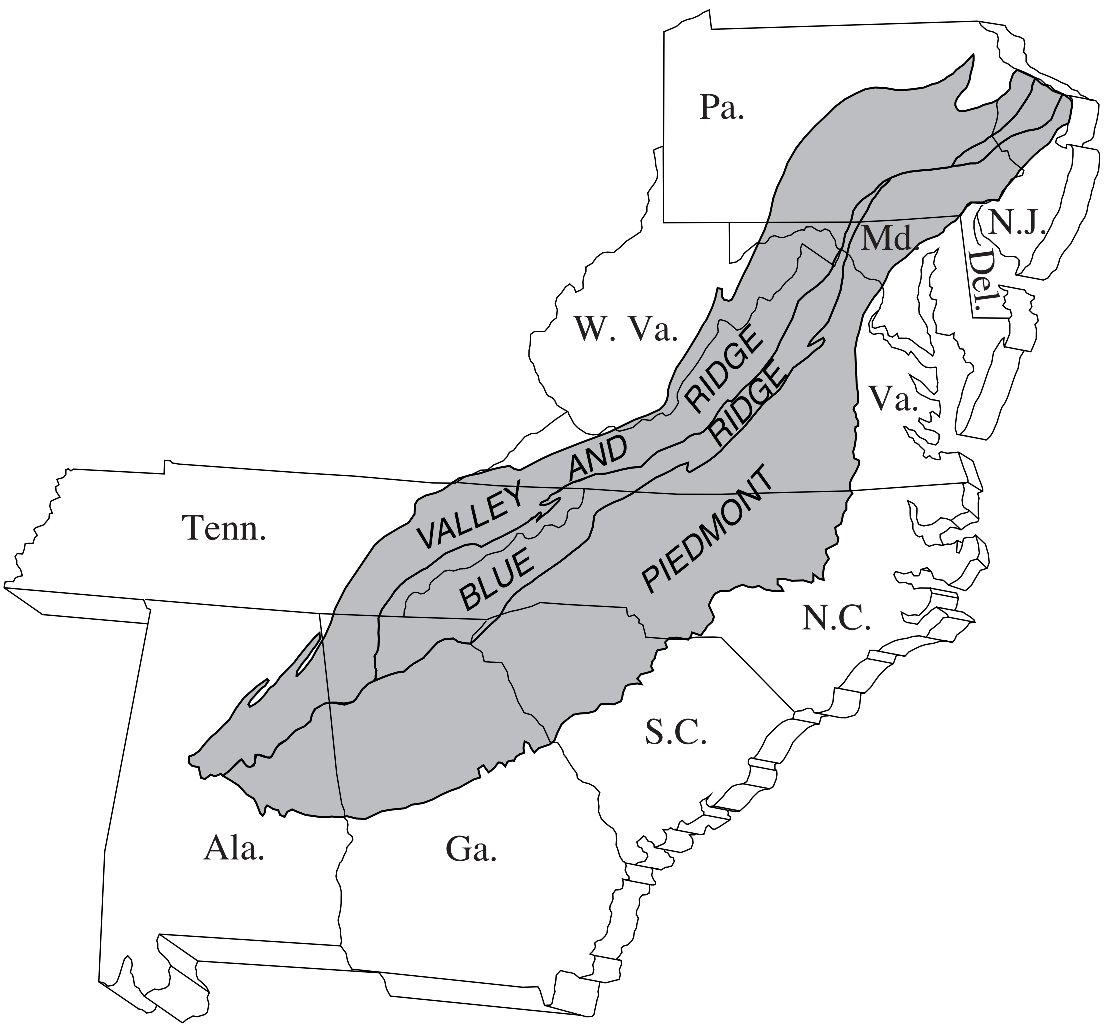
Regional Aquifer-System Analysis

Summary of the Hydrogeology of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States



Professional Paper 1422-A

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

Summary of the Hydrogeology of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States

By Lindsay A. Swain, Thomas O. Mesko, and Este F. Hollyday

Regional Aquifer-System Analysis—
Appalachian Valley and Piedmont

Professional Paper 1422-A

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

U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

U.S. Geological Survey, Reston, Virginia: 2004
For sale by U.S. Geological Survey, Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

For more information about the USGS and its products:
Telephone: 1-888-ASK-USGS
World Wide Web: http://www.usgs.gov/

Suggested citation:
Swain, L.A., Mesko, T.O., and Hollyday, E.F., 2004, Summary of the hydrogeology of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States: U.S. Geological Survey Professional Paper 1422-A, 23 p.

Library of Congress Cataloging-in-Publication Data

Swain, Lindsay A.
Summary of the hydrogeology of the Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces in the eastern United States / by Lindsay A. Swain, Thomas O. Mesko, and Este F. Hollyday.
p. cm. -- (Professional paper ; 1422) (Regional aquifer-system analysis--Appalachian Valley and Piedmont ; A)
Includes bibliographical references.
ISBN 0-607-98077-X (pbk.)
1. Aquifers--Appalachian Region. 2. Aqufers--Piedmont (U.S. : Region) I. Mesko, Thomas O. II. Hollyday, E. F. III. Title. IV. Series. V. Series: U.S. Geological Survey professional paper ; 1422.
GB1199.3.A6S93 2004
551.49'0974--dc22

2004053336

ISBN 0-607-98077-X

Foreword

The Regional Aquifer-System Analysis Program

The RASA Program represents a systematic effort to study a number of the Nation's most important aquifer systems, which, in aggregate, underlie much of the country and which represent an important component of the Nation's total water supply. In general, the boundaries of these studies are identified by the hydrologic extent of each system and, accordingly, transcend the political subdivisions to which investigations have often arbitrarily been limited in the past. The broad objective for each study is to assemble geologic, hydrologic, and geochemical information, to analyze and develop an understanding of the system, and to develop predictive capabilities that will contribute to the effective management of the system. The use of computer simulation is an important element of the RASA studies to develop an understanding of the natural, undisturbed hydrologic system and the changes brought about in it by human activities and to provide a means of predicting the regional effects of future pumping or other stresses.

The final interpretive results of the RASA Program are presented in a series of U.S. Geological Survey Professional Papers that describe the geology, hydrology, and geochemistry of each regional aquifer system. Each study within the RASA Program is assigned a single Professional Paper number beginning with Professional Paper 1400.

Charles G. Groat
Director

Contents

Figures

Tables

Conversion Factors and Horizontal Datum

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
billion gallons per day (Bgal/d)	3.785	billion liters per day (BL/d)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
gallon per minute per foot [(gal/min)/ft)]	0.2070	liter per second per meter [(L/s)/m]
foot squared per day (ft^2/d)	0.09290	meter squared per day (m^2/d)

Water-Quality Unit

milligram per liter (mg/L)

Horizontal coordinate information is referenced to the North American Datum of 1983.

Summary of the Hydrogeology of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States

By Lindsay A. Swain, Thomas O. Mesko, and Este F. Hollyday

Abstract

The Appalachian Valley and Piedmont Regional Aquifer-System Analysis study (1988-1993) analyzed rock types in the 142,000-square-mile study area, identified hydrogeologic terranes, determined transmissivity distributions, determined the contribution of ground water to streamflow, modeled ground-water flow, described water quality, and identified areas suitable for the potential development of municipal and industrial ground-water supplies. Ground-water use in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces exceeds 1.7 billion gallons per day.

Thirty-three rock types in the study area were analyzed, and the rock types with similar water-yielding characteristics were combined and mapped as 10 hydrogeologic terranes. Based on well records, the interquartile ranges of estimated transmissivities are between 180 to 17,000 feet squared per day (ft^2/d) for five hydrologic terranes in the Valley and Ridge; between 9 to 350 ft^2/d for two terranes in the Blue Ridge; and between 9 to 1,400 ft^2/d for three terranes in the Piedmont Physiographic Province. Based on streamflow records, the interquartile ranges of estimated transmissivities for all three physiographic provinces are between 290 and 2,900 ft^2/d. The mean ground-water contribution to streams from 157 drainage basins ranges from 32 to 94 percent of mean streamflow with a median of 67 percent. In three small areas in two of the physiographic provinces, more than 54 percent of ground-water flow was modeled as shallow and local. Although ground-water chemical composition in the three physiographic provinces is distinctly different, the water generally is not highly mineralized, with a median dissolved-solids concentration of 164 milligrams per liter, and is mostly calcium, magnesium, and bicarbonate. Based on aquifer properties and current pumpage, areas favorable for the development of municipal and industrial ground-water supplies are underlain by alluvium of glacial origin near the northeastern part of the study area, by clay-free carbonate rocks primarily in the Valley and Ridge Physiographic Province, and by siliciclastic rocks in the three northernmost Mesozoic basins.

Introduction

The aquifers of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces are a major source of drinking-water supplies in the United States. The aquifers underlie the District of Columbia and parts of 11 States—New Jersey, Delaware, Pennsylvania, Maryland, Virginia, West Virginia, Tennessee, North Carolina, South Carolina, Georgia, and Alabama—a total area of about 142,000 mi^2 (fig. 1). For the purposes of this report, the small area in the New England Physiographic Province that is within the study area in New Jersey and Pennsylvania was treated as part of the Piedmont Physiographic Province. The analysis of aquifers in that part of the Valley and Ridge, New England, and Piedmont Provinces that lie within New York State and the New England States is described in publications of the Northeastern Glacial Valleys Regional Aquifer-System Analysis.

An average annual rainfall of 43 inches provides an average of about 13 inches of recharge to the aquifers of the unglaciated part of the three physiographic provinces. In 1990, the aquifers provided water supplies for about 38 million people in rural households and municipal or county water systems in the area. The larger ground-water supply systems are within Bergen, Morris, Essex, and Union Counties, New Jersey; and Blair, Lehigh, and Montgomery Counties, Pennsylvania. In 1985, about 1.7 Bgal/d were withdrawn from the aquifers for all uses in the study area. Although pumping stresses have produced local cones of depression, almost 90 percent of the study area has no significant ground-water-level decline. However, despite the enormous amounts of untapped water available from the aquifers, sufficient quantities of ground water are not always available to meet local municipal or industrial needs.

During 1988-93, the U.S. Geological Survey (USGS) conducted a Regional Aquifer-System Analysis (RASA) of the aquifers of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces, which included the review and synthesis of many previous studies and hydrologic data, the acquisition of additional well records, and the extensive use of hydrograph recession analysis and statistical methods to organize and summarize hydraulic and water-quality data. The

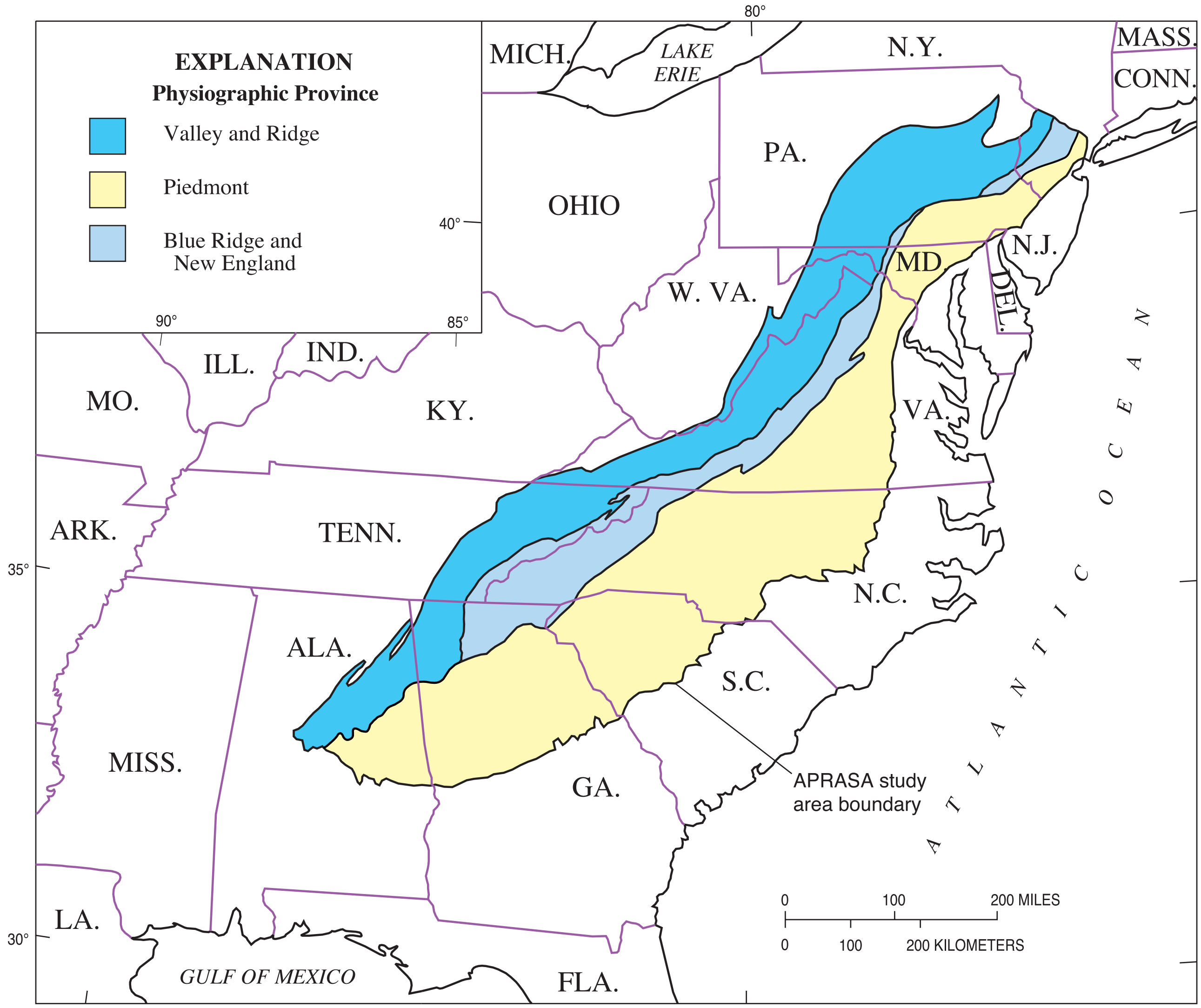


Figure 1. The Appalachian Valley and Piedmont Regional Aquifer-System Analysis (APRASA) study area and physiographic provinces.

