Low-Flow Characteristics of Streams in Virginia

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Prepared in cooperation
with the Virginia Water
Control Board

U.S. DEPARTMENT OF THE INTERIOR
March 3, 1849

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By DONALD C. HAYES

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METRIC CONVERSION FACTORS

For readers who wish to convert measurements from the inch-pound system of units to the metric system of units, the conversion factors are listed below:

Multiply inch-pound unit	By	To obtain metric unit
	Length	
inch (in)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06308	liter per second (L/s)
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer [$(m^3/s)/km^2$]

ALTITUDE DATUM

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

GLOSSARY

Base flow. The contribution of flow in a stream from ground-water or spring effluent.

Climatic year. A continuous 12-month period during which a complete climatic cycle exists, usually designated by the year in which most of the 12 months occur. In this report the climatic year is from April 1 through March 31. The year begins and ends during the period of increased flows so that the flows during a single dry season are included in annual values for that year.

Continuous-record gaging station. A site on a stream where continuous records of gage height are collected and daily mean discharge is computed. Data from a continuous-record station are expected to be representative of the hydrology in the basin upstream.

Cubic feet per second (ft^3/s). A unit expressing rate of flow; the volume of water passing a point on a stream per unit of time. 1 ft^3/s=448.8 gallons per minute.

Drainage area. The drainage area of a stream at a specified location is that area, measured in a horizontal plane, that is enclosed by a drainage divide. All streamflow that passes the specified location has its origin within the drainage basin.

Gage height. The water-surface elevation referenced to some arbitrary gage datum; often used interchangeably with the term "stage."

Partial-record gaging station. A site on a stream where periodic measurements are collected, usually for a period of years. The data collected at partial-record stations are often correlated with data at nearby continuous-record stations to estimate hydrologic information at the partial-record stations.

Recurrence interval. The average interval of time within which the magnitude of an extreme event will be exceeded once. For low flow, the recurrence interval is the average interval of time between occurrences of a flow less than a given magnitude. The major recurrence intervals used in this report are 2 years and 10 years. A 10-year low-flow discharge is a value that, on the average, the flow will be less than, once every 10 years. Thus, there is 1 chance in 10 that flows will drop below that discharge in any year. The 10-year low-flow discharge could be met in consecutive years; however, on the average, the discharge will be met only once in 10 years. The 7-day, 10-year low-flow discharge (7Q10) is the annual minimum average 7-consecutive-day discharge having a 10-year recurrence interval, and the 7-day, 2-year low-flow discharge (7Q2) is the annual minimum average 7-consecutive-day discharge having a 2-year recurrence interval.

Water year. The 12-month period October 1 through September 30, designated by the calendar year in which the period ends. For example, the 1984 water year is the period October 1, 1983, through September 30, 1984. Average discharge and flow-duration data are computed using the water-year time frame. In this report the water year ends and begins during the period of low flow, so the majority of runoff is included in annual values for a single year.

Low-Flow Characteristics of Streams in Virginia

By Donald C. Hayes

Abstract

Streamflow data were collected and low-flow characteristics computed for 715 gaged sites in Virginia. Annual minimum average 7-consecutive-day flows range from 0 to 2,195 cubic feet per second for a 2-year recurrence interval and from 0 to 1,423 cubic feet per second for a 10-year recurrence interval. Drainage areas range from 0.17 to 7,320 square miles. Existing and discontinued gaged sites are separated into three types: long-term continuous-record sites, short-term continuous-record sites, and partial-record sites. Low-flow characteristics for long-term continuous-record sites are determined from frequency curves of annual minimum average 7-consecutive-day flows. Low-flow characteristics for short-term continuous-record sites are estimated by relating daily mean base-flow discharge values at a short-term site to concurrent daily mean discharge values at nearby long-term continuous-record sites having similar basin characteristics. Low-flow characteristics for partial-record sites are estimated by relating base-flow measurements to daily mean discharge values at long-term continuous-record sites.

Information from the continuous-record sites and partial-record sites in Virginia are used to develop two techniques for estimating low-flow characteristics at ungaged sites. A flow-routing method is developed to estimate low-flow values at ungaged sites on gaged streams. Regional regression equations are developed for estimating low-flow values at ungaged sites on ungaged streams.

The flow-routing method consists of transferring low-flow characteristics from a gaged site, either upstream or downstream, to a desired ungaged site. A simple drainage-area proration is used to transfer values when there are no major tributaries between the gaged and ungaged sites. Standard errors of estimate for 108 test sites are 19 percent of the mean for estimates of low-flow characteristics having a 2-year recurrence interval and 52 percent of the mean for estimates of low-flow characteristics having a 10-year recurrence interval. A more complex transfer method must be used when major tributaries enter the stream between the gaged and ungaged sites. Twenty-four stream networks are analyzed, and predictions are made for 84 sites. Standard errors of estimate are 15 percent of the mean for estimates of low-flow characteristics having a 2-year recurrence interval and 22 percent of the mean for estimates of low-flow characteristics having a 10-year recurrence interval.

Regional regression equations were developed for estimating low-flow values at ungaged sites on ungaged streams. The State was divided into eight regions on the basis of physiography and geographic grouping of the residuals computed in regression analyses. Basin characteristics that were significant in the regression analysis were drainage area, rock type, and strip-mined area. Standard errors of prediction range from 60 to 139 percent for estimates of low-flow characteristics having a 2-year recurrence interval and 90 percent to 172 percent for estimates of low-flow characteristics having a 10-year recurrence interval.

INTRODUCTION

Understanding the hydrologic characteristics of streams during low-flow periods is essential to the development and management of our water resources. Planning of water-supply, water-control, and water-quality programs begins with an analysis of flow availability and variability. Low-flow characteristics determined from such an analysis commonly are the basis for water-quality standards and minimum-flow rates for regulated streams. This report is the result of a cooperative program between the U.S. Geological Survey (USGS) and the Virginia Water Control Board. Data were collected by the USGS and the Virginia Water Control Board.

Purpose and Scope

This report presents low-flow characteristics at gaged sites on streams in Virginia and techniques for estimating low-flow characteristics at both gaged and ungaged sites. Low-flow characteristics are presented for 254 continuous-record sites and 461 partial-record sites. Information from the gaged sites is used to develop two techniques for estimating low-flow characteristics at ungaged sites.

Approach

Records of the USGS and the Virginia Water Control Board were reviewed to identify current and discontinued continuous-record sites and to glean base-flow discharge measurements made at partial-record sites. A continuous-record site is a location on a stream where gage height is recorded continuously, and for which daily mean discharge is computed. A partial-record site is a location on a stream where limited hydrologic data, such as discharge measurements, are collected.

Continuous-record sites were analyzed to determine the degree of streamflow regulation and periods of unregulated flow. Partial-record sites were analyzed to determine the degree of streamflow regulation and the number of base-flow discharge measurements available. Analysis of the location and extent of unregulated flow at continuous-record sites and partial-record sites was performed. Areal coverage was completed by selection of additional partial-record sites.

Low-flow characteristics for long-term continuous-record sites (10 or more years of unregulated discharge record collected) were determined from frequency curves of annual minimum average 7-consecutive-day flows. Frequency curves were fitted to the logarithms of the data by use of the Pearson Type III distribution. Graphs of the plotted points were checked visually for accuracy of fit. Low-flow characteristics for the 2-yr (year) and 10-yr recurrence intervals were selected from the frequency curves. Low-flow characteristics for short-term continuous-record sites (fewer than 10 yr of unregulated discharge record collected) were estimated by relating daily mean base-flow discharge values at the short-term site to concurrent daily mean discharge values at nearby long-term continuous-record sites having similar basin characteristics. Low-flow characteristics for partial-record sites were estimated by relating base-flow discharge measurements to daily mean discharge values at long-term continuous-record sites. Low-flow characteristics at the long-term station were transferred through the relation line to determine low-flow characteristics at the short-term or partial-record site.

Two techniques were developed for estimating low-flow characteristics at ungaged sites. A flow-routing method was developed to estimate low-flow values at ungaged sites on gaged streams. Regional regression equations were developed for estimating low-flow values at ungaged sites on ungaged streams.

The flow-routing method consists of transferring low-flow characteristics from a gaged site, either upstream or downstream, to a desired ungaged site. A simple drainage-area proration is used to transfer values when there are no major tributaries between the gaged and ungaged site. A more complex transfer method, weighting the drainage area of each tributary, is used when major tributaries enter the stream between the gaged and ungaged site. Twenty-four stream networks were analyzed, and predictions were made for 84 sites.

Regional regression equations were developed for estimating low-flow values at ungaged sites on ungaged streams. This method divides the State into eight regions on the basis of physiography and geographic grouping of the residuals that were computed in regression analyses. Separate equations were developed for each region by testing basin characteristics. Basin characteristics that remained significant in the regression analysis were drainage area, rock type, and strip-mined area.

Previous Studies

Several previous investigators collected low-flow data on streams in Virginia or analyzed low-flow characteristics of streams in Virginia. The most comprehensive study was by Nuckels (1970), who analyzed long-term continuous-record stations throughout Virginia. Most of the other investigations have been concerned with only small portions of the State. Reports that contain data specific to Virginia and from which data were taken directly are Mohler and Hagan (1981), Smith (1981), Lynch (1987), and Lynch and others (1987). Other reports that present analyses of low-flow characteristics for part of Virginia are Cushing and others (1973), Trainer and Watkins (1975), and Wetzel and Bettandorff (1986). Information in these reports was instrumental in locating discontinued sites and analyzing basin characteristics that affect low flows.

PHYSICAL SETTING

Location

Virginia is centrally located on the Atlantic Coast, bordered to the north by Maryland and West Virginia, to the south by North Carolina and Tennessee, and to the west by Kentucky and West Virginia (fig. 1). The total area of Virginia is approximately 41,000 mi^2 (square miles), which includes almost 1,000 mi^2 of lakes, tidal rivers, and bays. There are more than 3,000 mi (miles) of nontidal rivers and 5,000 mi of shoreline along the Atlantic Coast and Chesapeake Bay (Sevebeck and others, undated).

