Base-Flow Characteristics of Streams in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia

United States Geological Survey Water-Supply Paper 2457

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By DAVID L. NELMS, GEORGE E. HARLOW, JR., and DONALD C. HAYES

U.S. GEOLOGICAL SURVEY WATER-SUPPLY PAPER 2457

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

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Library of Congress Cataloging in Publication Data

Nelms, David L.
Base-flow characteristics of streams in the Valley and Ridge, the Blue Ridge, and the Piedmont physiographic provinces of Virginia / by David L. Nelms, George E. Harlow, Jr., and Donald C. Hayes.
p. cm. -- (U.S. Geological Survey water-supply paper ; 2457)
Includes bibliographical references.
Supt. of Docs. no.: I 19.13:2457
1. Streamflow--Virginia. I. Harlow, George E. II. Hayes, Donald C. III. Title. IV. Series.
GB1225.V8N45 1997
551.48'3'09755--dc21 97-1129
CIP
ISBN 0-607-86841-4

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CONVERSION FACTORS, ABBREVIATIONS, AND VERTICAL DATUM

Multiply	By	To obtain
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
square mile (mi^2)	2.590	square kilometer
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer
gallon per minute (gal/min)	0.06308	liter per second
	Diffusivity and Transmissivity	
foot squared per day (ft^2/d)	0.09290	meter squared per day
	Temperature	

degrees Celsius (°C) can be converted to degrees Fahrenheit (°F) as follows:

$$°F = 1.8(°C) + 32$$

Abbreviations: For dimensions expressed in this report, L equals distance and T equals time.

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

Base-Flow Characteristics of Streams in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia

By David L. Nelms, George E. Harlow, Jr., *and* Donald C. Hayes

Abstract

Growth within the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia has focussed concern about allocation of surface-water flow and increased demands on the ground-water resources. The purpose of this report is to (1) describe the base-flow characteristics of streams, (2) identify the regional differences in these flow characteristics, and (3) describe, if possible, the potential surface-water and ground-water yields of basins on the basis of the base-flow characteristics.

Base-flow characteristics are presented for streams in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia. The provinces are separated into five regions: (1) Valley and Ridge, (2) Blue Ridge, (3) Piedmont/Blue Ridge transition, (4) Piedmont northern, and (5) Piedmont southern. Different flow statistics, which represent streamflows predominantly comprised of base flow, were determined for 217 continuous-record streamflow-gaging stations from historical mean daily discharge and for 192 partial-record streamflow-gaging stations by means of correlation of discharge measurements. Variability of base flow is represented by a duration ratio developed during this investigation. Effective recharge rates were also calculated.

Median values for the different flow statistics range from 0.05 cubic foot per second per square mile for the 90-percent discharge on the streamflow-duration curve to 0.61 cubic foot per second per square mile for mean base flow. An excellent estimator of mean base flow for the Piedmont/Blue Ridge transition region and Piedmont southern region is the 50-percent discharge on the streamflow-duration curve, but it tends to underestimate mean base flow for the remaining regions. The base-flow variability index ranges from 0.07 to 2.27, with a median value of 0.55. Effective recharge rates range from 0.07 to 33.07 inches per year, with a median value of 8.32 inches per year.

Differences in the base-flow characteristics exist between regions. The median discharges for the Valley and Ridge, the Blue Ridge, and the Piedmont/Blue Ridge transition regions are higher than those for the Piedmont regions. Results from statistical analysis indicate that the regions can be ranked in terms of base-flow characteristics from highest to lowest as follows: (1) Piedmont/Blue Ridge transition, (2) Valley and Ridge and Blue Ridge, (3) Piedmont southern, and (4) Piedmont northern. The flow statistics are consistently higher and the values for base-flow variability are lower for basins within the Piedmont/Blue Ridge transition region relative to those from the other regions, whereas the basins within the Piedmont northern region show the opposite pattern.

The group rankings of the base-flow characteristics were used to designate the potential surface-water yield for the regions. In addition, an approach developed for this investigation assigns a rank for potential surface-water yield to a basin according to the quartiles in which the

values for the base-flow characteristics are located. Both procedures indicate that the Valley and Ridge, the Blue Ridge, and the Piedmont/ Blue Ridge transition regions have moderate-to-high potential surface-water yield and the Piedmont regions have low-to-moderate potential surface-water yield.

In order to indicate potential ground-water yield from base-flow characteristics, aquifer properties for 51 streamflow-gaging stations with continuous record of streamflow data were determined by methods that use streamflow records and basin characteristics. Areal diffusivity ranges from 17,100 to 88,400 feet squared per day, with a median value of 38,400 feet squared per day. Areal transmissivity ranges from 63 to 830 feet squared per day, with a median value of 270 feet squared per day. Storage coefficients, which were estimated by dividing areal transmissivity by areal diffusivity, range from approximately 0.001 to 0.019 (dimensionless), with a median value of 0.007.

The median value for areal diffusivity decreases as potential surface-water yield of the basins increases. The ranking of areal diffusivity does not correspond with the ranking of potential surface-water yield for either the regions or the basins. Areal transmissivity generally increases as storage coefficient increases; however, basins with low potential surface-water yield generally have high values of areal transmissivity associated with low values of storage coefficient over a narrow range relative to those from basins designated as having moderate-to-high potential surface-water yield. Although the basins with high potential surface-water yield tend to have comparatively lower values for areal transmissivity, storage coefficients generally are large when compared to those from basins with similar values of areal transmissivity but different potential surface-water yield.

Aquifer properties were grouped by potential surface-water yield and were related to hydrogeologic units categorized by large, medium, and small well yields for the Valley and Ridge Physiographic Province and for the Blue Ridge and the Piedmont Physiographic Provinces. Generally, no trend is evident between areal diffusivity and the hydrogeologic units. Some of the high values of areal diffusivity are associated with basins predominantly underlain by hydrogeologic units with small well yields, especially basins with a low potential surface-water yield. Areal transmissivity and storage coefficient tend to decrease, which is the expected trend, as more of the basin is underlain by the hydrogeologic unit with small well yields in the Valley and Ridge Physiographic Province. A similar trend is indicated for the hydrogeologic unit with medium well yields in the Blue Ridge and the Piedmont Physiographic Provinces. Areal transmissivity and storage coefficient tend to increase, which is not the expected trend, as more of the basin is underlain by the hydrogeologic unit with small well yields in the Blue Ridge and the Piedmont Physiographic Provinces. The base-flow characteristics of a basin may provide a relative indication of the potential ground-water yield; but other factors need to be considered, such as geologic structure, lithology, precipitation, relief, and degree of hydraulic interconnection between the regolith and bedrock.

INTRODUCTION

Growth within the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia has focussed concern about allocation of surface-water flow and increased demands on the ground-water resources. Hydrogeologic systems within the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia are diverse and complex. Knowledge of these flow systems provides information needed to effectively manage the water resources within the study area. Base-flow characteristics of streams in these provinces were used to evaluate surface-water and ground-water flow systems. This investigation is part of the Appalachian Valley and Piedmont Regional Aquifer-System Analysis (APRASA) study, which is one of several regional investigations conducted by the U.S. Geological Survey (USGS) to assess the Nation's principal aquifer systems (Sun, 1986). The APRASA study area encompasses the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of the

Appalachian Highlands in the Eastern United States (Swain and others, 1991).

Purpose and Scope

The purpose of this report is to (1) describe the base-flow characteristics of streams within the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia, (2) identify the regional differences in these flow characteristics, and (3) describe, if possible, the potential surface-water and ground-water yields of basins on the basis of the base-flow characteristics. Base-flow characteristics of streams in the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia were used to evaluate the surface-water and ground-water-flow systems. The provinces were separated into five regions using the method described by Hayes (1991). Different flow statistics, which represent streamflows predominantly comprised of base flow, were determined for continuous-record streamflow-gaging stations from historical mean daily discharge and for partial-record streamflow-gaging stations by correlation of discharge measurements. Mean base flow and effective recharge values determined by hydrograph separation are discussed. Variability of base flow is represented by a duration ratio developed during this investigation. Regional differences in base-flow characteristics are assessed. Regions are grouped and ranked based on base-flow characteristics as an indicator of potential surface-water yield. Aquifer properties and hydrogeologic units classified on the basis of well yield are compared to potential surface-water yield to determine potential ground-water yield. Data from published reports and from streamflow records maintained by the USGS and the Virginia Department of Environmental Quality, Water Division, were used for these evaluations.

Description of Study Area

The Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces encompass approximately 29,900 mi^2 in the central part of Virginia (fig. 1). The study area is bordered by the Appalachian Plateaus Physiographic Province on the west and by the Coastal Plain Physiographic Province on the east. The entire study area is underlain by fractured rock aquifers locally covered by regolith consisting of soil, alluvium, colluvium, and residuum (commonly referred to as saprolite). Thickness of the regolith ranges from 0 to more than 150 ft throughout the study area (Swain and others, 1991, p. 12). A generalized lithologic map of the study area is shown in figure 2. In addition, the study area is divided (fig. 3) in terms of geologic province into the central and

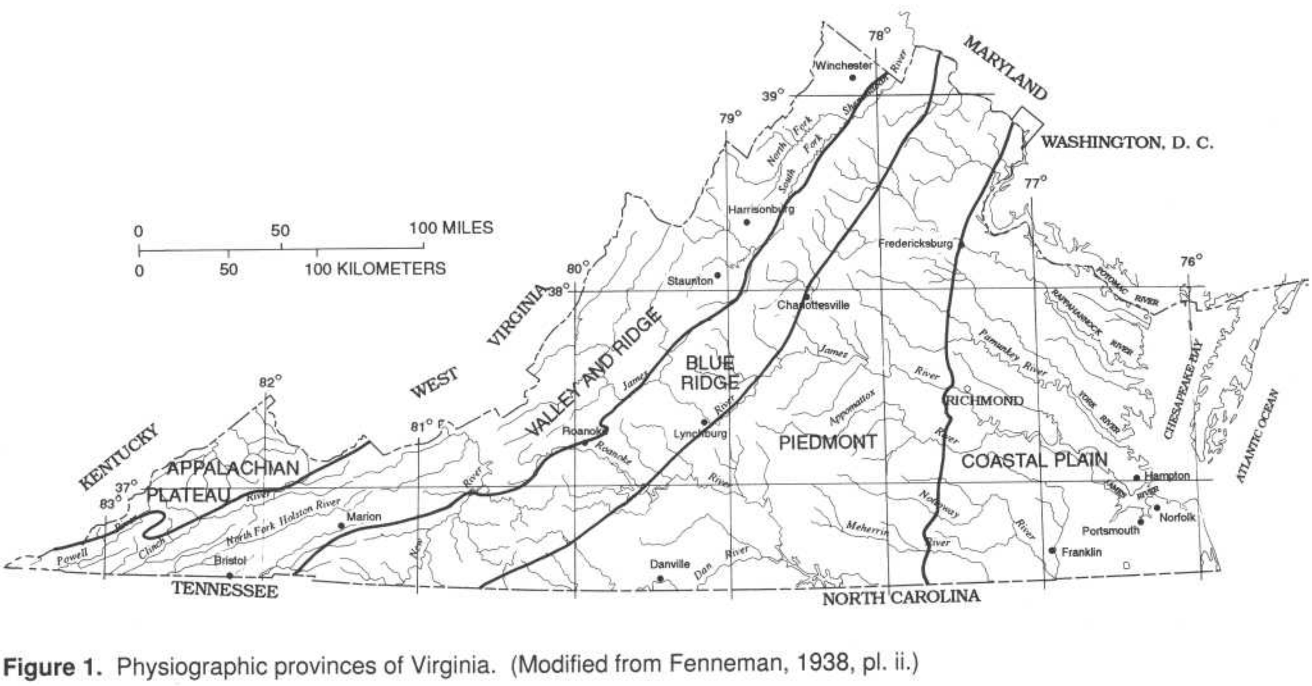


Figure 1. Physiographic provinces of Virginia. (Modified from Fenneman, 1938, pl. ii.)