Appalachian Valley and Piedmont Regional Aquifer-System Analysis (APRASA), summarized in this report, is one of about two dozen USGS RASA programs that provide quantitative appraisals of the major ground-water systems of the United States.

Background, Major Objectives, and Approach

The aquifer systems of the three physiographic provinces consist of hundreds of aquifers composed of metamorphic, igneous, and sedimentary rock units. Although the ground-water reservoirs in these units typically lack regional continuity, the rock units may be considered to form a complex regional aquifer system that is characterized primarily by local ground-water flow. Ground-water development has not been extensive. Large withdrawals have been concentrated in a few areas—primarily in the more densely populated northeastern part of the study area. In this area, rapid industrial growth and urban expansion have caused all sources of freshwater to be used at or near maximum capacity. Future growth and expansion is expected to cause the same problems in urban areas in the southern and western parts of the study area. Hydrologic processes of recharge, discharge, storage, ground-water flow, and stream-aquifer relations within the three physiographic provinces are poorly understood. This lack of hydrologic understanding is due primarily to the diverse and complex nature of the hydrologic system. The APRASA study advances understanding of the system and provides a basis for more efficient use and management of the ground-water resources in the three physiographic provinces.

Specifically, the objectives of the APRASA study were: (1) to provide a description of the hydrologic framework; (2) to identify the major processes that affect ground-water quantity and quality; (3) to quantify the components of ground-water flow in local “type areas;” (4) to provide regional estimates of the ground-water budget; (5) to determine the relation between surface-water and ground-water flow systems; (6) to provide a description of ground-water quality; and (7) to develop a database to aid in planning, development, and management of the ground-water resources in the three physiographic provinces. The hydrogeologic framework was described in terms of hydrogeologic terranes based on the relation between the hydraulic properties of the rocks and the lithology, structure, topography, or other relevant features. The type areas, where ground-water flow was simulated with digital models, were selected to be representative of the different hydrogeologic terranes and typical combinations of terranes. Within the type areas, emphasis was placed on factors controlling recharge and discharge and on response to ground-water development.

To meet the project objectives, efforts concentrated on the assembly and analysis of the vast amount of data primarily in the National Water Information System (NWIS) database of the USGS including the data for well records, streamflow daily values, water quality, and water use. Prior to the study, much information existed on the geologic framework, and aquifer hydraulic characteristics had been measured in several places. However, the greatest amount of hydrogeologic data and a few ground-water flow models were clustered in the northeast and at widely scattered waste-disposal sites throughout the study area. Data are scarce in many areas where large untapped ground-water supplies exist. A data-collection effort was undertaken to fill data gaps in well records southwest of Pennsylvania and Maryland.

Well records in the Ground-Water Site Inventory (GWSI) database of the USGS for Pennsylvania were analyzed statistically to determine factors related to the water-yielding potential of the rocks in order to classify hydrogeologic terranes (Knopman, 1990; Knopman and Hollyday, 1993). A computer-assisted analysis of streamflow recession was developed to determine recession characteristics, basin diffusivity, and ground-water recharge and discharge (Rutledge, 1998). A computer-assisted method was developed for compiling, analyzing, and plotting large quantities of water-quality data on trilinear diagrams (Briel, 1993). A geographic information system database of well records and mapped geologic units was developed to assist in the classification of hydrogeologic terranes and the analysis of ground-water recharge and discharge (Mesko, 1993).

Purpose and Scope

The APRASA was conducted to describe various aspects of the geology, hydrology, and geochemistry of the aquifers of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces. This report summarizes important aspects of the hydrogeologic framework, hydraulic properties of the hydrogeologic terranes, typical flow systems, and geochemistry, which are discussed in detail in USGS Professional Papers 1422-B through 1422-D (Rutledge and Mesko, 1996; Hollyday and Hileman, 1996; and Briel, 1997) and USGS Hydrologic Investigations Atlas HA-732-B (Mesko and others, 1999). Emphasis in those four reports is placed on classification and description of hydrogeologic terranes, surface-water and ground-water relations, and ground-water geochemistry. Descriptions of local ground-water flow systems are contained in the following three reports: USGS Water-Resources Investigations Reports 94-4090 (Chichester, 1996) and 94-4147 (Lewis-Brown and Jacobson, 1995), and USGS Water-Supply Paper 2341-C (Daniel and others, 1997).

Professional Paper 1422-B (Rutledge and Mesko, 1996) presents an analysis of streamflow hydrograph recession and base flow in 157 drainage basins in, or partially in, the APRASA study area. The analysis of streamflow recession provides estimates of master recession curves, recession indexes, and transmissivity of the rocks. The recession index is related to basin relief, precipitation, basin latitude, the yield of wells in the basin, and low-flow variables. The base flow analysis provides estimates of ground-water recharge and discharge, and the remaining components of the water budget of each basin. Ground-water recharge and base-flow index also are related to basin relief, precipitation, the well yields in the basin, and low-flow variables.

Professional Paper 1422-C (Hollyday and Hileman, 1996) presents an analysis of geology and records of wells in the Valley and Ridge Physiographic Province, which resulted in a classification and map of hydrogeologic terranes. Specific capacity and median value of reported drawdowns were used to estimate statistical parameters of potential municipal and industrial well yields in the five hydrogeologic terranes.

Hydrologic Investigations Atlas HA-732-B (Mesko and others, 1999) presents an analysis of geology and records of wells in the Blue Ridge and Piedmont Physiographic Provinces, which resulted in a classification and map of hydrogeologic terranes. Reported yields of nondomestic wells were used to estimate statistical parameters of nondomestic well yields in the two hydrogeologic terranes of the Blue Ridge and the three hydrogeologic terranes of the Piedmont Physiographic Provinces.

Professional Paper 1422-D (Briel, 1997) presents an analysis of the major-ion chemistry of water withdrawn from wells, issuing from springs, and from streams in the study area. Comparisons were made by physiographic province and water source. The principal chemical processes that operate in the ground-water flow system are explained using trilinear diagrams.

Summary of Previous Investigations

Hundreds of reports describing the hydrology, geology, and water chemistry of parts of the Appalachian Valley and Piedmont aquifer systems have been published. Many of these reports were used in making the observations described in the RASA series. A few of the reports provided major contributions to the knowledge of the aquifer system and are noted here.

Fuller (1905) related the importance of secondary openings to the storage and movement of ground water, particularly in joints in the crystalline-rock aquifers of the Blue Ridge and Piedmont, in open channels and caverns in the carbonate rocks of the Valley and Ridge, and at greater depth in the fractures and joints in the siliciclastic rocks in the Mesozoic basins of the Piedmont. McGuinness (1963) stated that the rocks of the Piedmont are among the Nation's most reliable aquifers for small yields needed for domestic supply; large yields are not common. McGuiness (1963) concluded that the carbonate rocks of the Valley and Ridge are erratic in the yield of water to wells. For the Piedmont, LeGrand (1967) succinctly summarized ground-water occurrence, flow, water quality, well siting, well hydraulics, and aquifer response to pumping. Parizek and others (1971) combined several papers and articles dealing with ground-water occurrence, flow, and geochemistry in carbonate rocks of the Valley and Ridge in central Pennsylvania. In a study of well yields in the northern quarter of the APRASA study area, Cederstrom (1972) stressed the desirability of relying on the hydrologic analysis of municipal and industrial well records, which he believed represented an effort to develop a maximum supply of water. Trainer and Watkins (1975) developed the concept of combining rock types and soil thicknesses into geohydrologic terranes for the Upper Potomac River Basin. Cressler and others (1983) stated that large well yields are available in the Piedmont near Atlanta, Ga., but only in areas where the rocks have localized increases in permeability, which are associated with selected stratigraphic or structural features.

The National Water Summary for 1984 (U.S. Geological Survey, 1985) provided a uniform discussion, with selected key references, of water use, principal aquifers, and ground-water development and management in each of the 11 states in the APRASA study area. The state geologic maps of each of the 11 states provided a wealth of stratigraphic and structural information. Patchen and others (1985a, b) provided a concise summary of the stratigraphy of the Valley and Ridge Physiographic Province, which allowed correlation of aquifers among states. Daniel (1989) discussed the importance of well diameter, well depth, topography, and the transition zone between regolith and bedrock on large well yields. Swain and others (1991) discussed the geology, hydrology, water use, and water problems in the APRASA study area and presented the planned objectives of and methods for the APRASA study. Daniel and others (1993) edited the proceedings from the first conference on ground water in the Piedmont. The proceedings contains more than 60 papers covering a vast variety of topics that deal with quantity and quality of ground water in the Piedmont.

Finally, the greatest source of information on the aquifer systems is contained in the hundreds of reports published by the 11 states and in USGS Open-File Reports and Water-Resources Investigations Reports series. Many of these studies were conducted by the USGS in cooperation with various State, county, and municipal governments. These reports and supporting computer files provide the basic hydrologic data, as well as interpretations of the local hydrology, without which, this regional study could not have been successfully completed.

Hydrogeologic Terranes

Hydrogeologic terranes, rather than aquifers and confining units, were identified because of the complexity of the geology in the APRASA study area. For the purpose of this study, a hydrogeologic terrane is defined as a regionally mappable area characterized by similar water-yielding properties in a grouping of selected rock types. The term "terrane" was used because the original intent was to include climatic, geomorphic, and pedologic variables, in addition to bedrock lithology, in the analysis. Five hydrogeologic terranes were identified in the Valley and Ridge, three in the Piedmont, and two in the Blue Ridge Physiographic Provinces.

The Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces are underlain by metamorphic, igneous, and sedimentary rocks; gneiss, schist, granite, and siliciclastic sedimentary rock underlie almost two-thirds of the study area. Following faulting and folding, as well as one or more periods of metamorphism and igneous intrusion of the rocks in most of the study area, the entire area was uplifted during the Cenozoic Era. Subsequent weathering and erosion enlarged existing fractures in the bedrock and may have created new fractures by stress relief.

The water-storage and transmissive characteristics of the bedrock and regolith, and the hydraulic connection between the bedrock and regolith determine the water-supply potential of the hydrogeologic terranes (fig. 2). Because of the relatively high porosity of the regolith, most recharge is stored in this unit and is released slowly to underlying bedrock fractures. Because fractures and dissolution openings in the bedrock are conduits for ground-water flow, well yields are greatest where wells intersect fractures or dissolution openings that are large, numerous, or both. Under natural (pre-pumping) conditions, most ground-water flow is within 200 feet below land surface. However, an analysis of well records in seven areas of the Piedmont Physiographic Province indicated that four of these seven areas have average well yields that are substantially greater for wells completed between 400 and 600 feet below land surface compared with wells completed between 100 and 200 feet below land surface (Mesko and others, 1999).

Hydrogeologic terranes were classified within each of the three physiographic provinces by relating rock type, as described in State geologic maps, to records of either specific capacity or well yields in the GWSI database. State geologic maps were scanned, edited, and annotated to produce coverages of the mapped occurrence of each geologic unit in the study area. Geologic units with the same rock type were merged to create a coverage of more than 50 rock types. Records of 62,345 wells in the APRASA part of the three physiographic provinces were retrieved from the GWSI database for each State. Values of either specific capacity (Valley and Ridge) or yield (Blue Ridge and Piedmont) were retrieved from each well record, grouped by province and rock type, and analyzed to derive statistical characteristics of specific capacity or yield for 33 rock types for which these data were sufficiently numerous for

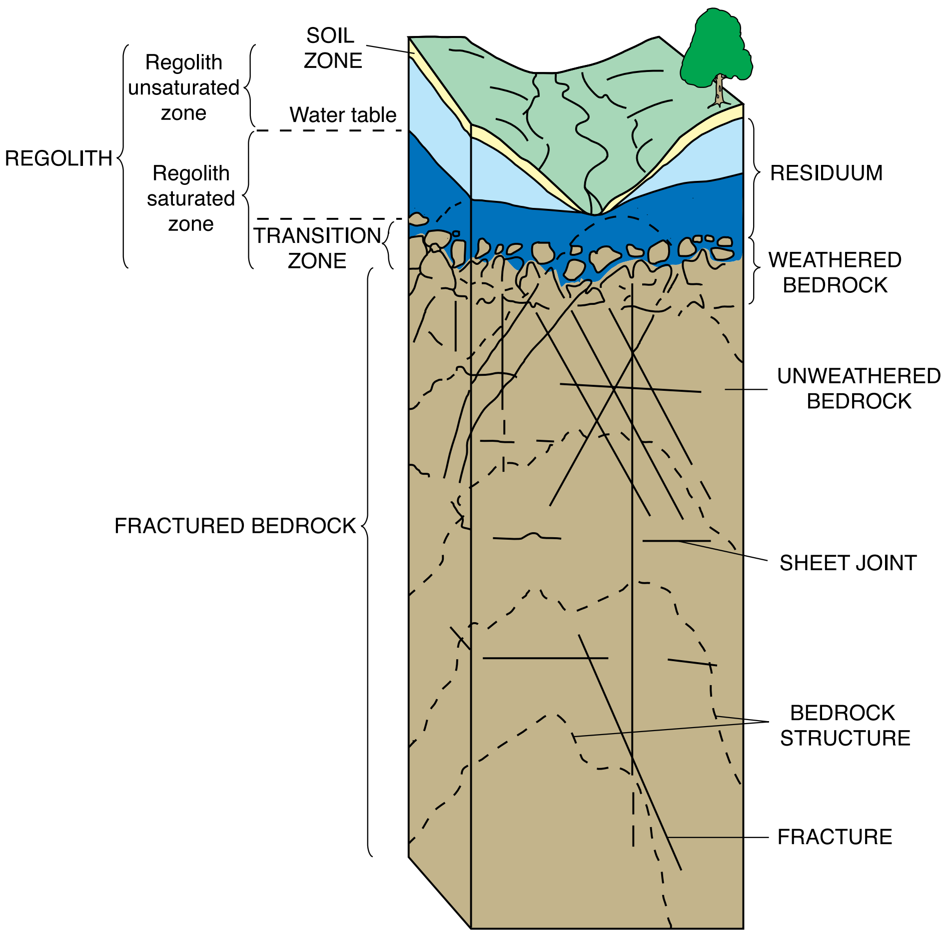


Figure 2. Principal hydrogeologic components of regolith and bedrock in the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces. (From Daniel and others, 1997, fig. 4.)

statistical analysis. For each physiographic province, the rock types were then ranked in order of increasing specific capacity or yield and grouped into two or more hydrogeologic terranes according to selected ranges in median specific capacity (Valley and Ridge) or median yield (Blue Ridge and Piedmont).

