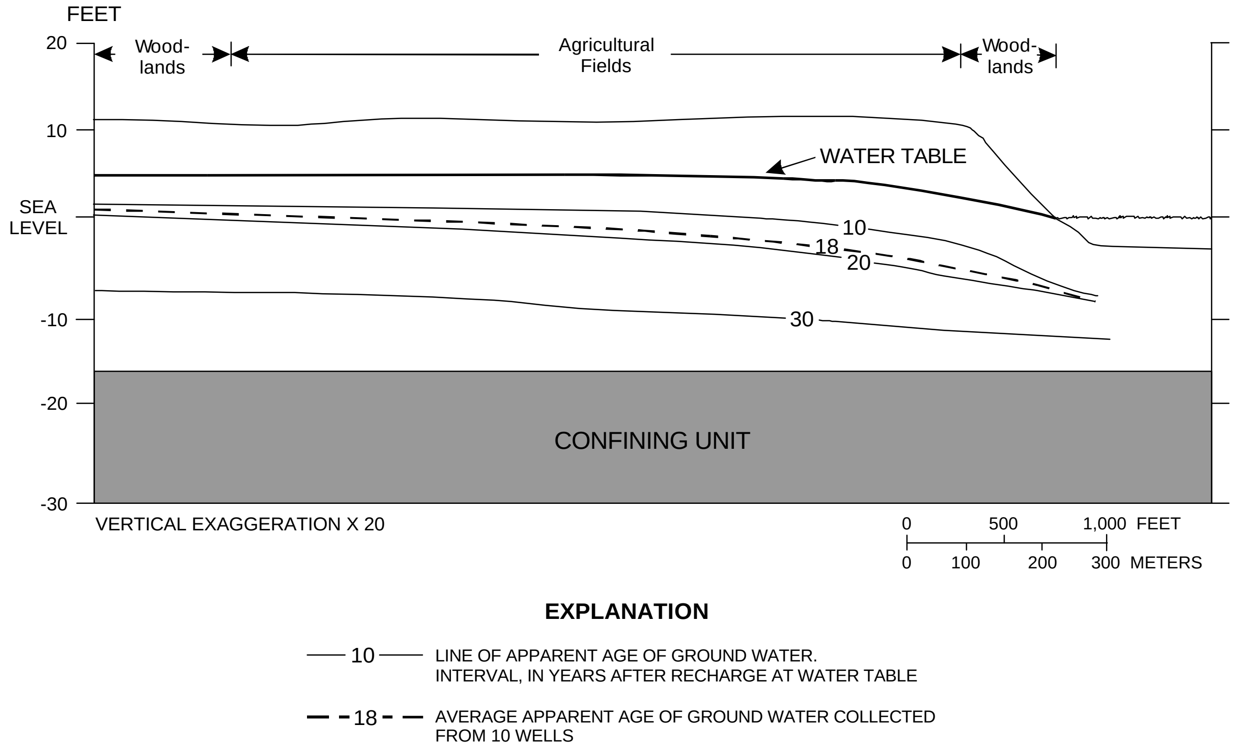

Figure 10. Shallow aquifer in the Coastal Plain with apparent ages of ground water (modified from Speiran, 1996).

Böhlke and Denver (1995) used several methods to investigate residence times and ages of water in the water-table aquifer at study sites on the Delmarva Peninsula. They used concentrations of conservative species in stream water, history of input variations in recharge, and assumed an exponential age distribution for the ground water discharging to the stream. The residence time derived from chemical data (23 to 33 yr) are reasonably consistent with residence times calculated using equation 6 (35 yr) with the observed aquifer thickness under the stream (80 ft), average recharge rate (0.8 ft/yr), and estimated porosity (0.35).

Reilly and others (1994) used a flow model and CFC analysis to analyze flow patterns in a section of the water-table aquifer on the Delmarva Peninsula at the same study site analyzed by Böhlke and Denver (1995). The apparent ages of water from 27 wells of varying depths averaged about 18 years (Dunkle and others, 1993). The average thickness of the section in Reilly and others (1994) was about 60 ft, and they used an average recharge rate of 1.0 ft/yr and a porosity of 0.30. The residence time for the part of the aquifer modeled by Reilly and others (1994) and estimated using equation 6 is 18 years, which is approximately in the center of the aquifer (fig. 11).

The previous studies show that the simple reservoir model can provide reasonable approximations for residence times in the Coastal Plain aquifers when accurate site-specific information is provided. It is informative, therefore, to apply the equation to regional values obtained from the literature.

Common values of aquifer thickness range from 20 to 80 ft, porosity ranges from 0.30 to 0.38, and recharge ranges from 0.33 to

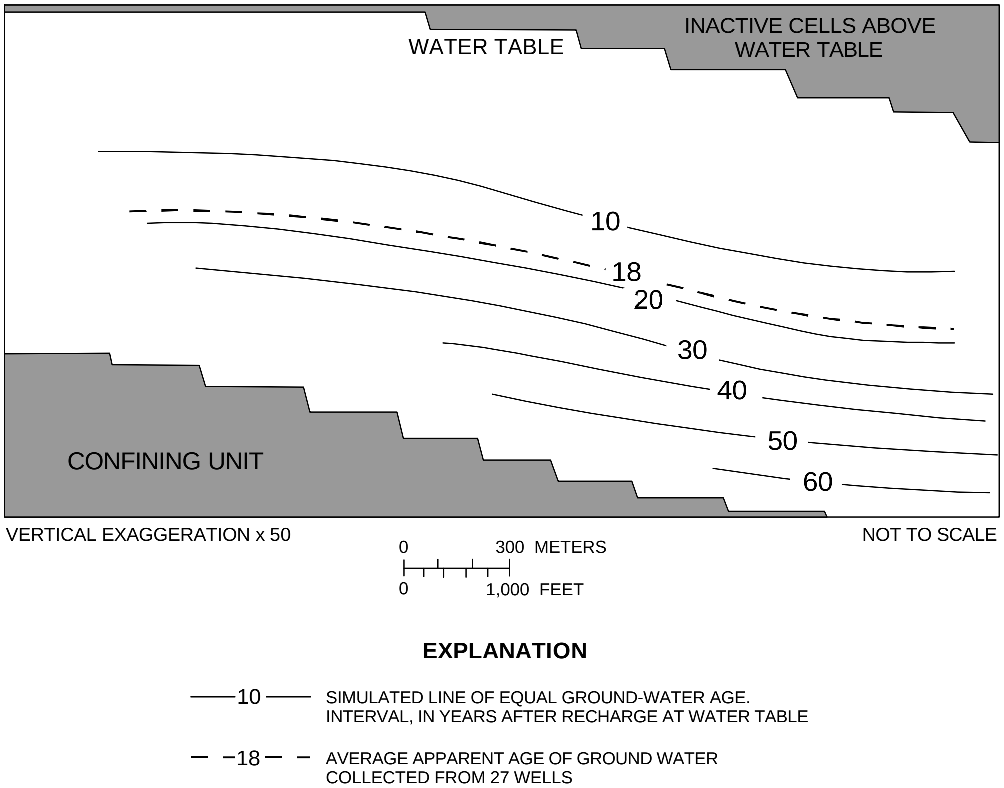

FIGURE 11. SHALLOW AQUIFER IN THE COASTAL PLAIN WITH APPARENT AGES OF GROUND WATER (MODIFIED FROM REILLY AND OTHERS, 1994).

1.8 ft/yr (table 2). The residence times estimated using these ranges of aquifer properties (eq. 6) ranges from slightly more than 1 to 152 years (fig. 12). The largest and smallest residence times are associated with relatively extreme values of porosity, recharge rate, and aquifer thickness. Some combinations of these extreme values probably do not exist. The HGMR residence time generalizations, therefore, must be interpreted within this context; the values listed in this report have been selected to be representative of a range of plausible approximations based on published data.

Two springs were sampled in the Coastal Plain HGMR near Yorktown, Va., for CFC analysis in August 1996. The apparent ages were 6 to 12 years (table 3; appendix B).

Piedmont Crystalline Hydrogeomorphic Region

The Piedmont crystalline hydrogeomorphic region is an area underlain by metamorphic and igneous rocks that form a gently rolling upland generally having less than 500 ft of local relief. The crystalline aquifers are the most common aquifers in the Piedmont and are overlain by unconsolidated material known as regolith. Regolith is composed of saprolite, colluvium, alluvium, and soil. Saprolite is bedrock material that has weathered in place. Colluvium is weathered rock material that has been transported from higher elevations. Alluvium is sediment that has been transported by running water. Generally, the water-table aquifer is in the regolith and extends to the underlying bedrock. The un-weathered bedrock usually is much less permeable than the regolith. The different components of the regolith have diverse hydraulic properties

Table 2. *Representative aquifer characteristics from previous studies in the Coastal Plain hydrogeomorphic region*

[ft/yr, feet per year; ft, feet; <, less than; --, not applicable; do., ditto]

Reference	Recharge (ft/yr)	Thickness (ft)	Porosity	Notes
Böhlke (written commun., 1997)	0.82	80	0.35	Study sites on the Delmarva Peninsula.
Brockman and Richardson (1994)	--	25 to 50	--	Depth to confining unit in York County, Va. Aquifer is composed of various unconsolidated deposits that cross stratigraphic boundaries locally and ranges in thickness from a few ft to more than 100 ft.
Harsh and Laczniak (1990)	.83	<80	--	The authors suggest that the water-table aquifer in the entire Virginia Coastal Plain is typically less than 80 ft.
McFarland (1995)	.66	20	.3	Aquifer in the Patuxent River Basin, Md.
Rasmussen and Andreasen (1959)	1.8	--	.36 to .38	Recharge value determined during 1 year of study. The range in porosity is for three different types of sediments in the Beaverdam Creek Basin, Md.
Reilly and others (1994)	1.0	60	.30	A cross sectional ground-water-flow model on the Delmarva Peninsula.
Richardson (1993)	.63 to 1.0	--	--	Recharge has a median of 0.83 ft/yr in Coastal Plain Physiographic Province of Virginia.
Speiran (1996) (1)	.33	20	.3	Cross section on the Eastern Shore of Virginia.
Speiran (1996) (2)	.75	35	--	do.
Speiran (1996) (3)	.45	30	--	do.

depending, in part, on grain size, macropores, foliations, lineations, and degree of sorting. The residence time of water in these aquifers depends on the primary and secondary porosity and permeability of the regolith, and of the underlying fractured bedrock and the interconnectedness of the fracture system from recharge to discharge locations (fig. 13). Most zones of high permeability in the Piedmont are related to joints, stress-relief fractures, or cleavage planes not associated with fault zones (Trapp and Horn, 1997). The thickness of Piedmont crystalline aquifers depends on the amount of regolith and the depth and interconnectedness of significant water-bearing fractures.

McFarland (1995) found the average residence time in the water-table aquifer in the Piedmont crystalline HGMR to be about 25 years when the regolith and underlying bedrock are not differentiated. For comparison, the residence time in the saprolite was 23 years, 1.3 years in the alluvium, and 6.2 years in the bedrock (McFarland, 1995). The average recharge age determined by CFC analysis from two samples (including one shallow well in the alluvium, and one deep well in the bedrock) was 17 years. McFarland (1995) used a flow model to show the age distribution within the water-table aquifer (fig. 14). The average thickness of the regolith is about 50 ft, the porosity is 0.4, and the average recharge rate is 0.66 ft/yr.

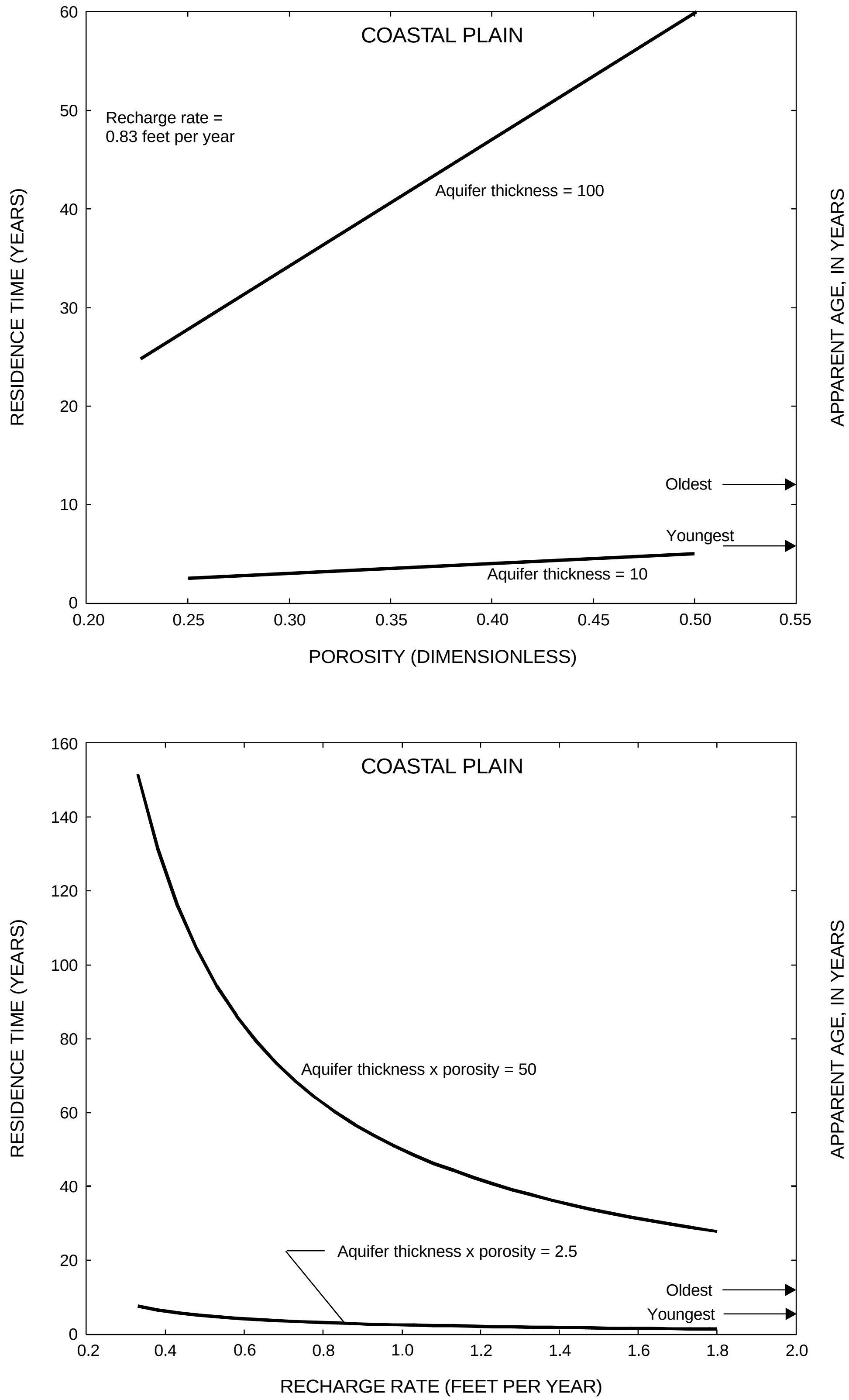

Figure 12. Ranges of aquifer properties, associated residence times, and apparent ages of water collected from springs in the Coastal Plain hydrogeomorphic region.

Table 3. *Apparent ages and estimated residence times of ground water in the Coastal Plain hydrogeomorphic region*

[avg, average; --, not applicable]

	Range in CFC apparent age (years)	**Average residence time from equation 6 (years)**
Speiran (1), (1996)	1 to 39 (avg = 17)	18
Speiran (2), (1996)	1 to 36 (avg = 14)	14
Speiran (3), (1996)	4 to 45 (avg = 24)	20
McFarland (1995)	4 to 6 (avg = 5)	9
Dunkle and others (1993)	2 to 47 (avg = 19)	18
Böhlke and Denver (1989)	Same site as Dunkle and others (1993)	35
Spring (this study)	6 to 12	--
HGMR generalization (this study)	-	1 to 152

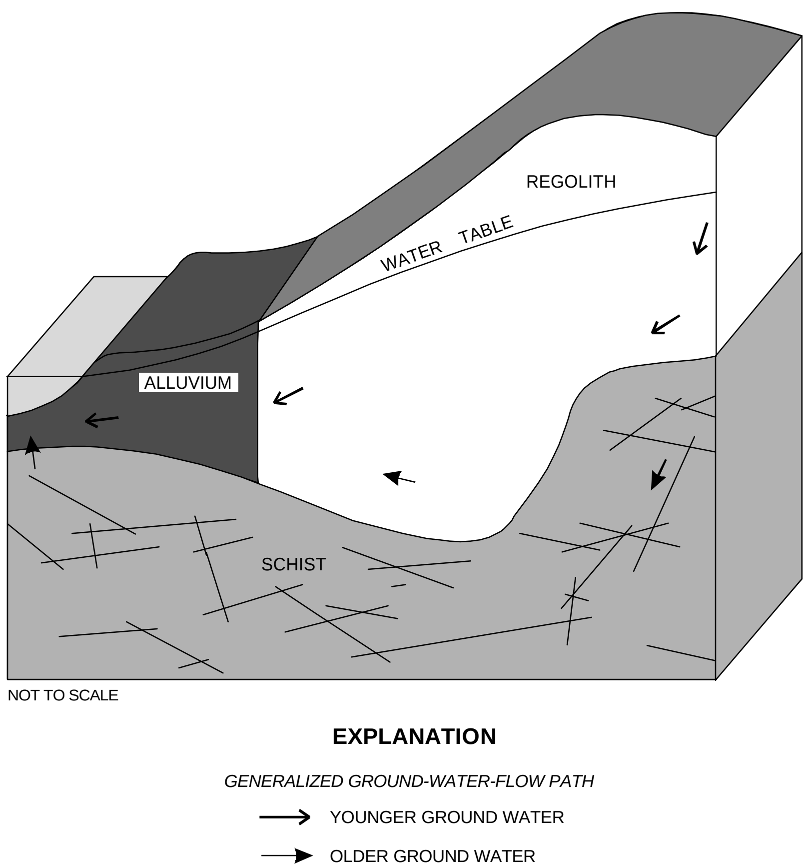

Figure 13. Conceptual ground-water-flow diagram showing the Piedmont crystalline hydrogeomorphic region (modified from McFarland, 1995).