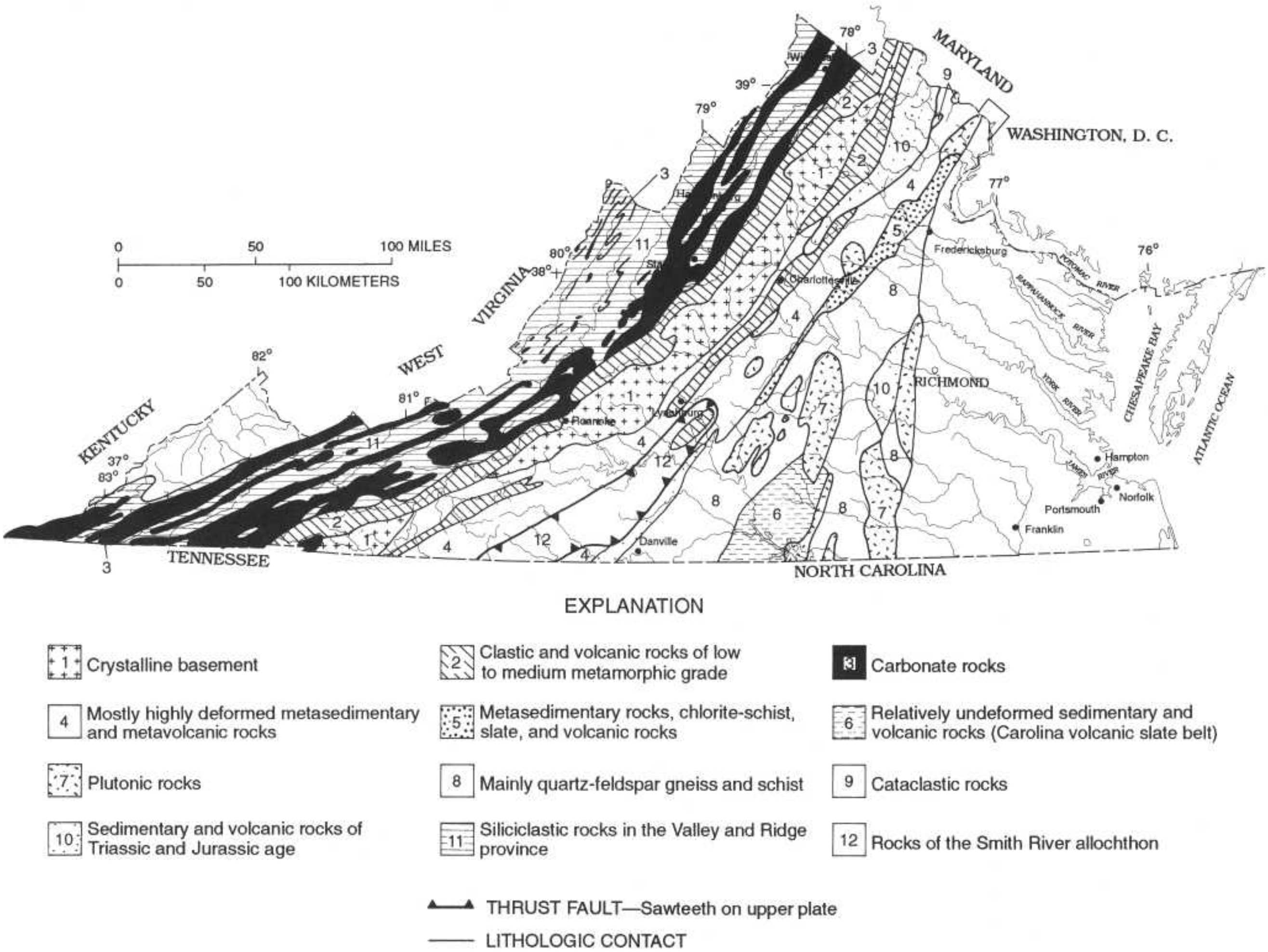
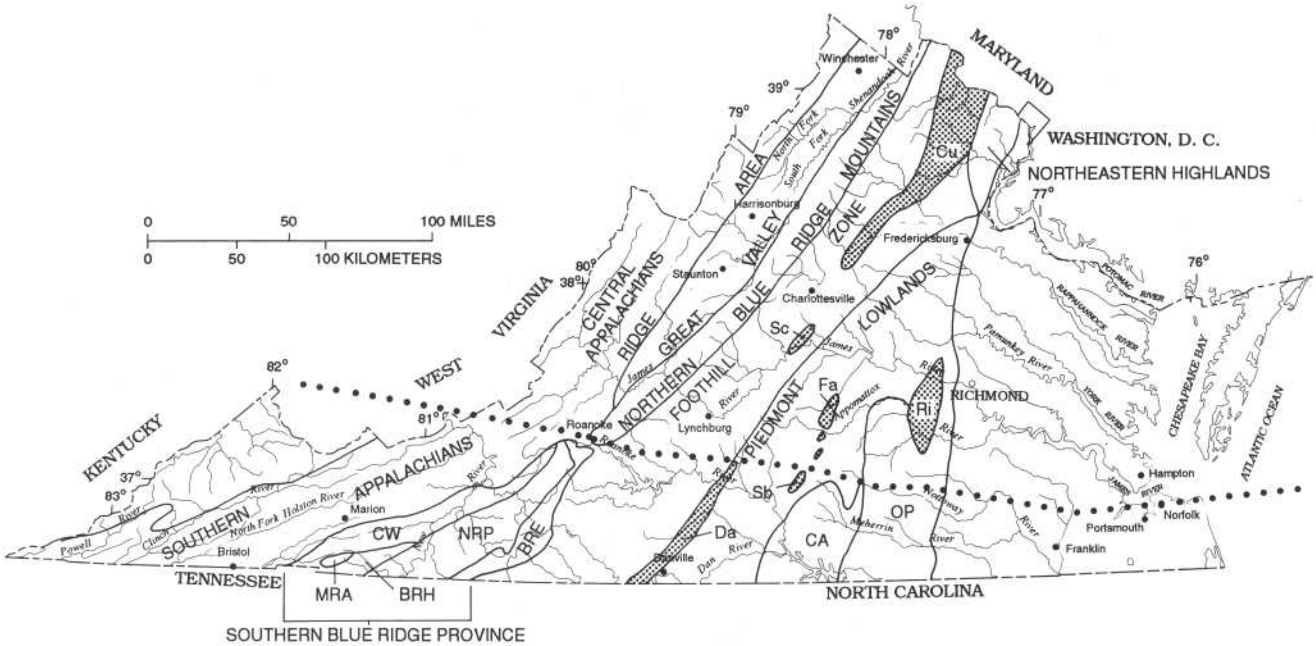


Figure 2. Generalized lithologic map of the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia. (Modified from Hack, 1982, fig. 2; Pavlides, 1981, fig. 9; Milici and others, 1963.)

southern sections of the Appalachians in the vicinity of Roanoke (Weaver, 1970, p. 125; Rast, 1989, p. 326).

The Valley and Ridge Physiographic Province encompasses approximately 10,600 mi^2 along the western part of the study area and consists of a belt of northeast/southwest trending ridges and valleys formed by the differential erosion of a thick sequence of folded and faulted Paleozoic sedimentary rocks (Pettijohn, 1970, p. 1). Elevations range from about 380 ft above sea level where the Shenandoah River flows out of Virginia into Maryland to 4,604 ft above sea level in southwestern Virginia (Butts, 1940, p. 14). North of Roanoke, the province is part of the central Appalachians and is separated into two subdivisions (fig. 3): (1) a southeastern valley area (commonly referred to as the Great Valley) underlain by Cambrian-age to Ordovician-age carbonate rocks and shales characterized by broad valleys with interspersed ridges or hills; and (2) a northwestern ridge area underlain by Silurian-age to Pennsylvanian-age sandstones and shales characterized by high ridges with interspersed narrow valleys (Hack, 1989, p. 463). Another feature of the province north of Roanoke is the presence of a thick mantle of residuum, talus, and alluvial deposits that overlie the Cambrian carbonate rocks on the eastern slope of the valley at the foot of the Blue Ridge (King, 1950, p. 54; Leonard, 1962; Hack, 1965, p. 48; Hack, 1989, p. 464). This belt of residuum termed the "Western Toe" of the Blue Ridge can exceed 600 ft in thickness (T.M. Gathright, II, Virginia Division of Mineral Resources, oral commun., 1994). South of Roanoke, the province is part of the southern Appalachians (fig. 3) and is characterized by



EXPLANATION

SUBDIVISIONS OF SOUTHERN BLUE RIDGE PROVINCE

- BRE Blue Ridge Escarpment
- BRH Blue Ridge Highlands
- CW Chilhowee-Walden Creek belt
- MRA Mount Rogers area
- NRP New River plateau

SUBDIVISIONS OF PIEDMONT LOWLANDS

- CA Carolina slate belt
- OP Outer Piedmont

MESOZOIC BASINS (dotted areas)

- Cu Culpeper
- Sc Scottsville
- Ri Richmond
- Fa Farmville
- Sb Scottsburg
- Da Danville

• • BOUNDARY BETWEEN CENTRAL AND SOUTHERN APPALACHIANS

—— SUBDIVISION BOUNDARY

Figure 3. Subdivisions within the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of Virginia. (Modified from Hack, 1982, fig. 1; Rast, 1989, fig.3.)

ridges and narrow valleys, and the predominant style of deformation within the province changes from folding to thrust faulting (Hack, 1989, p. 463).