For the Valley and Ridge, potential well yields were estimated by multiplying the values of specific capacity by the medians of reported drawdowns for municipal and industrial wells. Included in these estimates were all records of municipal and industrial wells with casing diameter equal to, or greater than, 7 inches that were located in valleys. The interquartile ranges in estimated potential yields of these most-productive wells in the five hydrogeologic terranes of the Valley and Ridge were 70 to 280 gal/min for siliciclastic rock, 65 to 850 gal/min for argillaceous carbonate rock, 80 to 720 gal/min for limestone, 210 to 1,400 gal/min for dolomite, and 170 to 580 gal/min for alluvium (Hollyday and Hileman, 1996). For the Blue Ridge, the interquartile ranges in reported yields of nondomestic wells in the two hydrogeologic terranes were 8 to 32 gal/min for gneiss-granite, and 10 to 61 gal/min for schist-sandstone (Mesko and others, 1999). For the Piedmont, the interquartile ranges in reported yields of nondomestic wells in the three hydrogeologic terranes were 5 to 20 gal/min for phyllite-gabbro, 10 to 60 gal/min for gneiss-schist, and 35 to 220 gal/min for shale-sandstone.

Hydrogeologic terranes were mapped (fig. 3) by assigning rock types to the appropriate hydrogeologic terrane based on specific capacity (Valley and Ridge) or yield (Blue Ridge and Piedmont). The dolomite hydrogeologic terrane in the Valley and Ridge Physiographic Province has the largest median potential well yield and is predominantly dolomite with limestone in widely distributed valleys of Alabama, Georgia, and Tennessee, and in valleys primarily along the southeastern margin of the Valley and Ridge in Maryland, New Jersey, Pennsylvania, Virginia, and West Virginia (fig. 3). The shale-sandstone hydrogeologic terrane in the Piedmont Physiographic Province has the largest median well yield of any hydrogeologic terrane in either the Blue Ridge or Piedmont Physiographic Provinces and is predominantly shale, sandstone, and siltstone in the Mesozoic basins in Maryland, New Jersey, Pennsylvania, and Virginia.

Hydrogeologic terranes with intermediate values of transmissivity may act as either an aquifer or a confining unit to an adjacent hydrogeologic terrane depending upon their relative transmissivities. Geologic structure is complex within the study area, and faults and folds, as much as stratigraphic position, may determine which hydrogeologic terranes are aquifers or confining units within a local structural setting (fig. 3).

Hydraulic Properties

The hydraulic properties of the terranes of the study area were estimated from well and streamflow data compiled from various sources and published reports describing the hydrogeologic characteristics of geologic units within the terranes. The sources of well data included site inventories by project staff, published reports, unpublished USGS well data, and data from the GWSI database in NWIS. The source of mean-daily streamflow data was the USGS data in NWIS.

Storage Coefficient and Specific Yield

A storage coefficient of 0.0005 was used for estimating the transmissivity of the hydrogeologic terranes from the specific

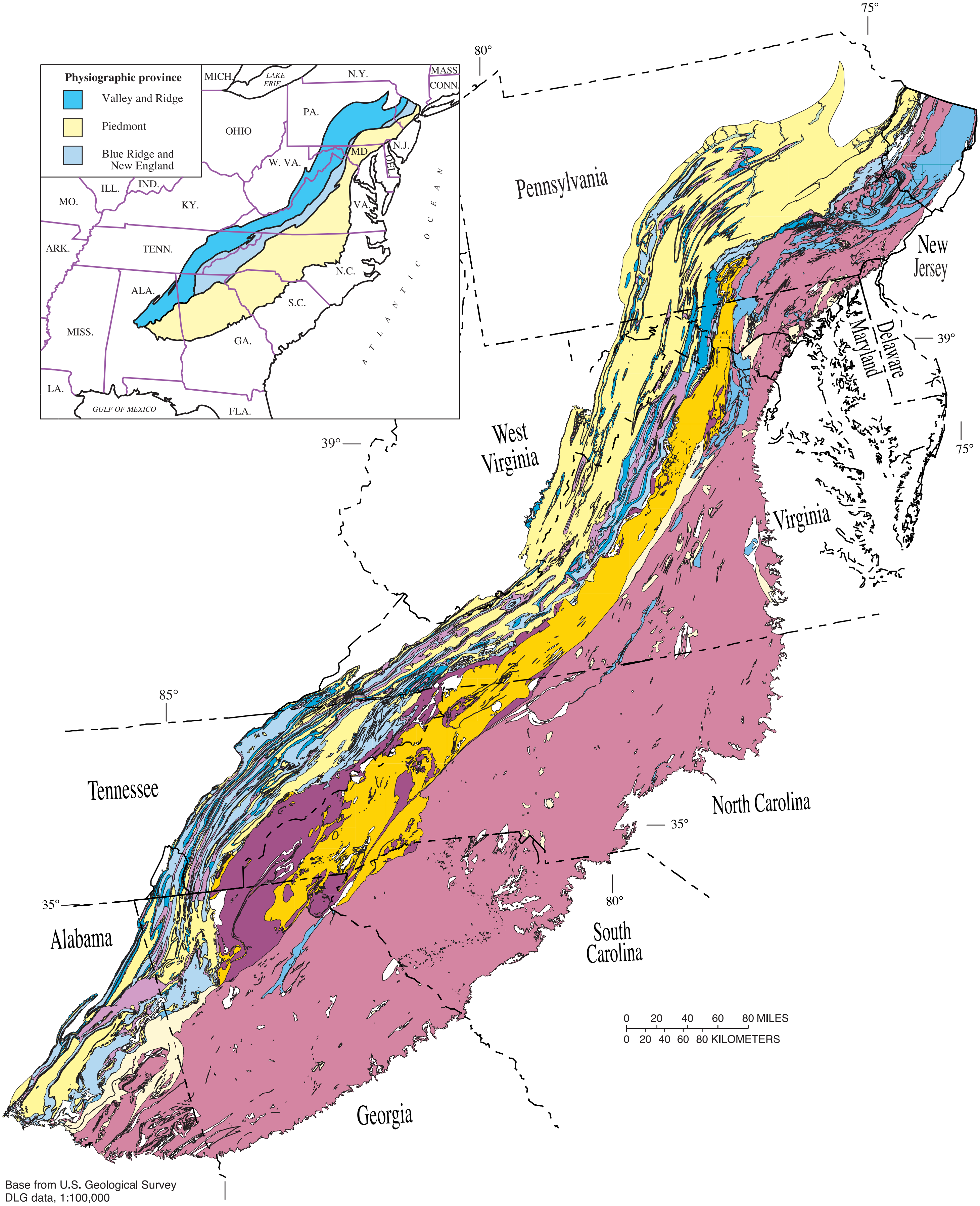


Figure 3. Hydrogeologic terranes of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States.

EXPLANATION

Description of hydrogeologic terranes—The sequence of units is not intended to imply stratigraphic position. See State geologic maps for stratigraphic position among geologic units in the hydrogeologic terranes.

Valley and Ridge Physiographic Province

Siliciclastic rock hydrogeologic terrane—Interquartile range in estimated potential yield to most-productive wells 70 to 280 gal/min. Includes geologic units that are predominantly shale with little or no carbonate content, claystone, siltstone, sandstone, and conglomerate that consists of clay minerals, quartz grains, or siliceous rock fragments

Argillaceous carbonate rock hydrogeologic terrane—Interquartile range in estimated potential yield to most-productive wells 65 to 850 gal/min. Includes geologic units that are predominantly clay-rich dolomite or limestone, as well as shale units that contain abundant calcite or magnesium calcite

Limestone hydrogeologic terrane—Interquartile range in estimated potential yield to most-productive wells 80 to 720 gal/min. Includes geologic units that are predominantly limestone and limestone with less than 30 percent dolomite

Dolomite hydrogeologic terrane—Interquartile range in estimated potential yield to most-productive wells 210 to 1,400 gal/min. Includes geologic units that are predominantly dolomite, a combination of dolomite and sandstone or chert, and dolomite and limestone with as much as 70 percent limestone

Alluvium hydrogeologic terrane—Interquartile range in estimated potential yield to most-productive wells 170 to 580 gal/min. Includes geologic units that are predominantly alluvium, outwash, and stratified drift in and adjacent to the glacial margin in northern New Jersey and northern and eastern Pennsylvania

Blue Ridge Physiographic Province

Gneiss-granite hydrogeologic terrane—Interquartile range in yield to nondomestic wells 8 to 32 gal/min. Includes geologic units that are predominantly basalt, gneiss, granite, phyllite, rhyolite, and shale

Schist-sandstone hydrogeologic terrane—Interquartile range in yield to nondomestic wells 10 to 61 gal/min. Includes geologic units that are predominantly amphibolite, dolomite, limestone, quartzite, sandstone, and schist

Piedmont Physiographic Province

Phyllite-gabbro hydrogeologic terrane—Interquartile range in yield to nondomestic wells 5 to 20 gal/min. Includes geologic units that are predominantly gabbro, greenstone, phyllite, and serpentine

Gneiss-schist hydrogeologic terrane—Interquartile range in yield to nondomestic wells 10 to 60 gal/min. Includes geologic units that are predominantly argillite, conglomerate, diabase, diorite, gneiss, granite, gravel, limestone, metavolcanics, mudstone, quartzite, sand, schist, tuff, and volcanics

Shale-sandstone hydrogeologic terrane—Interquartile range in yield to nondomestic wells 35 to 220 gal/min. Includes geologic units that are predominantly basalt, dolomite, graywacke, marble, sandstone, shale, and siltstone

Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces

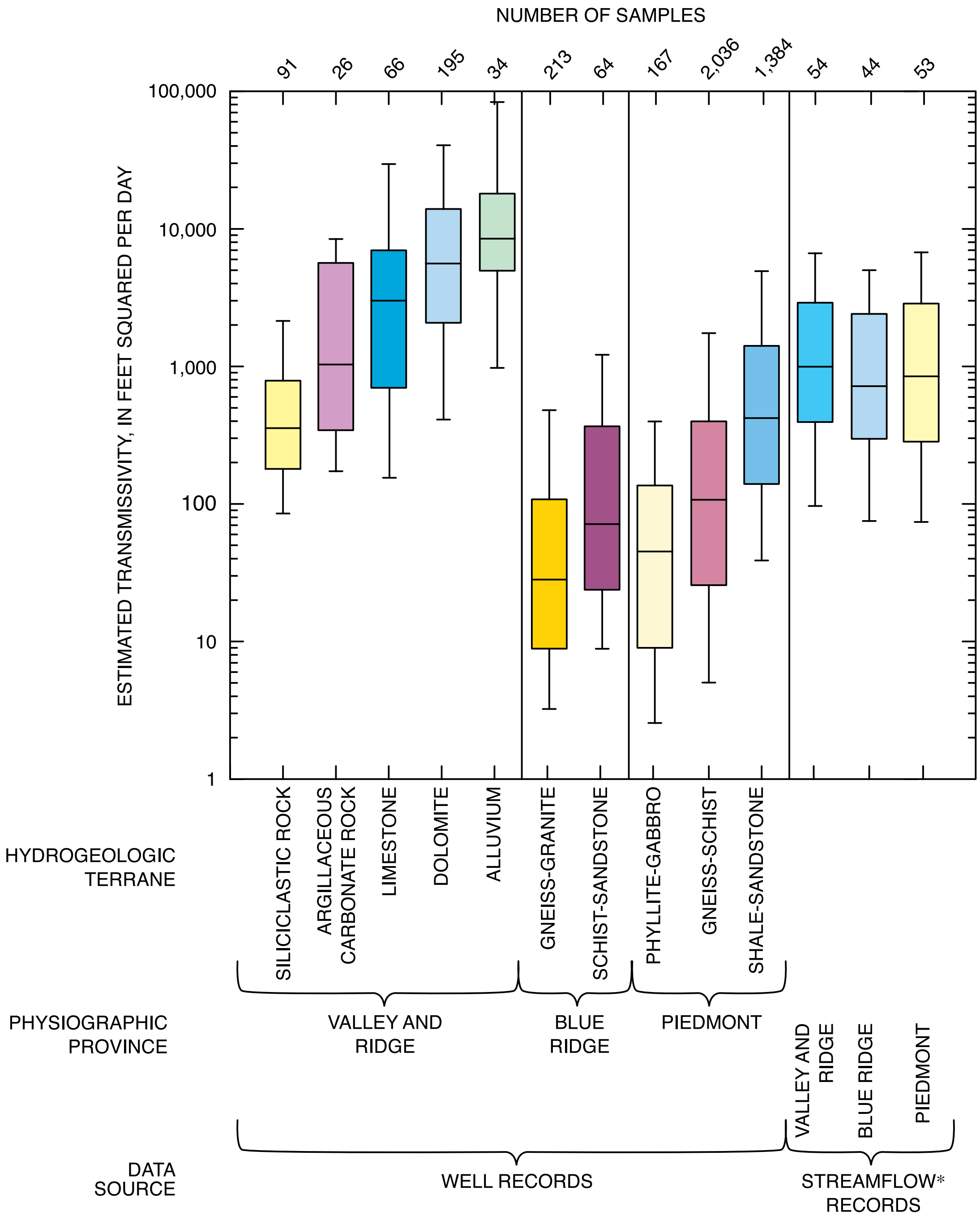
Hydrogeologic terranes not defined—Includes geologic units whose rock type had fewer than ten samples of either specific capacity or well yield or whose lithologic composition was too varied to assign a rock type. Also includes a few areas within the Valley and Ridge near the boundary with the Blue Ridge or the Piedmont that contain geologic units that are commonly associated with these latter two provinces

capacity of wells (Theis and others, 1963). This value is about an order of magnitude lower than the median value of storage coefficient reported by Trainer and Watkins (1975, table 2, p. 18) from aquifer tests in the carbonate and siliciclastic rocks of the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces in the Potomac River Basin. The value is within the mid-range of values of storage coefficient reported by Lewis-Brown and Jacobsen (1995, table 3, p. 19) for siliciclastic sedimentary rocks in the Newark Basin of New Jersey. The value is less than an order of magnitude higher than the storage coefficient selected by Daniel and others (1997, p. C58) for estimating the transmissivity of fractured gneiss and schist in the Piedmont of North Carolina.