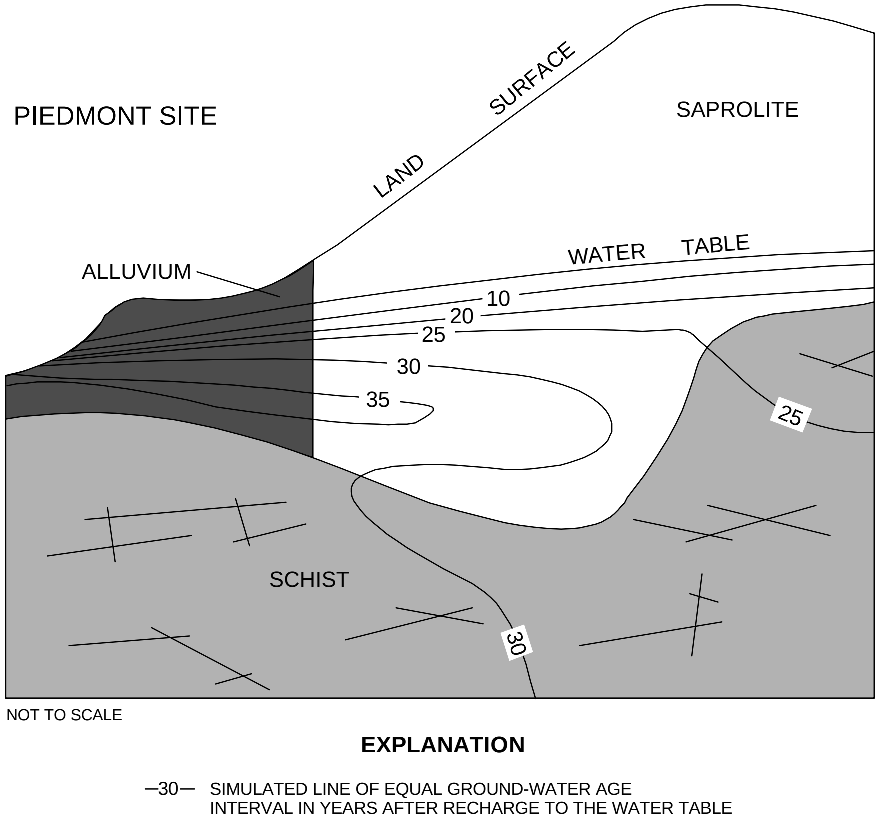

Figure 14. Shallow aquifer in the Piedmont crystalline hydrogeomorphic region and apparent ages of ground water (modified from McFarland, 1995).

Accordingly, the residence time for the regolith is 30 years (eq. 6; fig. 14). The undifferentiated aquifer (regolith and bedrock) is about 120 ft thick, the average porosity is 0.21, and the recharge rate is 0.66 ft/yr. The residence time calculated by equation 6 for the undifferentiated aquifer is 38 years. Nelms and Brockman (1997) sampled wells of varying depths in the Piedmont crystalline HGMR in Prince William County. The apparent ages of water sampled from 14 wells that include some multiple samples from individual wells ranged from modern (recharged within past 2 years) to 28 years and averaged 12 years. Some samples were contaminated by local sources of CFC’s and are not included in this analysis. The concentration of CFC in two wells indicated ages prior to introduction of CFC in the atmosphere about 46 years before sampling. The ages of water from these two wells, if known, would increase the average age of the analyses by an unknown amount; however, if 46 years is used as an approximation the average age would only change to about 17 years. Nelms (oral commun., 1997) states that the age distribution was not a function of depth in the Piedmont as it tends to be in Coastal Plain sediments. It is possible, therefore, to have younger water below (deeper in the aquifer than) older water in these, and similar, settings. Eight wells ranging in depth from 125 to 186 ft were sampled for tritium as part of the USGS National Water-Quality Assessment (NAWQA) program (U.S. Geological Survey, 1994). The tritium concentrations ranged from 21 to 57 pCi/L. The age of the water cannot be determined with this data alone; however, the concentrations indicate that water from all the wells contains at least a portion of post-1950’s water.

Generally, the porosity of regolith ranges from 0.20 to 0.50, but porosity decreases to only 0.0001 to 0.10 in bedrock (Trapp, 1997; McFarland, 1995; Freeze and Cherry, 1979). Accordingly, the overall porosity of the aquifer will depend on the relative contributions of porosity from regolith and the contribution from fractured rock. The part of the aquifer in regolith and the part in fractured rock depends on the thickness and permeability of the regolith and depth of water-bearing interconnected fractures in the bedrock. Representative values of aquifer thickness range from 30 to greater than 350 ft, porosity ranges from 0.01 to 0.5, and recharge ranges from 0.63 to 1.7 ft/yr (table 4). The large ranges in thickness and porosity represent aquifers composed of just the regolith material and aquifers composed of regolith with the underlying bedrock. The residence time estimated using equation 6 and aquifer properties range from less than 1 to 278 years (fig. 15). The largest and smallest residence times are associated with extreme values of porosity, recharge rate, and aquifer thickness. Some combinations of these extreme values probably do not exist. HGMR residence time generalizations, therefore, must be interpreted within this context. The values listed in this report have been selected to be representative of a range of plausible approximations based on published data.

Seven springs were sampled in the Piedmont crystalline HGMR. One of the springs was contaminated with a local source of CFC. The apparent ages of the remaining springs ranged from modern to 34 years (table 5; appendix B). The oldest apparent age was at Green Spring, Va., (PCx3) which also has the highest specific conductance (959 μS/cm) of all springs sampled, the lowest dissolved oxygen (1.44 mg/L) of the non-thermal springs; and other unique properties (sulfate concentration of 580 mg/L). The unique geochemistry of this spring suggests that the apparent age may also be uncommon. The apparent ages in this HGMR range from modern to 10 years if Green Spring is omitted.

Piedmont Carbonate Hydrogeomorphic Region

The Piedmont carbonate hydrogeomorphic region is underlain by metamorphosed carbonate rocks of Paleozoic and Precambrian age, surrounded by the low hills of the Piedmont crystalline HGMR. The relief is commonly less than 100 ft. The land use is heavily agricultural and urban. The carbonate aquifers are of limited areal extent but are significant local sources of water. The carbonate aquifers have little or no primary porosity or permeability, and water moves through secondary openings such as bedding planes, joints, faults, and other voids within the rock that may, or may not, have been enlarged by dissolution (fig. 16). The thickness of carbonate aquifers depends on the depth and interconnectedness of the fracture and dissolution zones and the thickness of the overlying regolith (often called residuum in carbonate areas).

Five wells ranging in depth from 150 to 200 ft were sampled for tritium as part of the USGS NAWQA program (U.S. Geological Survey, 1993) in this HGMR. The tritium concentrations ranged from 9 to 40 pCi/L. The age of the water cannot be determined with this data alone; however, the concentrations indicate that water from all the wells contains at least a fraction of post-1950's water.

Trapp (1997) states that base flow ranges from 57 to 66 percent of streamflow in crystalline rocks, and it is about 77 percent of streamflow in carbonate aquifers. Thus, where precipitation is similar, recharge rates typically are higher in the carbonate HGMR than in the crystalline HGMR. The porosity of carbonate rocks generally is not available because of the negligible primary porosity and the difficulties in estimating secondary porosity. Because the porosity is dominated by secondary controls in these systems, specific yield is sometimes used as a reasonable first approximation of the minimum porosity (Gburek and others, 1994). Values of aquifer thickness range from 100 to greater than 350 ft,

Table 4. *Representative aquifer characteristics from previous studies in the Piedmont crystalline hydrogeomorphic region*

[ft/yr, feet per year; ft, feet; <, less than; --, not applicable]

Reference	Recharge (ft/yr)	Thickness (ft)	Porosity	Notes
Harned (1989)	--	30	--	Most flow is within the upper 30 ft due to permeability contrasts at a study site in Md.
McFarland (1995)	0.66	50	0.40	Average values of the regolith at a study site in Md.
McFarland (1995)	.66	120	.21	Average values of the undifferentiated aquifer (including regolith and bedrock) at a study site in Md.
McFarland (1995)	--	30 to 106	--	McFarland (1995) showed that 30 to 106 ft of regolith overlaid a Piedmont crystalline aquifer in Md.
Pavich and others (1989)	--	45 to 90	--	Typical depth of regolith on schist, gneiss, and granite.
Richardson (1980)	--	300	--	Maximum depth of water-bearing fractures.
Rutledge (1996)	.63 to 1.7	--	--	Eight basins that were entirely in the Piedmont crystalline HGMR, averaging 1.1 ft/yr recharge.
Swain (1993)	--	350 to 650	--	Significant water-bearing zones in the Piedmont.
Trainer and Watkins (1975)	--	400	--	Transmissivity of schist aquifers becomes limiting below about 400 ft with the highest transmissive zones in the top 100 ft in the Potomac River Basin.
Trappe (1997), McFarland (1995) and Freeze and Cherry (1979)	--	--	.20 to.50 .0001 to.10	Averages of regolith and bedrock, respectively.

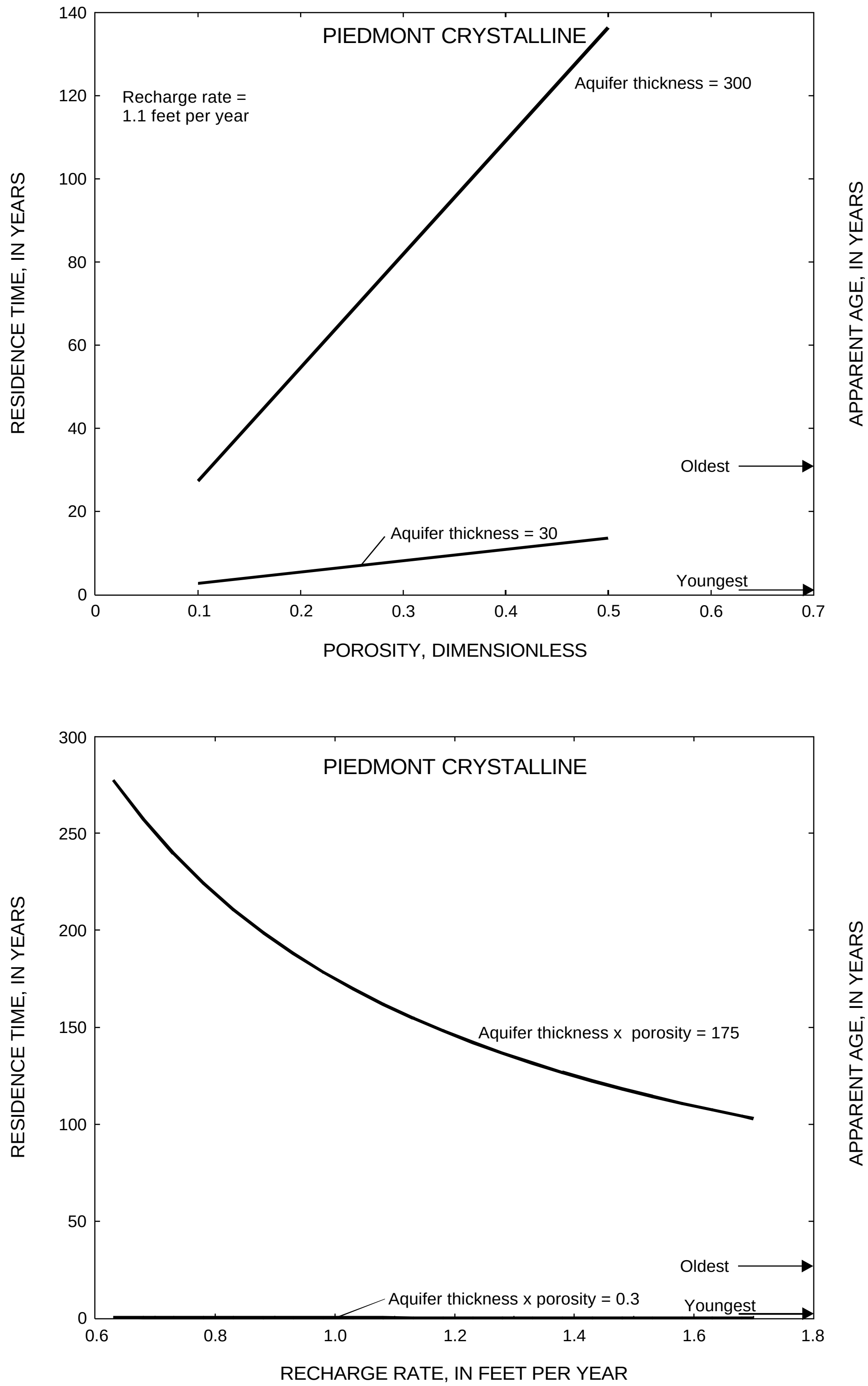

Figure 15. Ranges of aquifer properties, associated residence times, and apparent ages of water collected from springs in the Piedmont crystalline hydrogeomorphic region.

Table 5. *Apparent ages and estimated residence times of ground water in the Piedmont crystalline hydrogeomorphic region*

[avg, average; --, not applicable]

	Range in CFC apparent age (years)	**Average residence time from equation 6 (years)**
McFarland (1995)	4 to 30 (avg = 17)	30 to 38
Nelms (1997)	1 to 28 with several older than 46 (avg = 12)	--
Spring (this study)	Modern to 34	--

porosity ranges from 0.05 to 0.4, and recharge ranges from 1.75 to 1.92 ft/yr (table 6). In order to illustrate the extreme range of plausible aquifer thicknesses, a low value of 10 ft (representing a thin regolith) is used in the calculation of residence times. The residence time estimated using equation 6 and extreme aquifer properties ranges from less than 1 to 80 years (fig. 17). The largest and smallest residence times are associated with extreme values of porosity, recharge rate, and aquifer thickness. Some combinations of these extreme values probably do not exist. Therefore, the HGMR residence time generalizations must be interpreted within this context; the values listed in this report have been selected to be representative of a range of plausible approximations based on published data.

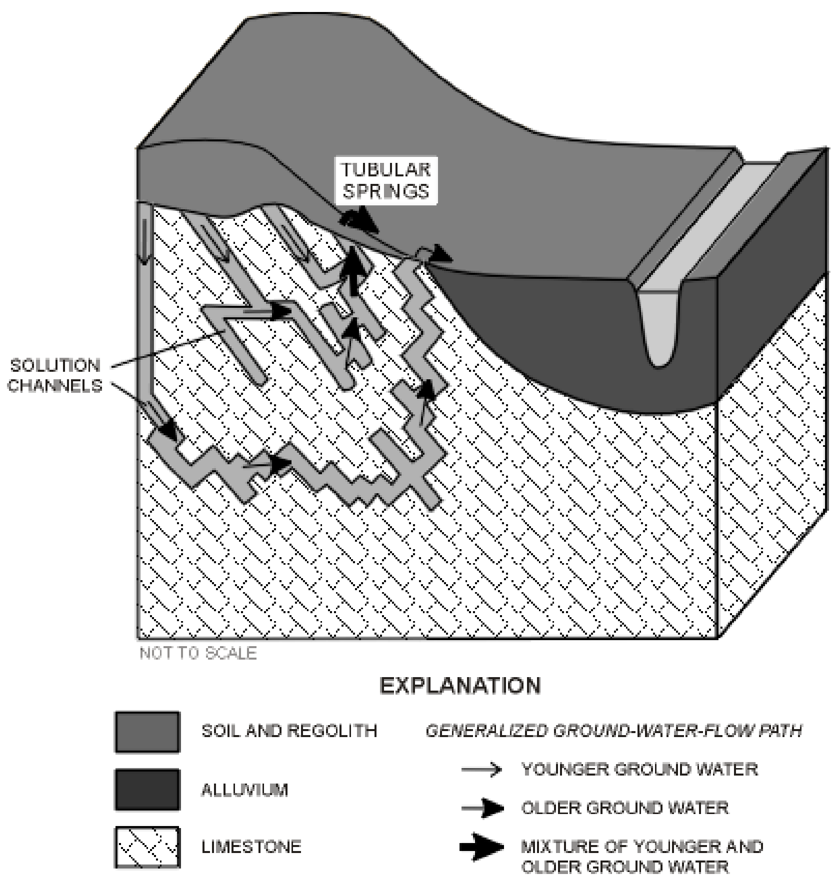

Figure 16. Conceptual ground-water-flow diagram showing the Piedmont carbonate and Valley and Ridge carbonate hydrogeomorphic regions (modified from Brahana and others, 1986).

Table 6. *Representative aquifer characteristics from previous studies in the Piedmont carbonate hydrogeomorphic region*

[ft/yr, feet per year; ft, feet; <, less than; --, not applicable]

Reference	Recharge (ft/yr)	Thickness (ft)	Porosity	Specific yield	Notes
Cecil (1988)	--	200	--	--	Thickness is based on the maximum depth to water-bearing zones in the Furnace Creek Basin, Pa.
Koerkle and others (1996)	1.92	--	--	.05 to.1	Carbonate aquifer in Lancaster County, Pa.
Nutter (1973)	--	--	.003 to .09 .48 to .53	--	Carbonates and residuum, respectively.
Sloto (1990)	1.75	100 420	--	.04 to.12	Five-year study of an aquifer that is chiefly composed of carbonate rock in Chester County, Pa., 50 percent of the water-bearing zones are encountered within 100 ft of land surface, and 99 percent are encountered within about 420 ft.
Sloto and others (1991)	1.81	350	--	.03 to.065	Study during a 9-year period in Lehigh County, Pa. Thickness is based on the maximum depth to water-bearing zones.
Trainer and Watkins (1975)	--	100 to 200	--	--	Transmissivity of carbonate aquifers in the Potomac River Basin, Md., decreases significantly below 100 to 200 ft.

Six springs in the Piedmont carbonate HGMR were sampled for CFC analysis in September1996. The apparent ages ranged from 0 to 7 years (table 7).