Physiography

Virginia lies within five physiographic provinces (fig. 1). The provinces are, from east to west, the Coastal Plain, Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateaus. Each province is characterized by distinctive geologic features and landforms resulting in substantial differences in basin characteristics. Geology ranges from

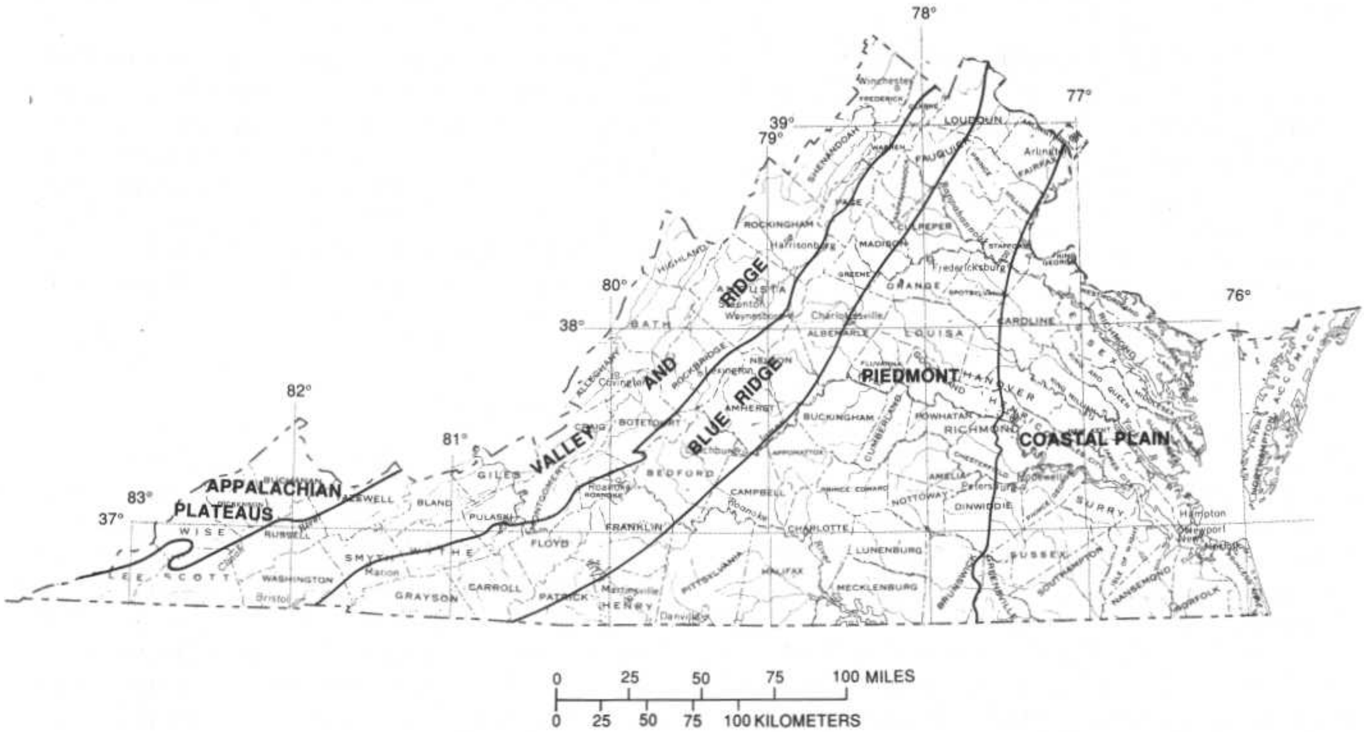

Figure 1. Physiographic provinces of Virginia (modified from Fenneman, 1938, pl. II).

unconsolidated sands and clays in the Coastal Plain province, to igneous and metamorphic rocks in the Piedmont and Blue Ridge provinces, and to sedimentary rocks (carbonate rocks, sandstone, and shale) in the Valley and Ridge and Appalachian Plateaus provinces. Topography in the State is diverse, ranging from virtually flat in the Coastal Plain to greater relief and rugged terrain along the Blue Ridge and Appalachian crests. The central Piedmont is characterized by rolling hills and valleys, and is separated from the ridges and valleys of the Valley and Ridge province by the Blue Ridge Mountains. Land-surface elevations range from sea level along the coast of the Coastal Plain province to more than 5,000 ft (feet) above sea level in the mountains of the Blue Ridge province (U.S. Geological Survey, 1985).

Coastal Plain Physiographic Province

The Coastal Plain physiographic province generally consists of unconsolidated, gently sloping layers of sand and gravel separated by layers of clay and marl. The eastern boundary of the Coastal Plain province is the Atlantic Ocean. The western boundary is the Fall Line, where the resistant rock of the Piedmont forms a contact with the weaker sediments of the Coastal Plain (Fenneman, 1938). Sediments are thin at the Fall Line and thicken to as much as 6,000 ft at the eastern edge of the Coastal Plain (U.S. Geological Survey, 1985). Rivers and streams are affected by tides over a substantial area. Base flows are moderate (average 7-consecutive-day low-flow discharge having a 2-yr recurrence interval approximately 0.1 $(ft^3/s)/mi^2$ (cubic feet per second per square mile). However, upper soils drain fairly well and tend to increase base-flow recession.

Piedmont Physiographic Province

The Piedmont physiographic province in Virginia consists of gently rolling terrain which extends from the base of the Blue Ridge Mountains east to the Fall Line. It is widest along the Virginia-North Carolina border (approximately 125 mi) and narrows to about 25 mi in northern Virginia. The Piedmont province is formed mainly of metamorphic and igneous rocks that consist of granite, gneiss, schist, slate, phyllite, and quartzite. Triassic and Jurassic sedimentary rocks form several early Mesozoic basins in the Piedmont that consist mainly of shales and sandstones intruded by diabase. Geologic formations of the Piedmont province trend northeast-southwest and are generally covered by a deep saprolite. Base flows are high (average 7-consecutive-day low-flow discharge having a 2-yr recurrence interval approximately 0.15 $(ft^3/s)/mi^2$). However, in areas where the saprolite is thin or nonexistent, such as the early Mesozoic basins, base flows are low (average 7-consecutive-day low-flow discharge having a 2-yr recurrence interval is less than 0.01 $(ft^3/s)/mi^2$).

Blue Ridge Physiographic Province

The Blue Ridge physiographic province lies between the Valley and Ridge province and the Piedmont province. It is a fairly thin ridge of northeast–southwest-trending mountains consisting mainly of metamorphic and igneous rocks, with some sedimentary rock on the western slope. Steep slopes allow only thin soils in some areas, thus reducing the amount of ground-water storage. Base flows are fairly high where the soils are thicker (average 7-consecutive-day low-flow discharge having a 2-yr recurrence interval approximately 0.14 (ft^3/s)/mi^2).

Valley and Ridge Physiographic Province

The Valley and Ridge physiographic province was formed by the folding and faulting of sedimentary rocks. Northeast-southwest-trending ridges are formed by resistant quartzite, sandstone, and conglomerates, while narrow valleys are underlain by limestone, shale, and dolomite. According to Smith and Ellison (1985), the alluvium-covered limestone valleys can maintain high base flows (average 7-consecutive-day low-flow discharge having a 2-yr recurrence interval approximately 0.14 (ft^3/s)/mi^2).

Appalachian Plateaus Physiographic Province

The Appalachian Plateaus physiographic province, known locally as the Cumberland Plateau, is an area of westward-dipping, consolidated, sedimentary rocks that consist mainly of sandstone, shale, and coal. It is the smallest physiographic province in Virginia and is located at the western end of Virginia, north of the southern region of the Valley and Ridge province. Extensive erosion has formed steep slopes and narrow valleys throughout this province. Base flows are fairly low (average 7-consecutive-day low-flow discharge having a 2-yr recurrence interval approximately 0.06 (ft^3/s)/mi^2).

Climate

The climate in Virginia is moderate, with wide variations in temperature and slight to moderate variations in precipitation. The average annual temperature in the Piedmont and Coastal Plain provinces is approximately 57 °F with extremes below 0 and above 100 °F. The average annual temperature in the mountains west of the Piedmont is approximately 51 °F with extremes as low as −30 and above 100 °F. Average annual precipitation is fairly uniform and ranges from 36 to 50 in/yr (inches per year) (fig. 2). The average annual precipitation for the State is approximately 42 in/yr. The greatest variation occurs in the northern Blue Ridge and Valley and Ridge provinces, where the average annual precipitation ranges from 36 to 48 in/yr over a distance of 50 mi.

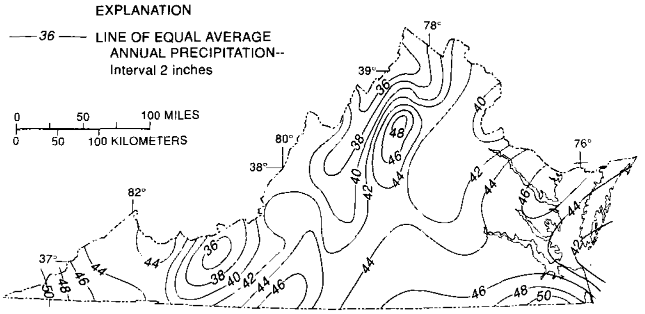

Figure 2. Average annual precipitation in Virginia (modified from Powell and Abe, 1985, fig. 2).

The entire State is subject to strong frontal passages during the winter and thunderstorms during the summer. Prevailing winds from the southwest bring warm, moist air from the Gulf of Mexico. Strong cold fronts move across the State from the northwest and clash with the warm, moist air, causing most of the State's precipitation. Precipitation during the summer, generally caused by thunderstorms, is heavy but sporadic.

LOW-FLOW CHARACTERISTICS

The adequacy of streamflow to supply the water needed for various instream and offstream uses commonly is evaluated by a statistical analysis of historical streamflow data. Statistical information based on streamflow data can be used to predict future variability of the streamflow, not in terms of specific events, but in terms of probability of occurrence over a span of years (Nuckels, 1970). The probability of occurrence of annual low flows (low-flow characteristics) may be described by duration curves, base-flow recession curves, and low-flow frequency curves (Riggs, 1972). This report uses statistics of annual low flows defined by low-flow frequency curves.