The Blue Ridge Physiographic Province encompasses approximately 3,000 mi^2 along a narrow northeast-trending belt between the Valley and Ridge and the Piedmont Physiographic Provinces and consists of a chain of mountains and highlands underlain by metamorphosed Proterozoic and Paleozoic rocks (Reed, 1970, p. 195). Elevations range from about 220 ft above sea level along the Potomac River at the State line to 5,729 ft above sea level on Mount Rogers. Generally, soils are thin and weathering profiles are shallow in the Blue Ridge Physiographic Province (Meyer and others, 1965). Hack (1982, p. 26) separated the province into two sections because the origins of the topography differ. The section north of the Roanoke River, the Northern Blue Ridge Mountains (fig. 3), is characterized by a narrow range of high mountains underlain by Precambrian-age to Cambrian-age quartzite, phyllite, metabasalt, and granodiorite that form the northwest limb of an anticlinorium. The section south of the Roanoke River, the Southern Blue Ridge Province, is much broader and was separated by Hack (1982, p. 28) into five subdivisions based on topography (fig. 3): (1) the Chilhowee-Walden Creek belt underlain by Cambrian-age quartzites and faulted carbonate rocks and shale that form long, steep ridges separated by parallel valleys along the northwest margin; (2) the Mount Rogers area underlain by Precambrian volcanic and metasedimentary rocks that form a few high ridges just north of the North Carolina/Virginia border; (3) the Blue Ridge Highlands underlain by massive Precambrian-age gneisses and amphibolites that form high mountains cut by deep valleys and basins; (4) the New River plateau, which encompasses the headwaters of the New River in North Carolina, underlain by thinly layered schist and gneiss that form a broad plateau with a few low mountains; and (5) the Blue Ridge escarpment underlain by finely laminated gneiss that form a narrow strip of land that drains southeastward to the Piedmont Physiographic Province.

The Piedmont Physiographic Province encompasses approximately 16,300 mi^2 along the eastern part of the study area and consists of a gently rolling plain underlain by polydeformed and metamorphosed Proterozoic and Paleozoic rocks (Fisher, 1970, p. 295). A thick mantle of soil and weathered rock that overlies the fractured crystalline bedrock is a characteristic feature of the province (Meyer and others, 1965; Conley, 1985, p. 1; Swain and others, 1991, p. 12). Generally, regolith developed on the crystalline rocks is thick under the hilltops and thin to absent in the stream valleys (Richardson, 1982, p. 6; Pavich and others, 1989, p. 43). Elevations range from about 200 ft above sea level along the eastern border to 1,000 ft above sea level along the western border of the province. Downfaulted Mesozoic sedimentary basins, which encompass approximately 1,340 mi^2, are located within the Piedmont Physiographic Province. These basins are underlain by shale, mudstone, sandstone, and basalt and are characterized by generally lower relief than the surrounding Piedmont (Hack, 1989, p. 461). Thin soils and shallow weathering profiles are characteristic features of the rocks in the Mesozoic Basins (Conley, 1985, p. 2; Froelich, 1985). Hack (1982, p. 3) noted that the Piedmont Physiographic Province of Virginia consists of the Foothill zone on the west, the Piedmont Lowlands on the east, and the Northeastern Highlands on the north (fig 3.). The Foothill zone also encompasses the southeastern part of the Blue Ridge Physiographic Province. The part of the Foothill zone north of the Roanoke River is underlain by resistant volcanic and metamorphic rocks that form chains of isolated hills and ridges. The part of the Foothill zone south of the Roanoke River is underlain by resistant rocks of the Smith River allochthon that form an upland (Hack, 1982, p. 24). The Piedmont Lowlands are underlain by feldspathic gneiss and schist intruded by granitic plutons with lesser amounts of metasedimentary and metavolcanic rocks that form low ridges or hills and ravines.

Climate

The climate in Virginia is moderate, with large variations in temperature and moderate variations in precipitation. Average annual temperatures range from 51°F in the Valley and Ridge and the Blue Ridge Physiographic Provinces to 57°F in the Piedmont Physiographic Province, with extremes ranging from −30 to above 100°F. Yearly precipitation is characterized by plentiful rain and snow derived from coastal cyclones and thunderstorms that move into the State from the Gulf of Mexico, the Caribbean Sea, and the Atlantic Ocean (Nuckels and Prugh, 1991, p. 543–544). Precipitation varies with location and elevation but averages 42 in/yr (fig. 4). In the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces, average annual precipitation ranges from 36 to 50 in/yr, 38 to 48 in/yr, and 40 to 46 in/yr, respectively. Rain shadows are present in both the northern and southern areas of the Valley and Ridge

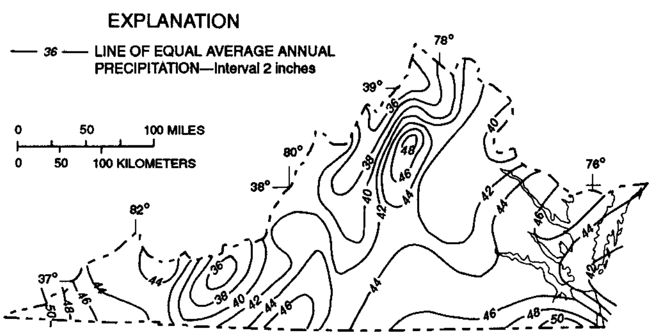


Figure 4. Average annual precipitation in Virginia. (Modified from Hayes, 1991, fig. 2.)

Methods of Study

Streamflow data for 217 continuous-record streamflow-gaging stations were used to estimate base-flow characteristics. Flow-duration statistics commonly are used in the evaluation of base-flow characteristics and are derived from a flow-duration curve, which is a cumulative frequency curve that shows the percentage of time a specified discharge is equalled or exceeded during a given period of record (Searcy, 1959). In this report, Q_x is the symbol that designates the discharge that is equalled or exceeded x-percent of the time. Values for the discharge equalled or exceeded 50 percent of the time or median discharge (Q_{50}), the discharge equalled or exceeded

90 percent of the time (Q_{90}), and the discharge equalled or exceeded 95 percent of the time (Q_{95}) on the flow-duration curve were derived from the Automated Data Processing System (ADAPS) data base maintained by the USGS (Dempster, 1990). Annual minimum average 7-consecutive-day low-flow discharges having 2-year and 10-year recurrence intervals ($7Q2$ and $7Q10$, respectively) were directly taken from Hayes (1991, appendix 1). Values for long-term mean base flow and effective recharge were estimated for 212 continuous-record streamflow-gaging stations by using a computerized streamflow-partitioning method developed for the APRASA study (Rutledge, 1992; 1993). The streamflow-partitioning method is a form of hydrograph separation that uses mean daily streamflow records to estimate base flow over a period of several years. The flow-duration statistics, mean base flow, and effective recharge were determined for the entire period of unregulated streamflow up to 1984 for each of the continuous-record streamflow-gaging stations, which duplicates the period considered by Hayes (1991).

In addition to the continuous-record streamflow-gaging stations, base-flow characteristics were estimated for 192 partial-record streamflow-gaging stations. The values for Q_{50}, Q_{90}, and Q_{95} were estimated by correlating streamflow measurements made at partial-record stations during recessional periods through a visually fitted relation line to concurrent mean daily discharge values at long-term continuous-record streamflow-gaging stations, which commonly are referred to as index stations. An example of this method is shown in figure 5, where the partial-record station is Goose Creek at Oatlands and the index station is Goose Creek at Leesburg. These base-flow characteristics were estimated by means of correlations developed by Hayes (1991), and the reader may consult Hayes (1991, p. 9–10) for further explanation. The values for $7Q2$ and $7Q10$ are from Hayes (1991, appendix 2). The streamflow-partitioning method used to compute mean base flow and effective

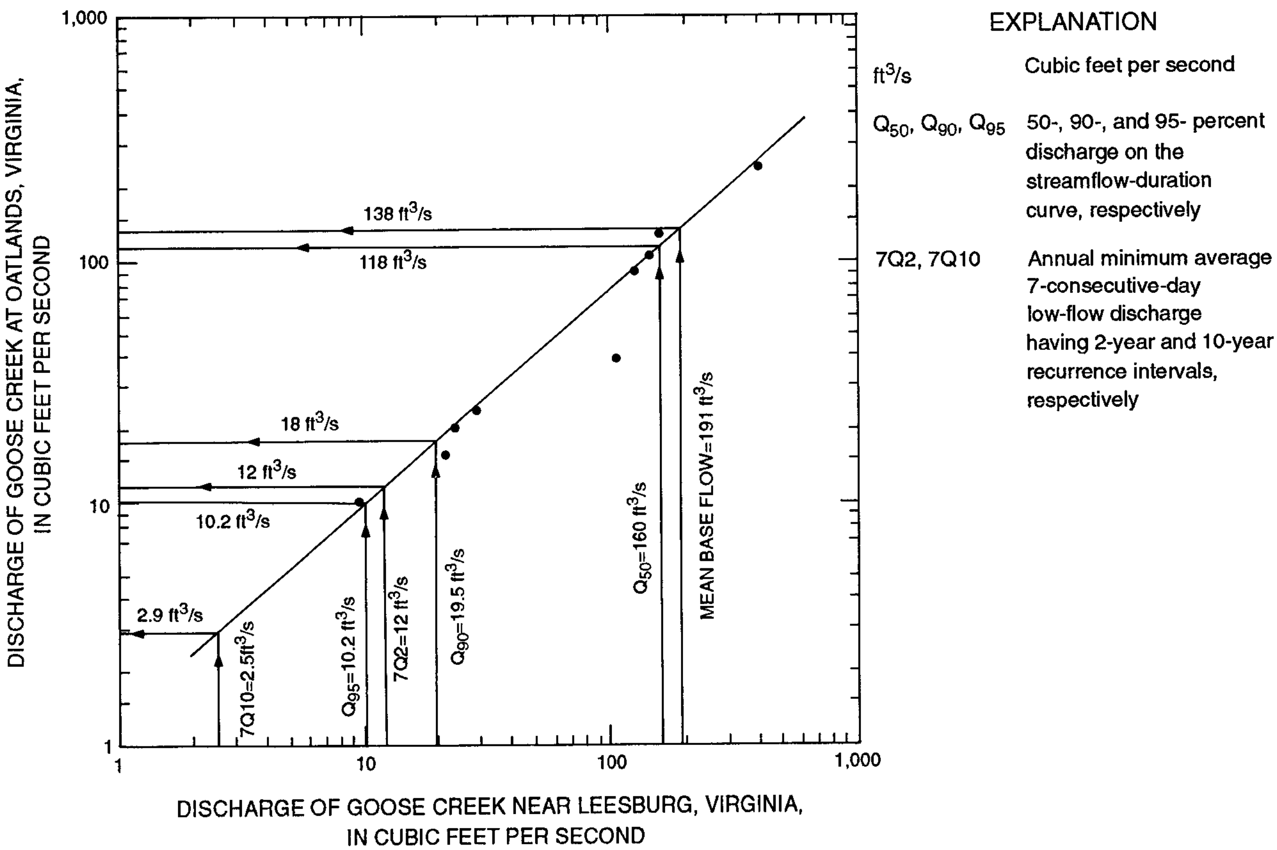


Figure 5. Relation of base flow of Goose Creek at Oatlands to concurrent mean daily discharge of Goose Creek near Leesburg.

recharge could not be applied directly to the partial-record stations because this method requires a continuous record of mean daily streamflow data. Therefore, values for mean base flow and effective recharge at 171 partial-record stations were estimated by use of the same correlations developed by Hayes (1991). The values for Q_{50} (mean base flow) and effective recharge were not estimated for some of the partial-record stations because these values required extrapolation of the relation lines established by Hayes (1991) beyond one log cycle, which was considered to be excessive. This criterion was established to improve the accuracy of the correlations for the higher flow statistics, which were not considered by Hayes (1991).