Table 7. *Apparent ages and estimated residence times of ground water in the Piedmont carbonate hydrogeomorphic region*

	Range in CFC apparent age (years)	Average residence time from equation 6 (years)
Spring (this study)	Modern to 7	--
HGMR generalizations (this study)	--	1 to 80

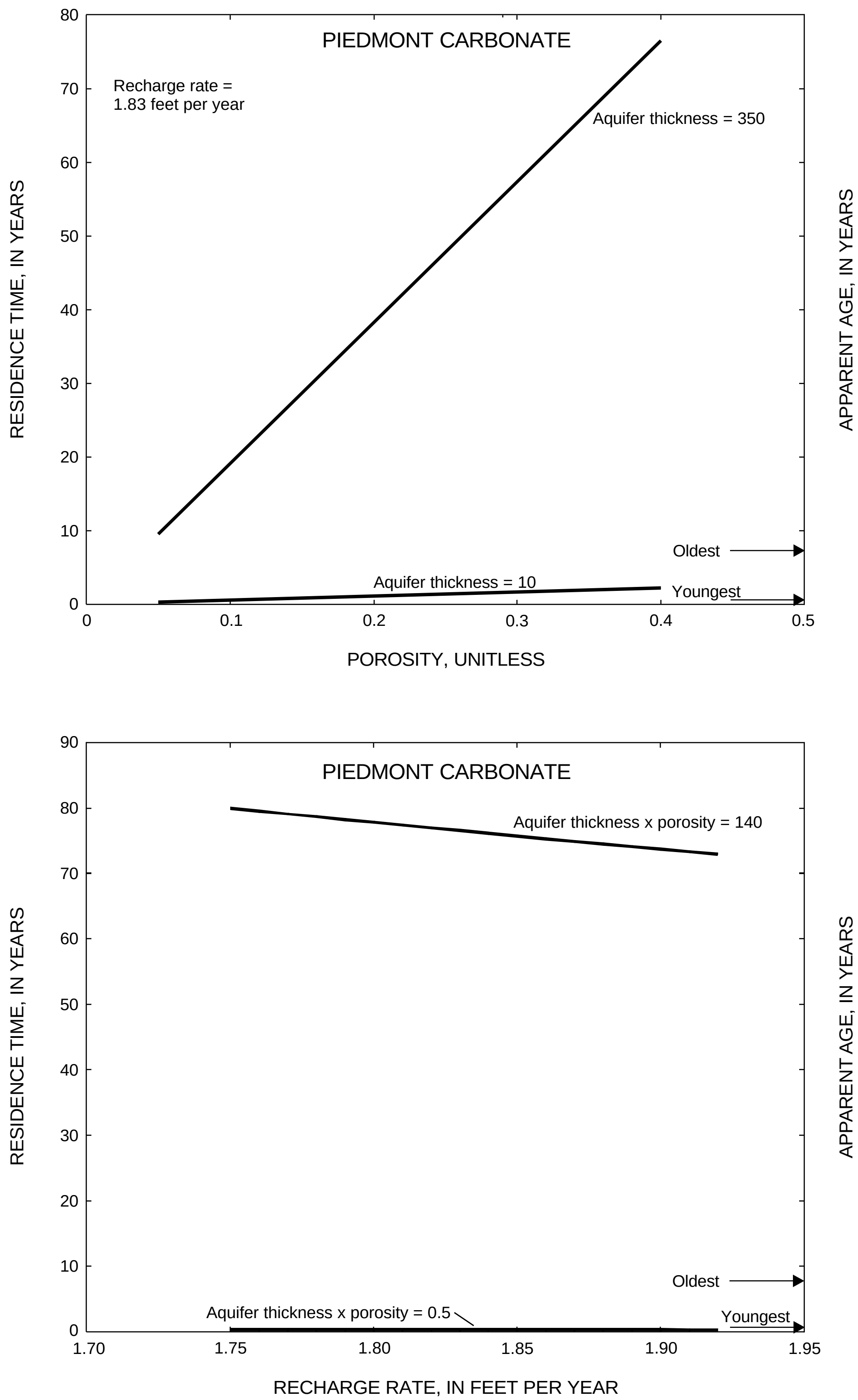

Figure 17. Ranges of aquifer properties, associated residence times, and apparent ages of water collected from springs in the Piedmont carbonate hydrogeomorphic region.

Mesozoic Lowland Hydrogeomorphic Region

The Mesozoic Lowland is an area underlain mostly by red sandstones and shales, but includes some igneous and metamorphic rocks. Relief is commonly less than 500 ft. The land use is heavily agricultural and urban. Aquifers in the Mesozoic Basins include sedimentary beds of sandstone, arkose, and conglomerate. These rocks have been consolidated and compacted, thus, ground-water movement in the primary pore spaces is limited. Additionally, igneous intrusions into these rocks have low primary porosity and in places, function as impermeable boundaries to ground-water flow. Consequently, water in these aquifers moves primarily along secondary features, such as joints, fractures, and bedding planes (fig. 18). Intervening confining units effectively inhibit flow and most ground water flows parallel to the strike of bedding planes. The permeability and water-yielding properties of these aquifers differs with depth and degree of weathering of the characteristically thin regolith, the interconnectedness of fractures, and the bedding plane controls. The thickness of these aquifers depends on the depth to the underlying confining unit, and could be limited by the depth and interconnectedness of fracturing and bedding planes. Confined aquifers with significant water-bearing potential likely exist at depths below the surficial water-table aquifer.

Nelms and Brockman (1997) sampled 30 wells in the Culpeper Basin in Virginia for CFC's, and list apparent ages that range from modern (0 to 4 years) to 33 years. Sixteen of the wells were contaminated by local sources of CFC's, indicating a source of modern water, and one well had a recharge age greater than 46 years. Assuming the water having a recharge age greater than 46 years is associated with the deeper more isolated

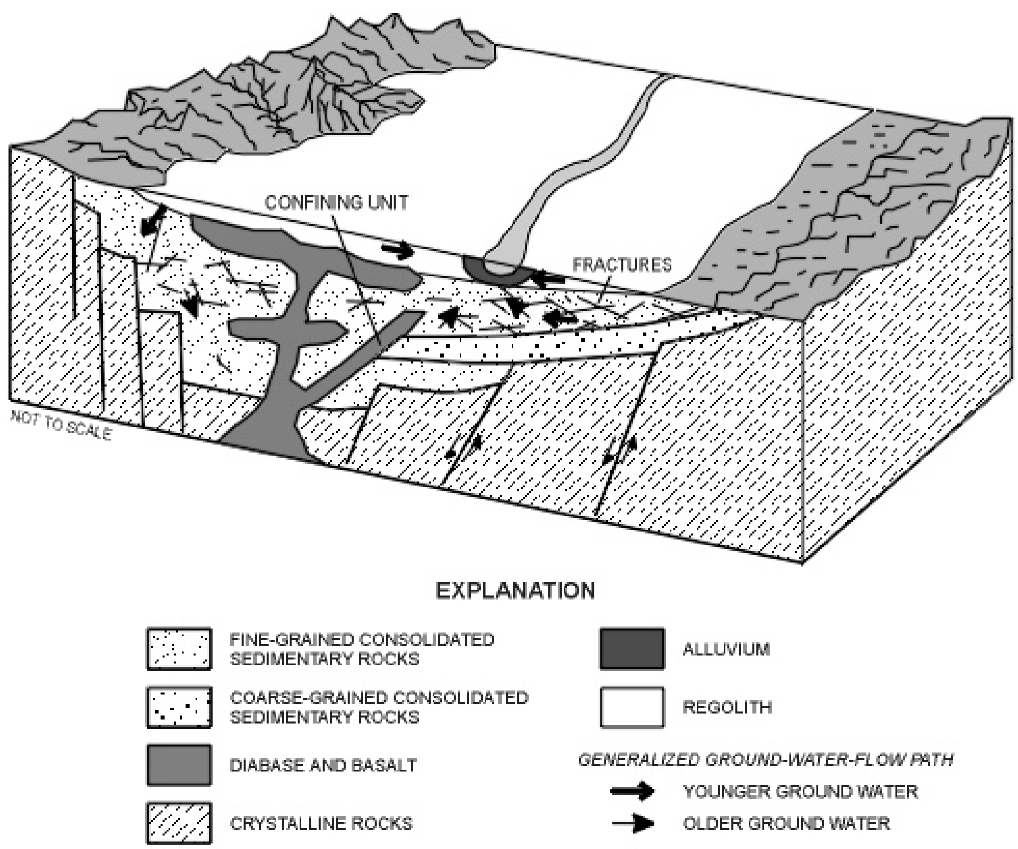

Figure 18. Conceptual ground-water-flow diagram showing the Mesozoic Lowland hydrogeomorphic region (modifed from Turner-Peterson and Smoot, 1985).

aquifers, the average recharge age of the remaining wells was 14 years. It is possible that young water can be found at depth and sometimes below (deeper in the aquifer) older water. In Prince William County, Va., Nelms and Richardson (1990) sampled a well that was contaminated with volatile organic compounds (VOC's). The only known source of VOC's in the area originated 10 to 15 years earlier and was 2 to 3 miles away. The first water-bearing zone in this well was about 800 ft below land surface--this suggests that even the deep parts of some of these systems can be hydraulically connected to shallow parts miles away.

Estimates of aquifer thickness based on the depth to water-bearing zones may be particularly inaccurate in this HGMR because of dikes, sills, confining units, and other restrictions to flow that effectively isolate the surficial aquifer from the deeper aquifers that are the major water sources. Also, as in all fractured rock aquifer systems, deeper aquifers may have hydraulic connections to shallower systems. Nutter (1975) notes that the residuum overlying the Triassic Basins generally is thin and difficult to relate to well yield. Nutter (1975) also notes that significant water-bearing zones in the Triassic Basins are often found at much greater depths than those in the metamorphic and igneous rocks found elsewhere in the Piedmont. Published values of aquifer thickness range from 100 to 500 ft, porosity ranges from 0.01 to 0.42, and recharge ranges from 0.3 to 1.1 ft/yr (table 8). In order to illustrate the extreme range of plausible aquifer thicknesses, a low value of 10 ft (representing a thin regolith) is used in the calculation of residence times. The residence time estimated using equation 6 and extreme aquifer properties ranges from less than 1 to 300 years (fig. 19).

Table 8. *Representative aquifer characteristics from previous studies in the Mesozoic Lowland hydrogeomorphic region*

[ft/yr, feet per year; ft, feet; <, less than; --, not applicable]

Reference	Recharge (ft/yr)	Thickness (ft)	Porosity	Notes
Becher (1989)	--	100 150	--	Depth to water-bearing zone in diabase sills and dikes are less than 100 ft deep and are rare below a depth of 150 ft.
Nutter (1975)	--	500	0.24 to.42 .01 to.06	Triassic rocks in Md.; residuum and hard rock, respectively. Thickness is based on the maximum depth to water-bearing zones in the sedimentary aquifers.
Otton (1981)	--	250	.01 to.14	Thickness is based on the maximum depth to water-bearing zones in the Triassic rocks of western Montgomery County, Md. Porosity is of the sedimentary rock.
Rutledge and Mesko (1996)	0.7 to 1.1	--	--	Range of four basins in the Mesozoic Lowland, averaging 0.9 ft/yr recharge.
Taylor and Werkheiser (1984)	.3 to 1.1	--	--	Recharge to the Triassic rocks of Pa., averaging 0.7 ft/yr.

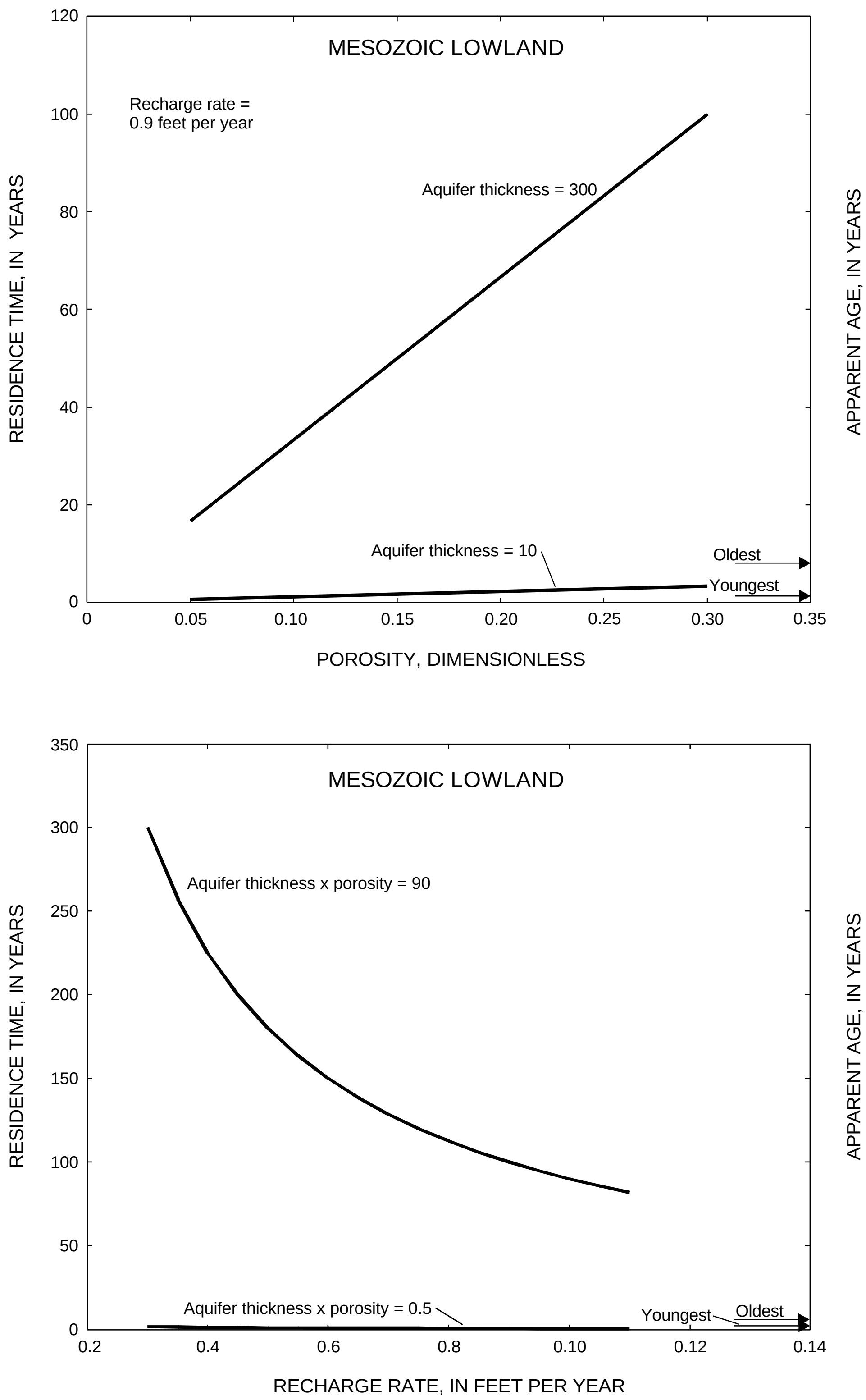

Figure 19. Ranges of published aquifer properties, corresponding residence times, and apparent ages of water collected from springs in the MesozoicLowland hydrogeomorphic region.

The largest and smallest residence times are associated with extreme values of porosity, recharge rate, and aquifer thickness. Some combinations of these extreme values probably do not exist. The HGMR residence time generalizations, therefore, must be interpreted within this context. The values listed in this report have been selected to be representative of a range of plausible approximations based on published data.

Three springs were sampled in this HGMR; one was sampled in September 1996, and two were sampled in November 1996. The apparent ages ranged from modern (0 to 4 years) to 9 years (table 9; appendix B).

Table 9. *Apparent ages and estimated residence times of ground water in the Mesozoic Lowland hydrogeomorphic region*

[avg, average; --, not applicable]

	Range in CFC apparent age (years)	Average residence time from equation 6 (years)
Nelms and Brockman (1997)	Modern to 33 (avg = 14)	--
Springs (this study)	Modern to 9	--
HGMR generalization (this study)	--	1 to 300

Blue Ridge Hydrogeomorphic Region

The Blue Ridge hydrogeomorphic region is an area underlain mostly by crystalline rocks having some minor siliciclastics. Relief is commonly greater than 500 ft, and the land use is mostly forested. The Blue Ridge aquifers chiefly consist of metamorphic and igneous rocks overlain by patches of regolith that generally are thinner than regolith found in the Piedmont (Trapp, 1997). The regolith increases in thickness down the flanks of mountains (fig. 20). Colluvium composed of gravel- to boulder-sized rocks dominates the regolith in many areas. The relief and consequently the hydraulic gradients are higher in the Blue Ridge than many other parts of the Chesapeake Bay watershed. Where regolith is thin or absent, however, flow can be limited or enhanced depending on the fracture system. Most zones of high secondary porosity and permeability in the Blue Ridge hard rock areas are related to joints, stress-relief fractures, or cleavage planes not associated with fault zones (Trapp, 1997). The thickness of these aquifers depends on the thickness of the regolith and depth and interconnectedness of significant water-bearing fractures.

Nelms and Brockman (1997) sampled eight wells in the Blue Ridge Physiographic Province in Prince William County, Va. The apparent ages from the eight wells ranged from 7 to 26 years and averaged 14 years. One well is listed as contaminated by local sources of CFC’s, indicating source of modern water (0 to 4 years). Plummer (unpub. data, 1996) used CFC data to determine that water from 17 wells with depths from 200 to more than 500 ft ranged from 0 to 22 years and averaged about 10 years.

Rutledge and Mesko (1996) showed that precipitation and recharge in the Chesapeake Bay watershed varied the most in the Blue Ridge Physiographic Province. Recharge ranged from 0.8 to about 3.8 ft/yr and averaged about 2.0 ft/yr. The high rate of recharge (3.8 ft/yr) is due to greater amounts of precipitation by orographic effects. Values of aquifer thickness range from 10 to 300 ft, porosity ranges from 0.05 to 0.2, and recharge ranges from 0.8 to 3.8 ft/yr (table 10). The residence time estimated using equation 6 and extreme aquifer properties ranges from less than 1 to 75 years (fig. 21). The largest and smallest residence times are associated with extreme values of porosity, recharge rate, and aquifer thickness. Some combinations of these extreme values probably do not exist. The HGMR residence time generalizations, therefore, must be interpreted within this context. The values listed in this report have been selected to be representative of a range of plausible approximations based on published data.

Plummer sampled 34 springs in this HGMR for CFC analyses in the spring of 1996. The apparent ages of the springs ranged from modern to about 8 years (table 11).