The most commonly used low-flow characteristics in Virginia are the annual minimum average 7-consecutive-day low-flow discharge having a 2-yr recurrence interval (7Q2) and the annual minimum average 7-consecutive-day low-flow discharge having a 10-yr recurrence interval (7Q10). These values are based on the minimum average 7-consecutive-day flow from each year of record (April 1 through March 31) with recurrence intervals of 2 and 10 yr, respectively (cumulative probability of 0.5 and 0.1). April 1 through March 31 is used as the low-flow climatic year so that the streamflow through an entire dry season is included in the annual value for only 1 yr. For example, a 7Q10 of 1.0 ft^3/s means that the probability is 1 in 10 that the annual minimum average 7-consecutive-day discharge for any year will be less than 1.0 ft^3/s, or that the annual minimum average 7-consecutive-day discharge of less than 1.0 ft^3/s should be expected at the site, on average, once every 10

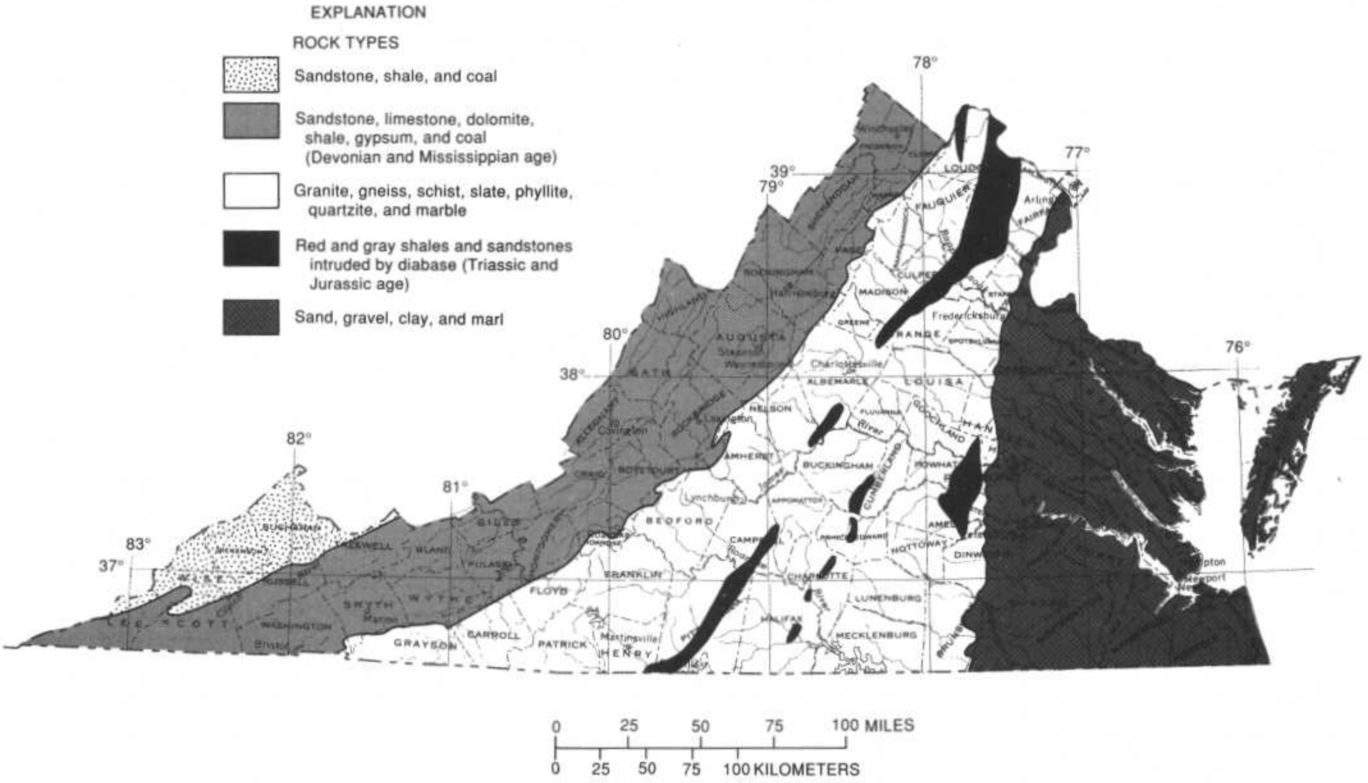

Figure 3. Generalized rock types in Virginia (modified from Virginia Division of Mineral Resources, 1964).

years. A more complete discussion of low-flow frequency analysis can be found in Riggs (1972). The 7Q2 can be a more accurately calculated low-flow characteristic than the 7Q10 because it occurs more often during a long period of record. The 7Q10, although a widely used low-flow characteristic, is considered less accurate because it is subject to greater time-sampling error. Data must be collected for long periods of time before sufficient data are collected to provide reliable estimates in the 10-year-recurrence time frame.

Factors Affecting Low Flows

A basin can be considered a large reservoir, with recharge, storage, and discharge of water (Trainer and Watkins, 1975). Recharge to this reservoir is primarily a function of precipitation, whereas storage and discharge are controlled primarily by the physical characteristics of the basin. During base-flow and low-flow conditions, groundwater discharge constitutes the majority of the streamflow. When sufficient streamflow data are collected, basin and climatological characteristics can be analyzed, with limited accuracy, to determine their influence on ground-water discharge to a stream. Some of the primary basin and climatological characteristics that influence low-flow characteristics are drainage area, rock type, soil type and depth, slope, land use, and precipitation.

Low-flow characteristics usually relate to drainage-basin size better than any other basin or climatological characteristic when a basin is homogeneous with respect to topography, geology, and climate. Low-flow discharge values generally increase with increasing drainage basin size; however, topography, geology, and climate have such a strong influence on low flows that minor differences in basin characteristics may cause substantial differences in low-flow discharges.

Rock type, soil type, and soil depth are major influences on streamflow during low-flow conditions. Rock type and the thickness and characteristics of the overburden determine the ability of the basin to accept, store, and transmit water. These properties affect the amount and rate at which precipitation enters the shallow ground-water system and how it is released to sustain streamflow. Wide variations in the rock type and overburden contribute to the variations in low flow for streams in Virginia (Mohler and Hagan, 1981). A generalized rock-type map of Virginia is shown in figure 3.

Land slope is related to several factors that also influence low flow. Generally, the steeper the stream slope (slope of the basin along the stream), the less regolith or overburden available to store precipitation. Runoff of precipitation is more rapid. These factors allow less time for infiltration. As a stream flows out of the mountains into valleys, the stream slope decreases. When the stream slope decreases rapidly, a stream at base flow can disappear into the coarse-grained alluvium. The stream may disappear and reappear as the streambed rises above and falls below the ground-water table. Side slope (slope of the basin perpendicular to the stream) also affects low flow. Shallow side slopes may allow more evapotranspiration because the ground-water table is closer to land surface, while steeper side slopes may reduce evapotranspiration and allow more seepage into a stream or creek.

Land use can affect low-flow characteristics more than any other factor. Humans can modify natural ground-water and surface-water hydrology to the extent that low-flow characteristics are drastically altered. The change can occur almost immediately or very gradually. Evapotranspiration, infiltration, and runoff rates are all affected by changes in land use. Examples of such changes are decreases in forest areas due to cutting for agricultural use or urban development, decreases in wetland areas due to draining or filling, and newly constructed lakes or ponds. Much of the precipitation that previously may have infiltrated into the ground-water system in undeveloped areas now becomes surface runoff. As a result, the ground-water contribution to streamflow during low-flow conditions may be reduced. Many localities that are underlain by highly permeable limestone or sand and gravel deposits use retention ponds to dispose of runoff from developed areas (Seaburn and Aronson, 1974). Retention ponds not only help recharge the ground-water system, but also keep the increased runoff from overloading small streams during heavy rainfall periods (Parker and others, 1955).

Diversion of water from a stream for irrigation or water supply during droughts seriously affects flow volume. Much of the water diverted for irrigation will not return to the stream because of evapotranspiration. Controlled releases from reservoirs and discharges from sewage-treatment plants can artificially augment streamflow during dry seasons. Strip mining and deep mining also can alter the characteristics of a basin by removing the vegetation and overburden, and by modifying the structure of the remaining rock (Larson and Powell, 1986).

Precipitation is the supply and driving force of water in the hydrologic cycle. Streamflow is the result of surface runoff of precipitation, or the result of infiltration, storage, and transfer of precipitation through the ground-water system. Precipitation is fairly uniform across the State. Average annual precipitation ranges from 36 to 50 in/yr. Amounts of average annual precipitation vary gradually over most of the State except in the Blue Ridge and Valley and Ridge provinces. The largest variation in average annual precipitation, 36 to 48 in/yr over a 50-mi distance, occurs in the northern sections of these two provinces. The large variation in average annual precipitation probably is due to prevailing wind direction and orographic effects (see fig. 1). The greater amounts of precipitation generally fall during the winter months. For this reason, base flows remain fairly high during these months. However, the highest rainfall intensities usually result from thunderstorms in the summer months, when base flows are declining. Because of the areal and temporal distribution of precipitation caused by thunderstorms, little effect is seen in base-flow conditions. Insufficient streamflow data have been collected on a statewide basis to determine how the seasonal distribution of precipitation affects low-flow characteristics.

Methods for Determining Low-Flow Characteristics

In this section, methods are presented for determining low-flow characteristics at gaged and ungaged sites in Virginia. Gaged sites are separated into three site types, and ungaged sites are separated into two site types. The site type can be determined by the streamflow data available at the site. Gaged sites consist of

1. Long-term continuous-record sites.
2. Short-term continuous-record sites.
3. Partial-record sites.

Ungaged sites consist of

1. Sites on gaged streams.
2. Sites on ungaged streams.

Methods used for determining low-flow values at long-term continuous-record sites, short-term continuous-record sites, and partial-record sites are discussed later in this section and are explained in detail in Riggs (1972). Low-flow values, 7Q2 and 7Q10, were computed for 254 continuous-record sites (appendix 1) and for 461 partial-record sites (appendix 2) in Virginia using these methods. Information from gaged sites was used to develop two techniques for estimating low-flow characteristics at ungaged sites—a flow-routing technique for estimating low-flow values at ungaged sites on gaged streams, and regional regression equations for estimating low-flow values at ungaged sites on ungaged streams.