The storage coefficient of granular material, including regolith, under water-table conditions is equal to the specific yield. A range in specific yield from 0.01 to 0.08 (Rutledge and Mesko, 1996, p. B15) was used for estimating the transmissivity of the rocks in the three physiographic provinces from stream-basin diffusivity methods (Rorabaugh and Simons, 1966). This range corresponds to the 25th and 75th percentiles in a distribution of 21 values of specific yield taken from published reports (Rutledge and Mesko, 1996, table 5, p. B18).

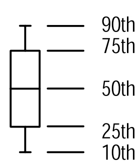
Transmissivity from Specific Capacity of Wells

Values of specific capacity were converted to estimates of transmissivity (fig. 4) by using the method described by Theis and others (1963). Percentile values of specific capacity of municipal and industrial wells in the Valley and Ridge Physiographic Province (Hollyday and Hileman, 1996, fig. 12, p. C21) and nondomestic wells in the Blue Ridge and Piedmont Physiographic Provinces (Mesko and others, 1999, fig. 5) were selected from boxplots of the distribution of specific-capacity values of wells in the 10 hydrogeologic terranes. The nondomestic wells recorded in GWSI for the study area are primarily used for municipal, industrial, and commercial water supply. The inclusion of water uses other than municipal and industrial in the nondomestic category would tend to lower the values of transmissivity compared to values derived from municipal and industrial data alone.



EXPLANATION

Percentile—Indicates percentage of measurements equal to or less than indicated values



*Note: Transmissivity values estimated from streamflow records are based upon an assumed log-normal distribution.

Figure 4. Variation of transmissivity values estimated from well records and streamflow records in the three physiographic provinces.

The equation given by Theis and others (1963, eq. 6, p. 337) computes a value of T′, which must be used in a diagram (Theis and others, 1963, fig. 99, p. 334) to estimate transmissivity from specific capacity. Because it is difficult to select values of transmissivity from this diagram for specific capacity values less than 1.0, the original equation given by Theis and others (1963, eq. 1, p. 332) was modified for contemporary units and programmed into a spreadsheet to iteratively calculate transmissivity. The modified equation is:

$$T = 15.32\frac{Q}{s}\left(-0.577 - \ln\left(\frac{r^2S'}{4Tt}\right)\right), \qquad (1)$$

where

- T is transmissivity, in feet squared per day;
- Q is discharge of the well, in gallons per minute;
- s is drawdown in the pumping well, in feet;
- Q/s is specific capacity, in gallons per minute per foot;
- ln is the natural logarithm;
- r is the radius of the pumped well, in feet;
- S is the storage coefficient, in feet per foot; and
- t is the time since pumping started, in days.

The following average values for well radius and duration of pumping were determined from data for municipal and industrial wells in the GWSI database; radius of 0.33 ft (8-inch diameter well) and time of 0.33 day (8 hours of pumping). A storage coefficient of 0.0005 was estimated from values in the literature as described heretofore. These three fixed values were used in all calculations of transmissivity from specific capacity. Using the spreadsheet, a final value of transmissivity was calculated by iteration from an initial estimate until final and initial transmissivity values differed by less than 0.01 percent. This convergence typically occurred within three to five manual iterations.

Considering all 10 of the hydrogeologic terranes, 80 percent (10th to 90th percentile) of the values for estimated transmissivity range from 2.6 to 84,000 ft^2/d (fig. 4). For any 1 of the 10 hydrogeologic terranes, the interquartile range (25th to 75th percentile) is typically slightly greater than one order of magnitude; the siliciclastic-rock and alluvium hydrogeologic terranes have the smallest ranges—slightly greater than one-half order of magnitude. Well records were analyzed separately for each of the three physiographic provinces. Consequently, pairs of terranes where each is selected from a different province may have estimated transmissivity distributions with considerable overlap. As examples, siliciclastic rock (Valley and Ridge) and shale-sandstone (Piedmont), gneiss-granite (Blue Ridge) and phyllite-gabbro (Piedmont), and schist-sandstone (Blue Ridge) and gneiss-schist (Piedmont) are three pairs of hydrogeologic terranes from different physiographic provinces that are not likely to have significant differences in their estimated transmissivities. In contrast, the rock types in the three hydrogeologic terranes of the Piedmont could be regrouped into five new terranes and still have significant differences among their median values of estimated transmissivity because of the large sample of wells in the Piedmont. However, the large overlap among the five distributions of estimated transmissivity for these five new terranes probably would not indicate a usable difference among the five terranes for water-supply purposes; fewer terranes (three) would be more useful.

The transmissivity varies greatly among the hydrogeologic terranes in part because of differences in the character of the water-yielding openings within each terrane. These openings include (1) intergranular openings in sand and gravel of glacial origin; (2) conduits and caverns dissolved in carbonate rocks; (3) networks of many small dissolution openings along joints, bedding planes, or fractures, that when acting together, provide a uniform distribution of permeability of large to moderate magnitude; and (4) networks of many openings along joints, bedding planes, or fractures that are partly plugged with clay residuum and, that when acting together, provide a uniform distribution of permeability of moderate to low magnitude. In those terranes that are characterized by openings of type 1, 3, and 4, laminar flow predominates; however, in terranes with conduits and caverns, turbulent flow may occur.

For the hydrogeologic terranes in which laminar flow predominates, the methods developed for aquifer-test analysis for porous media are applicable. For the hydrogeologic terranes in which turbulent flow may occur, these aquifer-test methods only generally indicate how an equivalent porous media might respond to stress. The response curves of aquifer tests outside of cavernous areas generally match the classic non-leaky type curves, especially for short tests, and the leaky or delayed-yield type curves for longer tests. Water-level response in cavernous areas can be unusually small, almost instantaneous, and approximately the same at the pumped well and at a considerable distance from the pumped well. In areas in which ground-water flow is predominantly in conduits, caverns, joints, bedding planes, and fractures, cones of depression are typically asymmetric.

When all 10 hydrogeologic terranes are considered together, the range in estimated transmissivity is more than 4 orders of magnitude (fig. 4) as a result of the wide variation in hydrogeologic conditions. The conditions that most affect transmissivity are the type of water-yielding openings (intergranular, conduit, or fracture), the rock composition, and the degree of dissolution. In unconsolidated deposits, high transmissivities usually are associated with clean, coarse-grained materials such as glacial outwash within the alluvium hydrogeologic terrane. In consolidated rocks, high transmissivities usually are associated with soluble rocks in areas in which vigorous ground-water flow has enhanced development and widening of dissolution openings. The variations in transmissivities for the geographic areas underlain by the terranes are produced by a combination of hydrologic and geologic conditions (table 1). The ranges in estimated transmissivities given in table 1 are a generalization of the interquartile ranges shown for each hydrogeologic terrane in figure 4. An exception is the western-toe, whose range was taken from a source document (see table 1, footnote b).

In general, the largest values of transmissivity (greater than 7,000 ft^2/d for the 75th percentile in table 1) occur in the alluvium hydrogeologic terrane near the northeastern end of the

Table 1. Hydrogeologic conditions that control the transmissivity of the hydrogeologic terranes in various provinces and locations in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.

[Range in estimated transmissivity is approximately between the 25th percentile and the 75th percentile of a distribution of estimated transmissivities (fig. 4, with the exception of western-toe); ft^2/d, foot squared per day]

Terrane[a]	Locality	Water-yielding opening	Rock composition	Degree of dissolution	Generalized, interquartile range in estimated transmissivity, in ft^2/d
Alluvium	Glacial margin in Pennsylvania and New Jersey	Intergranular	Siliciclastic, some carbonate	Not a factor	5,000 - 17,000
Western-toe subdivision of the dolomite terrane (Elkton aquifer)	Southeastern margin of the Valley and Ridge	Conduits and caverns	Dolomite	Well developed	900 - 17,000[b]
Dolomite	Valley and Ridge; carbonate-rock valleys in the Blue Ridge and the Piedmont	Conduits and dissolution networks	Dolomite, limestone, marble	Moderate to well developed	2,000 - 13,000
Limestone	Valley and Ridge; carbonate-rock valleys in the Blue Ridge and Piedmont	Dissolution networks and conduits	Limestone, marble	Moderate to well developed	700 - 7,000
Argillaceous carbonate rock	Valley and Ridge	Minor dissolution networks	Argillaceous limestone and dolomite; carbonate-rich shale	Poor to moderately developed	300 - 6,000
Siliciclastic rock; shale-sandstone	Valley and Ridge; Piedmont	Fracture networks; minor intergranular	Sandstone, siltstone, noncalcareous shale	Not a factor	130 - 1,300
Schist-sandstone; gneiss-schist	Blue Ridge; Piedmont	Fracture networks	Sandstone, schist, gneiss, etc.	Not a factor	20 - 400
Gneiss-granite; phyllite-gabbro	Blue Ridge; Piedmont	Fracture networks	Granite, gneiss, phyllite, gabbro, etc.	Not a factor	9 - 130

[a]With the exception of the western-toe, see figs. 3 and 4 for mapped distribution of hydrogeologic terrane, description, and estimated transmissivity. For western-toe subdivision of the dolomite terrane (Elkton aquifer) see Hollyday and Hileman, 1996, figs. 7 and 8, and p. C13-C16 for distribution and description.

[b]Based on an interquartile range in specific capacity of 3.3 to 55 (gal/min)/ft (Hollyday and Hileman, 1996, fig. 13, p. C23).

Valley and Ridge (fig. 3), in the western-toe subdivision of the dolomite terrane (Hollyday and Hileman, 1996, p. C13-C16) along the southeastern margin of the Valley and Ridge, in the dolomite hydrogeologic terrane throughout the Valley and Ridge, and within carbonate-rock valleys in the Blue Ridge and Piedmont Physiographic Provinces (Mesko and others, 1999, fig. 1). The alluvium hydrogeologic terrane is adjacent to the glacial margin. It is derived from outwash sand and gravel, and has large, well-connected intergranular pore spaces. The western-toe subdivision of the dolomite hydrogeologic terrane (renamed the Elkton aquifer in Hollyday and others, 1997) is in an area of high relief at the toe of the slope of the northwestern edge of the Blue Ridge Mountains. The western-toe subdivision (Elkton Aquifer) is dolomite overlain by saturated thick residuum, colluvium, and alluvium, and contains numerous caverns and conduits. The dolomite terrane throughout much of the Valley and Ridge has moderate relief resulting from a resistant, protective cap of residual chert. The terrane is predominantly dolomite and limestone, and contains conduits and dissolution networks. The carbonate-rock valleys are in four areas of low to moderate relief in the Piedmont and in two areas of high relief in the Blue Ridge. In the Blue Ridge, these valleys are typically adjacent to highlands underlain by quartzite. The erosion of the quartzite results in a colluvial and alluvial apron covering the limestone, dolomite, and marble in the valley, a hydrologic setting very similar to the Elkton aquifer.

The smallest values of transmissivity (less than 1,300 ft^2/d) occur in the hydrogeologic terranes of dense, consolidated rock that lack significant amounts of soluble, carbonate minerals throughout the three physiographic provinces. These terranes (siliciclastic rock, shale-sandstone, schist-sandstone, gneiss-schist, gneiss-granite, and phyllite-gabbro) occupy almost all of the Blue Ridge and Piedmont Physiographic Provinces and much of the northern half of the Valley and Ridge Province (fig. 3). The terranes include siliciclastic sedimentary, metamorphic, and igneous rocks with fracture networks that may be plugged, more or less, with fine-grained, insoluble residue.

Transmissivity from Streamflow Recession

Streamflow recession index values (Rutledge and Mesko, 1996) were transformed to estimates of transmissivity (fig. 4) using the method described by Rorabaugh and Simons (1966, p. 12). Percentile values of recession index for basins in each of the three physiographic provinces were picked from boxplots of the distribution of recession-index values (Rutledge and Mesko, 1996, fig. 7, p. B11).

The equation given by Rorabaugh and Simons (1966, p. 12) may be rearranged to the following form to estimate transmissivity from recession index (Rutledge and Mesko, 1996, p. B15):

$$T = \frac{0.933 S_y a^2}{K} , \qquad (2)$$

where

T is transmissivity, in feet squared per day;
S_y is the apparent specific yield of the zone of water-table fluctuation, in feet per foot;
a is the average distance from the stream to the hydrologic divide, in feet; and
K is the recession index, in days per log cycle of decline in discharge.