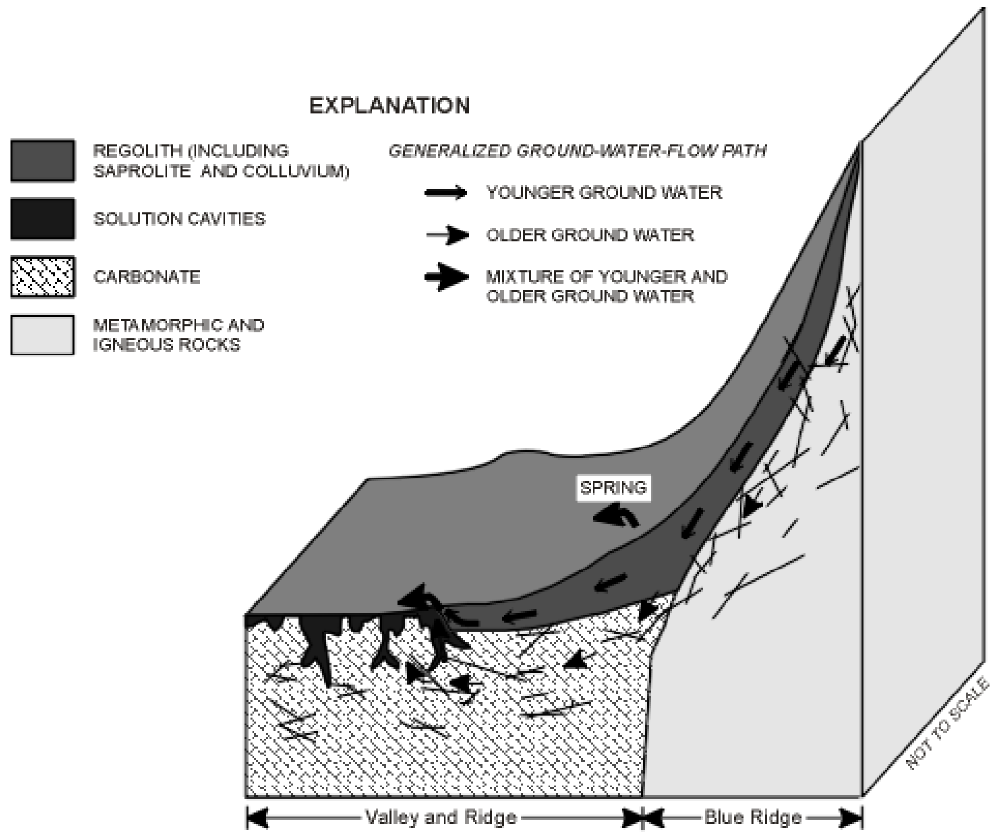

Figure 20. Conceptual ground-water-flow diagram showing the Blue Ridge hydrogeomorphic region (modified from Nutter, 1974).

Table 10. *Representative aquifer characteristics from previous studies in the Blue Ridge hydrogeomorphic region*

[ft/yr, feet per year; ft, feet; <, greater than; --, not applicable]

Reference	Recharge (ft/yr)	Thickness (ft)	Porosity	Specific yield	Notes
Becher and Root (1981)	--	150	--	--	Thickness is based on the maximum depth to water-bearing zone on the flanks of South Mountain in Pa.
Duigon and Dine (1987)	--	--	--	0.012 to.21	Various sites in Md.
Freeze and Cherry (1979)	---	--	0 to.1 .05 to.5	--	Fractured crystalline rock and fractured basalt, respectively.
Hinkle and Sterret (1978)	--	>100	--	--	Depth to bedrock in Augusta County, Va.
Rutledge and Mesko (1996)	0.8 to 3.8	--	--	--	Average recharge of 2.0 ft/yr throughout Blue Ridge Physiographic Province. High recharge is associated with orographic precipitation.
Taylor and Royer (1981)	--	100 300	--	--	Most major water-bearing zones in the igneous and metamorphic rocks are within 100 ft below land surface with few deeper than 300 ft in Pa.

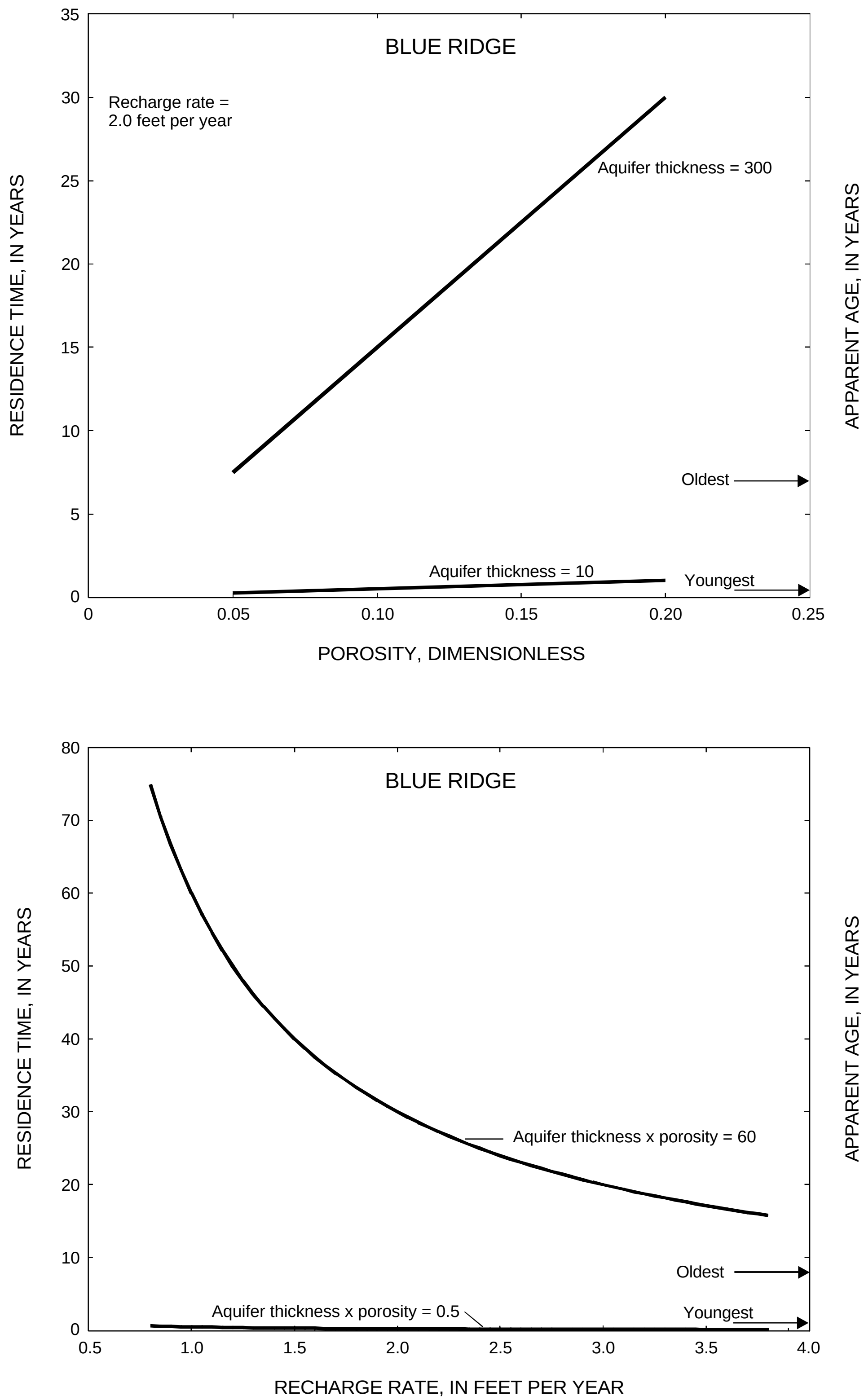

Figure 21. Ranges of aquifer properties, associated residence times, and apparent ages of spring water in the Blue Ridge hydrogeomorphic region.

Table 11. *Apparent ages and estimated residence times of ground water in the Blue Ridge hydrogeomorphic region*

[avg, average; --, not applicable]

	Range in CFC apparent age (years)	Average residence time from equation 6 (years)
Nelms and Brockman (1997)	7 to 26 (avg = 14)	--
Plummer (unpub. data, 1996)	modern to 22 (avg = 10)	--
Springs (Plummer, written commun., 1996; this study)	modern to 8	--
HGMR generalization (this study)	--	1 to 75

Valley and Ridge Siliciclastic Hydrogeomorphic Region

The Valley and Ridge siliciclastic region is an area of intensely folded siliclastic rocks, where relief is commonly greater than 500 ft. The land use is mostly forested with some agriculture in the valleys. Shales of Cambrian and Ordovician age and sandstones of Ordovician to Devonian age are the principal rocks that compose the siliciclastic aquifers in the Valley and Ridge Physiographic Province. Some primary porosity exists in these aquifers; however, intense folding and faulting of the rocks produced significant secondary porosity and permeability (fig. 22). Open tension fractures associated with anticlinal axes are common where large springs and significant water-bearing zones are present. In some areas the underlying fracture system extends to depths where geothermal heating of the ground water takes place.

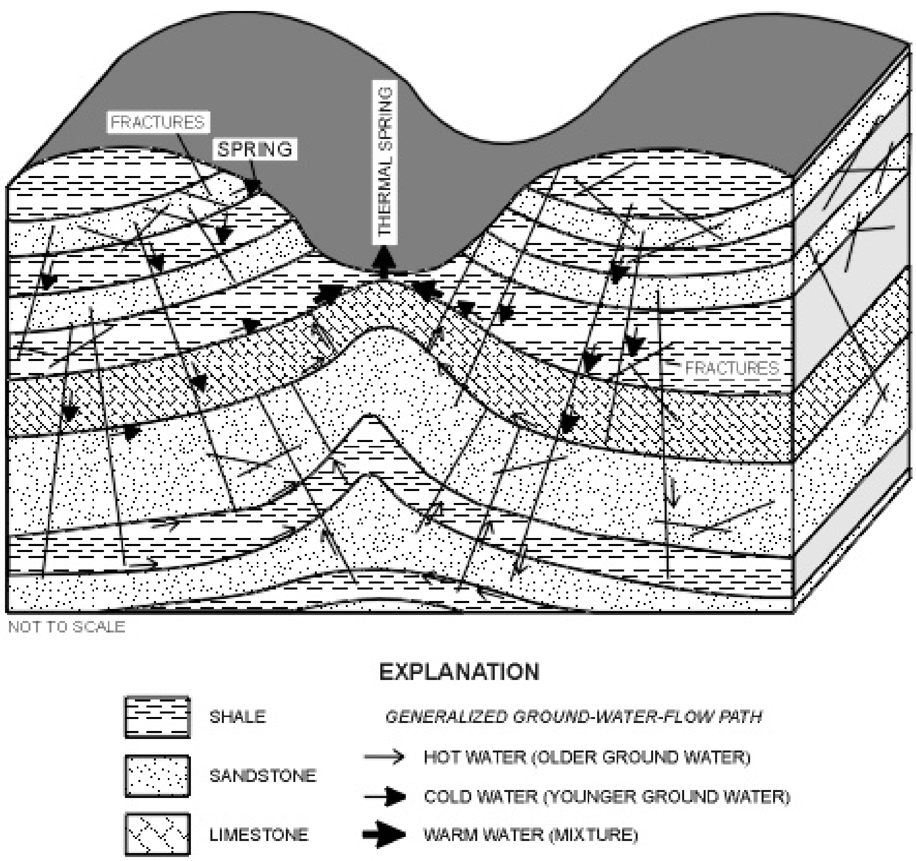

Figure 22. Conceptual ground-water-flow diagram showing the Valley and Ridge siliciclastic hydrogeomorphic region (modified from Hobba and others, 1979).

Residence time in thermally affected aquifers is likely much longer than in most other aquifers in the Chesapeake Bay watershed due to long flow paths associated with geothermal heat sources. The thickness of these aquifers depends on the thickness of the regolith and the depth and interconnectedness of the fracture and bedding plane zones.

Thirteen wells ranging in depth from 80 to 200 ft were sampled for tritium as part of the USGS NAWQA program (U.S. Geological Survey, 1993) in this HGMR. The tritium concentrations ranged from 6 to 57 pCi/L. The age of the water cannot be determined with this data alone; however, the concentrations indicate that water from all the wells contains at least some post-1950's water.

Gburek and others (1994) developed a ground-water-flow model of a siliciclastic aquifer in Pennsylvania. They showed that the aquifer consists of localized highly fractured zones superimposed on a regional flow system. The depth of the highly fractured zone is about 10 to 30 ft, the depth of a moderately fractured zone is about 30 to 75 ft, and the thickness of the regional aquifer is about 75 to 270 ft. The annual recharge rate to the aquifer was about 1.2 ft/yr, and the porosity estimated from the specific yield ranged from 0.0001 (regional aquifer) to 0.005 (local aquifer). Traveltimes in the aquifer system were shown to be on the order of tens of days (fig. 23). These short traveltimes are limited by the low values of porosity that Gburek and others (1994) used in their simulations; for example, the residence time (eq. 6) with an aquifer thickness of 270 ft, a porosity of 0.0001, and a recharge rate of 1.2 ft/yr is much less than 1 year.

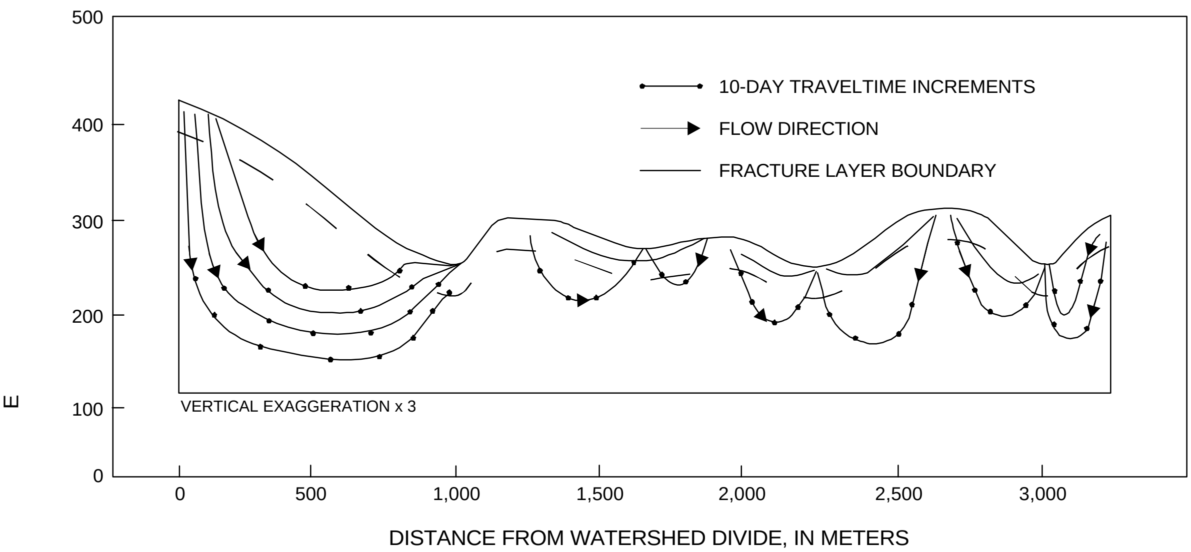

Figure 23. Simulated traveltimes of ground water in the Valley and Ridge siliciclastic hydrogeomorphic region (modified from Gburek and others, 1994).

Table 12. *Representative aquifer characteristics from previous studies in the Valley and Ridge siliciclastic hydrogeomorphic region*

[ft/yr, feet per year; ft, feet; <, less than; --, not applicable]

Reference	Recharge (ft/yr)	Thickness (ft)	Porosity	Specific yield	Notes
Becher and Taylor (1982)	--	--	--	0.005	Shales in the Valley and Ridge in Pa.
Freeze and Cherry (1979)	--	--	0.05 to.30	--	Sandstone.
Gburek and others (1994)	1.2	75 to 270	.0001 to.005	--	Highly fractured zone = 10 to 30 ft. Moderately fractured zone = 30 to 75 ft in ground-water-flow model in Pa.
Hinkle and Sterret (1978)	--	<50	--	--	Thickness is based on the maximum depth to bedrock in Augusta County, Va.
Lloyd and Carswell (1981)	--	150 to 200	--	--	Thickness is based on the maximum depth to water-bearing zones in the sandstone aquifers in Pa.
Royer (1984)	1.0	max 300 avg 100	--	--	Thickness is based on depths of major water-bearing zones in the siliciclastic aquifers, in Perry County, Pa.
Rutledge and Mesko (1996)	.9 to 1.5	--	--	--	Recharge for six subbasins of the Bay watershed that predominantly drain the Valley and Ridge Siliciclastic.
Williams and Eckhardt (1987)	--	50 to 100 200	--	--	Carbonate and siliciclastic aquifers, and noncarbonate aquifers, respectively, in east-central Pa.
Williams and Senko (1988)	--	600	--	.02 to .04	The thickness of an aquifer system which included a siliciclastic formation, a carbonate formation, and glacial outwash was recorded to be about 600 ft in a ground-water-flow model in Colombia County, Pa.
Wright (1988)	--	<80	--	--	Overburden thickness in Clarke County, Va.

Values of aquifer thickness range from 50 to greater than 300 ft, porosity ranges from 0.0001 to 0.3 and recharge ranges from 0.9 ft/yr to 1.5 ft/yr (table 12). The residence time estimated using equation 6 and extreme aquifer properties ranges from less than 1 to 100 years (fig. 24). The largest and smallest residence times are associated with relatively extreme values of porosity, recharge rate, and aquifer thickness. Some combinations of these extreme values probably do not exist. The HGMR residence time generalizations, therefore, must be interpreted within this context. The values listed in this report have been selected to be representative of a range of plausible approximations based on published data.