Some methods used to estimate low-flow characteristics are statistically based and assume a linear relation. However, the actual relations are not always linear throughout their extent. This nonlinearity commonly is characteristic of the relations at lower streamflows. These lower streamflows are of interest in this study. When a statistically based relation line was computed, an additional relation line was visually fitted through the data points for each analysis. The visually based relation line was not forced to be linear, and was compared with the statistically based relation line. If the two relation lines were substantially different in the area of interest, the visually based relation line was selected to estimate the low-flow characteristics.

Gaged Sites

Surface-water data collection in Virginia started as early as 1898. Daily mean discharges have been computed and published for approximately 300 sites in the State. Base-flow discharge measurements have been made at many sites as part of local studies where continuous records of daily mean discharges were not collected.

Continuous-record sites, generally located on medium to large drainage basins, were selected for the study on the basis of analysis of historical records. Sites located in highly urban basins were avoided because of rapid changes of basin characteristics within the basins. Continuous-record sites located on streams with major streamflow regulation were eliminated if no records had been collected when the streamflow was unregulated. Sites where data had been collected during both unregulated and regulated streamflow periods were retained, but only the data collected during periods of unregulated streamflow were used for determining low-flow characteristics. Because of the large number of regulated streams and the large number of users on many streams, it was impractical to exclude from the data base all sites with regulated streamflow. Therefore, sites on streams with minor streamflow regulation were retained. Streamflow regulation for continuous-record sites was determined by a review of the station descriptions. If a dam was capable of controlling the discharges at low flow by impoundment or releases, or if industry diverted or returned water that amounted to more than 10 percent of the 7Q10, the site was excluded from the data base. Sites with 10 or more years of unregulated discharge record were considered long-term continuous-record sites. Sites with fewer than 10 yr of unregulated discharge record were considered short-term continuous-record sites.

Partial-record sites were also selected through analysis of historical records. They were chosen so as to fill in areal gaps in the continuous-record data-collection network and to include smaller drainage basins in the study. The partial-record sites had to meet the same restrictions on basin urbanization and streamflow regulation as the continuous-record sites. Determining streamflow regulation on partial-record sites was more difficult than determining streamflow regulation on continuous-record sites because of the large number of sites, limited previous basin analysis, and the large number and small size of the water-use facilities that affect the flow. Streamflow regulation for partial-record sites was determined by reviewing the drainage basin on topographic maps. If a dam appeared capable of controlling the discharges at low flow by impoundment or releases, or if water-use facilities appeared capable of diverting or returning water that amounted to more than 10 percent of the 7Q10, the site was excluded from the data base.

Long-Term Continuous-Record Sites

For long-term continuous-record sites, low-flow characteristics are determined by developing low-flow frequency curves from the annual low-flow data. Low-flow frequency curves are developed by first determining the annual average minimum discharge for the desired number of consecutive days. Average minimum 7-consecutive-day flows were used in this study. These values are ordered by rank or size (smallest to largest), and a plotting position (nonexceedence probability) is calculated. The following formula is used to determine the plotting position:

$$P=1/T=m/(n+1), \qquad (1)$$

where

P = probability of a nonexceedence in any one year;
T = recurrence interval, in years;
m = order number of the annual events when arrayed according to size (Dalrymple, 1960); and
n = number of items in the sample (years).

Thus, recurrence interval, in years, is the reciprocal of the nonexceedence probability. The rank-ordered discharges are plotted with the nonexceedence probability, or recurrence interval, on log-probability paper to define the low-flow frequency curve. A typical low-flow frequency curve for average minimum 7-consecutive-day discharges is shown in figure 4.

The graphical curve is considered the basic frequency curve for low flows (Riggs, 1971). For consistency, however, annual low-flow data should be fit to a theoretical frequency distribution. Several theoretical distributions—log-Gumbel, log-normal, and Pearson Type III—have been used successfully to develop low-flow frequency curves. Because different basin characteristics can produce differently shaped frequency curves, no single theoretical frequency distribution can adequately describe all low-flow frequency curves (Riggs, 1972). A plot of the theoretical distribution is visually compared with the plotting position described above. When the theoretical distribution does not fit the data in the position plot, a smooth curve is drawn through the plotting positions. Low-flow characteristics are then estimated by transferring the recurrence interval or the nonexceedence probability through the curve. Because the Pearson Type III distribution has been found to match the graphical curve fairly well (Matalas, 1963) and is widely used to describe low-flow frequency curves, it was used in this study to fit frequency curves for the logarithms of annual low-flow data at long-term continuous-record sites.

Short-Term Continuous-Record Sites

Mathematical and graphical regression methods are used to relate logarithms of daily mean discharge at a short-term continuous-record site to logarithms of concurrent daily mean discharge at a nearby long-term continuous-

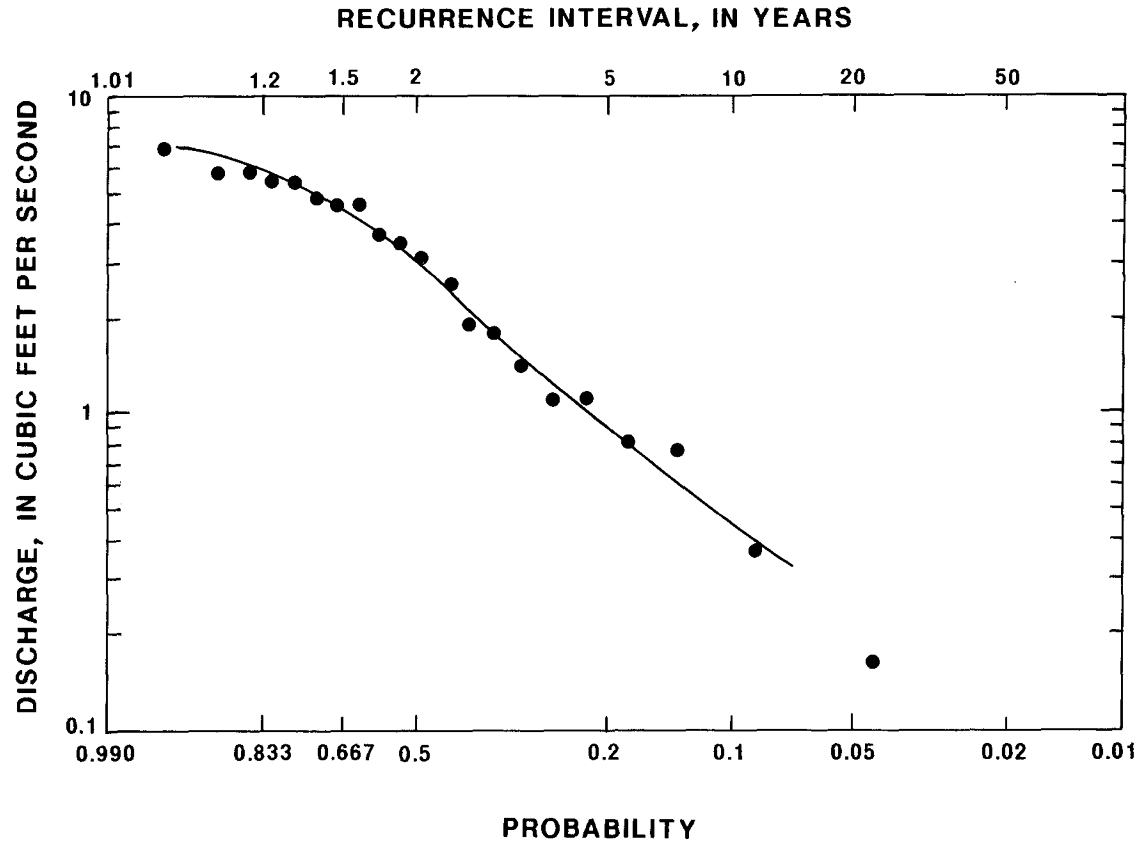

Figure 4. Low-flow frequency curve of average minimum 7-consecutive-day discharge for Accotink Creek near Annandale, Va.

record site (index site) for which low-flow characteristics have been determined. Between 10 and 25 concurrent daily mean discharges are selected during separate base-flow recessions to define the relation between two sites and to compute a regression equation. The mathematical method uses a linear least-squares regression method to compute the regression equation. The concurrent discharges are also plotted, and a visually fitted line is drawn to define the relation between the two sites. As stated earlier, the visually fitted relation line is compared with the statistically based relation line, and if they are substantially different in the area of interest, the visually fitted relation line is used to estimate low-flow statistics. Figure 5 shows how the desired low-flow value is graphically selected by transferring the low-flow characteristics from the index site (Wolf Creek near Narrows, Va.; 7Q2=35 ft^3/s, 7Q10=23 ft^3/s) through the relation line to the short-term continuous-record site (Walker Creek at Staffordsville, Va.; 7Q2=36 ft^3/s, 7Q10=24 ft^3/s). It is not necessary for the relation line to be linear as defined by the linear least-squares regression; however, a sufficient number of data points should be selected to define any changes in slope adequately.

For this study, discharge at a short-term continuous-record site was related to discharge at several index sites to increase confidence in the low-flow value selected. Discharge at the short-term continuous-record sites initially was related to discharge at index sites in the same basin. The index sites could be either upstream or downstream of the short-term continuous-record site, and could be in the same physiographic province or an adjacent province. When no index site in the same basin correlated well with the short-term continuous-record site, index sites in adjacent basins within the province were used. If these sites did not correlate well, sites in any basin within the province having similar basin characteristics were used. When necessary, index sites in a different province were used to define a relation; however, 50 percent of the drainage area of the index site was required to be located in the desired province, so the index sites still had characteristics similar to the short-term continuous-record site.