In addition to the flow characteristics previously mentioned, the $\log_{10}$ of the ratio of Q_{50} to Q_{90} was used as an index to represent the variability of base flow. This base-flow variability index is comparable to Lane's variability index (Searcy, 1959, p. 31–32), which is an index of streamflow variability from the Q_5 to Q_{95} on the flow-duration curve. The base-flow variability index, however, follows the assumption that the selected flow-duration discharges represent streamflows predominantly comprised of base flow or ground-water discharge. Arihood and Glatfelter (1991) developed a similar flow-duration ratio by dividing the Q_{20} by Q_{90}. Hely and Olmsted (1963) used the ratio of Q_{90} to average discharge as an indicator of the effects of terrestrial characteristics on base flow.

Nonparametric statistical techniques were used to perform hypothesis tests, which determine if differences in the data are by chance variability or are true statistical differences. Nonparametric techniques are less sensitive to outliers, and assumptions of equal variances or normality are not required. The hypothesis test consists of a null hypothesis which assumes that no real difference exists in the data. In this report, the alpha value (level of significance) used is 0.05, which represents the maximum probability of rejecting the null hypothesis when it is actually true at the 95-percent level of confidence. The probability for each test (p-value) represents the significance level attained by the test. In order to reject the null hypothesis, the p-value must be less than or equal to the alpha value (Hamilton and others, 1991, p. B28). Three hypothesis tests were used—Mann-Whitney, Kruskal-Wallis, and Tukey's multiple comparison. The Mann-Whitney test is a nonparametric rank-sum test that compares two groups. The Kruskal-Wallis test is a nonparametric one-way analysis of variance test that uses rank-transformed data to compare two or more groups. The Tukey's multiple comparison test (Tukey's MCT) is another nonparametric analysis of variance test performed on rank-transformed data to determine which group or groups are significantly different.

In order to facilitate a spatial analysis of the data, drainage-basin boundaries for the streamflow-gaging stations were digitized using a geographic information system by modifying the hydrologic unit coverage distributed by the Virginia Department of Conservation and Recreation, Division of Soil and Water Conservation (DCR–DSWC). The hydrologic unit coverage is based on the USGS hydrologic unit map of Virginia at a scale of 1:500,000 (U.S. Geological Survey, 1974); however, the DCR–DSWC and U.S. Department of Agriculture, Soil Conservation Service delineated these units at a scale of 1:24,000. These hydrologic unit delineations were then digitized at the Information Support Systems Laboratory of the Department of Agricultural Engineering at Virginia Polytechnic Institute and State University.

BASE-FLOW CHARACTERISTICS

Knowledge of base-flow characteristics of streams provides insight into hydrogeologic flow systems of the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces. In order to fully define these characteristics, different flow statistics were selected to represent streamflows predominantly comprised of base flow. Mean base flow indicates the long-term average contribution of ground water to streams and is commonly referred to as either ground-water discharge or ground-water runoff. The Q_{50} is commonly selected as an approximation of mean base flow. Effective recharge is equivalent to mean base flow (by means of unit conversion) because ground-water discharge over a long period of time approximately equals ground-water recharge (Richardson, 1982, p. 12). Effective recharge is defined as the amount of precipitation that infiltrates, but is not removed by evapotranspiration, and eventually discharges to streams (U.S. Environmental Protection Agency, 1987, p. 62). Values of Q_{90}, Q_{95}, $7Q2$, and $7Q10$ represent base flow after periods of sparse recharge and are collectively termed "low-flow statistics" in this report. Although the low-flow statistics are computed differently, these statistics are indicators of base-flow characteristics for basins during periods of drought.

The rationale for using a range of flow statistics to determine base-flow characteristics is based on values reported in the literature. Flow-duration statistics commonly are used to evaluate base flow. The Q_{50} is a flow-duration statistic commonly used to estimate mean base flow (Cushing and others, 1973). The Q_{90} is a relatively stable flow-duration statistic used as a conservative estimator of mean base flow (Hely and Olmsted, 1963; Wyrick, 1968; Lichtler and Wait, 1974). Wyrick (1968) used a discharge between Q_{90} and Q_{95} as an estimate of ground-water discharge (base flow) and as an indication of water-yielding properties of rocks in the Appalachian region. Trainer and Watkins (1975) used hydrograph separation to determine mean base-flow discharges in the upper Potomac River Basin, which corresponded to discharge values on the flow-duration curve that ranged from Q_{39} to Q_{61} and averaged Q_{52}. Laczniak and Zenone (1985) used a similar method to determine that mean annual base flow in the Culpeper Basin is represented by Q_{68}.

Another important aspect of base flow is the variability of discharge exhibited by the streams in the study area. The base-flow variability index represents the average slope of the flow-duration curve from Q_{50} to Q_{90}. Streams with low variability, which indicates sustained base-flow discharges over time in response to increased ground-water storage, will have values for the base-flow variability index that are closer to zero than those for streams with higher variability.

Regions

Many basin and climatological characteristics can affect base flow, such as geology, soils, drainage area, relief, streambed elevations, and distribution of precipitation. Hayes (1991) divided the State into eight regions by grouping the residuals from regression analyses approximately along physiographic boundaries. The variability of basin and climatological characteristics is limited by the design of these regions. Hayes (1991) subdivided the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces into five regions, which were used for this investigation (pl. 1) and for which the base-flow characteristics are described below. The five regions are (1) Valley and Ridge, (2) Blue Ridge, (3) Piedmont/Blue Ridge transition, (4) Piedmont northern, and (5) Piedmont southern. Summary statistics for base-flow characteristics by region are in figure 6 and in table 1. The actual base-flow characteristics determined for the individual continuous-record and partial-record stations are listed in appendixes 1 and 2, respectively. The spatial distribution of each base-flow characteristic is presented on plate 1, where the shade patterns represent values less than the 25th-percentile (lower quartile), between the 25th- and 75th-percentiles (interquartile range), and greater than the 75th-percentile (upper quartile) for the entire study area.

Valley and Ridge Region

The Valley and Ridge region nearly encompasses the Valley and Ridge Physiographic Province (pl. 1). Drainage areas range from 0.61 to 3,768 mi^2, with a median area of 50.8 mi^2. Mean base flow for this region ranges from 0.01 to 1.51 $(ft^3/s)/mi^2$, with a median value of 0.72 $(ft^3/s)/mi^2$. The Q_{50} ranges from 0.00 to 1.35 $(ft^3/s)/mi^2$, with a median value of 0.56 $(ft^3/s)/mi^2$, which is slightly lower than the mean base flow. The difference between the median values suggests that mean base flow may be equivalent to a higher discharge on the flow-duration curve than the Q_{50}. Rutledge and Mesko (1996) determined that Q_{42} on the flow-duration curve is a reasonable estimator of mean base flow for streams in the Valley and Ridge Physiographic Province of the Eastern United States. The values for the low-flow statistics range from 0.00 to 0.60 $(ft^3/s)/mi^2$. The median discharges for the low-flow statistics range from 0.09 $(ft^3/s)/mi^2$ for $7Q10$ to 0.16 $(ft^3/s)/mi^2$ for Q_{90}. The base-flow variability index ranges from 0.18 to 2.27, with a median value of 0.55. Effective recharge in the Valley and Ridge region ranges from 0.07 to 20.55 in/yr, with a median value of 9.73 in/yr.

The subdivision of the central and southern Appalachians is approximately located near latitude 37°30'. The Mann-Whitney test indicates that the median values for the base-flow characteristics for basins north of latitude 37°30', except $7Q2$ and $7Q10$ (p=0.059 and 0.143, respectively), are significantly different from those south of this latitude. Median values for mean base flow, Q_{50}, Q_{90}, Q_{95}, effective recharge, and base-flow variability index (p-values range from <0.001 to 0.035) are higher in the southern section of the Valley and Ridge region than in the northern section (table 1). The median drainage area in the southern section of the Valley and Ridge region