Although estimates of transmissivity could be made for specific basins, the intent was to give estimates of the range in transmissivities in each of the physiographic provinces in the APRASA study area. For this estimate, the 25th and 75th percentile values of recession indexes for each province as provided by Rutledge and Mesko (1996, fig. 7, p. B11) were used. A range in a of 1,000 to 2,000 ft and a range in S_y of 0.01 to 0.08 were obtained by reviewing the literature (Rutledge and Mesko, 1996, p. B15). These ranges were used in equation 2 in order to estimate log-normal distributions of transmissivity for the three physiographic provinces (fig. 4).

The distributions of transmissivities estimated from streamflow records generally lie within the midrange of distributions estimated from well records when all distributions are considered together (fig. 4). This similarity suggests that the two sets of distributions may be related to the same physical controls. The variation in the distributions estimated from streamflow records, however, is much less than the variation in distributions estimated from the well records. This difference may be due to the fact that streamflow is the integrated discharge from several rock types or terranes and is derived primarily from regolith and rock at shallow depths. Integrated discharge and release from shallow depths would tend to reduce the variation in estimated transmissivities. Creating subsets of the recession-index data by basins underlain by rocks with predominantly small well yields and basins underlain by rocks with large well yields resulted in greatly increased variation in the distributions of recession index (and, presumably, estimated transmissivity) for the Valley and Ridge and the Piedmont Physiographic Provinces (Rutledge and Mesko, 1996, figs. 13 and 14, p. B16 and B17).

Ground-Water Recharge and Discharge, and Hydrologic Budgets

Mean rates of ground-water recharge and discharge were estimated by an analysis of the base flow of streams (Rutledge and Mesko, 1996, p. B19-B28) (fig. 5). Ground-water recharge and discharge are important components of the hydrologic budget of any basin. The analytical methods were applied over 10- or 30-year periods of continuous record, so that the effects of changes in ground-water storage could be considered negligible. The mean ground-water discharge (base flow), therefore, may be considered to be equal to effective recharge. The mean ground-water recharge should exceed the mean effective

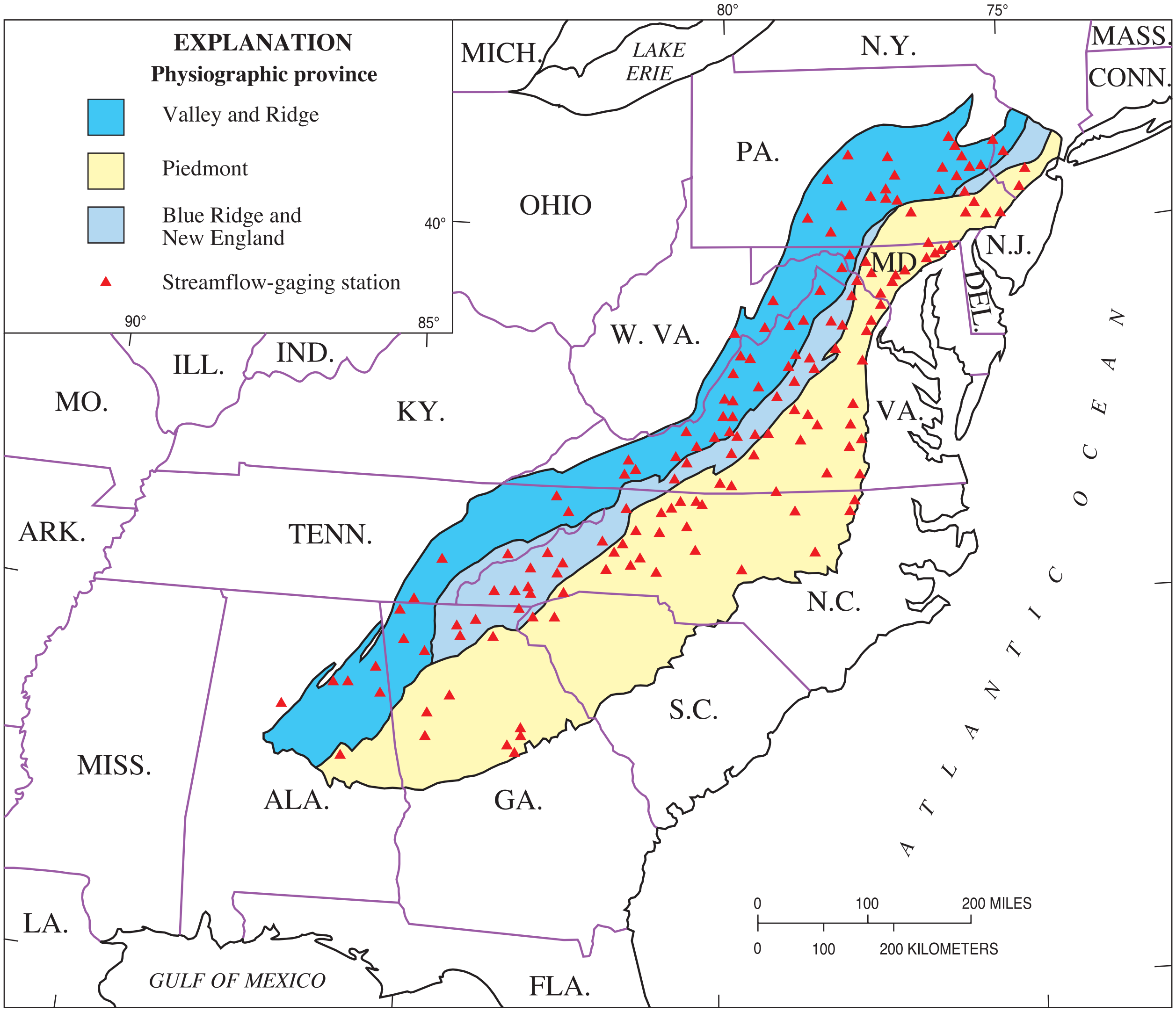


Figure 5. Distribution of streamflow-gaging stations in the study area that were used in recession and base-flow analysis.

recharge by an amount equal to the riparian evapotranspiration—losses to the atmosphere from the stream channel and adjacent, shallow ground water.

Two computerized methods were used in base-flow analysis—recession-curve displacement, which estimates ground-water recharge; and base-flow record estimation (adapted from methods called streamflow partitioning), which estimates ground-water discharge. The documentation of the computerized methods, including detailed discussion of the mathematical development of the methods, instructions for execution of the programs, and comparisons between results of the programs and those of the corresponding manual methods were reported by Rutledge (1998).

Ground-water recharge and discharge (effective recharge) were determined by independent methods. Yet the sense and magnitude of the difference between recharge and discharge (table 2) is to be expected if a small amount of evapotranspiration were occuring from the ground-water reservoir. Riparian-zone evapotranspiration ranges between 0.4 and 3.8 in/yr (Rutledge and Mesko, 1996, p. B21), and mean riparian-zone evapotranspiration (the difference between mean recharge and mean discharge) is usually between 1 and 2 in/yr (table 2).

The median of the mean ground-water discharge (table 2) may be used to calculate a rough estimate of total ground-water discharge in the study area. If the 157 basins are assumed to be representative of the entire study area, then a median ground-water discharge of 12 in/yr (table 2) indicates that as much as 90 Bgal/d of ground water may be available for use in the 142,000 mi^2 study area.

A comparison of precipitation and recharge for the study area shows a considerable amount of scatter (Rutledge and Mesko, 1996, fig. 19); however, the best-fit linear equation has an approximate unit gradient of 0.86 and an X-intercept of about 28 in/yr. The intercept may depend on total evapotranspiration and may represent a threshold that must be exceeded by precipitation before recharge is significant. The relation between precipitation and recharge for each physiographic province is positive (Rutledge and Mesko, 1996, fig. 20). The

Table 2. Statistical distribution of ground-water recharge and discharge, in inches per year, for basins in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.

Distribution	1981 to 1990 (number of samples, 157)		1961 to 1990 (number of samples, 89)	
	Mean recharge	Mean discharge	Mean recharge	Mean discharge
Maximum	46	42	50	46
75th percentile	18	16	19	17
Median	13	12	13	12
25th percentile	10	9	10	9
Minimum	5	4	6	5

relation between basin relief and recharge tends to be negative for the Valley and Ridge Physiographic Province; however, the relation is positive for the Blue Ridge and Piedmont Physiographic Provinces (Rutledge and Mesko, 1996, fig. 21). For these two physiographic provinces, a reasonably good estimator of recharge can be derived from precipitation and basin relief (fig. 6).

The base-flow index is calculated as the ratio of mean ground-water discharge (base flow) to mean streamflow. This index is ideal for basin comparisons when the various basins have differing periods of streamflow record or when the available period of record is short. The base-flow index of 157 basins in the APRASA study area ranges from 32 to 94 percent, and the 25th, 50th, and 75th percentiles are 59, 67, and 75 percent, respectively. The base-flow index is exceptionally large in the Blue Ridge Physiographic Province for the 28 basins south of Roanoke, Va., as compared with the index for 16 basins in the northern part of the province. This anomaly is accompanied by a significant increase in precipitation and a very slight decrease in evapotranspiration south of Roanoke.

Simple water-budget equations were combined with the results of the base-flow analysis to obtain hydrologic budgets of basins in the study area. Except for the Blue Ridge Physiographic Province south of Roanoke, Va., the median values for components of the budgets of the study area (sample size, 72) are precipitation, 43 in/yr; evapotranspiration, 26 in/yr; streamflow, 16 in/yr; ground-water recharge, 12 in/yr; ground-water discharge, 11 in/yr; and storm runoff, 6 in/yr. For the southern part of the Blue Ridge Physiographic Province (sample size, 17), the median values are precipitation, 58 in/yr; evapotranspiration, 25 in/yr; streamflow, 38 in/yr; ground-water recharge, 33 in/yr; ground-water discharge, 29 in/yr; and storm runoff, 8 in/yr. The map location, physical characteristics, streamflow recession characteristics, components of hydrologic budgets, and base-flow index for each basin are listed in Rutledge and Mesko (1996, tables 1, 2, 3, and 4).

Ground-Water Flow in Selected Basins

The fundamental approach to quantifying ground-water flow in the APRASA was similar to that of other RASA studies (Sun, 1986) in that available geologic and hydrologic data were compiled and used to describe the regional aquifer systems. In the APRASA study, however, the lack of regional continuity of the ground-water reservoirs and the diverse nature of the aquifers devalued the development of a regional ground-water flow model for the entire study area. A more logical approach was to select “type areas” that were considered representative of conditions in those settings and hydrogeologic terranes that are most important to water supply. For this approach, a flow system was conceptualized for each hydrogeologic terrane or combination of terranes, and ground-water flow in selected type areas was analyzed and simulated by using ground-water flow models. These models were used primarily to improve the understanding of ground-water flow related to various hydrogeologic components and streams. At the time of the study, pumping stresses were so small or localized in the type areas that it would have been very difficult to calibrate a transient-flow model with any regional significance. Techniques used to quantify recharge, discharge, storage, and flow

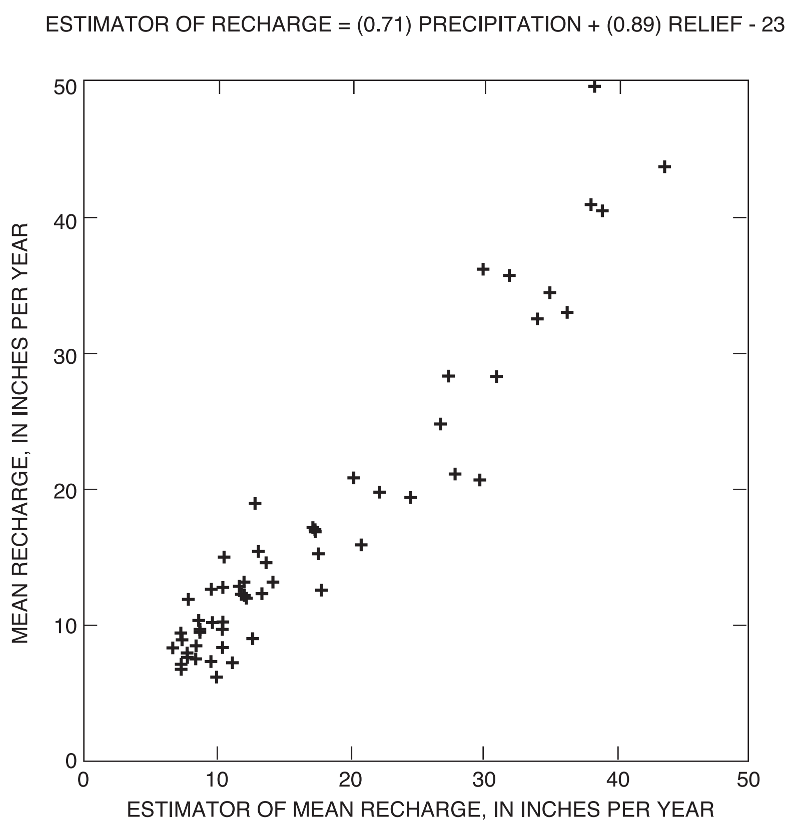


Figure 6. Relation between mean recharge and an estimator of mean recharge that is a linear function of precipitation and relief for the Blue Ridge and Piedmont Physiographic Provinces.

within the type areas may be transferable to other areas with similar hydrologic settings and hydrogeologic terranes.