Final selection of the site or sites to be used in the correlation as index sites was determined by analysis of the coefficient of determination and by visual examination of the linear least-squares regression line with the plotted daily mean discharges. No minimally acceptable coefficient of determination was defined; however, the index sites that gave the higher coefficients of determination were selected for further analysis. Plots of the concurrent daily mean

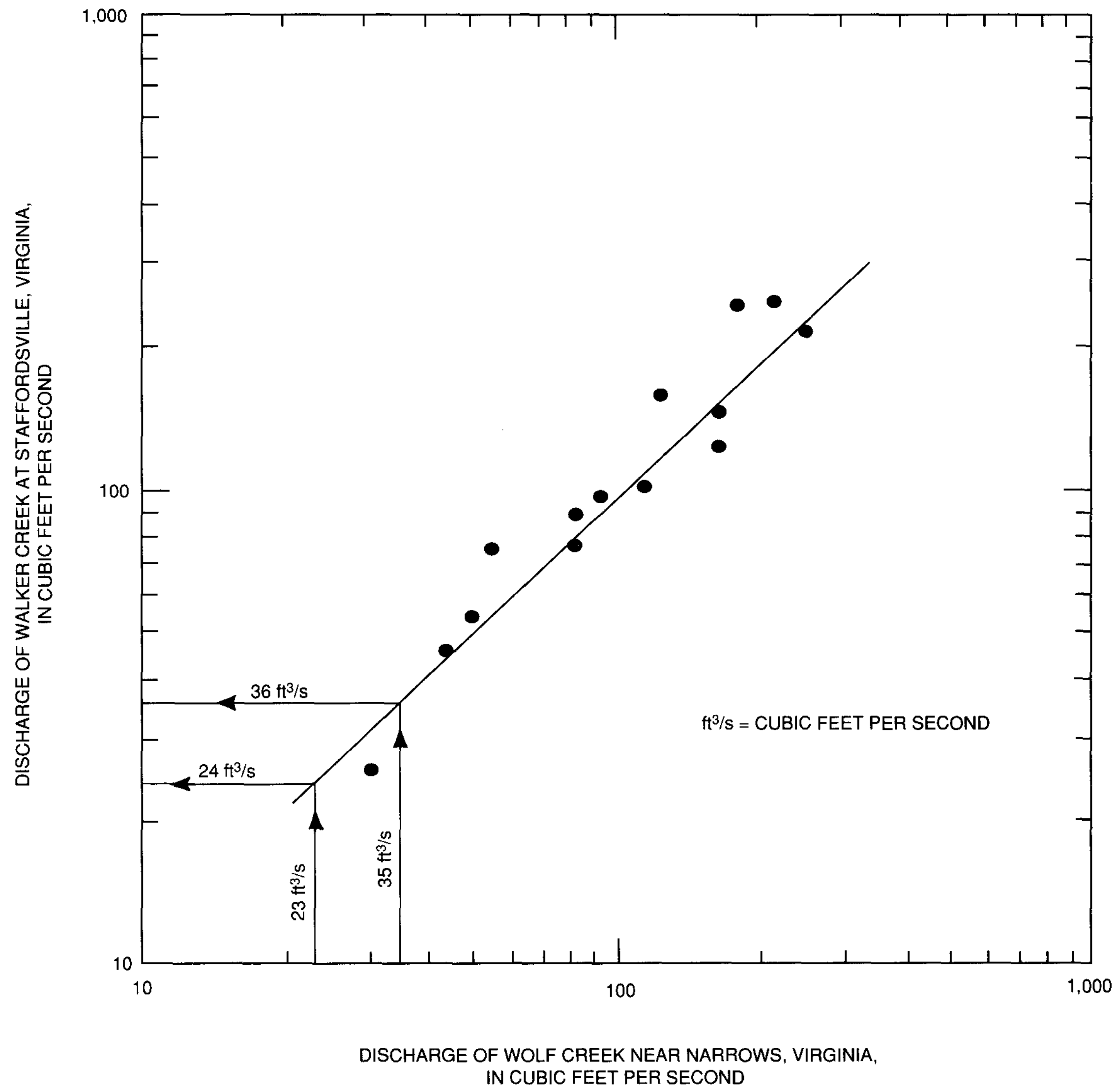

Figure 5. Relation of daily mean discharge of Walker Creek to concurrent daily mean discharge of Wolf Creek.

discharges at the short-term continuous-record site and the index sites were reviewed, and low-flow values were computed for each relation from either the mathematical regression equation or the visually fitted relation line. When more than one index site was used for the correlation, values obtained from the regression were averaged unless large differences were found among the low-flow estimates. When large differences were found, the index site having basin characteristics most nearly resembling the basin characteristics of the short-term continuous-record site was selected for the regression. A relation line having a slope close to unit value indicates that the two streams have similar flow characteristics (Riggs, 1972).

Partial-Record Sites

Graphical regression methods are used to relate logarithms of base-flow discharge measurements at a partial-record site to logarithms of concurrent daily mean discharge at nearby index sites. Ideally, two or three discharge measurements a year should be made during separate base-flow recessions at the partial-record site, with 10 to 12 base-flow discharge measurements made during a 3- or 4-yr period. The measured discharges at the partial-record site are plotted, on log-log paper, against the concurrent daily mean discharge values at nearby index sites. A curve is visually fitted to the data points. Low-flow characteristics are then estimated by transferring the low-flow characteristic from the long-term continuous-record site through the relation line to the partial-record site in the same manner as shown in figure 5. No mathematical regression was calculated because many of the partial-record sites had fewer than 10 base-flow discharge measurements.

For this study, an average of 8 discharge measurements (as few as 3 and as many as 31) were made at partial-record sites. All base-flow discharge measurements at a partial-record site were used, providing nearby index sites were being operated. At some partial-record sites where a few discharge measurements had been made during droughts in the 1950's and early 1960's, additional discharge measurements were made during this study to increase the number of base-flow discharge measurements at the partial-record site and also to increase the number of possible index sites used for regressions. Measurement notes for the partial-record site, climatological data from nearby rain gages, and discharge hydrographs at the index sites were reviewed to determine if both the partial-record site and the index site were at base-flow conditions. Approximately 30 percent of the discharge measurements were not used because either the partial-record site or the index site was affected by surface runoff.

Selection of index sites was the same for the partial-record sites as for the short-term continuous-record sites, except visual examination of the visually fitted relation line was the only method used to determine which sites showed good fit. Values from those index sites showing good fit were compared, and if the values were consistent, a weighted average was used. The weight given to each value was determined by the distance between the partial-record site and the index site, comparison of basin characteristics, and spread of data points about the relation lines. When the values from those index sites showing good fit were compared and found not consistent, the value from a single index site was used. The index site having basin characteristics most closely resembling the basin characteristics of the partial-record site was selected for the regression. The procedure was performed graphically on log-log paper. The relation line was visually fitted to the data because of the limited number of discharge measurements normally available and the nonlinearity of many of the relations.

Ungaged Sites

It is commonly necessary to estimate low-flow characteristics at sites for which continuous records of daily mean discharge or base-flow discharge measurements are not available. Methods are presented here for estimating values at ungaged sites on gaged streams and at ungaged sites on ungaged streams.

Sites on Gaged Streams

A flow-routing method uses low-flow characteristics derived from streamflow records at gaged sites to estimate low-flow characteristics at ungaged sites. The method uses drainage-area proration to estimate low-flow characteristics at an ungaged site on the basis of low-flow values from gaged sites on the same stream. The low-flow values are transferred from a gaged site, either upstream or downstream, to the ungaged site. If it is necessary to proceed beyond a confluence, low-flow values at the confluence are estimated, and then added or subtracted (depending on direction of routing), and the sum is routed to the next confluence. This procedure is continued until the location of the ungaged site is reached. The flow-routing method can be used for basins that cross physiographic boundaries or drain regions underlain by different rock types; however, judgment must be used when basin characteristics, such as channel slope or rock type, change considerably between the gaged site and the ungaged site. Changes in basin characteristics can alter the base-flow characteristics of a stream.

The flow-routing equation for estimating low-flow characteristics (eq. 2) consists of a simple drainage-area ratio to the 1.2 power and is limited to drainage-area ratios of 0.25 to 4.0:

$$7QT_j = 7QT_i\left[\frac{A_j}{A_i}\right]^{1.2} \text{ for } 0.25 \leq \left[\frac{A_j}{A_i}\right] \leq 4.0, \qquad (2)$$

where

$7QT$ = average minimum 7-consecutive-day discharge having a T-year recurrence interval, in cubic feet per second;
j = location at an ungaged site or confluence where the low-flow value is to be determined;
i = location at a gaged site where low-flow values previously have been determined; and
A = drainage area, in square miles.

Any computed low-flow value that is calculated as negative is assumed to be zero.

The exponent and drainage-area ratio range in equation 2 were computed by analyzing low-flow characteristics at paired long-term and short-term continuous-record sites. Locations of all continuous-record sites for which low-flow characteristics previously were determined were plotted on a stream-network map of the State. Paired sites were selected on streams where no major tributaries entered the stream at any point between the selected sites. Paired sites with a tributary that entered the stream between the sites and caused the drainage area to increase at the confluence by more than 25 percent were not analyzed. Analysis was conducted on 77 paired continuous-record sites. Only continuous-record sites were used in the analysis because of greater confidence in the low-flow values. Confidence is less for the values at partial-record sites because the values were determined by correlation of point data and because many partial-record sites have small drainage areas with large natural variations in streamflow.

The following method was used to determine the exponent in the flow-routing equation. Logarithms of the ratios of the low-flow characteristics at the upstream site to the low-flow characteristics at the downstream site (7Q2 and 7Q10) were related to logarithms of the ratios of the drainage area at the upstream site to the drainage area at the downstream site. A relation line was determined using a least-squares regression method. A graph of the plotted points and the relation line was checked visually for linearity. The linearity of the relation line also was checked mathematically by assuming that the data fit an equation of the form

$$7QT_j = 7QT_i \left[\frac{A_j}{A_i}\right]^b \left[\frac{A_j}{A_i}\right]^c , \qquad (3)$$

where

$7QT$ = average minimum 7-consecutive-day discharge having a T-year recurrence interval, in cubic feet per second;

j = location at an ungaged site or confluence where the low-flow value is to be determined;

i = location at a site where low-flow values previously have been determined;

A = drainage area, in square miles;

b = exponent computed by least-squares regression; and

c = exponent selected by trial and error.

For every value of c selected from -1.0 to $+1.0$, a value of b and a standard error of estimate were computed. The minimum standard error of estimate occurred for a value of c of 0.0 to $+0.05$, resulting in a computed value of b of 1.2. Because the value of c was very close to zero, equation 3 reduced to the form of equation 2. When only the 7Q2 data were used to determine the exponent, the computed value of b was 1.12. When only the 7Q10 data were used to determine the exponent, the computed value of the exponent was 1.28. Using separate equations for transferring the 7Q2 and 7Q10 values yielded only slight improvements in the standard errors of estimate; therefore, the single equation for transferring both characteristics was selected.