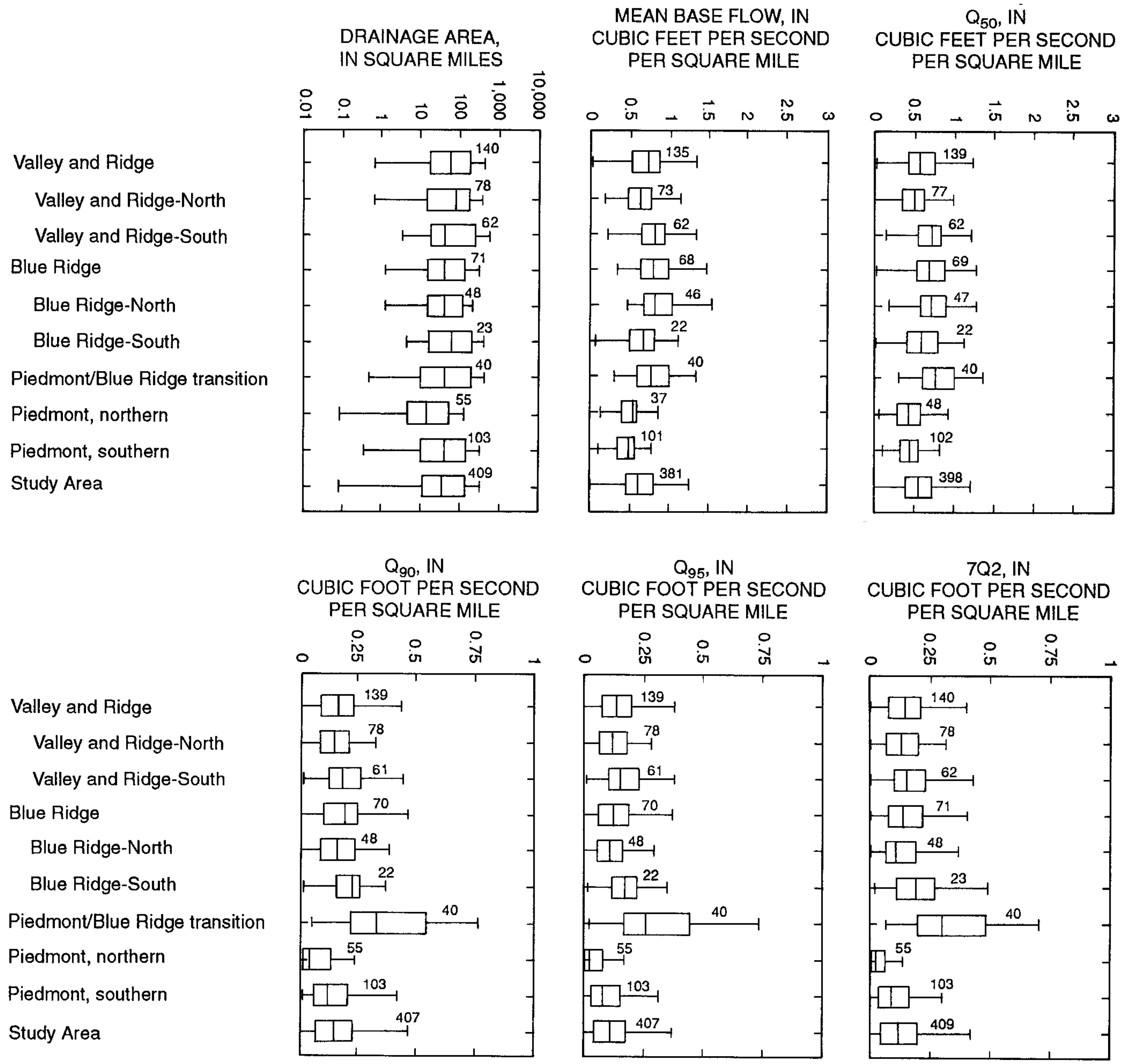
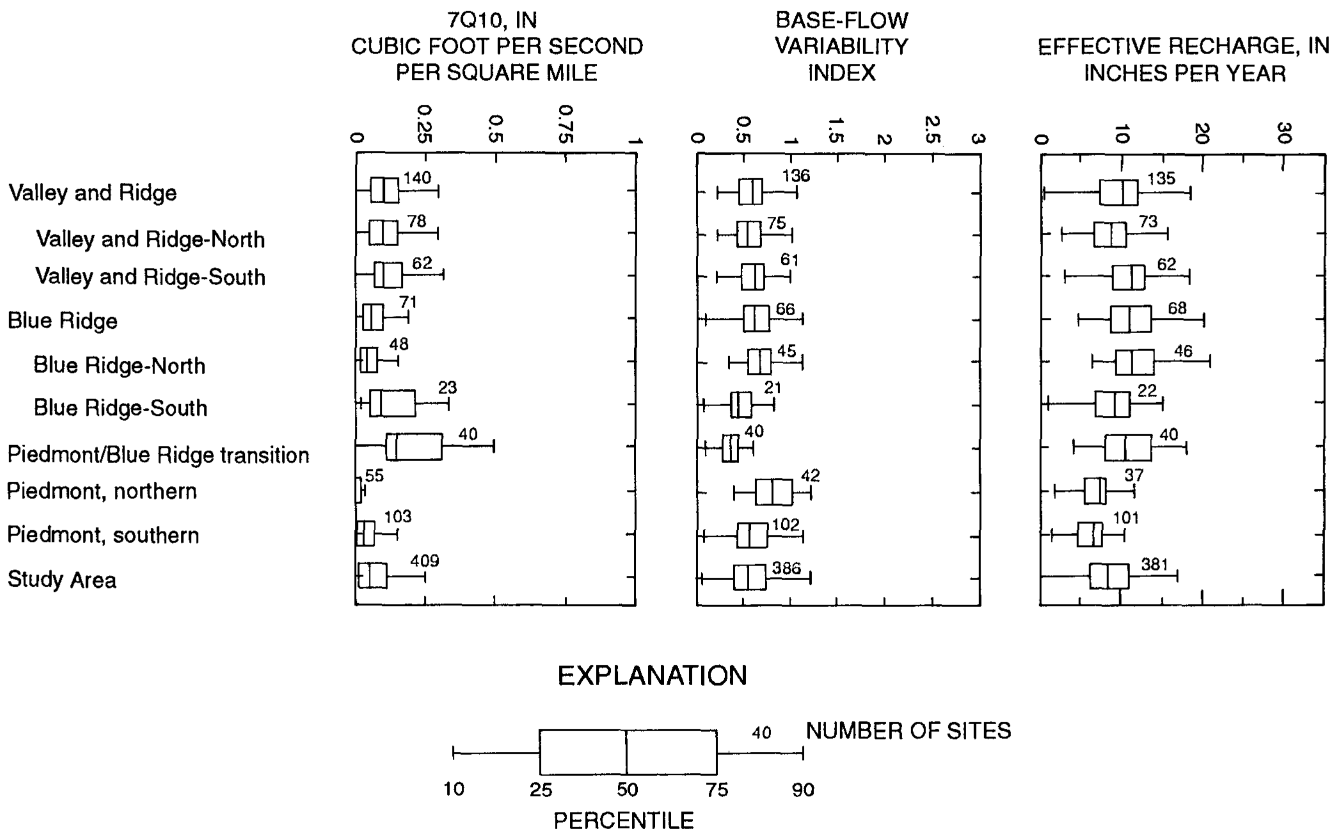


Figure 6. Summary statistics of base-flow characteristics by region.

is not significantly different from the median area in the northern section ($p = 0.461$).

The difference in base-flow characteristics between the northern and southern sections of the Valley and Ridge may be attributed to the distribution of precipitation and geology. In the northern section, the Shenandoah Valley is located in a rain shadow; where annual precipitation is the smallest recorded for a location so far south and east in the United States (Nuckels and Prugh, 1991, p. 543). Annual precipitation in the southern section generally is 10 to 14 in/yr higher than in the northern section (fig. 4). Carbonate rocks that have a high water-yielding potential, are characteristic of the southern section (fig. 2); whereas low-yielding siliciclastic rocks are characteristic of the northern section (Schneider and Friel, 1965; Cederstrom, 1972, p. 4). In addition, the differences in water-yielding potential may be related to the predominant style of deformation–faulting in the southern section and folding in the northern section. One



Q_{50}, Q_{90}, AND Q_{95} 50-, 90- AND 95-PERCENT DISCHARGE ON THE STREAMFLOW-DURATION CURVE, RESPECTIVELY

7Q2 AND 7Q10 ANNUAL MINIMUM AVERAGE 7-CONSECUTIVE-DAY LOW-FLOW DISCHARGE HAVING 2-YEAR AND 10-YEAR RECURRENCE INTERVALS, RESPECTIVELY

Figure 6.—Continued.

notable exception in the northern section is the area on the eastern margin of the Valley and Ridge just east of Staunton commonly termed the "Western Toe" of the Blue Ridge. This area is underlain by a thick sequence of unconsolidated alluvium and colluvium covering the bedrock (King, 1950; Leonard, 1962; Hack, 1965, 1989); therefore, base-flow characteristics determined for this area are not representative of consolidated rocks typically found in the Valley and Ridge region.

Blue Ridge Region

The Blue Ridge region encompasses most of the Blue Ridge Physiographic Province, except for a small section in the eastern part of the province that extends from the North Carolina/Virginia border to just north of Lynchburg (pl. 1). Drainage areas range from 1.17 to 3,259 mi^2, with a median area of 37 mi^2. Mean base flow for this region ranges from 0.02 to 2.44 $(ft^3/s)/mi^2$, with a median value of 0.79 $(ft^3/s)/mi^2$. The Q_{50} ranges from 0.01 to 2.26 $(ft^3/s)/mi^2$, with a median value of 0.67 $(ft^3/s)/mi^2$. As was the case with the Valley and Ridge region, the Q_{50} may underestimate mean base flow. Rutledge and Mesko (1996) determined that Q_{46} can serve as a surrogate for mean base flow in the Blue Ridge and the Piedmont Physiographic Provinces of the Eastern United States. The values for the low-flow statistics range from 0.00 to 0.52 $(ft^3/s)/mi^2$. The median discharges for the low-flow statistics range from 0.04 $(ft^3/s)/mi^2$ for 7Q10 to 0.19 $(ft^3/s)/mi^2$ for Q_{90}. The base-flow variability index ranges from 0.07 to 1.19, with a median value of 0.58. Effective recharge in this region ranges from 0.29 to 33.07 in/yr, with a median value of 10.71 in/yr.

Table 1. Summary statistics for base-flow characteristics by region
[mi^2, square mile; $(ft^3/s)/mi^2$, cubic foot per second per square mile; Q_{50} and Q_{90}, the 50- and 90-percent discharge on the streamflow-duration curve, respectively]

	Number of sites	Median	25th percentile	75th percentile	Minimum	Maximum
Drainage Area (mi^2)						
Valley and Ridge	140	50.8	15.9	163	0.61	3,768
North	78	71.4	12.7	157	.61	2,075
South	62	37.9	17.4	222	2.99	3,768
Blue Ridge	71	37.0	14.2	123	1.17	3,259
North	48	35.8	13.8	109	1.17	3,259
South	23	56.8	15.1	188	4.02	2,202
Piedmont/Blue Ridge transition	40	40.0	9.61	185	.46	2,415
Piedmont, northern	55	13.8	4.51	50.5	.08	1,596
Piedmont, southern	103	39.7	9.94	135	.33	7,320
Study area	409	36.3	11.5	137	.08	7,320
Mean Base Flow [$(ft^3/s)/mi^2$]						
Valley and Ridge	135	.72	.51	.86	.01	1.51
North	73	.62	.47	.75	.01	1.51
South	62	.81	.64	.93	.05	1.34
Blue Ridge	68	.79	.62	.98	.02	2.44
North	46	.82	.67	1.02	.47	2.44
South	22	.67	.50	.81	.02	1.47
Piedmont/Blue Ridge transition	40	.77	.59	1.00	.30	1.34
Piedmont, northern	37	.54	.41	.59	.07	.86
Piedmont, southern	101	.49	.35	.56	.11	.78
Study area	381	.61	.46	.81	.01	2.44
Q_{50} [$(ft^3/s)/mi^2$]						
Valley and Ridge	139	.56	.41	.74	.00	1.35
North	77	.49	.34	.61	.00	1.35
South	62	.71	.54	.82	.03	1.21
Blue Ridge	69	.67	.52	.88	.01	2.26
North	47	.70	.56	.88	.18	2.26
South	22	.59	.41	.80	.01	1.12
Piedmont/Blue Ridge transition	40	.76	.60	1.00	.30	1.36
Piedmont, northern	48	.43	.29	.58	.06	.93
Piedmont, southern	102	.44	.33	.56	.10	.83
Study area	398	.55	.39	.72	.00	2.26
Q_{90} [$(ft^3/s)/mi^2$]						
Valley and Ridge	139	.16	.09	.23	.00	.60
North	78	.14	.08	.21	.00	.60
South	61	.18	.12	.26	.01	.49
Blue Ridge	70	.19	.10	.25	.00	.52
North	48	.16	.09	.24	.00	.51
South	22	.22	.16	.26	.01	.52
Piedmont/Blue Ridge transition	40	.33	.22	.54	.05	.76
Piedmont, northern	55	.04	.02	.14	.00	.24
Piedmont, southern	103	.12	.06	.21	.01	.42
Study area	407	.15	.07	.23	.00	.76

Table 1. Summary statistics for base-flow characteristics by region—Continued

[$(ft^3/s)/mi^2$, cubic foot per second per square mile; Q_{95}, the 95-percent discharge on the streamflow-duration curve; $7Q2$ and $7Q10$, annual minimum average 7-consecutive-day low-flow discharge having 2-year and 10-year recurrence intervals, respectively]