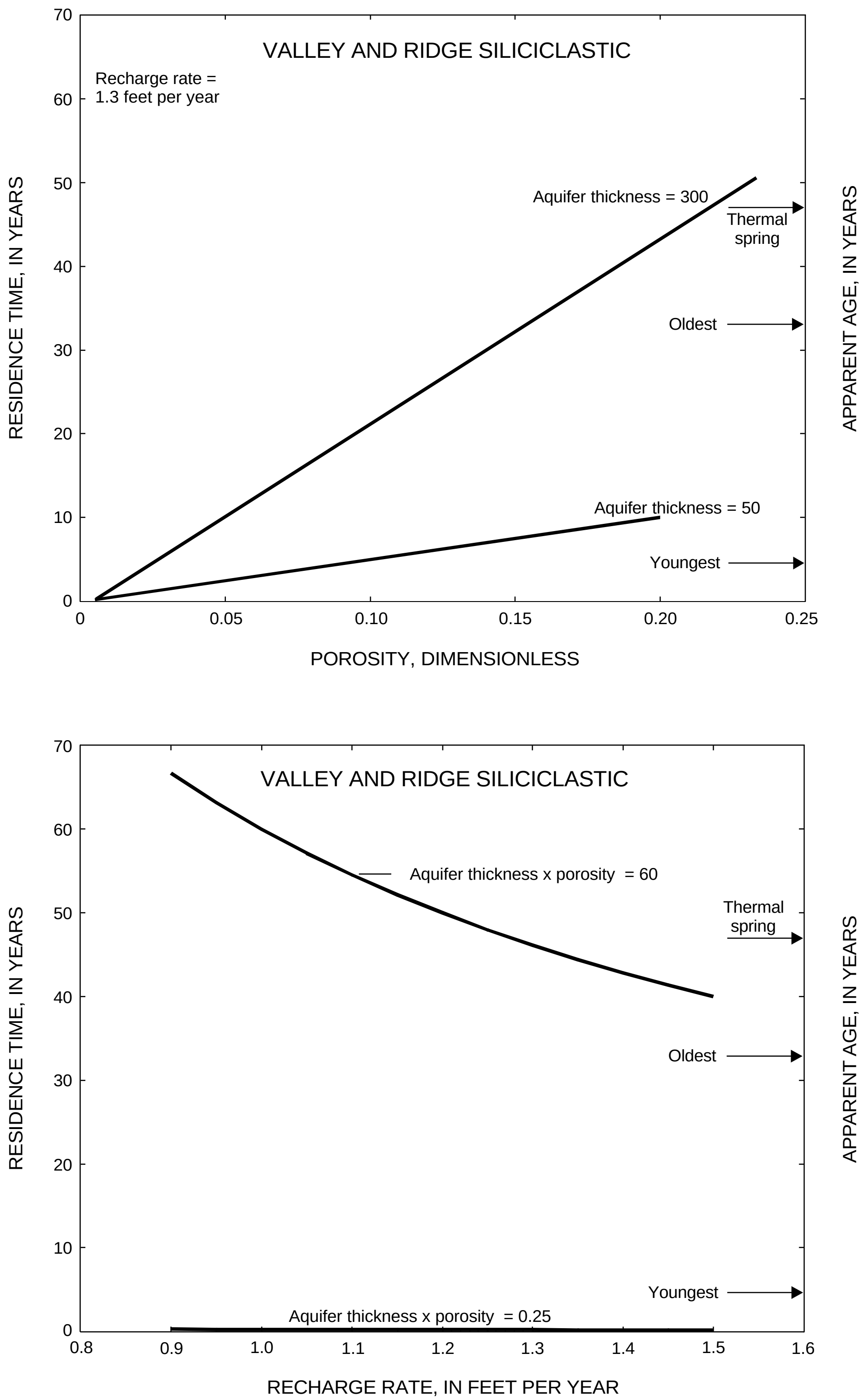

Figure 24. Ranges of aquifer properties, associated residence times, and apparent ages of water collected from springs in the Valley and Ridge siliciclastic hydrogeomorphic region.

Seven springs were sampled in September 1996 for CFC analysis. The apparent ages ranged from 5 to 40 years (table 13; appendix B). The oldest recharge age (40 years) was in a thermally influenced spring from Berkeley, W. Va. Excluding the thermal spring, the apparent ages range from 5 to 33 years.

Valley and Ridge Carbonate Hydrogeomorphic Region

The Valley and Ridge carbonate region is an area of intensely folded limestone and dolomite, where relief is usually less than 500 ft. The land use is heavily agricultural and karst topography is widespread. Generally, the carbonate aquifers in this region are limestones of Cambrian, early Ordovician, late Silurian, and early Devonian age. These limestone aquifers are typically found in the valleys and the water-yielding zones, and permeability depends on the degree of fracturing and development of solution cavities. The thickness of the regolith (often referred to as residuum in carbonate terrane) is highly varied, but tends to be thinner over carbonate rocks than other rocks (Nutter, 1973) in Maryland. In some areas the underlying fracture system extends to depths where geothermal heating of the ground water takes place (fig. 22). Residence time in geothermally affected aquifers is likely much longer than in most other aquifers in the Chesapeake Bay watershed due to the long flow paths necessary to reach geothermal heat sources. The thickness of these aquifers depends on the depth and interconnectedness of the fracture, joints, bedding-plane partings, and solution-cavity zones.

Matthew Ferrari (oral commun., 1997) sampled water from wells at depths ranging from 12 to 62 ft in the Muddy Creek Basin in Virginia. The apparent ages of water from the wells ranged from modern (less than 4 years) to about 20 years. Twenty wells ranging in depth from 65 to 243 ft were sampled for tritium as part of the USGS NAWQA program (U.S. Geological Survey, 1994; 1995). The tritium concentrations ranged from 33 to 60 pCi/L. The age of the water cannot be determined with this data alone; however, the concentrations indicate that water from all the wells contains at least some post-1950's water.

Table 13. *Apparent ages and estimated residence times of ground water in the Valley and Ridge siliciclastic hydrogeomorphic region*

[--, not applicable]

	Range in CFC apparent age (years)	Average residence time from equation 6 (years)
Springs (this study)	5 to 40 (thermally influenced spring = 40)	--
HGMR generalization (this study)	--	1 to 100

Values of aquifer thickness range from 50 to greater than 350 ft, porosity ranges from 0.003 to 0.53, and recharge ranges from 0.8 to 1.9 ft/yr (table 14). The estimated residence time (eq. 6 and extreme aquifer properties) ranges from about 1 to 232 years (fig. 25). The longest and shortest residence times are associated with extreme values of porosity, recharge rate, and aquifer thickness. Some combinations of these extreme values probably do not exist. Therefore, the HGMR residence time generalizations must be interpreted within this context. The values listed in this report have been selected to be representative of a range of plausible approximations based on published data.

Twenty-one springs were sampled in September 1996 for CFC analysis, including one at Warm Springs, Va., which is geothermally affected. The apparent age of the water issuing from the thermally influenced spring was greater than 50 years. The apparent ages of the remaining 20 springs ranged from modern (0 to 4 years) to 32 years (table 15; appendix B).

Appalachian Plateau Siliciclastic Hydrogeomorphic Region

The Appalachian Plateau Siliciclastic region is an area of flat-lying to gently folded (dips rarely exceeding 10 degrees) siliciclastic rocks. The area has high relief, commonly exceeding 500 ft; with resulting steep hydraulic gradients, it is mostly

Table 14. *Representative aquifer characteristics from previous studies in the Valley and Ridge carbonate hydrogeomorphic region*

[ft/yr, feet per year; ft, feet; <, less than; --, not applicable]

Reference	Recharge (ft/yr)	Thickness (ft)	Porosity	Specific yield	Notes
Chichester (1996)	1.0 1.3 1.9	650	--	--	Ground-water-flow model for three different basins in the Cumberland Valley, Pa., where thickness is based on the maximum depth to water-bearing zones.
Freeze and Cherry (1979)	--	---	0.05 to.50	--	Ranges in karst limestone.
Hinkle and Sterret (1977)	--	400 to 500	--	--	Highest well yields in Shenandoah County, Va.
Kozar and others (1991)	--	400	.03 to.06	--	Thickness is based on the maximum depth to water-bearing zones in carbonate aquifers of Jefferson County, W. Va.
Nutter (1973)	.8	300	.003 to.09 .48 to.53	--	Frederick and Hagerstown Valleys, Md. Porosities are of carbonates and residuum, respectively. Thickness represents the maximum depth of solution cavities.
Rutledge and Mesko (1996)	.92 to 1.2	--	--	--	Five basins in the Valley and Ridge carbonates in Chesapeake Bay watershed.
Shultz and others (1995)	---	--	--	0.05	Carbonate rocks of Berkeley County, W. Va.
Sloto (1990) (1)	1.8	600	--	--	Carbonate-dominated drainage basin in Eastern Chester County, Pa.
Sloto (1990) (2)	--	100 200	--	.04 to.12	Thickness is based on the maximum depth to water-bearing zones in carbonate-rock aquifers in Eastern Chester County, Pa.
Sloto and others (1991)	1.8	150 250	--	.034 to .065 avg .051	Carbonate rocks of Lehigh County, Pa. Thickness is based on the maximum depth to water-bearing zones.
Trainer and Watkins (1975)	--	--	--	.03 to .04	Carbonate aquifers in the Potomac River Basin.

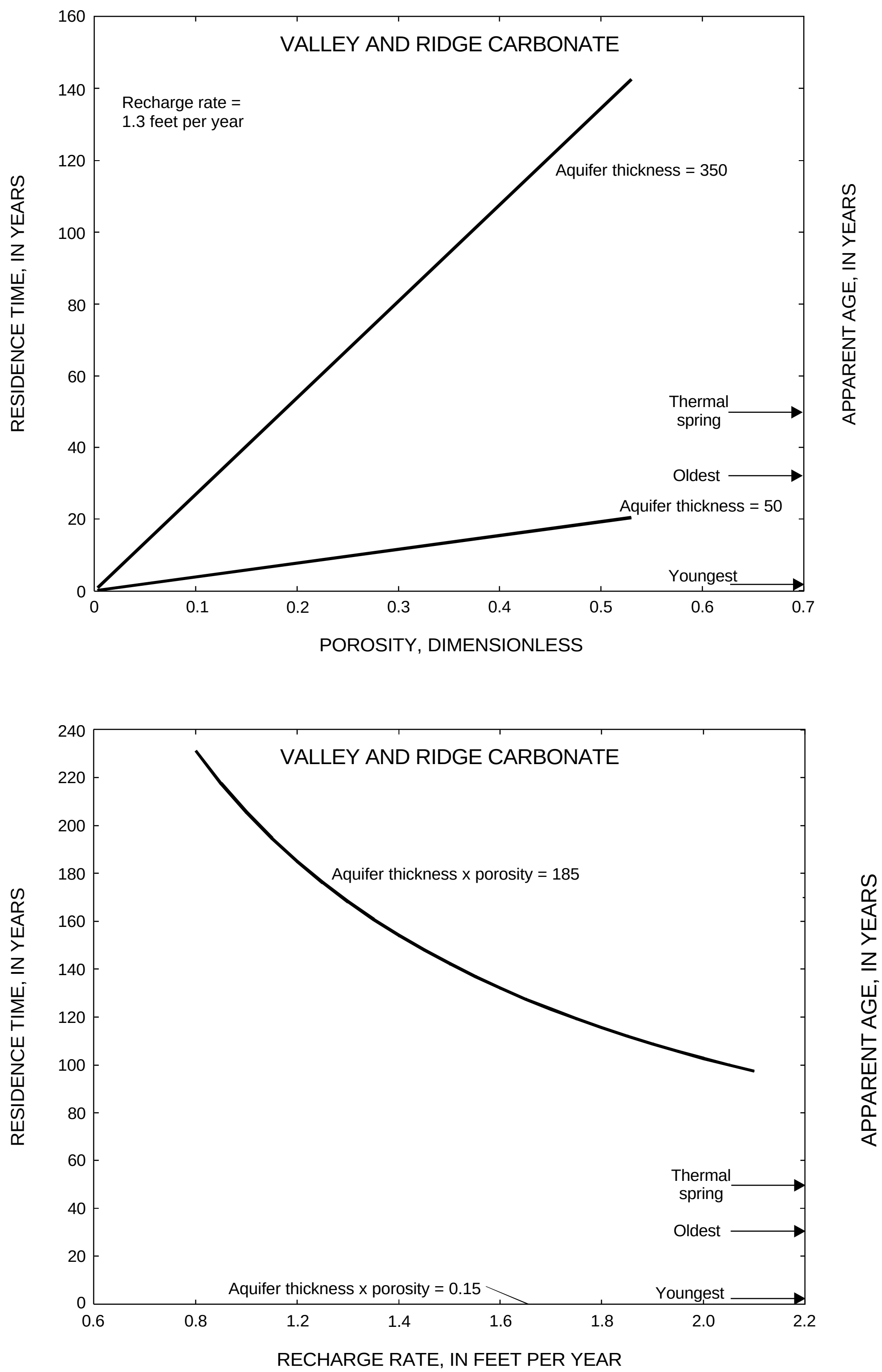

Figure 25. Ranges of aquifer properties, associated residence times, and apparent ages of water collected from springs in the Valley and Ridge carbonate hydrogeomorphic region.

Table 15. *Apparent ages and estimated residence times of ground water in the Valley and Ridge carbonate hydrogeomorphic region*

[--, not applicable]

	Range in CFC apparent age (years)	Average residence time from equation 6 (years)
M.J. Ferrari (oral commun., 1997)	modern to 20	--
Springs (this study)	modern to 32 (thermally influenced springs older than 50)	--
HGMR generalization (this study)	--	1 to 232

forested except for small towns and areas that have been disturbed by strip mining for bituminous coal. Aquifer material in this unit is composed of flat-lying to gently folded, consolidated sedimentary rocks of Mississippian to Permian age (fig. 26). The principal water-yielding rocks are sandstones, though transmissive zones are found in coal seams and other rocks. The less permeable siliciclastics that are usually siltstones and shales can function as confining units. The thickness of the surficial aquifer depends on the depth to the confining units and it is limited by the depth and interconnectedness of fracturing in the aquifer.

Tritium was analyzed in water from 13 springs in the Appalachian Plateau Physiographic Province of West Virginia in 1993 (M.D. Kozar, oral commun., 1997). The tritium values indicated that water from all springs

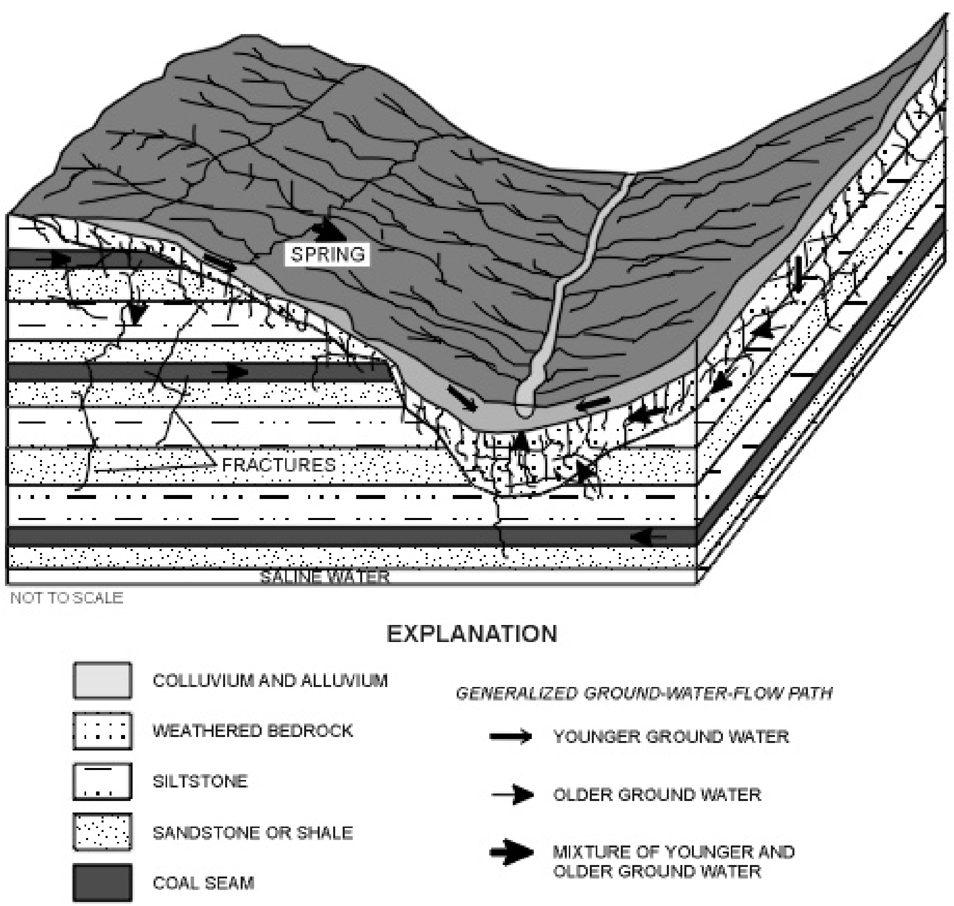

Figure 26. Conceptual ground-water-flow diagram showing the Appalachian Plateau siliciclastic hydrogeomorphic region (modified from Harlow and LeCain, 1991).

Table 16. *Representative aquifer characteristics from previous studies in the Appalachian Plateau siliciclastic hydrogeomorphic region*

[ft/yr, feet per year; ft, feet; <, less than; --, not applicable]

Reference	Recharge (ft/yr)	Thickness (ft)	Porosity	Notes
Freeze and Cherry (1979)	--	--	0.05 to 0.3	Porosity of sandstone.
Lohman (1938)	--	100 to 150	--	South-central Pennsylvania confined siliciclastics. Thickness is based on the maximum depth to water-bearing zones.
Rutledge and Mesko (1996)	1.4 1.7	--	--	Two basins draining the Appalachian Plateau in the Bay watershed.
Taylor and others (1983)	1.3	250	--	West Branch Susquehanna River, Pa. Thickness is based on the maximum depth to water-bearing zones in the sandstone and shale of the Appalachian Plateaus.
Taylor (1984)	.86 1.0	< 200	--	Two basins underlain by siliciclastics in the Upper Susquehanna River Basin. Thickness is based on the maximum depth to water-bearing zones.

contained at least some post-1950’s water, and some had mixtures of water from the early to possibly mid-1970’s (L.N. Plummer, oral commun., 1997).

Values of aquifer thickness range from 100 to 250 ft in the previous studies cited in this report (table 16) but values of 50 to 300 ft were used to represent a range. Porosity ranges from 0.05 to 0.3 and recharge ranges from 0.9 to 1.7 ft/yr (table 16). The residence time estimated using equation 6 and extreme aquifer properties ranges from about 1 to 100 years (fig. 27). The largest and smallest residence times are associated with extreme values of porosity, recharge rate, and aquifer thickness. Some combinations of these extreme values probably do not exist. The HGMR residence time generalizations, therefore, must be interpreted within this context; the values listed in this report have been selected to be representative of a range of plausible approximations based on published data.

No springs were sampled in this HGMR. Table 17 summarizes results from previous studies.