The following examples from the Tye River basin show use of the method and an indication of the accuracy of the method. Figure 6 shows the general location of the gaging stations, and table 1 gives the data needed from the continuous-record stations as well as additional drainage areas needed in the calculations. The simplest predictions are made when the ungaged site is on the same stream as the gaged site and no major tributaries enter the stream at any point between the selected sites.

Example.—Determine the low-flow values, 7Q2 and 7Q10, of the Tye River near Lovingston, Va. (station 02027000), on the basis of low-flow values for Tye River at Roseland, Va. (station 02026500). A review of a geologic map and a topographic map shows that there are no major changes in basin characteristics between the two sites. The drainage-area proration is performed using the information known for the two sites and equation 2:

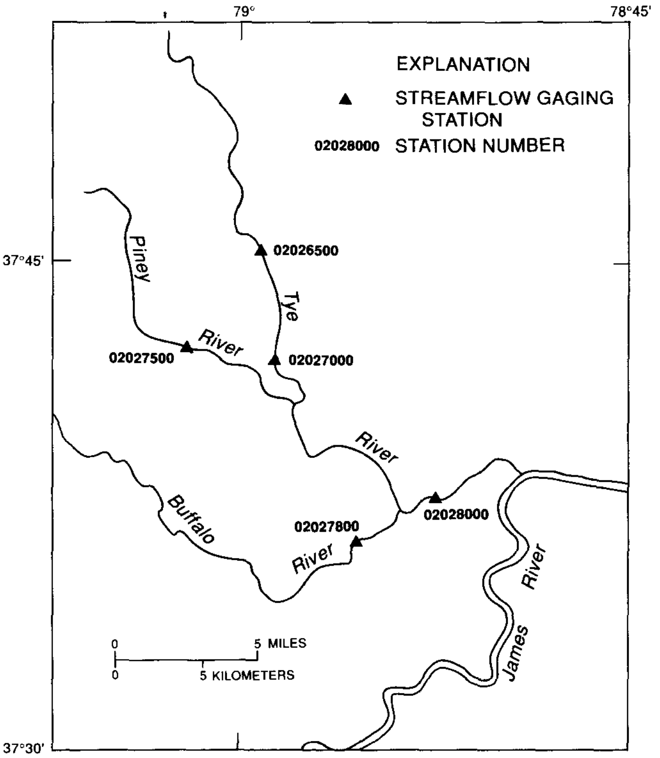

Figure 6. Tye River basin and location of gaging stations.

$$7Q2 = 15 \times \left[\frac{92.8}{68.0}\right]^{1.2} = 22 \text{ ft}^3\text{/s},$$

and

$$7Q10 = 3.1 \times \left[\frac{92.8}{68.0}\right]^{1.2} = 4.5 \text{ ft}^3\text{/s}.$$

Low-flow values computed from streamflow records for the Tye River near Lovingston are 19 ft^3/s for 7Q2, and 5.0 ft^3/s for 7Q10, resulting in errors of +16 percent and −10 percent, respectively. The simple drainage-area proration using equation 2 was performed on 154 gaged sites. A comparison was made between the low-flow values estimated from the drainage-area proration and the low-flow values computed from streamflow records. Results are discussed in the section "Results, Reliability, and Limitations of Estimating Methods."

Where major tributaries join, a more complex flow-routing analysis must be performed to estimate the low-flow characteristics. Low-flow characteristics should be known or determined for locations on each major tributary of the stream network.

Table 1. Drainage areas and low-flow values for selected continuous-record gaging stations in the Tye River basin, Virginia

[Dashes indicate station number not assigned and statistic not computed]

River name and location	Station	Drainage area, in square miles	Annual 7-day low flow for indicated recurrence interval, in cubic feet per second	
			2-year	10-year
Tye River at Roseland, Va.	02026500	68	15	3.1
Tye River near Lovingston, Va.	02027000	92.8	19	5.0
Tye River above Piney River	—	96	—	—
Piney River at Piney River, Va.	02027500	47.6	7.9	3.2
Piney River at mouth	—	71	—	—
Tye River above Buffalo River	—	206	—	—
Buffalo River near Tye River, Va.	02027800	147	28	7.9
Buffalo River at mouth	—	153	—	—
Tye (Buffalo) River near Norwood, Va.	02028000	360	81	37

Example.—Determine the low-flow values of the Tye (Buffalo) River near Norwood, Va. (station 02028000). Three streams must be used: the Tye River, the Piney River, and the Buffalo River (fig. 6, table 1). A review of a geologic map and a topographic map shows that there is some geologic variation in the basin, but the effects are well integrated into the low-flow characteristics of the existing streamflow sites. Using equation 2, low-flow values at the Tye River near Lovingston (station 02027000) are used to estimate low-flow values for the Tye River above the confluence of the Piney River, and low-flow values at the Piney River at Piney River (station 02027500) are used to estimate low-flow values at the mouth of the Piney River. The drainage area of the Tye River above the Piney River is approximately 96 mi^2, and the drainage area of the Piney River at the mouth is approximately 71 mi^2. The 7Q2 of the Tye River above the confluence of the Piney River is calculated from the 7Q2 value from the Tye River near Lovingston as follows:

$$7Q2=19\times\left[\frac{96.0}{92.8}\right]^{1.2}=19.8\ \text{ft}^3/\text{s}.$$

The 7Q2 at the mouth of the Piney River is calculated from the 7Q2 value at the Piney River at Piney River as follows:

$$7Q2=7.9\times\left[\frac{71.0}{47.6}\right]^{1.2}=12.8\ \text{ft}^3/\text{s}.$$

The 7Q2 value is estimated for the confluence of the Tye River and Piney River by adding the estimated values together:

$$7Q2=19.8+12.8=32.6\ \text{ft}^3/\text{s}.$$

The 7Q2 for the Tye River above the Buffalo River is calculated using this value, as follows:

$$7Q2=32.6\times\left[\frac{206}{71+96}\right]^{1.2}=41.9\ \text{ft}^3/\text{s}.$$

The 7Q2 at the mouth of the Buffalo River is calculated from the low-flow value of the Buffalo River near Tye River (station 02027800), as follows:

$$7Q2=28\times\left[\frac{153}{147}\right]^{1.2}=29.4\ \text{ft}^3/\text{s}.$$

The low-flow value is estimated at the confluence of the Tye River and Buffalo River by adding the two values:

$$7Q2=41.9+29.4=71.3\ \text{ft}^3/\text{s}.$$

Finally, this value is used to estimate the 7Q2 at station 02028000, as follows:

$$7Q2=71.3\times\left[\frac{360}{359}\right]^{1.2}=71.5,\ \text{or}\ 72\ \text{ft}^3/\text{s}.$$

The estimated 7Q2 value of 72 ft^3/s is 11 percent less than the value of 81 ft^3/s determined from streamflow records. Similar computations would predict a 7Q10 value of 21 ft^3/s, 43 percent less than the value of 37 ft^3/s determined from streamflow records.

The method can also be used in the upstream direction.

Example.—Estimate the 7Q2 for the Buffalo River near Tye River (station 02027800) using data from the other sites. Computed values for the Tye River at the confluence of the Buffalo River (7Q2=41.9 ft^3/s) would be the same in this example as in the previous example. The value from the Tye (Buffalo) River near Norwood (station 02028000) would be used to estimate the 7Q2 below the confluence with the Buffalo River:

$$7Q2=81\times\left[\frac{359}{360}\right]^{1.2}=80.7\ \mathrm{ft^3/s}.$$

Subtracting the value above the confluence from the value below the confluence gives the contribution of the Buffalo River at the mouth, as follows:

$$7Q2=80.7-41.9=38.8\ \mathrm{ft^3/s}.$$

Estimating the value upstream at the desired location,

$$7Q2=38.8\times\left[\frac{147}{153}\right]^{1.2}=37.0\ \mathrm{ft^3/s}.$$

The estimated 7Q2 value of 37 $\mathrm{ft^3/s}$ is 32 percent greater than the value determined from streamflow records of 28 $\mathrm{ft^3/s}$. Similar computations would predict a 7Q10 value of 23 $\mathrm{ft^3/s}$, 191 percent greater than the value of 7.9 $\mathrm{ft^3/s}$ determined from streamflow records.

The flow-routing analysis was performed on 24 stream networks, with predictions made at 84 sites. A comparison was made between the low-flow value estimated by the flow-routing method and the low-flow value computed from streamflow records at each site. Results are discussed in the section "Results, Reliability, and Limitations of Estimating Methods."

Sites on Ungaged Streams

It is not possible to collect streamflow data on every stream and tributary in the State; therefore, a method for estimating low-flow characteristics at ungaged sites on ungaged streams also is needed. Regional equations can be developed using multiple-regression analyses of basin and climatological characteristic values and available low-flow values. The regression model used in this study is of the form

$$7QT=a(A)^b(B)^c(C)^d\ldots, \tag{4}$$

where a, b, c, and d are the coefficients determined by regression analyses and A, B, and C are the basin and climatological characteristic values. By taking the logarithms of both sides of equation 4, the model takes a linear form:

$$\log(7QT)=\log(a)+b\log(A)+c\log(B)+d\log(C)+. \tag{5}$$

and a least-squares solution can be used to determine the coefficients.

Regression equations were developed by dividing the State into geographic regions. The regions were developed from five physiographic provinces in Virginia and on the basis of topography and geology. Continuous-record and partial-record stations were assigned to the particular region in which more than 75 percent of the stream's drainage basin for that site was located, and for which the slope of the streambed at the measuring point was consistent with the general slope of the assigned region. To develop regression equations, multiple-regression analyses were performed for each region on the low-flow values and the basin and climatological characteristic values for the stations. After initial regression equations were calculated for the five regions, the residuals were examined. Three additional regions were formed, on the basis of geographic grouping of the residuals. The eight resulting regions are shown in figure 7 and plates 1 and 2, and are listed below:

1. Coastal Plain, northern region.
2. Coastal Plain, southern region.
3. Piedmont, northern region.
4. Piedmont, southern region.
5. Piedmont/Blue Ridge transition region.
6. Blue Ridge region.
7. Valley and Ridge region.
8. Appalachian Plateaus region.