The three published type-area studies (fig. 7) and the hydrogeologic settings (conceptual flow systems) that they represent are Cumberland Valley, Pa., (Chichester, 1996) with folded crystalline carbonate rocks mantled by thick and thin regolith; Indian Creek, N.C., (Daniel and others, 1997) with massive and foliated crystalline silicic rocks mantled by thick regolith; and Stony Brook, N.J., (Lewis-Brown and Jacobsen, 1995) with Mesozoic sedimentary and igneous rocks mantled by very thin regolith. The Cumberland Valley type area is mostly within the Valley and Ridge Physiographic Province. The Indian Creek and Stony Brook type areas are within the Piedmont Physiographic Province. No type area was selected in the Blue Ridge Physiographic Province because of the lack of available data to construct or calibrate a model. However, the hydrogeologic setting in most of the Blue Ridge Physiographic Province is similar to the Indian Creek type area, provided that the greater relief—typical of the Blue Ridge—is taken into account. Small areas of the Blue Ridge that are underlain by carbonate rocks have a hydrogeologic setting similar to the Cumberland Valley type area.

The type areas and each associated model are similar in several ways. The average annual precipitation for all three sites is between 40 and 48 inches. The ground-water flow model selected for simulation in each type area was a modular, three-dimensional, finite-difference, ground-water flow model (MODFLOW) documented by McDonald and Harbaugh (1988). In both the conceptual and digital models, flow through fractured and dissolved rock was simulated as flow through an equivalent porous medium. All three models were designed to simulate steady-state conditions. All model grids had equal spacing and were set parallel to bedding or foliation. Permeability was not considered isotropic and typically was least in the direction perpendicular to bedding or foliation. The water table was considered as the top of the model and impermeable rock

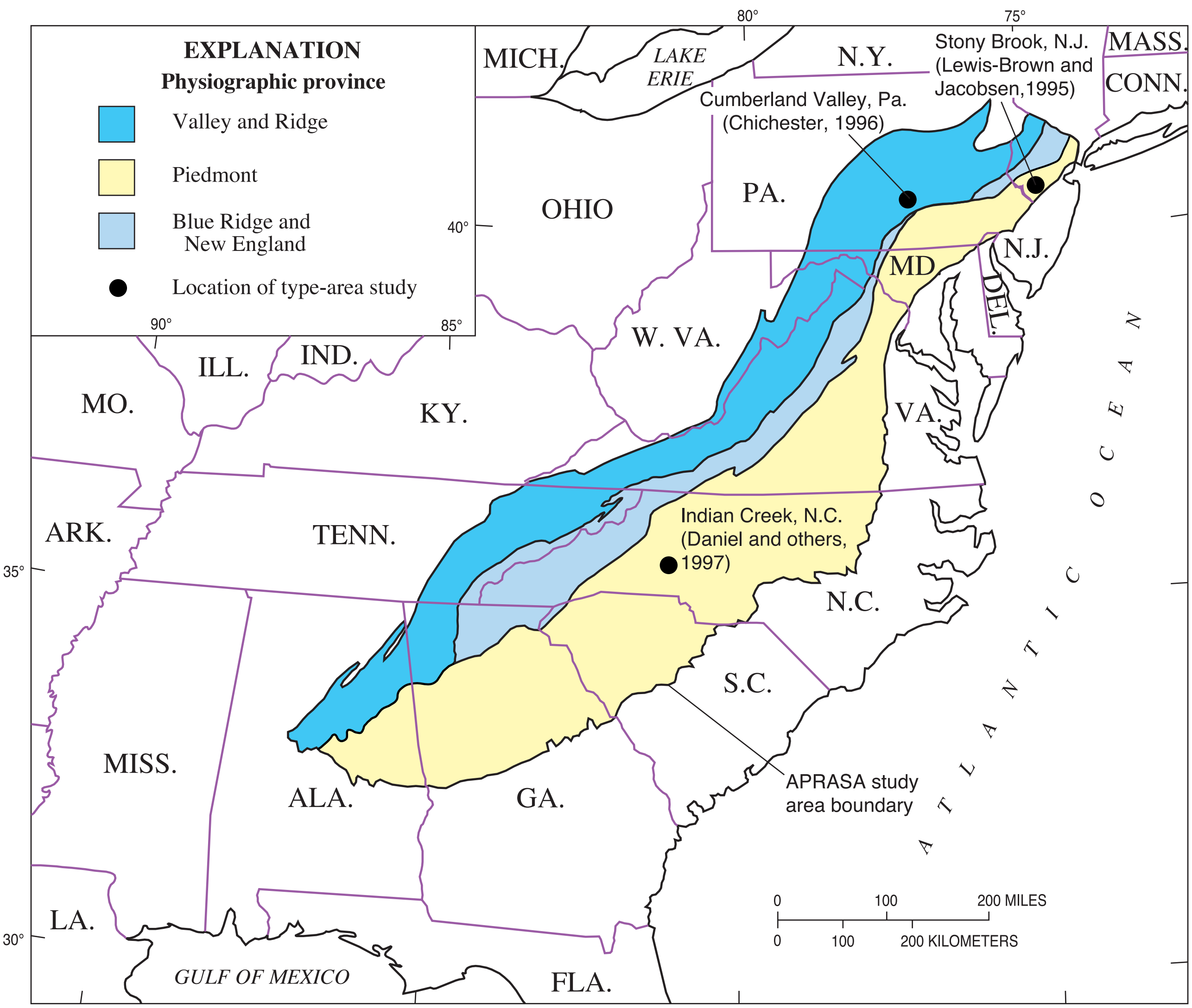


Figure 7. The Appalachian Valley and Piedmont Regional Aquifer-System Analysis (APRASA) study area and location of three type-area studies where ground-water flow was modeled.

as the bottom of the model. Vertical changes in transmissivity were incorporated into the models, with the simulated transmissivity decreasing rapidly with depth below the water table and decreasing rapidly downdip in the case of gently dipping beds (Stony Brook type area). Results indicate that the volume of lateral ground-water flow decreases significantly in layers deeper than the first one to three layers below the water table. For all three type-area models, more than 54 percent of the ground-water flow occurs in the top one to three layers.

The three type areas and the models have several differences (table 3). The Cumberland Valley, Pa., type area contains four of the five hydrogeologic terranes of the Valley and Ridge Physiographic Province and has the largest stream basin area. The Stony Brook and Indian Creek type areas contain the most transmissive hydrogeologic terranes in the Piedmont, but within much smaller stream basins. The Cumberland Valley, Pa., type area has much thicker regolith in some areas, greater depth to water, greater recharge, greater bedrock transmissivity, and larger ground-water withdrawals than the other two type areas. The Cumberland Valley, Pa., type-area model had an intermediate number of layers and the least anisotropy. Results indicate that the Cumberland Valley, Pa., type area had significantly more interbasin flow compared to the Stony Brook, N.J., type area—the only other type area with more than a single stream drainage basin. The larger interbasin flow appears to be related to the karst carbonate rocks that underlie the two basins within the Cumberland Valley, Pa., type area. Although specific values of model parameters are unlikely to be transferable to other areas, the methods and results of ground-water flow simulation used for the type area could guide further investigations to quantify ground-water conditions and flow in similar hydrogeologic settings and terranes.

Water Geochemistry

The chemistry of the water in rocks (including alluvium), springs, and streams in the three physiographic provinces was determined by assembling and interpreting 196,852 analyses of water from 15,263 sites stored primarily in the water-quality database in NWIS. The geographic distribution of water-quality sites in the study area is highly uneven (Briel, 1997, figs. 1, 2, and 3). For ground-water and surface-water sites, the majority of data are for the Piedmont Physiographic Province with emphasis on sites in Maryland, New Jersey, and Pennsylvania. For springs, most of the data are for the Valley and Ridge Physiographic Province with emphasis on sites in Maryland and Pennsylvania. For all three types of sites, the least amount of data is for the Blue Ridge Physiographic Province.

In the study area as a whole, typical ground water is not highly mineralized: the median dissolved-solids concentration is 164 mg/L. Typical ground water also is nearly neutral (median pH is 6.9) and is classified as moderately hard (median hardness is 82 mg/L as $CaCO_3$). The chemical quality of ground water in each physiographic province, however, differs substantially.

Ground water in the Valley and Ridge Physiographic Province has the largest median dissolved-solids concentration (226 mg/L, fig. 8), is slightly basic (median pH is 7.3), and is classified as hard (median hardness is 149 mg/L as $CaCO_3$). Ground water in this province also has high alkalinity and large concentrations of calcium, magnesium, sulfate, bicarbonate,

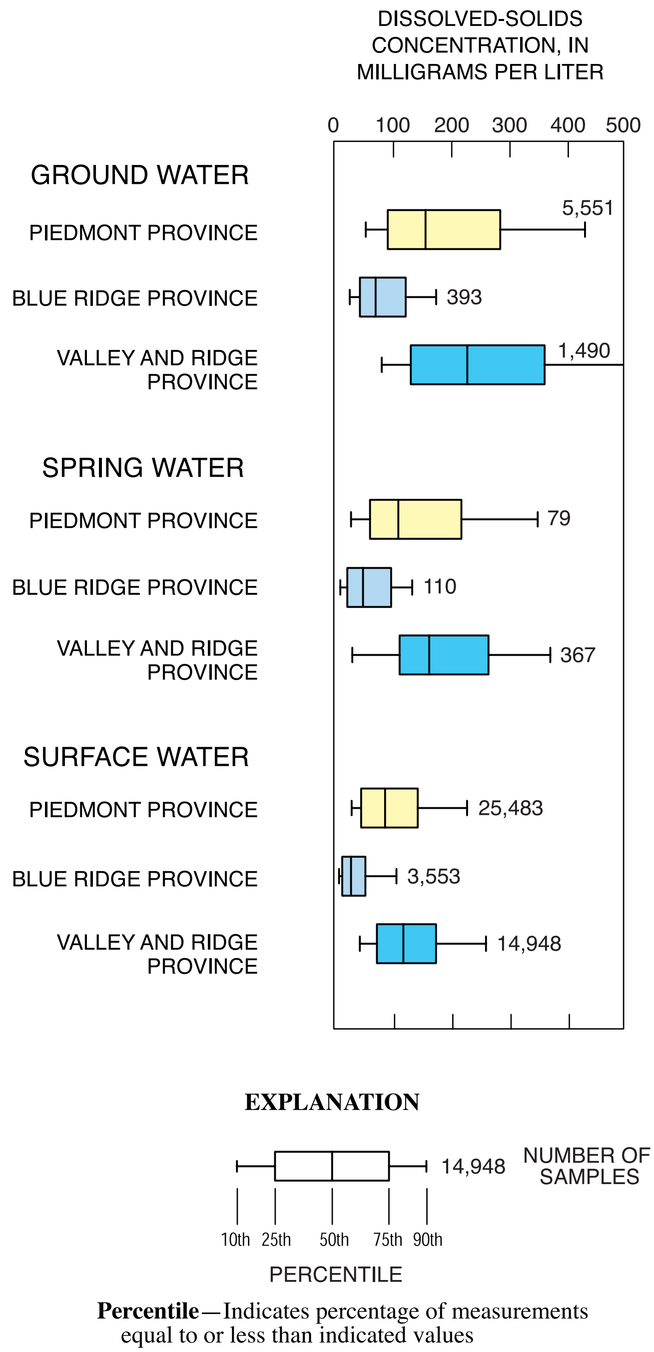


Figure 8. Distribution of dissolved-solids concentrations in ground water, spring water, and surface water in the three physiographic provinces.

Table 3. Comparison of selected characteristics of the three type areas and ground-water flow models in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.

[---, not available or not determined]

Characteristics	Type areas		
	Cumberland Valley, Pa.	Indian Creek, N.C.	Stony Brook, N.J.
Setting			
Physiographic province	Mostly Valley and Ridge	Piedmont	Piedmont
Physiographic region	Mostly Great Valley	Inner Piedmont	Newark Basin
Hydrogeologic setting (Conceptual flow system)	Folded crystalline carbonate rocks mantled by thick and thin regolith	Massive and foliated crystalline silicic rocks mantled by thick regolith	Mesozoic sedimentary and igneous rocks mantled by very thin regolith
Hydrogeologic terranes	Dolomite, limestone, argillaceous carbonate, and siliciclastic rocks	Gneiss-schist	Shale-sandstone, gneiss-schist
Rock types	Limestone, dolomite, shale, diabase	Hornblende gneiss, granite	Siltstone, shale, sandstone, diabase
Stream basins	Conodoguinet and Yellow Breeches Creeks	Indian Creek	Stony and Beden Brooks and Jacobs Creek
Basin area, in square miles	686	69	89
Regolith thickness, in feet	0 to 450	63	less than 10
Average or range in depth to water table, in feet	41	26	10 to 35
Recharge, in inches	12 to 15	10.4	8.6
Estimated storativity, regolith	0.05	0.01 to 0.20	0.01 to 0.10
Estimated storativity, bedrock	Less than 0.02	0.0002	0.0001 to 0.001
Estimated transmissivity of regolith, in feet squared per day	140 to 1,000	180 to 3,600	---
Estimated transmissivity of bedrock, in feet squared per day	1,000 to 40,000	92 to 330	200 to 3,200
Estimated streambed hydraulic conductivity, in feet per day	0.15 to 5.0	---	0.025 to 0.38
Ground-water withdrawals, in million gallons per day	About 6	0.96	1.1
Base-flow distribution	Losing upper stream reaches, gaining middle and lower reaches	Uniform across study area	Too little data to estimate distribution
Model			
Model area, in square miles	350	146	89
Grid spacing, in feet	1,320	500	500

Table 3. Comparison of selected characteristics of the three type areas and ground-water flow models in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.—Continued