	Number of sites	Median	25th percentile	75th percentile	Minimum	Maximum
			Q_{95} [$(ft^3/s)/mi^2$]			
Valley and Ridge	139	0.13	0.06	0.19	0.00	0.53
North	78	.11	.06	.17	.00	.53
South	61	.15	.10	.22	.01	.44
Blue Ridge	70	.12	.06	.18	.00	.43
North	48	.10	.05	.16	.00	.37
South	22	.17	.11	.22	.01	.43
Piedmont/Blue Ridge transition	40	.26	.16	.44	.02	.74
Piedmont, northern	55	.02	.01	.08	.00	.17
Piedmont, southern	103	.08	.03	.15	.00	.36
Study area	407	.11	.04	.17	.00	.74
			$7Q2$ [$(ft^3/s)/mi^2$]			
Valley and Ridge	140	.14	.07	.20	.00	.58
North	78	.13	.06	.19	.00	.58
South	62	.15	.09	.23	.00	.45
Blue Ridge	71	.13	.07	.22	.00	.49
North	48	.11	.06	.19	.00	.40
South	23	.19	.11	.27	.02	.49
Piedmont/Blue Ridge transition	40	.30	.20	.48	.07	.71
Piedmont, northern	55	.03	.01	.06	.00	.21
Piedmont, southern	103	.09	.04	.16	.00	.36
Study area	409	.12	.05	.20	.00	.71
			$7Q10$ [$(ft^3/s)/mi^2$]			
Valley and Ridge	140	.09	.04	.14	.00	.39
North	78	.08	.03	.14	.00	.39
South	62	.09	.05	.16	.00	.37
Blue Ridge	71	.04	.01	.09	.00	.33
North	48	.03	.01	.07	.00	.30
South	23	.08	.04	.21	.01	.33
Piedmont/Blue Ridge transition	40	.14	.11	.31	.00	.50
Piedmont, northern	55	.00	.00	.02	.00	.09
Piedmont, southern	103	.03	.01	.06	.00	.25
Study area	409	.05	.01	.11	.00	.50
			Base-Flow Variability Index			
Valley and Ridge	136	.55	.41	.66	.18	2.27
North	75	.50	.39	.64	.18	2.27
South	61	.59	.45	.68	.18	1.17
Blue Ridge	66	.58	.47	.74	.07	1.19
North	45	.65	.53	.76	.33	1.19
South	21	.42	.35	.57	.07	.90
Piedmont/Blue Ridge transition	40	.35	.27	.43	.09	1.29
Piedmont, northern	42	.79	.62	1.01	.39	2.10
Piedmont, southern	102	.55	.43	.74	.09	1.33
Study area	386	.55	.41	.74	.07	2.27

Table 1. Summary statistics for base-flow characteristics by region—Continued
[in/yr, inch per year]

	Number of sites	Median	25th percentile	75th percentile	Minimum	Maximum
Effective Recharge (in/yr)						
Valley and Ridge	135	9.73	6.95	11.66	0.07	20.55
North	73	8.38	6.38	10.23	.07	20.55
South	62	10.99	8.69	12.65	.64	18.12
Blue Ridge	68	10.71	8.44	13.32	.29	33.07
North	46	11.07	9.11	13.90	6.31	33.07
South	22	9.09	6.73	10.96	.29	19.92
Piedmont/Blue Ridge transition	40	10.40	7.97	13.61	4.10	18.13
Piedmont, northern	37	7.35	5.47	8.01	.99	11.68
Piedmont, southern	101	6.61	4.76	7.65	1.43	10.54
Study area	381	8.32	6.22	10.93	.07	33.07

The subdivision of the Northern Blue Ridge Mountains and the Southern Blue Ridge Province is located in the vicinity of Roanoke. The Mann-Whitney test indicates that the median values for the base-flow characteristics are significantly different for the sections north and south of Roanoke (table 1). Median values for mean base flow and Q_{50} in the northern section are significantly higher than those in the southern section (p=0.003 and 0.028), whereas the opposite is true for the median values for the low-flow statistics (p-values range from <0.001 to 0.043). The median value for the base-flow variability index in the northern section is higher than in the southern section (p<0.001). The median value for effective recharge in the northern section is higher than in the southern section (p=0.003). The median drainage area in the northern section is not significantly different from the median area in the southern section (p=0.246).

The difference in base-flow characteristics in the Blue Ridge region may be the result of several factors. Generally, average annual precipitation is higher and average annual runoff is lower in the northern section than in the southern section (Prugh and Scott, 1986, p. 469). The combination of these two factors can explain the high median values for mean base flow and effective recharge in the northern section. Both sections have steep mountains with relief of more than 350 ft in a 5-mi^2 area; but a large part of the southern section, called the New River plateau (fig. 3), has moderate relief of 640 ft in a 50-mi^2 area (Hack, 1982, p. 26–35). Runoff generally increases with increasing relief, which reduces the amount of infiltration and recharge. Rutledge and Mesko (1996) observed a positive correlation between basin relief and mean recharge for the Blue Ridge Physiographic Province and suggested orographic effects on precipitation as a possible explanation for this correlation. Median values for the low-flow statistics, however, are higher and the median value for base-flow variability index is lower in the southern section than in the northern section, suggesting differences in ground-water storage. One possible explanation for these differences within the Blue Ridge region may be related to the abrupt change in the geologic structure in the vicinity of Roanoke from an anticlinorium represented by steep flexures in the north to large thrust faults or imbricate stacks in the south (Reed, 1970, p. 196; Wehr and Glover, 1985, p. 285; Hack, 1989, p. 461–463).

Piedmont/Blue Ridge Transition Region

The Piedmont/Blue Ridge transition region encompasses a part of the southwestern section of the Piedmont Physiographic Province and the small part of the Blue Ridge Physiographic Province not included in the Blue Ridge region (pl. 1). Drainage areas range from 0.46 to 2,415 mi^2, with a median area of 40 mi^2. Mean base flow for this region ranges from 0.30 to 1.34 (ft^3/s)/mi^2, with a median value of 0.77 (ft^3/s)/mi^2. The Q_{50} ranges from 0.30 to 1.36 (ft^3/s)/mi^2, with a median value of 0.76 (ft^3/s)/mi^2. The values for mean base flow and Q_{50} are virtually identical; therefore, Q_{50} is a reasonable estimator of mean base flow for this particular region. The values for the low-flow statistics range from 0.00 to 0.76 (ft^3/s)/mi^2. The median discharges for the low-flow statistics range from 0.14 (ft^3/s)/mi^2 for $7Q10$ to 0.33 (ft^3/s)/mi^2 for Q_{90}. The base-flow variability index ranges from 0.09 to 1.29, with a median value of 0.35.

Effective recharge in this region ranges from 4.10 to 18.13 in/yr, with a median value of 10.40 in/yr.

The Piedmont/Blue Ridge transition region approximately encompasses a fault-bounded, shallow, sheet-like synform of metasedimentary, metavolcanic, and plutonic-igneous rocks, referred to as the Smith River allochthon, which was emplaced over the Sauratown Mountains anticlinorium and eastern part of the Blue Ridge Province. The allochthon has been described as either the upper or lower limb of a detached recumbent nappe by Conley and Henika (1973, p. 50) and Henika (1977, p. 16). An alternative interpretation by Drake and others (1989, p. 158) suggests that the allochthon may represent a thrust stack. Both interpretations reveal the intensive deformation that rocks of the Smith River allochthon have undergone. The transition region is an upland with relief greater than the Piedmont but not as mountainous as the Blue Ridge (Hack, 1982, p. 24; Hayes, 1991, p. 23). The relation between the complex geologic history, geomorphic evolution, and base-flow characteristics of streams in the Piedmont/Blue Ridge transition region warrants future investigation.

Piedmont Regions

The Piedmont Physiographic Province is divided into two regions, northern and southern (pl. 1). Drainage areas in the Piedmont northern region range from 0.08 to 1,596 mi^2, with a median area of 13.8 mi^2. Mean base flow for this region ranges from 0.07 to 0.86 $(ft^3/s)/mi^2$, with a median value of 0.54 $(ft^3/s)/mi^2$. The Q_{50} ranges from 0.06 to 0.93 $(ft^3/s)/mi^2$, with a median value of 0.43 $(ft^3/s)/mi^2$. Similar to other regions, the Q_{50} may underestimate mean base flow and the Q_{46} may be a more appropriate flow-duration statistic to use (Rutledge and Mesko, 1996). The values for the low-flow statistics range from 0.00 to 0.24 $(ft^3/s)/mi^2$. The median discharges for the low-flow statistics range from 0.00 $(ft^3/s)/mi^2$ for $7Q10$ to 0.04 $(ft^3/s)/mi^2$ for Q_{90}. The base-flow variability index ranges from 0.39 to 2.10, with a median value of 0.79. Effective recharge in this region ranges from 0.99 to 11.68 in/yr, with a median value of 7.35 in/yr.

Drainage areas in the Piedmont southern region range from 0.33 to 7,320 mi^2, with a median area of 39.7 mi^2. Mean base flow for this region ranges from 0.11 to 0.78 $(ft^3/s)/mi^2$, with a median value of 0.49 $(ft^3/s)/mi^2$. The Q_{50} ranges from 0.10 to 0.83 $(ft^3/s)/mi^2$, with a median value of 0.44 $(ft^3/s)/mi^2$. As was the case with the Piedmont/Blue Ridge transition region, the difference between mean base flow and Q_{50} is extremely small; therefore, Q_{50} probably is a reasonable estimator of mean base flow for this region. The values for the low-flow statistics range from 0.00 to 0.42 $(ft^3/s)/mi^2$. The median discharges for the low-flow statistics range from 0.03 $(ft^3/s)/mi^2$ for $7Q10$ to 0.12 $(ft^3/s)/mi^2$ for Q_{90}. The base-flow variability index ranges from 0.09 to 1.33, with a median value of 0.55. Effective recharge in this region ranges from 1.43 to 10.54 in/yr, with a median value of 6.61 in/yr.

The Mann-Whitney test indicates that the median values for base-flow characteristics, except for mean base flow, Q_{50}, and effective recharge (p-values range from 0.065 to 0.349), are significantly different for the Piedmont northern and southern regions (table 1). Median values for the low-flow statistics in the southern region are significantly higher than those in the northern region ($p<0.001$). The median value for the base-flow variability index in the northern region is higher than the median index in the southern region ($p<0.001$). The median drainage area in the northern region is significantly smaller than the median area in the southern region ($p=0.007$).

The difference in base-flow characteristics between the Piedmont northern and southern regions may be the result of several factors. Large variations in base-flow characteristics may be the result of variability associated with small drainage basins, which are characteristic of the northern region. A large percentage of the total area in the Piedmont northern region is underlain by sedimentary, igneous, and metamorphic rocks of the early Mesozoic Culpeper Basin (fig. 3) that generally result in low base-flow characteristics (Trainer and Watkins, 1975; Laczniak and Zenone, 1985; Lynch and others, 1987; Hayes, 1991). In addition, the Piedmont northern region is somewhat urbanized in response to growth associated with proximity to the Washington, D.C., area. Another factor that can affect base-flow characteristics is relief. A large percentage of the Piedmont northern region is in the Foothill zone and Northeastern Highlands (fig. 3), where relief is low to moderate and ranges from 250 to 640 ft in a 50-mi^2 area. Only a small part of the Piedmont southern region is in the Foothill zone, whereas a large percentage of the area is in the Piedmont Lowlands (fig. 3), where relief is low and ranges from 130 to 250 ft in a 50-mi^2 area (Hack, 1982). This difference in topographic relief may significantly affect ground-water gradients to streams, runoff, recharge, and ground-water storage. Pavich and others (1989, p. 42–43) stated that regolith thickness is related to parent rock type and local topography. The two regions in the Piedmont have similar rock types and ranges of regolith thickness; however, the low relief in the southern region may allow for the development of a thick sequence of regolith over a large percentage of the entire region. Ground-water storage may be greater in the southern region than in the northern region in response to a possible increase in regolith thickness, which may explain the high median values for the low-flow statistics and the low base-flow variability index in the southern region.