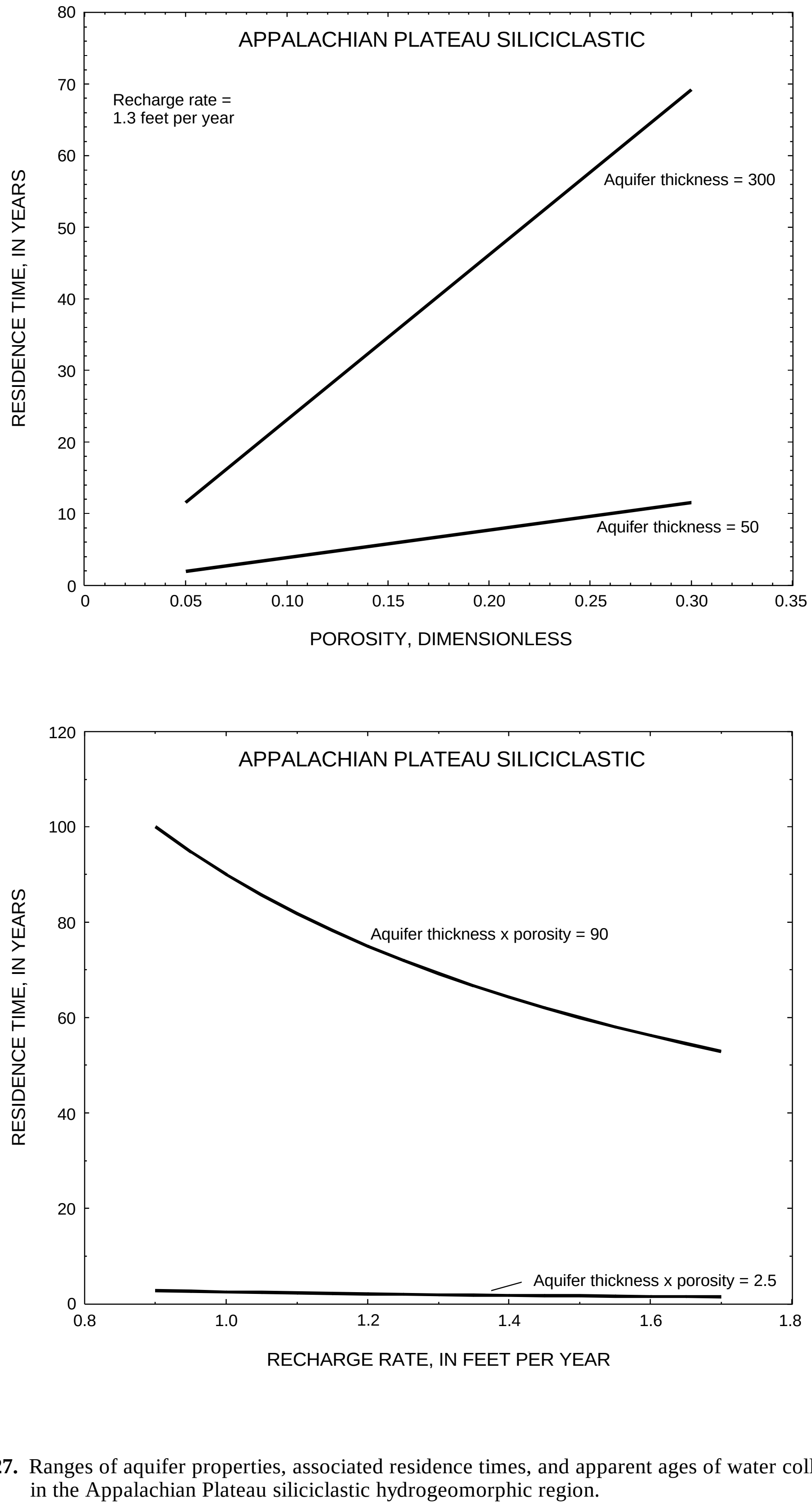

Figure 27. Ranges of aquifer properties, associated residence times, and apparent ages of water collected from springs in the Appalachian Plateau siliciclastic hydrogeomorphic region.

Table 17. *Apparent ages and estimated residence times of ground water in the Appalachian Plateau siliciclastic hydrogeomorphic region*

[<, younger than; --, not applicable]

	Range in CFC apparent age (years)	Average residence time from equation 6 (years)	Tritium analyses (years)
Springs (this study)	None	--	--
HGMR generalization (previous studies)	--	1 to 100	--
M.D. Kozar (oral commun., 1997)	--	--	<47

DISCUSSION

Aquifer characteristics obtained from the published literature and used to estimate ground-water residence times for this report are considered representative of reasonable ranges in values. Actual values of aquifer thickness, porosity, and recharge rates will vary locally, and specific data from some local-scale studies may not be presented in this report. Illustrations have been developed that depict the relation of a reasonable range of aquifer characteristics and associated residence times as a continuum for each HGMR studied. In this way, the natural variability of aquifer characteristics can be seen graphically with data from selected representative studies. The illustrations show that the range in measured apparent ages is not associated with the extreme ranges in estimated residence time. This supports the assertion that some combinations of extreme aquifer values are probably unrealistic. The most reasonable ranges in aquifer properties (and associated residence times) likely are somewhere between the two extreme curves in each of the figures. The apparent ages also tend to lie between the two extreme curves in each figure. Thus, the reservoir model and apparent ages provide corroborative evidence that limit the most reasonable estimates of residence times for the HGMR's. Most of the apparent ages are less than 20 years throughout the study area with many less than 10 years. The youngest apparent ages (and similarly, the shortest residence times) tend to be in the Blue Ridge and northern carbonate areas; however, the data are preliminary and not appropriate for statistical tests of significance or variance. In addition, the range of estimates within a given HGMR can be as large as the range between HGMR's.

Thicknesses in consolidated rock aquifers are estimated largely on the basis of the depth below land surface to water-bearing zones. This approach is potentially biased because the data are typically associated with water-supply objectives, and not necessarily with understanding the shallow unconfined aquifers that are important pathways for nutrient delivery to streams and rivers. For example, the Appalachian Plateau siliciclastic HGMR may have major water-bearing zones that are 200 ft deep but only tens of feet thick in a confined aquifer system that may, or may not, be associated with a significant amount of discharge to surface water. In this area, the most important part of the aquifer system for the objectives of this study may be entirely within the regolith. This is also likely in other consolidated rock areas where the regolith stores and transmits most of the recharge water of the shallow aquifer system, and the underlying fracture system does not contribute significantly to the shallow flow system. Nelms and Brockman (1997) and McFarland (1996) have shown, however, that ground water recharged relatively recently is found in wells hundreds of feet deep in fractured rock. Therefore, estimates of aquifer thicknesses are made, in this report, using a range that includes estimates where most shallow flow would be in the regolith and estimates where significant amounts of shallow flow would be in the underlying consolidated rock and the regolith. The latter would produce thicker aquifers and longer residence times if other variables were held constant.

Porosity values probably are the least well documented or understood. The difference between primary and secondary porosity can be orders of magnitude in consolidated rocks and commonly only the primary porosity values are published. In many consolidated rocks the primary porosity is negligible. The specific yield is often used as an indication of the porosity in many consolidated rock aquifers where secondary porosity is assumed to be dominant. Therefore, estimates of porosity are made, in this report, using a range that includes published data on primary porosity, specific yield, and secondary porosity. Lower values of porosities (primary porosity in consolidated rock aquifers) would tend to cause shorter residence times when all other variables are constant.

The authors of the literature cited in this report used different methods to determine recharge rates and variation in the estimates is likely due to methodology. Other sources of variability include differences in precipitation patterns. The recharge rates were compiled from many studies, including a Regional Aquifer Systems Analysis (RASA) of the Appalachian Valley and Piedmont aquifer system (Rutledge and Mesko, 1996). The RASA study showed a strong correlation between recharge and precipitation in one HGMR (Blue Ridge). Though the data included Blue Ridge areas outside of the Bay watershed, this illustrates the potential for variability in recharge, which in this case is presumably caused by orographic precipitation effects and not by aquifer hydraulic properties. Additionally, recharge rates are typically estimated by hydrograph separation and assume, among other things, that the ground-water drainage divide coincides with the surface-water drainage divide. It is possible that some aquifers in a given HGMR are recharged, at least in part, by water from areas that are in a different HGMR.

Aquifer properties, and associated residence times within a given HGMR may have as much or more variation as aquifer properties in a different HGMR. For example, the springs sampled in the Coastal Plain HGMR are all located in a small area in, and near, Yorktown, Va. The aquifers that supply these springs are composed of shelly formations, where the landscape is characterized by deep ravines, and karst-like features. In comparison, in other Coastal Plain areas water flows chiefly through primary pore spaces in mineral sediments where the landscape is characterized by flat topography. Another example is the Town of Elkton spring located in an area known as the western toe of the Blue Ridge and listed in this report in the Valley and Ridge carbonate HGMR. The aquifer properties that affect the Elkton spring may not be typical of the HGMR in which it is located. The aquifer thickness and porosity may be dependent on the colluvium that has been transported from the Blue Ridge, whereas the aquifer thicknesses and porosity elsewhere in the Valley carbonates are more dependent on fracture and dissolution features. In addition, if there is a hydraulic connection from the ridge tops through the colluvium and underlying fracture system to the spring, then parts of the recharge area for the Elkton spring may actually be located within the Blue Ridge.

The absence of nitrate in water from Elkton spring suggests that the recharge area for the spring is not affected by nearby agricultural land uses. The apparent age of ground water from the Elkton spring is 32 years, one of the oldest non-thermal springs analyzed. The apparent ages of ground water from springs in the Blue Ridge are typically modern to 8 years (L.N. Plummer, unpub. data, 1998) and the apparent age of ground water from a nearby spring (Bear Lithia) in the Valley and Ridge Carbonate is 19 years. Ground water from other nearby springs in this HGMR ranges from 16 to 22 years. The reason for the older water at Elkton spring is not known but is indicative of the substantial difference in aquifer characteristics as compared to the other aquifers in the same HGMR. Hinkle and Sterret (1976) showed that wells hundreds of feet deep in the western toe in Rockingham County are capable of producing higher yields with less drawdown than in other parts of the HGMR. Similarly, Becher and Root (1981) showed that colluvium thickness on the western flanks of South Mountain, Pa., averages about 150 ft and is quite variable. Residence times and other associated ground-water characteristics could differ substantially within this HGMR as much, or more than, other HGMR’s; consequently, it is not advisable at this time to interpret residence times as a function of HGMR.

The water samples collected from springs are indicative of the unusual hydrologic event that occurred during the time of sampling and are interesting and informative from an overall hydrologic perspective, but must be qualified when used to represent "average" conditions. Further work is being done to see how apparent ages differ at other flow conditions. It also will be important to review these and new data in terms of the limitations of using a piston-flow model instead of an exponential model to determine apparent ages, and implications of interpreting spring water that may be a mixture of water of different ages.

Conclusions

Improvement in estuary water quality is partially dependent on the amount of time from when nutrients are applied to the land surface, migrate through the shallow ground-water system, and discharge to the estuary or other surface-water body draining to the estuary. Consequently, results of management practices that reduce dissolved-nutrient loadings to ground water may not be seen in surface waters for many years after the practices are in place. This study indicates that the preliminary apparent ages of ground water discharging from springs is modern (0 to 4 years) to 20 years in most of the hydrogeologic environments analyzed and is greater than 20 years in some areas. The apparent age of water from thermally influenced springs is greater than 40 years. Residence times estimated with the most plausible ranges of aquifer properties and results of previous dating analyses generally corroborate the apparent age analysis but suggest that residence times could be much longer in some areas. Nitrate and $\delta^{15}N$ values in water from many springs are similar to those of shallow ground water recharged beneath fertilized fields, whereas some are high enough to indicate probable animal-waste source components. Thus, ground water discharging from some of the springs is a source of nutrients to surface-water bodies.

The results of this study provide important preliminary information for general policy making and land-use planning because they indicate that the residence time of shallow ground water in the Chesapeake Bay watershed commonly is on the order of several years to 2 decades. Additional work to determine how residence times of dissolved nutrients in ground water vary with hydrologic condition, hydrogeologic environment, geochemistry, and land use is suggested before this information could be interpreted and directly incorporated into site-specific resource-management plans or tools.

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Appendixes A through D

Appendix A. *Field parameters of spring water collected in the Chesapeake Bay watershed, September and November 1996*

[^{o}, degrees; ’, seconds; ", minutes; ^{o}C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; µs/cm, microsiemens per centimeter at 25 ^{o}C Celsius; --, missing data]

Spring no.	Name	State	Location	Latitude (^{o} ’ ")	Longtude (^{o} ’ ")	Station no.	Date	Time	Temp (^{o}C)	DO (mg/L)	pH	Specific conductance (µs/cm)
				Coastal Plain Hydrogeomorphic Region								
CP 1	George Washington	VA	Colonial National Historical Park	37 12 11	76 31 53	VA 13	09/01/1996	0800	15.0	2.70	7.20	437
CP 2	CNHP28	VA	Colonial National Historical Park	37 13 55	76 31 02	VA 14	09/01/1996	1300	18.0	6.60	6.60	456
				Piedmont Carbonate Hydrogeomorphic Region								
PC 1	Donegal Spring (1)	PA	Mount Joy	40 06 05	76 33 56	PA-LN-14	09/11/1996	1850	12.3	4.88	6.76	676
PC 1	Donegal Spring (2)	PA	Mount Joy	40 06 05	76 33 56	PA-LN-14	11/20/1996	1445	10.1	5.03	7.67	686
PC 2	Ft. Detrick field hole	MD	Frederick	39 26 49	77 24 44	MD-FR-DE-70	09/24/1996	1620	15.9	3.20	6.81	788
PC 3	Ft. Detrick spring house	MD	Frederick	39 26 51	77 24 53	MD-FR-DE-2	09/24/1996	1737	13.3	4.27	6.70	603
PC 4	Lilypons Spring	MD	Buckeystown	39 16 43	77 27 52	MD-FR-FD-55	09/27/1996	1013	12.5	7.22	6.80	692
PC 5	Oregon Ridge Spring (1)	MD	Oregon Ridge Park	39 29 51	76 41 15	MD-BA-DC-440	09/23/1996	1032	13.0	2.53	7.02	424
PC 5	Oregon Ridge Spring (2) (L2)	MD	Oregon Ridge Park	39 29 51	76 41 15	MD-BA-DC-440	11/19/1996	1230	12.7	3.25	7.22	301
PC 5	Oregon Ridge Spring (2) (L5)	MD	Oregon Ridge Park	39 29 51	76 41 15	MD-BA-DC-440	11/19/1996	1205	12.7	3.25	7.22	301
PC 6	Retirement Center	MD	Baltimore County	39 26 35	76 30 47	MD-BA-DE1	09/23/1996	1420	12.8	5.50	7.05	511
				Piedmont Crystalline Hydrogeomorphic Region								
PCx 1	4-H Camp spring (1)	MD	Harford County	39 37 59	76 24 00	MD-HA-Bc-30	09/23/1996	1717	13.0	8.04	5.23	46
PCx 1	4-H Camp spring (2)	MD	Harford County	39 37 59	76 34 00	MD-HA-Bc-30	11/19/1996	0944	11.7	6.53	5.07	36
PCx 2	Camp 2 Spring	VA	Prince William Forest Park	38 34 41	77 25 08	VA 11	09/20/1996	1010	12.4	7.40	5.26	38
PCx 3	Green Spring	VA	Green Springs	38 00 57	78 09 52	VA 12	11/12/1996	1355	12.9	1.44	7.85	959
PCx 4	Hanover Spring (1)	PA	Hanover	39 50 55	76 57 47	PA-YO-19	09/12/1996	1050	12.2	8.62	5.66	36
PCx 4	Hanover Spring (2)	PA	Hanover	39 50 55	76 57 47	PA-YO-19	11/20/1996	1215	11.1	8.37	6.36	37
PCx 5	Hazelwood Farms	MD	Frederick County	39 28 51	77 12 46	MD-FR-Dg-11	09/24/1996	1101	12.8	7.29	6.48	322

Appendix A. *Field parameters of spring water collected in the Chesapeake Bay watershed, September and November 1996--Continued*

Spring no.	Name	State	Location	Latitude (° ' ")	Longtude (° ' ")	Station no.	Date	Time	Temp (°C)	DO (mg/L)	pH	Specific conductance (µs/cm)
				Piedmont Crystalline Hydrogeomorphic Region--Continued								
PCx 6	Manchester Spring	MD	Westside Memorial Park	39 39 43	76 53 30	MD CL Bf 183	09/27/1996	1332	13.0	3.94	5.81	439
PCx 7	South of Gum Spring	MD	Brunswick City Park	39 18 47	77 37 05	MD-FR-FB-12	09/26/1996	1801	13.9	8.00	6.19	402
				Mesozoic Lowland Hydrogeomorphic Region								
ML 1	Hillbilly Spring (L1)	MD	Feagaville	39 23 16	77 28 28	MD-FR ED 82	11/14/1996	1430	11.5	7.33	7.06	303
ML 1	Hillbilly Spring (L5)	MD	Feagaville	39 23 16	77 28 28	MD-FR ED 82	11/14/1996	1336	11.5	7.33	7.06	303
ML 2	Moravian Church	MD	Thurmont	39 3 656	77 22 43	MD-FR BE 60	09/24/1996	1412	15.6	7.20	5.62	250
ML 3	Phillips Spring	MD	Frederick	39 32 11	77 26 21	MD-FR-PHILS	11/18/1996	0805	12.1	6.69	6.05	174
				Valley and Ridge Carbonate Hydrogeomorphic Region								
VRC 1	Alexander Spring	PA	Carlisle	40 10 05	77 15 53	PA-CU-16	09/10/1996	1605	14.6	8.01	7.05	591
VRC 2	Arthur Weiss Spring (1)	VA	Clarke County	39 08 39	77 54 58	VA 10	09/19/1996	1145	13.9	8.50	6.79	602
VRC 2	Arthur Weiss Spring (2)	VA	Clarke County	39 08 39	77 54 58	VA 10	11/12/1996	1725	11.8	4.93	7.32	445
VRC 3	Bear Lithia Spring	VA	Rockingham County	38 26 08	78 37 08	VA 09	09/18/1996	1425	11.8	8.60	7.23	175
VRC 4	Bellfonte Fishery Spring	PA	Bellfonte	40 52 48	77 47 38	PA-CE-12	09/13/1996	1020	12.8	5.47	6.95	458
VRC 5	Benner Spring	PA	State College	40 51 08	77 49 17	PA-CE-18	09/13/1996	1320	11.7	8.40	6.87	478
VRC 6	Big Spring	PA	Newville	40 07 42	77 24 28	PA-CU-22	09/10/1996	1213	13.7	7.62	6.98	471
VRC 7	Black Rock Spring (1)	MD	Funkstown	39 40 09	77 14 22	MD-WA-CJ-23	09/25/1996	1214	13.1	4.35	6.79	420
VRC 7	Black Rock Spring (2)	MD	Funkstown	39 40 09	77 14 22	MD-WA-CJ-23	11/18/1996	1043	12.2	4.73	6.87	313
VRC 8	Coyner Spring (1)	VA	Waynesboro	38 03 10	78 55 54	VA 01	09/11/1996	1350	12.7	9.40	7.69	197
VRC 8	Coyner Spring (2)	VA	Waynesboro	38 03 10	78 55 54	VA 01	11/12/1996	1121	11.7	6.94	8.16	143
VRC 9	Deerfield Spring	VA	Deerfield	38 11 31	79 24 19	VA 07	09/17/1996	1325	15.7	5.90	6.57	81
VRC 10	Dykeman Spring	PA	Shippensburg	40 02 32	77 30 55	PA-CU-24	09/10/1996	0948	12.5	7.65	7.27	320
VRC 11	Elkton Spring	VA	Elkton	38 24 15	78 36 12	VA 08	09/18/1996	1135	13.7	9.70	7.30	211
VRC 12	Gypsy Hilll Golf Course	VA	Staunton	38 09 25	79 05 16	VA 05	09/13/1996	1305	14.1	9.10	6.91	589