	Type areas		
Characteristics	Cumberland Valley, Pa.	Indian Creek, N.C.	Stony Brook, N.J.
Number of active cells per layer	5,579	17,400	9,919
Anisotropy, row to column	1.33:1	Varies with topography	2:1, layer 1; 10:1, layer 2
Number of layers	5	11	2
Layer representation and thickness, in feet	Top 3 layers, regolith, bedrock, or both, 240, total; bottom 2 layers, bedrock, 410, total	Top layer, saprolite, 20 to 30; second layer, saprolite-bedrock transition, 25; lower 9 layers, bedrock, 800, total	Top layer, soil and weathered rock, 75 to 208; bottom layer, bedrock, 292 to 425
Lateral changes in transmissivity occur with	Each geologic unit	Three topographic settings	Faults or geologic unit by parts of study area
Boundaries	Primarily head-dependent flux, specified flux, and no flow	Primarily specified flux at boundary and interior streams	Primarily no-flow, and head-dependent flux and specified flux at interior streams
Recharge distributed by	Percent of distributed mean-annual precipitation	Uniform over study area	Base-flow estimates and geologic unit
Results			
Lateral flow in top layer	---	55 percent of recharge	94 percent of recharge
Travel time in top layer, in years	8 to more than 10	10 to 20	---
Interbasin flow	11.5 percent of one of two basin budgets	---	Less than 1 percent of any one of three basin budgets
Strong points of flow analysis	Detailed head data; distributed base-flow data; analysis of interbasin flow in karst by particle tracking; consideration of effects of diabase dike	Distributed base-flow data; discretization of transmissivity by topography; use of water-quality data to verify concept of flow	Discretization of transmissivity of dipping beds; consideration of the hydrologic effects of a normal fault

nitrate, and dissolved iron. Ground water in the Piedmont Physiographic Province, by contrast, has a smaller median dissolved-solids concentration (159 mg/L, fig. 8), is slightly acidic (median pH is 6.7), and is classified as moderately hard (median hardness is 65 mg/L as $CaCO_3$). Ground water in this province has large concentrations of sodium, potassium, chloride, silica, ammonia, phosphorus, total iron, and manganese. Ground water in the Blue Ridge Physiographic Province has the smallest median dissolved-solids concentration (73 mg/L, fig. 8), is slightly acidic (median pH is 6.6), and is classified as soft (median hardness is 29 mg/L as $CaCO_3$). Chemical quality of spring water in the study area is similar to that of water from wells, but more dilute (median dissolved-solids concentration is 136 mg/L). Chemical quality of surface water in the study area is similar to that of ground water, but like spring water, is more dilute. Median concentrations of dissolved solids in surface water (107 mg/L) indicates that surface water typically contains about 35 percent less dissolved solids than ground water and 21 percent less dissolved solids than spring water.

Typically, the order of abundance of major cations in ground water in all three provinces is calcium>magnesium>sodium; and for major anions, the order is bicarbonate>sulfate or chloride (table 4). For most water in the study area, the major dissolved ions are calcium, magnesium, and bicarbonate, which are produced by the dissolution of calcite and dolomite in the rocks. In parts of the Valley and Ridge Physiographic Province in Pennsylvania, the rocks contain significant amounts of either pyrite or gypsum, and sulfate becomes the dominant anion at higher ionic concentrations. Chloride typically is the third most abundant anion in water in the study area (the interquartile range in concentrations in ground water is 2.8 to 17 mg/L). The concentration of chloride and the variation in concentration in ground water is greatest in the Piedmont Physiographic Province. The geographic pattern, by county, of median chloride concentration in ground water (Briel, 1997, fig. 35) is similar to that for sodium (Briel, 1997, fig. 25). In addition, the geographic pattern of median chloride concentrations greater than 4.1 mg/L (Briel, 1997, fig. 35) is similar to the pattern of dense population distribution (greater than 100,000 per county; Swain and others, 1991, fig. 4), particularly in New Jersey, southeastern Pennsylvania, and the Atlanta, Georgia area.

Table 4. Typical proportions of major ions in ground water in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area.

[Ca, calcium; Mg, magnesium; Na, sodium; HCO_3, bicarbonate; SO_4, sulfate; Cl, chloride]

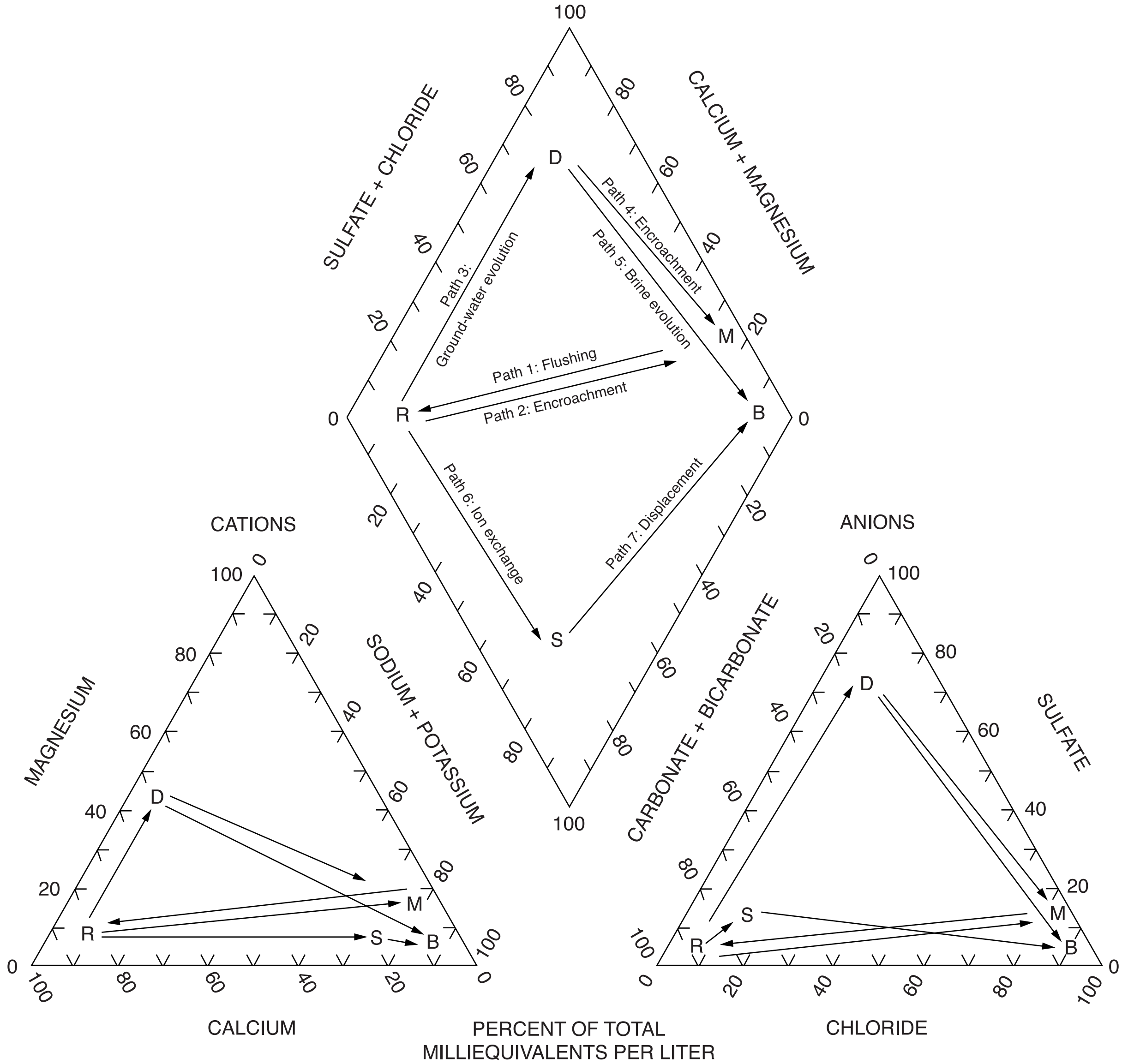
Physiographic province	Cation proportions Ca:Mg:Na	Anion proportions HCO_3:SO_4:Cl
Valley and Ridge	70:20:10	85:08:07
Blue Ridge	50:25:25	80:04:16
Piedmont	50:30:20	80:08:12

As part of the study of water chemistry in the APRASA study area, specific changes in the relative proportions of all major ions within the total concentration of solutes in water analyses are related to seven geochemical processes. These processes take specific reaction paths in a trilinear diagram (fig. 9). The most common reaction path (fig. 9, path 3) shows an evolutionary change in chemical composition of water that results from downgradient flow in recharge areas to deeper areas of more confined flow. Along this path, dissolved-solids concentration increases slightly, and chemical composition changes from a calcium-bicarbonate water to a mixed water containing calcium, magnesium, bicarbonate, and calcium sulfate. The dominant processes along this path involve the dissolution of dolomite and gypsum, and dedolomitization. Magnesium and sulfate concentrations increase, whereas calcium and bicarbonate concentrations remain constant. In the Blue Ridge and Piedmont Physiographic Provinces, secondary processes that affect water chemistry are represented by path 6 and path 2 (fig. 9). Along path 6, chemical composition changes as a result of the replacement of calcium and magnesium in the ground water by sodium ions loosely bound to clay minerals. Along path 2, chemical composition changes as a result of conservative mixing of freshwater with a sodium-chloride-sulfate water in areas of less vigorous ground-water circulation within the aquifer.

Ground-Water Development and Potential for Future Development

During development of the study area in the early 19th century, homes were located near streams and springs for transportation as well as water supply. Larger springs were developed for municipal supplies, and treatment plants eventually were constructed along streams to treat surface water. As population moved away from streams, shallow dug wells became a widespread source of household supply. Beginning in 1824 in New Brunswick, New Jersey (Carlston, 1943, p. 123), drilled wells began replacing dug wells as the main source of household supplies. Ground water withdrawn in 1985 for all uses in the study area was estimated in this study to be 1.7 Bgal/d. This represents only about 2 percent of the 90 Bgal/d estimated to be available from ground-water discharge.

Approximately 82 percent of the 1.7 Bgal/d is withdrawn from widely dispersed locations throughout the study area. Only 18 percent of the ground water used is withdrawn at pumping centers within a few counties (fig. 10). For the most part, unusual water-level declines in response to pumping in these centers have corresponded primarily with times of drought, and water levels have recovered during times of normal precipitation. As a consequence, much of the study area, including these pumping centers, could be developed for additional municipal and industrial ground-water supplies. Because ground-water flow paths in the study area are relatively shallow



EXPLANATION

CHEMICAL COMPOSITION	REACTION PATHS	DOMINANT PROCESS
M MARINE WATER	Path 1 M ➞ R	Recrystallization of aragonite to calcite. Selective dissolution of aragonite. Inversion of calcite from high-magnesium to low-magnesium. Cementation
R RECHARGE WATER	Path 2 R ➞ M	Simple mixing. Dissolution in dispersion zone
S SOFT WATER	Path 3 R ➞ D	Dissolution of dolomite and gypsum. Dedolomitization
D DOWNGRADIENT WATER	Path 4 D ➞ M	Dolomitization
B BRINE	Path 5 D ➞ B	Dissolution of halite
	Path 6 R ➞ S	Ion exchange on clay sediments. Replacement of calcium and magnesium ions by sodium ions
	Path 7 S ➞ B	Displacement of soft water by mineralized water within a confined aquifer

Figure 9. Reaction paths for evolution of chemical composition of ground water in the Appalachian Valley and Piedmont Regional Aquifer-System Analysis study area. (Modified from Hanshaw and Back, 1979.)

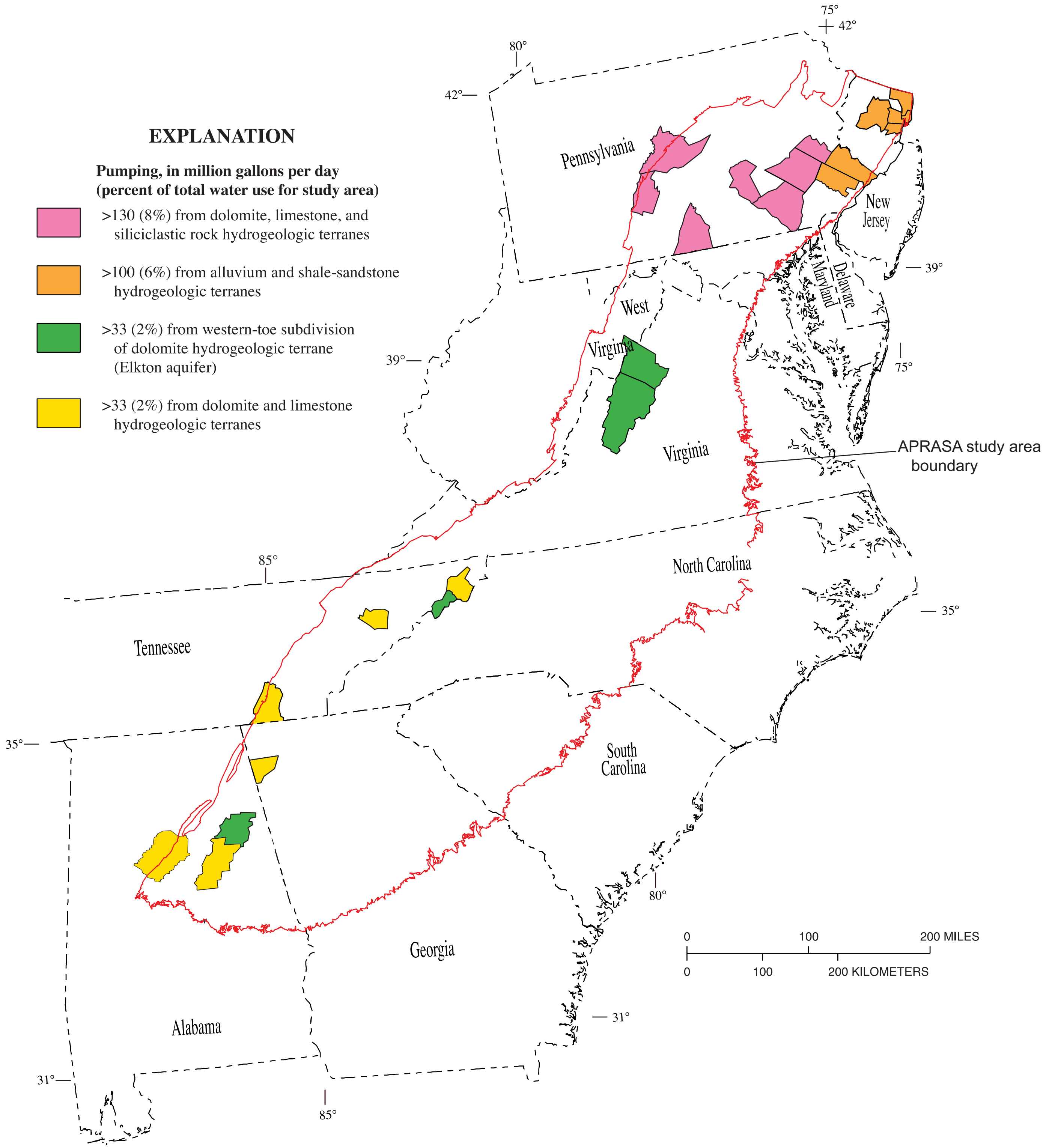


Figure 10. Estimated withdrawals at pumping centers, by county, in the Appalachian Valley and Piedmont aquifer system.

and short, however, ground-water interactions with surface water in regard to both water quantity and water quality are important constraints to consider in planning additional development.