Regional Differences

Differences in the base-flow characteristics exist between regions, as well as within regions. The distribution of median discharges for the regions is shown in figure 7. The median discharges for the Valley and Ridge, the Blue Ridge, and the Piedmont/Blue Ridge transition regions are higher than those for both of the Piedmont regions. The Kruskal-Wallis test indicates that significant differences exist ($p<0.001$) in median values for the base-flow characteristics of each region. Tukey's MCT was used to further investigate patterns within the base-flow characteristics among regions. A graphical representation of the results from the Tukey's MCT is shown in figure 8. For an individual base-flow characteristic, regions with identical group ranking have the same shade pattern in figure 8. In some cases, one region may be represented by two shade patterns for a particular base-flow characteristic, which indicates the region overlaps two group rankings and cannot be statistically separated from either group. The group rankings are only relative to the study area because basin and climatological characteristics are known to vary within the Valley and Ridge, the Blue Ridge, and the Piedmont Physiographic Provinces of the Eastern United States.

The Tukey's MCT indicates that the regions can be separated into three groups for mean base flow and Q_{50} ($p<0.001$). The Blue Ridge and the Piedmont/Blue Ridge transition regions are assigned the highest group ranking and the Piedmont regions are the lowest. The Valley and Ridge region is assigned the second highest group ranking; but the Piedmont/Blue Ridge transition region is not significantly different from either the Blue Ridge or the Valley and Ridge regions for mean base flow (fig. 8).

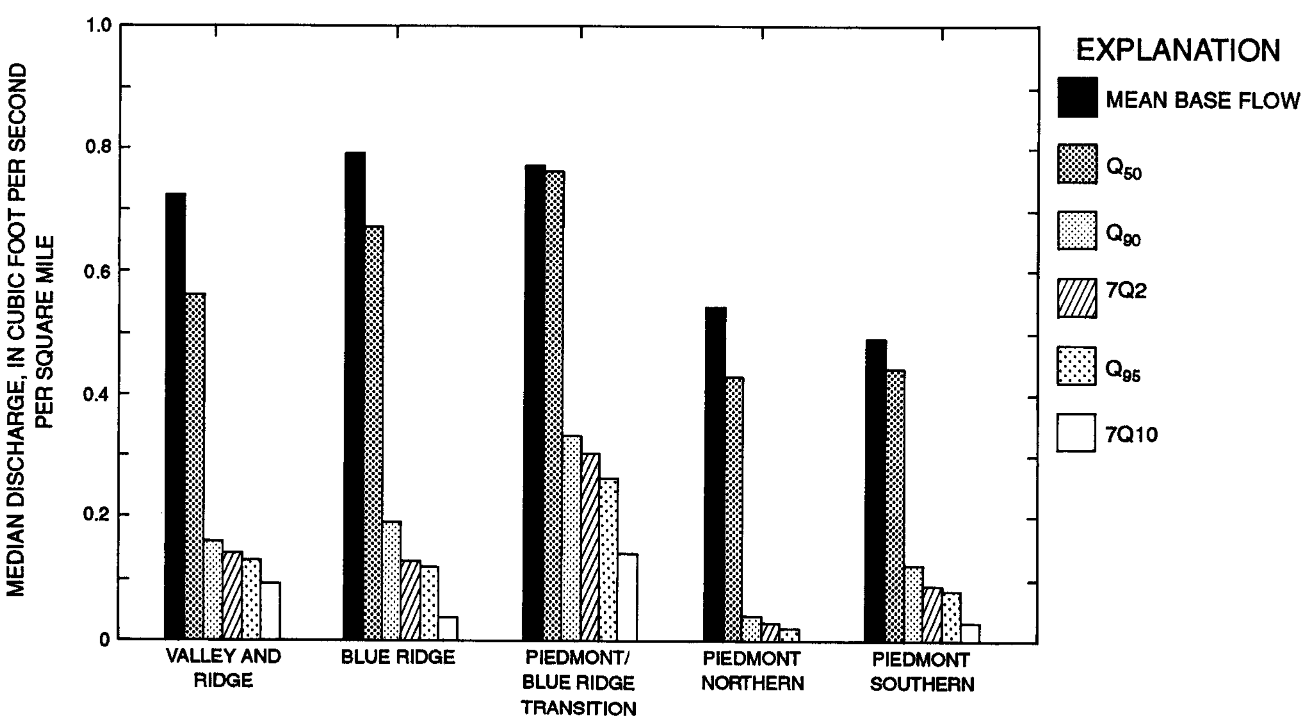
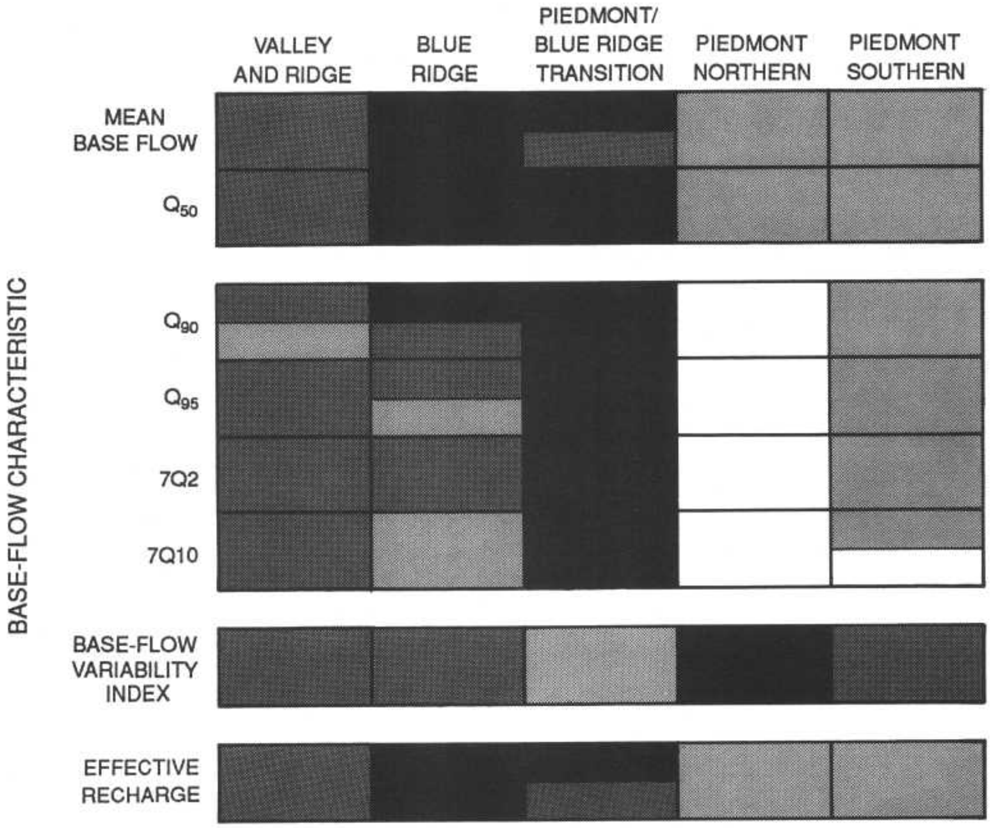


Figure 7. Distribution of median discharges for the various flow statistics by region.



EXPLANATION

GROUP RANKING FROM TUKEY'S MULTIPLE COMPARISON TEST (*p*-values <0.001)

HIGH

MODERATE TO HIGH

LOW TO MODERATE

LOW

TUKEY'S MULTIPLE COMPARISON TEST—Hypothesis test to examine real versus chance difference in data. The test involves a null hypothesis stating that no real difference exists. An alpha value, or level of significance, is used in the hypothesis test representing the maximum probability of rejecting the null hypothesis when it is actually true. The alpha value used in this report is 0.05

Q_{50}, Q_{90}, and Q_{95} 50-, 90-, and 95-PERCENT DISCHARGE ON THE STREAMFLOW-DURATION CURVE, RESPECTIVELY

7Q2 and 7Q10 ANNUAL MINIMUM AVERAGE 7-CONSECUTIVE-DAY LOW-FLOW DISCHARGE HAVING 2-YEAR AND 10-YEAR RECURRENCE INTERVALS, RESPECTIVELY

p-values <0.001 *p*-value—Probability representing the attained significance level. If the *p*-value is smaller than or equal to the alpha value, the null hypothesis is rejected and significant differences are assumed to exist among the data

Figure 8. Group ranking from Tukey's multiple comparison test.

The Tukey's MCT indicates that the regions can be separated into four groups for the low-flow statistics ($p<0.001$). The Piedmont/Blue Ridge transition region and the Piedmont northern regions are assigned consistently the highest and lowest group rankings, respectively. The Valley and Ridge and the Blue Ridge regions are assigned generally the second highest group ranking followed by the Piedmont southern region (fig. 8).

The Tukey's MCT indicates that the regions can be separated into three groups for base-flow variability index ($p<0.001$). The Piedmont northern region is assigned the highest variability index and the Piedmont/Blue Ridge transition region is assigned the lowest variability index. The remaining regions are not significantly different with regard to the variability index and are, therefore, grouped together (fig. 8).

The Tukey's MCT indicates that the regions can be separated into three groups for effective recharge ($p<0.001$). The Blue Ridge region is assigned the highest group ranking and the Piedmont regions are the lowest. The Valley and Ridge region is assigned the second highest group ranking, but the Piedmont/Blue Ridge transition region is not significantly different from either the Blue Ridge or the Valley and Ridge regions for effective recharge (fig. 8).

Analysis of the Tukey's MCT indicates that the Piedmont/Blue Ridge transition region is assigned the highest overall group ranking for base-flow characteristics in the study area, which can be attributed to high median values for mean base flow, Q_{50}, and low-flow statistics associated with low base-flow variability and high effective-recharge rates. The Valley and Ridge and the Blue Ridge regions have similar base-flow characteristics and, thus, both regions are assigned the second highest overall group ranking. The Piedmont southern region is assigned the next overall group ranking. Finally, the Piedmont northern region is assigned the lowest overall group ranking in response to low median values for mean base flow, Q_{50}, and low-flow statistics with high base-flow variability and low effective recharge rates.

The spatial representation of these groups is shown on plate 1. The base-flow characteristics are ordered by decreasing discharge from left to right on the first two rows of the plate. The base-flow variability index and effective recharge are found on the last row. The discharges are consistently high and values for the base-flow variability index are low for the basins within the Piedmont/Blue Ridge transition region. The basins within the Piedmont northern region show the opposite pattern.