Basin and climatological characteristics used as variables in the regression analysis were drainage area, area underlain by specific rock type, soil type and depth, stream length, strip-mined area, streambed slope, elevation, percent forest cover, surface storage, flow direction, and mean-annual precipitation. The following is a description of the basin and climatological characteristics analyzed and the methods used to determine the values of the characteristics.

Drainage area (*A*), in square miles, was computed for all continuous-record and partial-record sites from 1:24,000-scale topographic maps using mechanical planimeters and electronic planimeters. Drainage area is considered the predominant factor explaining variation in low-flow characteristics and is used in some form in each equation. One set of equations was developed with drainage area as the only indicator.

Drainage area underlain by a specific rock type was identified using a grid sampling method from the 1:500,000-scale State geologic map (Virginia Division of Mineral Resources, 1963). Generalized rock types were computed as percent of the total drainage area—Triassic and Jurassic sedimentary rock (*TJ*) for the Piedmont northern region, Piedmont southern region, and Piedmont/Blue Ridge transition region, and Devonian and Mississippian sedimentary rock (*DM*) for the Valley and Ridge region. For the Coastal Plain, Blue Ridge, and Appalachian Plateaus regions, general rock type and structure are hydrologically similar throughout each region and were not evaluated.

Soils maps show the type and depth of overburden. A statewide soil map (U.S. Department of Agriculture and Soil Conservation Service, 1979) closely resembles the

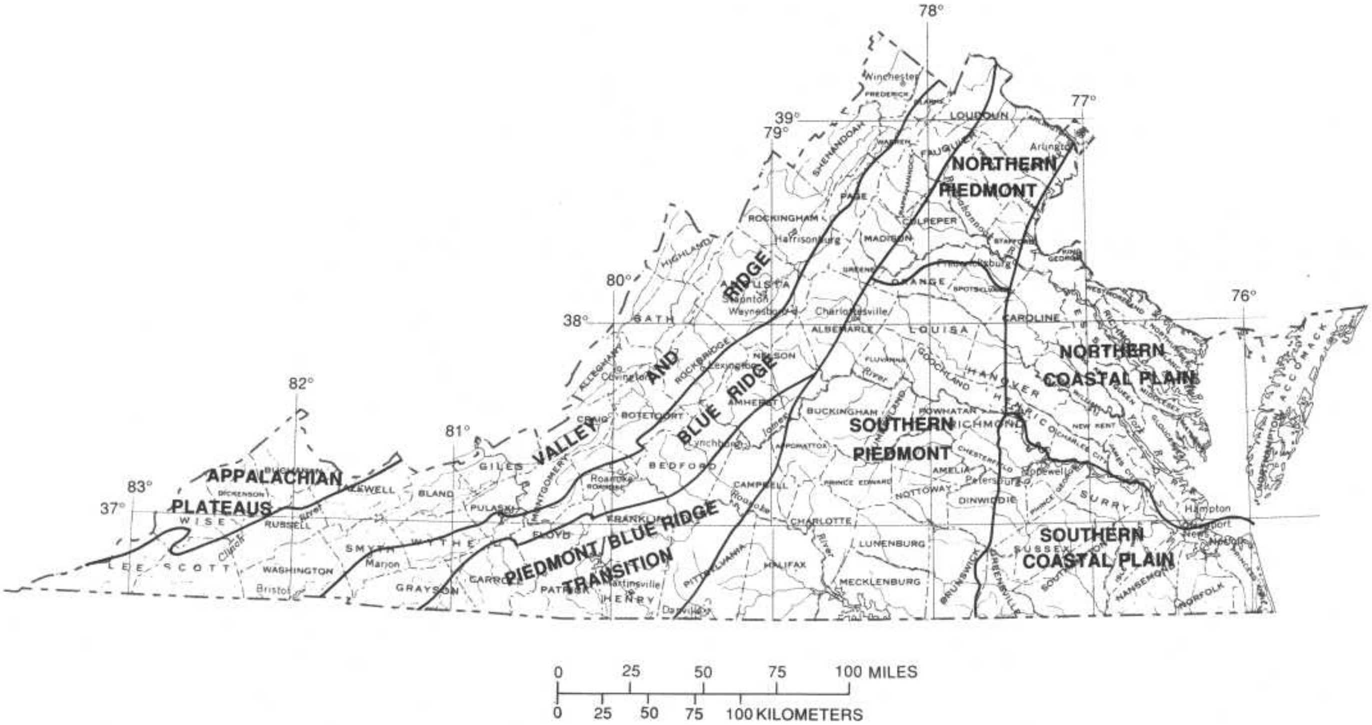

Figure 7. Regions in Virginia for application of low-flow estimating equations.

State geologic map (Virginia Division of Mineral Resources, 1963). Because the soil map may be difficult to obtain and because the map closely resembles the geologic map, soil type and depth were excluded, and rock type was retained as the variable to indicate the effects of soil type and depth.

Stream length, in miles, was measured from 1:24,000-scale topographic maps for the longest stream length from the gage site to the basin divide. Stream length, in conjunction with drainage area, should indicate basin shape and distinguishes long, narrow basins from more rounded, dendritic basins. Stream lengths were measured and evaluated for all sites in the Appalachian Plateaus, Valley and Ridge, and Blue Ridge regions and the Piedmont/Blue Ridge transition region. In the Coastal Plain, northern Piedmont, and southern Piedmont regions, stream length was measured for approximately one-third of the sites and tested for significance. If preliminary regression analyses indicated that stream length was significant, stream length for the remaining sites in that region was measured, and was tested again for significance.

Strip mining is done primarily in southwestern Virginia, specifically in the Appalachian Plateaus region. Strip-mined area (*SM*), as a percentage of total drainage area, was computed from USGS 1:24,000-scale topographic maps for each basin in the Appalachian Plateaus region using mechanical planimeters or electronic planimeters.

Streambed slope, in feet per mile, was computed from points at 10 percent and 85 percent of stream length upstream from the gage for approximately one-third of the stations in each region. Values were used in preliminary regression analyses to determine if slope was significant. If preliminary regression analyses indicated that slope was significant, slope for the remaining sites in that region, was computed and was tested again for significance.

Basin elevation, in feet above sea level, was computed by averaging the elevation of points at 10 percent and 85 percent of stream length upstream from the gage for approximately one-third of the stations in each region. Values were used in preliminary regression analyses to determine if basin elevation was significant. If preliminary regression analyses indicated that basin elevation was significant, elevation for the remaining sites in that region, was computed and was tested again for significance.

Percent forest cover, as percentage of total drainage area, was computed by a grid sampling method for approximately one-third of the stations in each region. Values were used in preliminary regression analyses to determine if percent forest cover was significant. If preliminary regression analyses indicated that percent forest cover was significant, percent forest cover for the remaining sites in that region, was computed and was tested again for significance.

Surface storage, as percentage of total drainage area, was computed by adding the areas of lakes, ponds, and swamps measured by a grid sampling method for approximately one-third of the stations in each region. Values were used in preliminary regression analyses to determine if storage was significant. If preliminary regression analyses indicated that storage was significant, storage for the remaining sites in that region, was computed and was tested for significance.

Flow direction of the streams was determined from available maps. Directions were either east or west and were used specifically for the Blue Ridge region in an attempt to qualify differences in slope and overburden.

Mean annual precipitation is an approximate measure of the amount of water available to a basin for surface runoff, evapotranspiration, storage, and ground-water recharge and transfer. Mean annual precipitation, in inches, was computed by a grid sampling method for approximately half the stations in each region. If preliminary regression analyses indicated that mean annual precipitation was significant, mean annual precipitation for the remaining sites in that region was computed and was tested again for significance.

The regression analysis used for deriving the equations for ungaged sites on ungaged streams assumes that the independent variables are independent of each other; however, it is difficult to find hydrologic characteristics that are totally independent of each other. If the independent variables are strongly related, unstable and misleading results may be obtained. A simple correlation matrix of the variables for each region was developed. Analyses of the correlation coefficients in the matrix were used to determine which independent variables produce the best model and, more important, which independent variables were strongly related among themselves. The correlation matrix indicated that drainage area was highly related to stream length, and that stream length was highly related to strip-mined area. Normally, when two independent variables are highly related, only one is chosen as an indicator.

Low-flow characteristics (dependent variables) were plotted with basin and climatological characteristics (independent variables) for each region. The plots indicated that the relation between the dependent and independent variables is not linear in arithmetic space, and that a transformation of the variables would be necessary to obtain a linear-regression model with equal variance about the relation line. Logarithmic transformation of the variables (eq. 5), which normally works well with hydrologic data, was used in this study.

Initially, one model was developed for each low-flow characteristic in each region, with drainage area as the only independent variable. These equations were designed to estimate the low-flow characteristic when other basin and climatological characteristics are not readily available. Finally, all independent variables were included in the regression analyses in an attempt to improve the model.

Multiple regressions were run to determine the effects of the independent variables on the dependent variables. A backward elimination technique (SPSS Inc., 1986) was used to determine the final model form and coefficient values. The independent variables that were significant at a 95-percent confidence level were retained in the model.

Preliminary regressions were run using many different regression methods and data transformations in attempts to determine which independent variables were significant. The independent variables that remained significant were drainage area, percent area underlain by a specific rock type, and percent strip-mined area.

Zero values in the data sets caused problems with log transformations of both dependent and independent variables. Two solutions to the problem were (1) eliminate the zero flows (dependent variables) from the analysis and add a constant to the independent variables that could be zero, and (2) retain the zero flows in the analysis and add constants to both the dependent and independent variables. Zero flows were retained in the analysis because of the large number of zero flows in the data and the need to predict zero flows at a site.

Separate constants were determined for each dependent variable in the eight regions. Zero-flow values were excluded from the data base, and regressions were run using drainage area as the only independent variable. The slope of the linear-regression line was determined from this regression. The zero-flow values were then included in the data set, and constants (0.001, 0.01, 0.1, 0.5, 1.0, 5.0, and 10.0) were added to the dependent variables. The constant that generated the slope of the regression line closest to the slope of the previous regression line (that is, with zero flows excluded) was chosen for the final equation. In this manner, the zero flows caused minimal change in the slope of the regression line; in addition, the procedure allows the user to predict zero flows.