Areas favorable for development of municipal and industrial ground-water supplies (fig. 11) may be summarized into four categories: (1) valley bottoms underlain by alluvium of glacial origin in New Jersey and Pennsylvania; (2) the Elkton aquifer along the southeastern edge of the Valley and Ridge Physiographic Province; (3) valley bottoms and rolling uplands underlain by relatively clay-free dolomite, limestone, and marble bedrock in all three physiographic provinces; and (4) the three (Mesko and others, 1999, fig. 1) northernmost Mesozoic basins in the study area. These areas were selected for their potential ability to provide municipal and industrial water supplies compared to other parts of the study area. Additionally, the northernmost Mesozoic basins were selected because of a large population with a rapidly growing need for water.

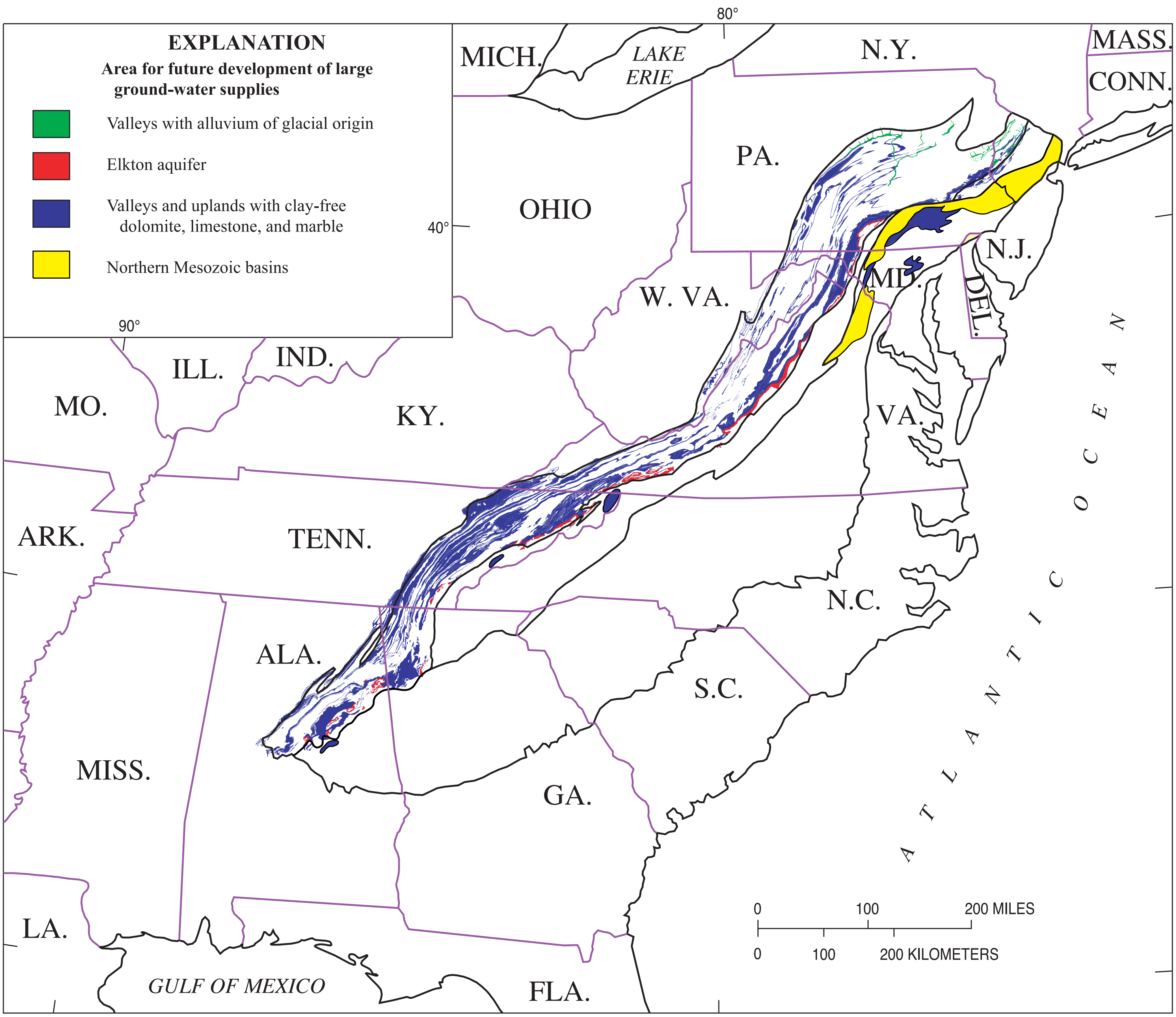


Figure 11. Areas where future development of municipal and industrial ground-water supplies from the Appalachian Valley and Piedmont aquifer system has good potential.

References Cited

Briel, L.I., 1993, Documentation of a multiple-technique computer program for plotting major-ion composition of natural waters: U.S. Geological Survey Open-File Report 93-74, 88 p.

Briel, L.I., 1997, Water quality in the Appalachian Valley and Ridge, the Blue Ridge, and the Piedmont physiographic provinces, eastern United States: U.S. Geological Survey Professional Paper 1422-D, 115 p.

Carlston, C.W., 1943, Notes on the early history of water-well drilling in the United States: Economic Geology, v. 38, no. 2, p. 119-136.

Cederstrom, D.J., 1972, Evaluation of yields of wells in consolidated rocks, Virginia to Maine: U.S. Geological Survey Water-Supply Paper 2021, 38 p.

Chichester, D.C., 1996, Hydrogeology of, and simulation of ground-water flow in, a mantled carbonate-rock system, Cumberland Valley, Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 94-4090, 39 p.

Cressler, C.W., Thurmond, C.J., and Hester, W.G., 1983, Ground water in the greater Atlanta region: Georgia Geologic Survey Information Circular 63, 144 p.

Daniel, C.C., III, 1989, Statistical analysis relating well yield to construction practices and siting of wells in the Piedmont and Blue Ridge provinces of North Carolina: U.S. Geological Survey Water-Supply Paper 2341-A, 27 p.

Daniel, C.C., III, Smith, D.G., and Eimers, J.L., 1997, Hydrogeology and simulation of ground-water flow in the thick regolith-fractured crystalline rock aquifer system of the Indian Creek Basin, North Carolina: U.S. Geological Survey Water-Supply Paper 2341-C, 137 p.

Daniel, C.C., III, White, R.K., and Stone, P.A., eds., [1993], Ground water in the Piedmont—Proceedings of a conference on ground water in the Piedmont of the eastern United States, October 16-18, 1989, Charlotte, North Carolina: Clemson, S.C., Clemson University, 693 p.

Fuller, M.L., 1905, Underground waters of Eastern United States: U.S. Geological Survey Water-Supply and Irrigation Paper 114, 285 p.

Hanshaw, B.B., and Back, William, 1979, Major geochemical processes in the evolution of carbonate-aquifer systems, *in* Journal of Hydrology, v. 43, no. 1/4, p. 287-312.

Hollyday, E.F., and Hileman, G.E., 1996, Hydrogeologic terranes and potential yield of water to wells in the Valley and Ridge Physiographic Province in the Eastern and Southeastern United States: U.S. Geological Survey Professional Paper 1422-C, 30 p.

Hollyday, E.F., Hileman, G.E., and Duke, J.E., 1997, The Elkton aquifer or western toe aquifer of the Blue Ridge Mountains—A regional perspective, *in* Younos, Tamim, Burbey, T.J., Kastning, E.H., and Poff, J.A., eds., Proceedings of the Karst-Water Environment Symposium, October 30-31, 1997, Roanoke, Va.: Blacksburg, Va.,Virginia Polytechnic Institute and State University, p. 71-79.

Knopman, D.S., 1990, Factors related to the water-yielding potential of rocks in the Piedmont and Valley and Ridge provinces of Pennsylvania: U.S. Geological Survey Water-Resources Investigations Report 90-4174, 52 p.

Knopman, D.S., and Hollyday, E.F., 1993, Variation in specific capacity in fractured rocks, Pennsylvania: Ground Water, v. 31, no. 1, p. 135-145.

LeGrand, H.E., 1967, Ground water of the Piedmont and Blue Ridge provinces in the Southeastern States: U.S. Geological Survey Circular 538, 11 p.

Lewis-Brown, J.C., and Jacobsen, Eric, 1995, Hydrogeology and ground-water flow, fractured Mesozoic structural-basin rocks, Stony Brook, Beden Brook, and Jacobs Creek drainage basins, west-central New Jersey: U.S. Geological Survey Water-Resources Investigations Report 94-4147, 83 p.

McDonald, M.G., and Harbaugh, A.W., 1988, A modular three-dimensional finite-difference ground-water flow model: U.S. Geological Survey Techniques of Water-Resources Investigations, book 6, chap. A1, variously paginated.

McGuinness, C.L., 1963, The role of ground water in the national water situation: U.S. Geological Survey Water-Supply Paper 1800, 1121 p.

Mesko, T.O., 1993, Delineation of hydrogeologic terranes in the Piedmont and Blue Ridge physiographic provinces—Southeastern and Mid-Atlantic United States [abs.]: American Association of Petroleum Geologists Bulletin, v. 77, no. 8, p. 1471.

Mesko, T.O., Swain, L.A., and Hollyday, E.F., 1999, Hydrogeology and hydrogeologic terranes of the Blue Ridge and Piedmont physiographic provinces in the Eastern United States: U.S. Geological Survey Hydrologic-Investigations Atlas HA-732-B, 1 sheet, scale 1:2,000,000.

Parizek, R.R., White, W.B., and Langmuir, Donald, 1971, Hydrogeology and geochemistry of folded and faulted carbonate rocks of the central Appalachian type and related land use problems—field trip guidebook for Geological Society of America annual meeting, Washington, D.C., November 1971: State College, Pa., The Pennsylvania State University, College of Earth and Mineral Sciences Circular 82, 181 p.

Patchen, D.G., Avary, K.L., and Erwin, R.B., regional coords., 1985a, Correlation of stratigraphic units of North America (COSUNA) project—Northern Appalachian region: American Association of Petroleum Geologists, 1 sheet.

Patchen, D.G., Avary, K.L., and Erwin, R.B., regional coords., 1985b, Correlation of stratigraphic units of North America (COSUNA) project—Southern Appalachian region: American Association of Petroleum Geologists, 1 sheet.

Rorabaugh, M.I., and Simons, W.D., 1966, Exploration of methods of relating ground water to surface water, Columbia River basin—Second phase: U.S. Geological Survey Open-File Report 66-117, 99 p.

Rutledge, A.T., 1998, Computer programs for describing the recession of ground-water discharge and for estimating mean ground-water recharge and discharge from streamflow records—Update: U.S. Geological Survey Water-Resources Investigations Report 98-4148, 43 p.

Rutledge, A.T., and Mesko, T.O., 1996, Estimated hydrologic characteristics of shallow aquifer systems in the Valley and Ridge, the Blue Ridge, and the Piedmont physiographic provinces based on analysis of streamflow recession and base flow: U.S. Geological Survey Professional Paper 1422-B, 58 p.

Sun, R.J., ed., 1986, Regional Aquifer-System Analysis program of the U.S. Geological Survey, Summary of projects, 1978-84: U.S. Geological Survey Circular 1002, 264 p.

Swain, L.A., Hollyday, E.F., Daniel, C.C., III, and Zapecza, O.S., 1991, Plan of study for the Regional Aquifer-System Analysis of the Appalachian Valley and Ridge, Piedmont, and Blue Ridge physiographic provinces of the Eastern and Southeastern United States, *with a description of* study-area geology and hydrogeology: U.S. Geological Survey Water-Resources Investigations Report 91-4066, 44 p.

Theis, C.V., Brown, R.H., and Meyer, R.R., 1963, Estimating the transmissibility of aquifers from the specific capacity of wells, *in* Bentall, Ray, comp., Methods of determining permeability, transmissibility, and drawdown: U.S. Geological Survey Water-Supply Paper 1536-I, p. 331-340.

Trainer, F.W., and Watkins, F.A., Jr., 1975, Geohydrologic reconnaissance of the upper Potomac River basin: U.S. Geological Survey Water-Supply Paper 2035, 68 p.

U.S. Geological Survey, 1985, National Water Summary 1984—Hydrologic events, selected water-quality trends, and ground-water resources: U.S. Geological Survey Water-Supply Paper 2275, 467 p.

USGS

Swain, Mesko, and Hollyday—**Summary of the Hydrogeology of the Valley and Ridge, Blue Ridge, and Piedmont Physiographic Provinces in the Eastern United States**—Professional Paper 1422-A

125 years of science for America 1879–2004

ISBN 0-607-98077-X

9 790607 980775

Printed on recycled paper