Relation to Potential Surface-Water Yield

Potential surface-water yield is a qualitative designation of the capacity of streams within a region or individual basin to sustain base flow and is based on the statistical analysis of base-flow characteristics of streams in the study area. In terms of regions, the group rankings of the base-flow characteristics were used to designate the potential surface-water yield. The Piedmont/Blue Ridge transition region is designated as having high potential surface-water yield because the median values for the flow statistics (mean base flow, Q_{50}, and low-flow statistics) and effective recharge consistently are in the groups with the highest rank, whereas the median value for the base-flow variability index is in the group with lowest rank (fig 8). The Valley and Ridge and the Blue Ridge regions are designated as having moderate-to-high potential surface-water yield because the median values for the flow statistics are in the groups with moderate-to-high ranks and the median values for the base-flow variability index are in the group with moderate rank (fig 8). The Piedmont southern region is designated as having low-to-moderate potential surface-water yield because the median values for the flow statistics are in the groups with low-to-moderate rank and the median value for the base-flow variability index is in the group with moderate rank (fig 8). The Piedmont northern region is designated as having low potential surface-water yield because the median values for the flow statistics and effective recharge consistently are in the groups with the lowest rank, whereas the median value for the base-flow variability index is in the group with highest rank (fig 8).

Although the designation of potential surface-water yield is based on the base-flow characteristics of streams in the study area, comparison with the findings of previous studies can provide insight into the relevance of these designations within the entire Appalachian Highlands. Schneider and Friel (1965) determined that streams in the Blue Ridge and the Piedmont Physiographic Provinces had high sustained flows and actually ranked these provinces higher than the Valley and Ridge Physiographic Province. The section of the Piedmont Physiographic Province in Virginia considered by Schneider and Friel (1965) is the Piedmont/Blue Ridge transition region. Extension of the transition region along strike into western North Carolina corresponds to (1) the area delineated by Schneider and Friel (1965) with the highest average annual low flows in the Appalachian region, (2) the area delineated by Wyrick (1968) with moderate to high values for ground-water discharge, and (3) the area delineated by Giese and Mason (1993, p.7) with the highest potential for sustaining low flows in North Carolina (the western Piedmont and mountains physiographic area). These areas in North Carolina have average annual precipitation values that range from 50 in/yr to more than 80 in/yr; whereas average annual precipitation in the Piedmont/Blue Ridge transition region is lower, approximately 42 in/yr (Swain and others, 1991, fig. 2; Giese and Mason, 1993, p. 7). Evidently, the Piedmont/Blue Ridge transition region represents the northernmost extent of an area in the Appalachian Highlands designated as having high potential surface-water yield associated with high annual precipitation. Median values for $7Q2$ and $7Q10$ in the western Piedmont and mountains physiographic area of North Carolina (Giese and Mason, 1993, p. 7), however, are about twice those for the Piedmont/Blue Ridge transition region. The difference in these median values demonstrates the possible effect that the amount of annual precipitation can have on the determination of potential surface-water yield. Other areas in Virginia have similar annual precipitation as the transition region but the potential surface-water yield differs, which indicates that other basin characteristics also need to be considered.

In terms of individual basins, previous investigations have used a single flow statistic or ratio to determine potential surface-water yield. For example, Trainer and Watkins (1975, p. 49–51) ranked tributary basins of the upper Potomac River Basin based on values for annual minimum average 7-consecutive-day low-flow discharges having a 20-year recurrence interval ($7Q20$) to indicate areal distribution of water-yielding potential. An alternative approach developed for this investigation assigns a rank for potential surface-water yield to a basin according to the quartiles in which the values for the base-flow characteristics are located. For example, a high rank for potential surface-water yield was assigned to a basin where values for the flow statistics are in the upper quartile and the variability index is in the lower quartile for the respective base-flow characteristic. A moderate rank was assigned to a basin where the values for the flow statistics and variability index are within the interquartile range for the respective base-flow characteristic. A low rank was assigned to a basin where values for the flow statistics are in the lower quartile and the variability index is in the upper quartile for the respective base-flow characteristic. The results from this ranking procedure are shown in figure 9. Most of the basins

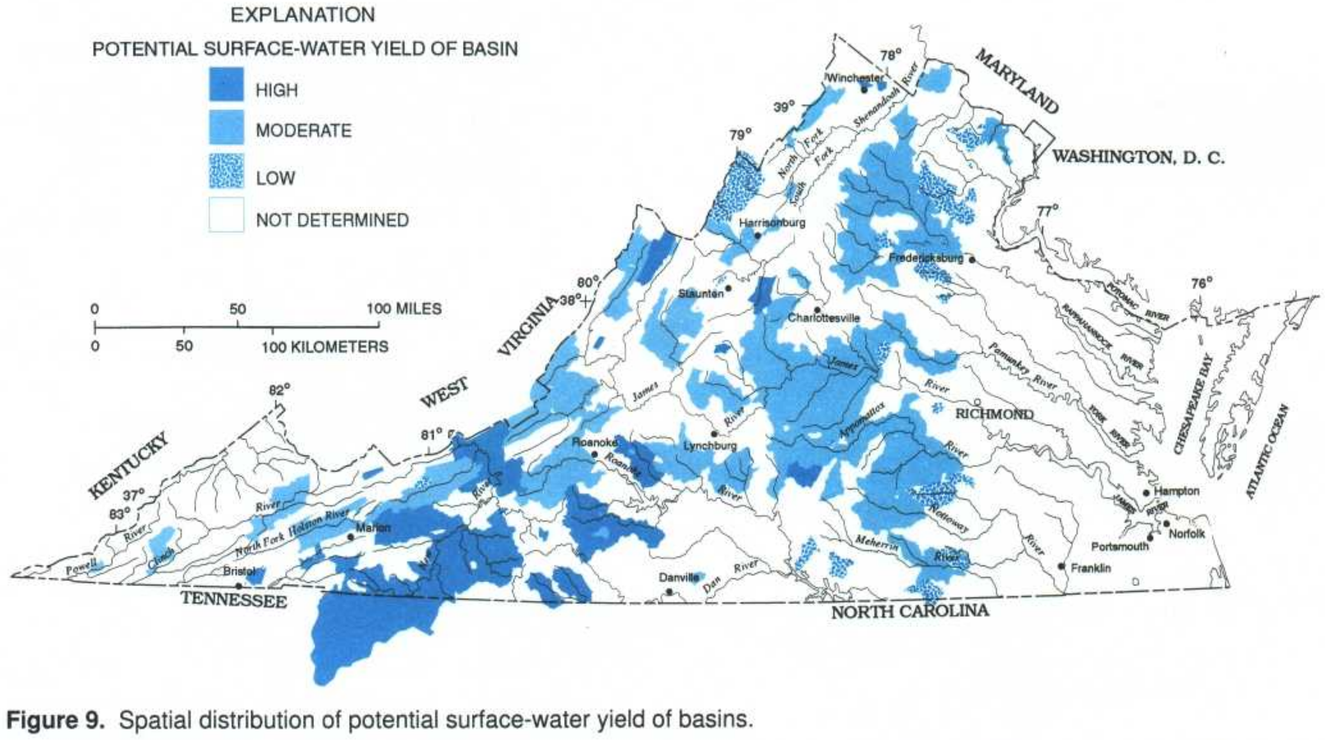


Figure 9. Spatial distribution of potential surface-water yield of basins.

with a high rank for potential surface-water yield are located in the Piedmont/Blue Ridge transition, the Valley and Ridge, and the Blue Ridge regions, and a majority of the basins that represent low-to-moderate ranks are located in the Piedmont regions (fig. 9). The differences in water-yielding potential are only relative to the study area but should be considered in the process of managing surface-water resources.

Relation to Potential Ground-Water Yield

Potential ground-water yield is the capacity of the ground-water reservoir to store and transmit water. Knopman (1990) used specific capacity data as an indicator of potential ground-water yield. An alternative approach for areas that lack sufficient specific capacity or well-yield data is to use base-flow characteristics as indicators of potential ground-water yield. Trainer and Watkins (1975, p. 50) suggested that areas with favorable potential ground-water yield, where values for transmissivity and base flow are high, could be delineated by using base flow as an indicator. However, Olmsted and Hely (1962, p. A21) stated that the relation between base flow and the amount of ground water available for development is not simple. In order to indicate potential ground-water yield from base-flow characteristics, aquifer properties for selected basins with continuous streamflow data were determined by methods that use streamflow records and basin characteristics. The basin characteristics and aquifer properties are listed in appendix 3.

Rorabaugh (1960, 1964) developed an equation that relates the slope of the master recession curve to the transmissivity and storage coefficient of the ground-water reservoir. An abbreviated form of the equation (Rorabaugh and Simons, 1966, p. 12) was used for 51 continuous-record streamflow-gaging stations to calculate areal diffusivity, which is the ratio of transmissivity to storage coefficient:

$$\frac{T}{S} = \frac{0.933a^2}{K}, \tag{1}$$

where

T is areal transmissivity (L^2/T),
S is storage coefficient (dimensionless),
a is aquifer half-width (L), and
K is recession index (T).

The recession index (K) values were determined by Rutledge and Mesko (1996) by using a computerized method that calculates a mathematical expression of the master recession curve of streamflow recession for each station. Aquifer half-width (a) is the average distance from the stream to the hydrologic divide. The distance a for each gaged station is equal to half the reciprocal of drainage density, which is the ratio of the total length of streams in a basin to the drainage area (Horton, 1945, p. 284; Olmsted and Hely, 1962, p. A19; Carlston, 1963, p. C5; Trainer, 1969, p. C179). Summation of all stream-segment lengths upstream of each streamflow-gaging station was accomplished by applying the ARC/INFO network analysis procedure to the U.S. Environmental Protection Agency Reach File, Version 3 (RF3) coverage. In some cases, the RF3 coverage does not contain all of the stream segments within the basin; therefore, the distance a was estimated by using the mean drainage density from either the same hydrologic unit code or similar unit code.

Values of areal diffusivity range from 17,100 to 88,400 ft^2/d, with a median value of 38,400 ft^2/d (table 2), which are consistent with values reported in the literature (Olmsted and Hely, 1962; Hely and Olmsted, 1963; Trainer and Watkins, 1974, 1975). The Kruskal-Wallis test indicates that significant differences exist (p=0.037) in median values for areal diffusivity among the regions. The Tukey's MCT indicates that the Piedmont northern and southern, the Valley and Ridge, and the Blue Ridge regions do not differ significantly from each other and that the latter three regions are not significantly different from the Piedmont/Blue Ridge transition region but that the median value for areal diffusivity in the Piedmont northern region is significantly higher than in the Piedmont/Blue Ridge transition region (p=0.026). In terms of the potential surface-water yield of the basins, the Tukey's MCT indicates that the median value for areal diffusivity decreases as the group ranking increases (p<0.001). The group ranking of areal diffusivity does not correspond with the group ranking of potential surface-water yield for either the regions or the basins, which illustrates the difficulty of establishing the relation between base-flow characteristics and potential ground-water yield solely based on areal diffusivity. However, insight is provided by plotting areal diffusivity, which is grouped by potential surface-water yield, against the base-flow variability index (fig. 10). A smooth line, determined by means of a smoothing procedure (referred to as LOWESS) that uses robust least squares (Helsel and Hirsch, 1992, p. 46), suggests that areal diffusivity increases and potential surface-water yield decreases with