Appendix A. *Field parameters of spring water collected in the Chesapeake Bay watershed, September and November 1996--Continued*

Spring no.	Name	State	Location	Latitude (° ' ")	Longtude (° ' ")	Station no.	Date	Time	Temp (°C)	DO (mg/L)	pH	Specific conductance (µs/cm)
				Valley and Ridge Carbonate Hydrogeomorphic Region--Continued								
VRC 13	Harver Spring	MD	Smithsburg	39 40 39	77 34 18	MD-WA-AK-3	09/25/1996	0945	13.8	6.19	6.73	222
VRC 14	Keedysville Spring	MD	Keedysville	39 29 16	77 41 33	MD-WA-DI-6	09/25/1996	1428	12.7	5.62	6.85	545
VRC 14	Keedysville Spring (L5)	MD	Keedysville	39 29 16	77 4133	MD-WA-DI-6	11/18/1996	1215	11.9	5.69	6.87	410
VRC 14	Keedysville Spring (L2)	MD	Keedysville	39 29 16	7741 33	MD-WA-DI-6	11/18/1996	1245	11.9	5.69	6.87	410
VRC 15	Loth Spring	VA	Waynesboro	38 03 36	78 53 34	VA 02	09/11/1996	1715	12.9	8.80	7.85	158
VRC 16	Massanetta Spring	VA	Harrisonburg	38 24 02	78 50 13	VA 04	09/18/1996	1625	14.9	9.20	7.01	577
VRC 17	Mount Rock Spring	PA	Mount Rock	40 09 41	77 18 59	PA-CU-17	09/10/1996	1426	12.5	7.61	7.25	549
VRC 18	Pennrythe Spring	PA	Annville	40 19 46	76 29 45	PA-LB-18	09/09/1996	1325	13.4	5.16	7.24	623
VRC 19	PSU Ag Spring	PA	Rock Spring	40 42 28	77 56 58	PA-CE-33	09/12/1996	1800	14.6	4.60	6.88	429
VRC 20	Timberville Spring	VA	Timberville	38 40 00	78 48 09	VA 03	09/12/1996	1045	12.1	9.60	6.85	597
VRC 21	Trout Spring (1)	PA	Mechanicsburg	40 09 44	77 00 47	PA-CU-30	09/09/1996	0955	12.4	7.24	7.39	545
VRC 21	Trout Spring (2)	PA	Mechanicsburg	40 09 44	77 0 047	PA-CU-30	11/21/1996	1320	11.1	7.55	--	552
VRC 22	Warm Spring	VA	Warm Springs	38 03 13	79 46 52	VA 06	09/17/1996	0850	35.2	0.41	7.00	746
				Valley and Ridge Siliciclastic Hydrogeomorphic Region								
VRS 1	Berkeley Spring	WV	Berkeley Springs	39 37 37	78 13 44	WV-BS-1	09/25/1996	1810	22.6	3.68	6.77	303
VRS 1	Berkeley Spring (L5)	WV	Berkeley Springs	39 37 37	78 13 44	WV-BS-1	11/18/1996	1556	22.0	3.40	6.77	286
VRS 2	Blue Hole Spring	MD	C&O canal near Cumberland	39 34 31	78 43 49	MD-AL-CE-1	09/26/1996	1120	11.6	9.24	7.07	370
VRS 3	Clouser Spring	PA	Duncannon	40 23 09	77 04 21	PA-PE-10	09/11/1996	1530	15.7	5.41	5.11	148
VRS 4	Jefferson Davis Spring	MD	Alegany County	39 33 56	78 39 22	MD-AL-CF-46	09/26/1996	1412	13.1	7.70	6.76	159
VRS 5	McAllisterville Spring (1)	PA	McAllisterville	40 39 56	77 17 49	PA-JU-01	09/11/1996	1135	12.3	7.82	4.65	27
VRS 5	McAllisterville Spring (2)	PA	McAllisterville	40 3956	77 17 49	PA-JU-01	11/21/1996	0940	9.9	8.44	5.39	24
VRS 6	Tylerville Spring	PA	Tylerville	40 58 56	77 28 01	PA-CN-09	09/13/1996	1645	12.9	8.68	6.89	224

Appendix B. *Apparent ages of water collected from spring and ancillary data used for modeled recharge dates*

[ft, feet; mg/L, milligrams per liter; °C, degrees Celsius; cc/L, cubic centimeters per liter; --, missing data; C, contaminated; M, modern; <, less than; >, greater than]

Spring no.	Name	Elevation (ft)	Nitrogen gas (mg/L)	Argon gas (mg/L)	Recharge temperature (°C)	Excess air (cc/L)	CFC compounds used to determine date	Preliminary recharge date	Apparent age (years)
				Coastal Plain Hydrogeomorphic Region					
CP 1	George Washington	25	--	7.20	9.8	2.0	12, 113	1985	12
CP 2	CNHP28	10	--	6.60	15.2	0.6	12, 113	1991	6
				Piedmont Carbonate Hydrogeomorphic Region					
PC 1	Donegal Spring (1)	354	20.2	0.71	11.1	2.6	113	M	M
	Donegal Spring (2)	354	20.3	0.71	11.4	2.9	113	M	M
PC 2	Ft. Detrick field hole	340	18.9	0.69	11.0	1.3	113	1990	7
PC 3	Ft. Detrick spring house	340	19.7	0.69	11.5	2.3	C	C	C
PC 4	Lilypons Spring	280	23.7	0.47	10.7	--	113	1990	7
PC 5	Oregon Ridge Spring (1)	400	20.3	0.71	11.4	2.7	113	1991	6
	Oregon Ridge Spring (2) (L2)	400	21.0	0.73	9.5	2.8	113	1989	8
	Oregon Ridge Spring (2) (L5)	400	21.0	0.73	9.5	--	113	1989	8
PC 6	Retirement Center	220	20.1	0.71	10.6	2.3	C	C	C
				Piedmont Crystalline Hydgeomorphic Region					
PCx 1	4-H camp spring (1)	380	23.3	0.77	10.1	5.4	113	1988	9
	4-H camp spring (2)	380	18.5	0.69	9.7	0.4	113	1990	7
PCx 2	Camp 2 Spring	265	19.9	0.72	9.5	1.7	12, 113	1987	10
PCx 3	Green Spring	345	20.8	0.72	10.8	3.1	11, 12	1963	34

Appendix B. *Apparent ages of water collected from spring and ancillary data used for modeled recharge dates--Continued*

Spring no.	Name	Elevation (ft)	Nitrogen gas (mg/L)	Argon gas (mg/L)	Recharge temperature (°C)	Excess air (cc/L)	CFC compounds used to determine date	Preliminary recharge date	Apparent age (years)
				Piedmont Crystalline Hydgeomorphic Region--Continued					
PCx 4	Hanover Spring (1)	852	17.5	0.66	10.3	-0.1	113	1990	7
	Hanover Spring (2)	852	17.4	0.67	9.0	-0.6	113	1988	9
PCx 5	Hazelwood Farms	500	18.9	0.68	11.3	1.5	12, 113	1990	7
PCx 6	Manchester Spring	890	18.7	0.67	11.7	1.7	C	C	C
PCx 7	South of Gum Spring	300	16.7	0.63	13.8	0.0	113	M	M
				Mesozoic Lowland Hydrogeomorphic Region					
ML 1	Hillbilly Spring (L1)	350	21.5	0.73	10.5	--	113	1991	6
	Hillbilly Spring (L5)	350	21.5	0.73	10.5	3.7	113	1991	6
ML 2	Morivian Church	440	16.8	0.61	15.2	0.7	113	M?	M?
ML 3	Phillips Spring	440	19.8	0.71	10.2	2.0	11, 113	1988	9
				Valley and Ridge Carbonate Hydrogeomorphic Region					
VRC 1	Alexander Spring	512	20.8	0.72	10.5	3.1	C	C	C
VRC 2	Arthur Weiss Spring (1)	460	18.8	0.67	12.5	1.8	12, 113	1990	7
	Arthur Weiss Spring (2)	460	18.5	0.67	11.4	1.1	12, 113	1989	8
VRC 3	Bear Lithia Spring	936	20.4	0.70	11.8	3.5	11, 12	1978	19
VRC 4	Bellfonte Fishery Spring	824	17.6	0.64	13.5	1.2	C	C	C
VRC 5	Benner Spring	920	21.8	0.73	10.5	4.4	C	C	C

Appendix B. *Apparent ages of water collected from spring and ancillary data used for modeled recharge dates--Continued*

Spring no.	Name	Elevation (ft)	Nitrogen gas (mg/L)	Argon gas (mg/L)	Recharge temperature (°C)	Excess air (cc/L)	CFC compounds used to determine date	Preliminary recharge date	Apparent age (years)
				Valley and Ridge Carbonate Hydrogeomorphic Region--Continued					
VRC 6	Big Spring	520	21.8	0.75	9.4	3.7	C	C	C
VRC 7	Black Rock Spring (1)	540	19.4	0.69	11.3	2.1	113	M	M
	Black Rock Spring (2)	540	20.2	0.73	8.3	1.7	113	M	M
VRC 8	Coyner Spring (1)	1310	21.9	0.70	13.7	5.9	11, 12	1984	13
	Coyner Spring (2)	1310	21.1	0.70	9.5	3.5	11, 12	1980	17
VRC 9	Deerfield Spring	1730	16.3	0.59	15.0	0.9	11, 113	1988	9
VRC 10	Dykeman Spring	680	20.6	0.72	9.5	2.6	113	1989	8
VRC 11	Elkton Spring	1005	19.4	0.69	10.2	1.9	11, 12	1965	32
VRC 12	Gypsy Hill Golf Course	1470	19.3	0.68	10.4	2.2	C	C	C
VRC 13	Harver Spring	660	26.8	0.76	12.6	2.1	12, 113	M	M
VRC 14	Keedysville Spring	380	18.9	0.68	11.9	1.8	113	1992	5
	Keedysville Spring (L5)	380	18.9	0.69	11.1	--	113	1992	5
	Keedysville Spring (L2)	380	18.9	0.69	11.1	1.4	113	1991	6
VRC 15	Loth Spring	1285	19.1	0.67	11.6	2.3	11	1981	16
VRC 16	Massanetta	1385	26.3	0.81	9.5	8.8	11	1975	22
VRC 17	Mount Rock Spring	530	21.5	0.73	10.9	4.0	113	1987	10
VRC 18	Pennrythe Spring	450	--	--	11.0	1.8	C	C	C
VRC 19	PSU Ag Spring	1242	17.7	0.65	11.7	0.9	12, 113	1990	7
VRC 20	Timberville Spring	1260	23.3	0.77	8.1	5.2	11, 12, 113	1989	8

Appendix B. *Apparent ages of water collected from spring and ancillary data used for modeled recharge dates--Continued*

Spring no.	Name	Elevation (ft)	Nitrogen gas (mg/L)	Argon gas (mg/L)	Recharge temperature (°C)	Excess air (cc/L)	CFC compounds used to determine date	Preliminary recharge date	Apparent age (years)
Valley and Ridge Carbonate Hydrogeomorphic Region--Continued									
VRC 21	Trout Spring (1)	440	18.5	0.69	10.2	0.7	C	C	C
Valley and Ridge Siliciclastic Hydrogeomorphic Region									
VRS 1	Berkeley Spring	620	19.3	0.63	11.5	--	11, 12, 113	1957	40
	Berkeley Spring (L5)	620	21.0	.71	11.5	3.8	12	1949	48
VRS 2	Blue Hole Spring	560	17.8	.65	12.9	1.1	113	1991	6
VRS 3	Clouser Spring	500	17.7	.65	12.2	0.6	11, 113	1990	7
VRS 4	Jefferson Davis Spring	660	17.7	.66	11.1	0.3	11, 12	1964	33
VRS 5	McAllisterville Spring (1)	1120	17.7	.67	9.4	0.0	11, 113	1987	10
	McAllisterville Spring (2)	1120	17.8	.67	9.6	0.2	11, 113	1987	10
VRS 6	Tylerville Spring	1040	17.1	.62	13.9	1.0	11	1992	5

Appendix C. *Concentration of CFC-11, 12, and 113 in all samples*

[Precision of chlorofluorocarbon analyses is approximately ± 5 percent; Detection limits of CFC-11 and 12 are approximately 0.3 pg/kg and 1 pg/kg for CFC-113; picograms per kilogram; C, contaminated]

				Concentration in solution		
Spring no.	**Name**	**Ampule no.**	**Sampling date**	**CFC-11 (pg/kg)**	**CFC-12 (pg/kg)**	**CFC-113 (pg/kg)**
		Coastal Plain Hydrogeomorphic Region				
CP 1	George Washington	2	08/05/1996	454.3	258.4	56.6
		4	08/05/1996	446.7	252.7	53.4
		5	08/05/1996	449.0	253.3	55.1
CP 2	CNHP28	2	08/08/1996	507.5	254.4	73.5
		4	08/08/1996	510.9	258.6	77.0
		5	08/08/1996	510.9	267.9	56.3
		Piedmont Carbonate Hydrogeomorphic Region				
PC 1	Donegal Spring (1)	2	09/11/1996	1,523.9	678.5	99.9
		4	09/11/1996	2,314.9	685.8	110.2
		5	09/11/1996	1,746.7	874.6	107.4
PC 1	Donegal Spring (2)	2	11/20/1996	1,668.5	560.0	129.7
		4	11/20/1996	683.8	340.4	101.6
		5	11/20/1996	1,438.8	622.3	102.0
PC 2	Ft. Detrick field hole	2	09/24/1996	1,302.9	2,504.5	92.1
		4	09/24/1996	2,041.4	2,340.0	79.2
		5	09/24/1996	1,355.8	2,469.1	91.6
PC 3	Ft. Detrick spring house	2	09/24/1996	1,337.3	1,092.9	136.8
		4	09/24/1996	2,138.1	1,061.9	135.0
		5	09/24/1996	1,431.1	1,157.5	141.0
PC 4	Lilypons Spring	2	09/27/1996	1,192.2	358.6	99.7
		4	09/27/1996	1,896.5	350.2	89.9
		5	09/27/1996	1,250.8	385.4	86.3

Appendix C. *Concentration of CFC-11, 12, and 113 in all samples--Continued*

Spring no.	Name	Ampule no.	Sampling date	Concentration in solution CFC-11 (pg/kg)	CFC-12 (pg/kg)	CFC-113 (pg/kg)
			Piedmont Carbonate Hydrogeomorphic Region--Continued			
PC 5	Oregon Ridge Spring (1)	2	09/23/1996	553.9	349.9	89.7
		4	09/23/1996	626.3	351.7	91.7
		5	09/23/1996	535.1	322.1	82.6
PC 5	Oregon Ridge Spring (2) (L2)	2	11/19/1996	545.1	356.7	85.0
		4	11/19/1996	551.3	339.1	84.6
		5	11/19/1996	531.2	360.1	90.0
PC 5	Oregon Ridge Spring (2) (L5)	2	11/19/1996	547.4	355.8	82.9
		4	11/19/1996	554.6	340.7	83.6
		5	11/19/1996	541.1	370.4	97.0
PC 6	Retirement Center	2	09/23/1996	12,424.5	1,123.8	393.6
		4	09/23/1996	7,121.0	1,104.9	435.4
		5	09/23/1996	11,598.2	1,168.0	393.3
			Piedmont Crystalline Hydrogeomorphic Region			
PCx 1	4-H Camp Spring (1)	2	09/23/1996	636.6	373.2	85.3
		4	09/23/1996	659.5	358.8	73.7
		5	09/23/1996	623.1	376.8	86.6
PCx 1	4-H Camp Spring (2)	2	11/19/1996	631.5	368.9	84.5
		4	11/19/1996	653.9	358.3	95.7
		5	11/19/1996	617.0	376.2	95.5
PCx 2	Camp 2 Spring	2	09/20/1996	552.7	281.4	65.7
		4	09/20/1996	579.3	299.2	76.2
		5	09/20/1996	540.4	284.6	67.8
PCx 3	Green Spring	2	11/12/1996	66.1	36.6	10.4
		4	11/12/1996	64.5	31.4	6.1
		5	11/12/1996	63.0	31.9	12.5

Appendix C. *Concentration of CFC-11, 12, and 113 in all samples--Continued*

Spring no.	Name	Ampule no.	Sampling date	Concentration in solution CFC-11 (pg/kg)	CFC-12 (pg/kg)	CFC-113 (pg/kg)
			Piedmont Crystalline Hydrogeomorphic Region--Continued			
PCx 4	Hanover Spring (1)	2	09/12/1996	1,362.9	622.8	82.6
		4	09/12/1996	3,709.9	621.6	94.7
		5	09/12/1996	1,392.8	615.3	84.8
PCx 4	Hanover Spring (2)	2	11/20/1996	1,228.6	584.6	80.7
		4	11/20/1996	1,235.6	585.3	75.9
		5	11/20/1996	1,142.4	597.7	87.8
PCx 5	Hazelwood Farms	2	09/24/1996	19,459.1	305.9	70.2
		4	09/24/1996	5,708.4	306.2	74.9
		5	09/24/1996	7,632.5	329.9	73.5
PCx 6	Manchester Spring	2	09/27/1996	1,198.5	11,883.4	154.7
		4	09/27/1996	2,008.5	12,764.9	130.7
		5	09/27/1996	1,206.9	2,248.0	105.4
PCx 7	South of Gum Spring	2	09/26/1996	1,023.4	428.1	89.7
		4	09/26/1996	1341.2	407.9	102.2
		5	09/26/1996	987.2	469.5	233.7
			Mesozoic Lowland Hydrogeomorphic Region			
ML 1	Hillbilly Spring (L1)	2	11/14/1996	9,135.0	882.5	85.4
		4	11/14/1996	5,767.0	903.0	91.0
		5	11/14/1996	9,001.1	942.4	93.5
ML 1	Hillbilly Spring (L5)	2	11/14/1996	9,241.1	887.2	91.5
		4	11/14/1996	5,832.5	885.1	95.9
		5	11/14/1996	8,850.3	911.1	91.9
ML 2	Moravian Church	2	09/24/1996	752.3	1,621.2	101.2
		4	09/24/1996	812.4	1,534.7	78.3
		5	09/24/1996	714.3	1,545.5	82.7

Appendix C. *Concentration of CFC-11, 12, and 113 in all samples--Continued*

				Concentration in solution		
Spring no.	**Name**	**Ampule no.**	**Sampling date**	**CFC-11 (pg/kg)**	**CFC-12 (pg/kg)**	**CFC-113 (pg/kg)**
		Mesozoic Lowland Hydrogeomorphic Region--Continued				
ML 3	Phillips Spring	2	11/18/1996	650.3	509.1	73.7
		3	11/18/1996	650.4	506.6	86.0
		4	11/18/1996	1,988.3	512.2	174.3
		Valley and Ridge Carbonate Hydrogeomorphic Region				
VRC 1	Alexander Spring	2	09/10/1996	6,328.3	682.4	10,273.3
		4	09/10/1996	4,347.2	687.8	12,853.9
		5	09/10/1996	5,402.3	764.5	10,413.1
VRC 2	Arthur Weiss Spring (1)	2	09/19/1996	550.8	1,270.2	82.9
		4	09/19/1996	574.9	274.7	61.4
		5	09/19/1996	531.7	344.3	84.5
VRC 2	Arthur Weiss Spring (2)	2	11/12/1996	526.0	277.1	72.8
		4	11/12/1996	542.1	288.4	72.5
		5	11/12/1996	523.0	332.5	73.7
VRC 3	Bear Lithia Spring	2	09/18/1996	322.2	148.9	106.0
		4	09/18/1996	346.6	158.6	99.9
		5	09/18/1996	333.9	176.8	118.0
VRC 4	Bellfonte Fishery Spring	2	09/13/1996	16,960.3	1,749.5	56,438.2
		4	09/13/1996	8,258.5	1,723.8	59,153.4
		5	09/13/1996	1,129.0	312.8	1,452.1
VRC 5	Benner Spring	2	09/13/1996	17,237.5	2,800.1	172,829.8
		4	09/13/1996	8,331.1	5,88.4	96,148.9
		5	09/13/1996	16,833.3	3,461.7	140,732.7

Appendix C. *Concentration of CFC-11, 12, and 113 in all samples--Continued*

Spring no.	Name	Ampule no.	Sampling date	Concentration in solution CFC-11 (pg/kg)	CFC-12 (pg/kg)	CFC-113 (pg/kg)
			Valley and Ridge Carbonate Hydrogeomorphic Region--Continued			
VRC 6	Big Spring	2	09/10/1996	1,955.0	924.2	1,802.0
		4	09/10/1996	2,875.0	916.3	1,866.8
		5	09/10/1996	2,786.2	1,000.8	1,745.4
VRC 7	Black Rock Spring (1)	2	09/25/1996	3,818.9	494.8	110.4
		4	09/25/1996	4,415.6	474.9	106.5
		5	09/25/1996	17,579.6	523.8	103.9
VRC 7	Black Rock Spring (2)	2	11/18/1996	7,997.1	1,471.3	110.3
		4	11/18/1996	4,622.1	1,479.2	120.1
		5	11/18/1996	4,064.4	1,512.1	119.0
VRC 8	Coyner Spring (1)	2	09/11/1996	466.0	181.1	620.5
		4	09/11/1996	464.2	189.8	634.4
		5	09/11/1996	423.3	188.1	614.4
VRC 8	Coyner Spring (2)	2	11/12/1996	484.3	192.0	674.9
		3	11/12/1996	468.7	179.7	621.9
		4	11/12/1996	459.5	186.4	571.4
VRC 9	Deerfield Spring	2	09/17/1996	523.4	262.0	79.0
		4	09/17/1996	544.2	257.5	57.7
		5	09/17/1996	516.7	263.9	64.4
VRC 10	Dykeman Spring	2	09/10/1996	3,420.6	1,400.0	82.6
		4	09/10/1996	2,599.5	1,349.7	90.5
		5	09/10/1996	1,312.4	1,464.1	80.1
VRC 11	Elkton Spring	2	09/18/1996	78.5	38.4	4.8
		4	09/18/1996	78.3	40.4	0.0
		5	09/18/1996	78.6	39.1	7.6

Appendix D. *Concentrations of major ions in water from springs collected in the Chesapeake Bay watershed, September and November 1996*

[Chemical concentration is reported in mg/L (milligrams per liter) unless otherwise noted; meq, milliequivalent; %, percent, δ, delta; <, less than; --, not applicable]

Spring no.	Date	Calcium (Ca^{2+})	Magnesium (Mg^{2+})	Strontium (Sr^{2+})	Silica (SiO_2)	Sodium (Na^{+})	Potassium (K^{+})	Iron (Fe^{2+})	Silicon (Si)
				Piedmont Carbonate Hydrogeomorphic Region					
PC1	09/11/1996	101.0	16.9	0.308	7.188	8.02	3.6	0.113	3.36
PC1	11/20/1996	102.0	17.8	.326	7.573	8.25	3.89	.100	3.54
PC2	09/24/1996	113.0	15.8	.749	9.071	26.90	2.10	.129	4.24
PC3	09/24/1996	104.0	11.0	.483	8.664	5.89	1.10	.091	4.05
PC4	09/27/1996	110.3	13.3	.399	9.392	7.98	4.28	.098	4.39
PC5	09/23/1996	68.7	11	.085	8.707	5.46	1.15	.066	4.07
PC5	11/19/1996	64.4	10.5	.08	8.408	4.34	1.11	.069	3.93
PC5	11/19/1996	64.1	10.2	.077	8.172	4.38	1.09	.067	3.82
PC6	09/23/1996	71.9	20.9	.157	12.32	4.86	3.52	.085	5.76
				Piedmont Crystalline Hydrogeomorphic Region					
PCx1	09/23/1996	2.7	1.9	0.021	10.46	2.78	0.8	<0.015	4.89
PCx1	11/19/1996	2.29	1.84	.021	10.63	2.84	.79	<.015	4.97
PCx2	09/20/1996	1.79	1.47	.014	11.6	2.64	.98	<.015	5.42
PCx3	11/12/1996	240	22.7	5.62	46.42	15.5	5.4	.741	21.70
PCx4	09/12/1996	2.34	1.45	.01	6.225	1.59	.54	<.015	2.91
PCx4	11/20/1996	2.38	1.48	.01	6.225	1.67	.53	<.015	2.91
PCx5	09/24/1996	40.7	5.12	.065	6.504	9.51	1.46	.047	3.04
PCx6	09/27/1996	39.4	11.9	.138	9.969	22.3	1.62	.179	4.66
PCx7	09/26/1996	35.2	12.3	.129	19.83	19.3	1.47	.043	9.27
				Mesozoic Lowland Hydrogeomorphic Region					
ML1	11/14/1996	52.7	17.8	0.072	8.087	6.67	1.93	0.071	3.78
ML1	11/14/1996	52.2	18.4	.074	8.365	6.79	1.94	.072	3.91
ML2	09/24/1996	13.2	10.7	.084	11.89	12.8	5.43	.023	5.56
ML3	11/18/1996	27.1	6.96	.044	8.964	6.62	1.51	.029	4.19

Aluminum (Al^{3+})	Bi-carbonate (HCO_3^-)	Chloride (Cl^-)	Sulfate (SO_4^{2-})	Nitrogen (NO_3^-)	Cation (meq)	Anion (meq)	Dif-fer-ence	% charge balance	Nitrate $\delta^{15}N$ (per mil)	Spring no.
0.012	272.4	17.80	24.80	105.00	6.88	7.17	-0.28	-4.08	10.2	PC1
.094	260.5	19.40	28.30	112.30	7.03	7.21	-.17	-2.49	10.9	PC1
.001	340.7	68.90	39.40	10.60	8.18	8.51	-.33	-3.98	7.1	PC2
.003	264.6	16.50	24.10	15.40	6.39	5.55	.84	14.09	3.6	PC3
.098	279.0	31.30	32.00	47.30	7.07	6.88	.19	2.78	7.2	PC4
.004	256.6	9.93	10.80	7.39	4.60	4.82	-.22	-4.75	4.9	PC5
.005	235.6	7.93	9.90	8.23	4.29	4.42	-.12	-2.84	4.9	PC5
.006	235.0	7.96	9.87	8.24	4.26	4.41	-.15	-3.52	4.7	PC5
.003	292.3	11.00	16.70	21.30	5.61	5.79	-.17	-3.08	5.7	PC6
0.008	14.4	3.00	0.84	4.70	0.43	0.41	0.22	5.24	7.3	PCx1
.006	14.1	3.10	.89	5.20	.41	.42	-.00	-1.91	7.4	PCx1
.015	13.0	2.29	4.32	.12	.35	.36	-.01	-2.75	--	PCx2
.021	151.0	4.88	580.0	<.02	15.34	14.68	.65	4.36	--	PCx3
.004	12.9	3.38	2.76	.58	.32	.37	-.05	-14.65	--	PCx4
.004	13.0	2.72	1.46	.58	.33	.32	.00	.14	--	PCx4
.002	81.1	38.30	7.94	26.70	2.90	3.00	-.09	-3.32	3.4	PCx5
.006	35.0	98.30	2.75	32.10	3.96	3.92	.04	1.19	9.1	PCx6
.009	66.3	50.30	41.50	19.30	3.65	3.68	-.02	-.80	6.4	PCx7
0.009	186.6	21.40	11.20	26.00	4.43	4.31	.12	2.86	4.3	ML1
.007	187.3	23.20	11.90	25.90	4.46	4.38	.07	1.80	4.1	ML1
.003	35.8	27.30	7.69	40.00	2.23	2.16	.07	3.45	8.4	ML2
.003	87.1	19.50	3.64	13.90	2.25	2.27	-.02	-1.03	6.3	ML3

Appendix D. *Concentrations of major ions in water from springs collected in the Chesapeake Bay watershed, September and November 1996--Continued*

Spring no.	Date	Calcium (Ca^{2+})	Magnesium (Mg^{2+})	Strontium (Sr^{2+})	Silica (SiO_2)	Sodium (Na^{+})	Potassium (K^{+})	Iron (Fe^{2+})	Silicon (Si)
					Valley and Ridge Carbonate Hydrogeomorphic Region				
VRC1	09/10/1996	98.8	15.2	0.435	7.851	7.63	1.79	0.097	3.67
VRC2	09/19/1996	66.7	30.4	.198	8.194	6.08	10.2	.111	3.83
VRC2	11/12/1996	70.4	32.1	.238	8.194	6.25	9.2	.125	3.83
VRC3	09/18/1996	20	9.42	.044	9.413	1.72	1.66	<.015	4.40
VRC4	09/13/1996	57.5	20	.246	5.306	11.2	1.91	.079	2.48
VRC5	09/13/1996	65.7	18	.081	5.691	12.7	2.0	.085	2.66
VRC6	09/10/1996	80.1	10	.219	6.974	4.89	1.98	.064	3.26
VRC7	09/25/1996	54.7	23.6	.06	6.461	3.56	2.09	.065	3.02
VRC7	11/18/1996	53.8	22.8	.056	6.14	3.5	2.03	.060	2.87
VRC8	09/11/1996	21.3	11	.096	8.022	1.2	1.92	.026	3.75
VRC8	11/12/1996	21.1	11	.095	7.98	1.11	1.88	<.015	3.73
VRC9	09/17/1996	11.1	1.9	.044	6.118	1.21	1.14	.024	2.86
VRC10	09/10/1996	46.4	11.1	.158	7.145	4.48	2.41	.059	3.34
VRC11	09/18/1996	22.8	12	.021	10.91	1.54	2.68	.030	5.10
VRC12	09/13/1996	73.7	31.1	.066	6.782	5.53	1.72	.086	3.17
VRC13	09/25/1996	26.6	7.45	.067	9.178	6.63	1.40	.033	4.29
VRC14	11/18/1996	88.6	14.5	.376	8.985	6.3	2.53	.087	4.20
VRC14	11/18/1996	89.9	14.5	.375	8.985	6.29	2.54	.088	4.20
VRC14	09/25/1996	89.3	14.4	.366	8.707	6.31	2.52	.074	4.07
VRC15	09/11/1996	15.8	8.62	.022	6.354	1.82	1.37	.036	2.97
VRC16	09/12/1996	65.5	35.6	.049	6.696	6.33	1.75	.069	3.13
VRC17	09/10/1996	83.1	18.9	.329	7.316	7.39	2.00	.093	3.42
VRC18	09/09/1996	91.8	18.6	.248	8.365	9.56	3.90	.097	3.91
VRC19	09/12/1996	85.6	4.89	.533	6.76	1.66	2.62	.078	3.16
VRC20	09/12/1996	82.2	27.7	.141	7.573	2.56	1.98	.075	3.54
VRC21	09/09/1996	76.8	22.0	.301	7.958	6.70	2.80	.096	3.72
VRC21	11/21/1996	77.1	21.9	.298	7.744	6.73	2.80	.091	3.62
VRC22	09/17/1996	119.3	26.5	2.39	17.99	3.74	7.40	.149	8.41

Aluminum (Al^{3+})	Bicarbonate (HCO_3^-)	Chloride (Cl^-)	Sulfate (SO_4^{2-})	Nitrogen (NO_3^-)	Cation (meq)	Anion (meq)	Difference	% charge balance	Nitrate $\delta^{15}N$ (per mil)	Spring no.
0.020	323.1	18.30	18.40	24.20	6.57	6.58	-0.00	-0.11	4.0	VRC1
.008	323.2	14.75	21.80	39.30	6.37	6.80	-.42	-6.47	6.9	VRC2
.003	320.0	15.80	20.70	42.00	6.67	6.79	-.12	-1.80	6.8	VRC2
.008	107.2	2.12	3.82	2.47	1.90	1.93	-.03	-1.82	7.0	VRC3
.012	232.7	20.90	18.00	12.70	5.06	4.98	.08	1.64	5.8	VRC4
.016	248.6	23.60	15.30	14.80	5.37	5.29	.07	1.44	5.1	VRC5
.014	256.6	11.90	14.50	21.70	5.09	5.19	-.09	-1.89	4.7	VRC6
.002	254.2	7.25	8.26	14.60	4.88	4.77	.10	2.19	5.7	VRC7
.002	246.3	7.16	8.35	15.10	4.76	4.65	.11	2.39	5.7	VRC7
.012	109.7	1.71	10.10	3.93	2.08	2.11	-.03	-1.75	6.5	VRC8
.003	109.6	2.83	9.53	4.30	2.06	2.14	-.08	-3.93	6.0	VRC8
.011	39.8	1.14	5.82	1.90	.80	.83	-.03	-3.97	4.0	VRC9
.011	157.7	10.20	10.10	18.80	3.49	3.38	.11	3.21	4.8	VRC10
.008	137.9	2.14	1.74	.68	2.27	2.36	-.09	-4.14	--	VRC11
.006	377.3	12.10	6.36	9.28	6.53	6.80	-.27	-4.09	6.8	VRC12
.006	105.9	10.00	10.40	6.33	2.26	2.33	-.06	-2.96	6.3	VRC13
.003	314.8	13.50	16.50	18.40	5.96	6.18	-.21	-3.53	5.2	VRC14
.002	314.2	14.20	18.20	18.50	6.03	6.22	-.19	-3.21	5.3	VRC14
.005	306.4	14.50	16.60	18.40	5.99	6.07	-.08	-1.34	5.2	VRC14
.008	90.8	3.07	3.94	2.77	1.62	1.70	-.07	-4.74	6.2	VRC15
.007	365.5	13.80	7.49	7.54	6.52	6.65	-.12	-1.92	6.4	VRC16
.016	285.7	20.10	21.20	38.40	6.09	6.30	-.21	-3.53	4.2	VRC17
.011	301.0	20.40	41.10	25.70	6.63	6.77	-.14	-2.10	5.3	VRC18
.009	271.2	3.00	16.90	6.33	4.83	4.98	-.14	-3.02	8.6	VRC19
.008	356.3	6.81	12.80	30.80	6.55	6.79	-.23	-3.52	7.6	VRC20
.018	268.9	17.20	25.40	42.50	6.01	6.10	-.08	-1.45	5.5	VRC21
.014	229.8	17.00	25.10	42.80	6.02	5.45	.56	9.87	5.6	VRC21
.007	205.4	1.72	241.00	<.02	8.56	8.43	.13	1.53	--	VRC22

Appendix D. *Concentrations of major ions in water from springs collected in the Chesapeake Bay watershed, September and November 1996--Continued*

Spring no.	Date	Calcium (Ca^{2+})	Magnesium (Mg^{2+})	Strontium (Sr^{2+})	Silica (SiO_2)	Sodium (Na^{+})	Potassium (K^{+})	Iron (Fe^{2+})	Silicon (Si)
				Valley and Ridge Siliciclastic Hydrogeomorphic Region					
VRS1	09/25/1996	55.2	5.06	0.51	8.536	4.49	0.93	0.045	3.99
VRS1	11/18/1996	53.4	5.2	.529	8.771	4.64	.93	.042	4.10
VRS2	09/26/1996	57.3	8.15	.577	6.29	3.9	1.26	.081	2.94
VRS3	09/11/1996	6.69	3.83	.04	8.514	10.3	2.92	.022	3.98
VRS4	09/26/1996	28.6	2.44	.113	8.408	1.72	.65	.023	3.93
VRS5	09/11/1996	1.25	1.13	.005	5.113	.54	.73	.027	2.39
VRS5	11/21/1996	1.1	.99	.004	5.113	.5	.67	<.015	2.39
VRS6	09/13/1996	32.2	5.49	.217	5.199	4.53	1.51	.056	2.43

Aluminum (Al^{3+})	Bi-carbonate (HCO_3^-)	Chloride (Cl^-)	Sulfate (SO_4^{2-})	Nitrogen (NO_3^-)	Cation (meq)	Anion (meq)	Dif-fer-ence	% charge balance	Nitrate $\delta^{15}N$ (per mil)	Spring no.
0.011	185.3	2.71	13.90	<0.02	3.41	3.40	0.01	0.24	--	VRS1
.043	180.2	1.60	15.20	.54	3.34	3.32	.01	.57	--	VRS1
.043	185.5	7.11	23.00	3.67	3.75	3.77	-.02	-.68	4.1	VRS2
.014	9.7	10.90	15.50	21.00	1.18	1.12	.05	4.85	6.1	VRS3
.004	92.8	1.93	8.02	<.02	1.72	1.74	-.01	-1.10	--	VRS4
.012	5.3	.85	4.30	.20	.20	.20	-.00	-.07	--	VRS5
.010	5.4	.90	3.20	.20	.17	.18	-.00	-2.40	--	VRS5
.009	107.5	7.02	11.80	7.95	2.30	2.33	-.02	-1.15	5.7	VRS6

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