Separate constants were determined in a similar manner for each independent variable that could be zero. Zero values in the data base were excluded from the dependent variables as well as the independent variables, and regressions were run for each of the eight regions. Drainage area and percent area underlain by specific rock type, and drainage area and percent strip-mined area, were the independent variables used. The slope of the linear-regression line was determined from this regression for each independent variable. The zero values were then included in the data set for the independent variables, and constants (0.001, 0.01, 0.1, 0.5, 1.0, 5.0, and 10.0) were added to the independent variables. The constant that generated the slope of the regression line closest to the slope of the previous regression line (that is, with zero values for the dependent and independent variables excluded) was chosen to be included in the final equation. The final equations (table 2) were determined by including the constants for the dependent and independent variables as determined above, log transforming all the variables, and using the complete data set (including zero values) in the regression analysis.

The equation for the standard error of estimate was modified to represent the error along the entire regression line. This error, now called the standard error of prediction, in percent, is defined as

Table 2. Predictive equations applicable to designated regions in Virginia

[Table gives equations and standard errors of prediction for annual minimum average 7-consecutive-day flows having a 2-year recurrence interval (7Q2) and a 10-year recurrence interval (7Q10). Values in equations are in cubic feet per second. Basin characteristics used in the equations are as follows: *A*, drainage area, in square miles; *TJ*, area underlain by Triassic and Jurassic sedimentary rock, as a percentage of total drainage area; *DM*, area underlain by Devonian and Mississippian sedimentary rock, as a percentage of total drainage area; and *SM*, area strip mined, as a percentage of total drainage area. Dashes indicate statistic not computed]

Region	Equation	Standard error of prediction, in percent	Number of partial-record sites used	Number of continuous-record sites used	Drainage area, in square miles	
					Maximum	Minimum
Coastal Plain						
Northern region			62	11	108	0.28
	$7Q2=0.084\ (A)^{1.010}\ -0.01$	88				
	$7Q10=0.041\ (A)^{0.728}\ -0.01$	118				
Southern region			28	4	456	.61
	7Q2–Could not be determined	–				
	7Q10–Approximately 0.0	–				
Piedmont						
Northern region			59	23	155	.08
	$7Q2=0.258\ (A)^{0.918}\ (TJ+5.0)^{-0.846}\ -0.01$	124				
	7Q10–*TJ* not significant	–				
	or					
	$7Q2=0.027\ (A)^{0.833}\ -0.01$	139				
	$7Q10=0.002\ (A)^{0.844}\ -0.001$	172				
Southern region			59	27	269	.33
	$7Q2=0.042\ (A)^{1.101}\ -0.01$	98				
	$7Q10=0.015\ (A)^{1.025}\ -0.01$	125				
Piedmont/Blue Ridge transition region			24	11	278	.46
	$7Q2=0.226\ (A)^{1.098}\ -0.0$	60				
	$7Q10=0.120\ (A)^{1.045}\ -0.01$	90				

the errors from the split sample for that variable and region. Reliability of the regional equations was determined from the standard errors of prediction, which are also given in table 2 and are discussed in the section "Results, Reliability, and Limitations of Estimating Methods."

To use the equations, first locate the desired basin in figure 7 or on plates 1 or 2. Determine which of the eight regions contains the basin. From equations in table 2, determine which basin characteristics are needed and compute them using the best available maps. When two equations are given for a low-flow value, the more complex equation should be used. However, if the basin characteristics needed for the equation cannot be determined, the equation using drainage area (*A*) only may be used. When the basin is in two or more regions, compute the amount contributed by each region and combine. The predicted value, 7Q2 or 7Q10, should be set to zero if the value computed from the equation is negative.

Example.—Determine the low-flow characteristics, 7Q2 and 7Q10, of the Tye River near Lovingston, Va. (station 02027000). From plate 1, the entire basin is located in the Blue Ridge region. Drainage area is the only basin characteristic needed and is known to be 92.8 mi^2. Using the equations in table 2 for the Blue Ridge region, the low-flow values 7Q2 and 7Q10 are computed as 9.8 and 2.6 ft^3/s, respectively. These differ from the low-flow values computed by actual streamflow data (19 and 5.0 ft^3/s, respectively) by 48 percent for both 7Q2 and 7Q10.

Results, Reliability, and Limitations of Estimating Methods

Low-flow characteristics at a site are based on natural and manmade factors that affect low flows. Data collected to estimate these low-flow characteristics are subject to time-sampling errors primarily because of changes in climate and land use. Also, attempts to use low-flow values determined from unregulated conditions in basins that have become highly regulated or have experienced rapidly changing land use should be avoided because current low flows are based on the nature of the regulation and land use. Measures of reliability of low-flow values and problems that cause inaccurate estimates are discussed below for each site type.

Long-Term Continuous-Record Sites

The reliability of calculated low-flow values at long-term continuous-record sites depends on the length of data recorded, the time period during which the data were recorded, the stability of basin characteristics, and the type of statistical analysis applied to the data. The longer the period of record, the more representative of the hydrology of the site the record should be. Estimates of low-flow characteristics for a site based on 20 yr of record normally would be better than estimates based on 10 yr of record. More wet and dry periods may be sampled by the longer record, and representative low-flow values can be determined. The shorter the period of record or the more extreme the climatological conditions, the greater the time-sampling error of the estimated low-flow value. Streamflow records collected during extremely wet or dry climatic cycles may bias the low-flow characteristics. Characteristics based on data recorded 40 or 50 yr earlier may have changed with changes in land use, and unless historical and current data are supplied, no knowledge of this land-use change will exist. The easiest method of determining if the low-flow values are biased because of time-sampling error or changes in land use is through analyses of climatological data and streamflow records at stations spanning long time periods. Changes in land use may be very gradual and not easily recognizable. Plots of annual low-flow values over time should be analyzed to determine if any trends exist before the data are used to determine the low-flow statistics.

Leatherwood Creek near Old Liberty, Va. (station 02073500), provides an example of several of the problems mentioned above. Continuous data were collected for 8 climatic years between 1925 and 1934. Frequency curves were graphically fit to the annual low-flow data even though there are only 8 yr of record. The estimated 7Q2 and 7Q10 values are 6.5 ft^3/s and 1.0 ft^3/s, respectively. Mean daily discharges from this station were related to concurrent mean daily discharges at stations 02070000 and 02074500 (both having more than 50 yr of record). From these relations, estimates of the 7Q2 and 7Q10 values are 7.5 and 2.7 ft^3/s, respectively. Finally, 10 base-flow discharge measurements were made from 1981 to 1985. These were related to mean daily discharges at stations 02070000, 02074500, and 02069700, with resulting estimates of 7Q2 and 7Q10 of 15 and 7.5 ft^3/s, respectively. Because of a severe drought during the early 1930's, estimates from the graphical frequency distribution should be less than estimates from correlation of daily mean flows. Also, low-flow estimates from correlation of the 1930's continuous-record data should be close to low-flow estimates from correlation of the 1980's base-flow discharge measurement data. However, the estimates from the 1930's continuous-record data are substantially less than the estimates from the 1980's base-flow discharge measurement data. Because two of the correlation stations are used for both sets of relations, possible explanations for the differences are a change in land use or diversion of streamflow. A change in land use is probably the best explanation because all the data correlate extremely well with the long-term continuous-record sites.

Where current data were not available, attempts were made to update the low-flow characteristics at unregulated sites to present-day values; however, this was not always possible. For example, 8 yr of continuous-record daily mean discharges collected during the drought of the 1930's

Table 2. Predictive equations applicable to designated regions in Virginia—Continued

Region	Equation	Standard error of prediction, in percent	Number of partial-record sites used	Number of continuous-record sites used	Drainage area, in square miles	
					Maximum	Minimum
Blue Ridge region			61	22	188	.78
	$7Q2=0.062\ (A)^{1.117}-0.01$	85				
	$7Q10=0.016\ (A)^{1.124}-0.01$	111				
Valley and Ridge region			58	49	277	0.61
	$7Q2=0.467\ (A)^{1.034}\ (DM+10.0)^{-0.491}-0.1$	87				
	$7Q10=0.416\ (A)^{0.983}\ (DM+10.0)^{-0.532}-0.1$	96				
	or					
	$7Q2=0.112\ (A)^{0.958}-0.1$	91				
	$7Q10=0.088\ (A)^{0.900}-0.1$	102				
Appalachian Plateaus region			107	10	87.4	.17
	$7Q2=0.015\ (A)^{1.165}\ (SM+1.0)^{0.354}-0.01$	103				
	$7Q10=0.003\ (A)^{0.958}\ (SM+5.0)^{0.680}-0.01$	115				
	or					
	$7Q2=0.027\ (A)^{1.202}-0.01$	105				
	$7Q10=0.017\ (A)^{0.962}-0.01$	123				

$$\left[\frac{\Sigma\left[\dfrac{A-P}{(A+P)/2}\right]^{2}}{N}\right]^{0.5}, \qquad (6)$$

where

A=actual value;

P=predicted value; and

N=number of data points.

A modified estimate of the mean, $(A+P)/2$, is necessary because of the large number of actual and predicted zero values. When both A and P are zero, the error term for that point is set to zero.

Because of the size of the data sets, a split sample was used to determine the errors. The sites were rank ordered according to drainage basin size and type of data collected (partial record or continuous record). The data sets then were split by selection of alternate sites. Equations were developed for each split data set by using the constants previously determined from analysis of the entire data set. Errors for each split data set were computed by predicting values in the alternate data set and using equation 6. The standard error of prediction was computed as the average of are available for the Rivanna River below Moores Creek near Charlottesville, Va. There are no nearby long-term continuous-record stations with concurrent streamflow data available for correlation. The estimated low-flow values are known to be low but cannot be adjusted.

Low-flow characteristics derived from unregulated periods at a site that has become regulated have only regional importance, and characteristics based on regulated periods are useful only while the regulation scheme remains constant. Extreme caution must be used when discussing characteristics at regulated sites. Generally, low-flow characteristics for stream reaches that are affected by regulation cannot be used for planning purposes or for correlation with unregulated sites. In this report, low-flow values computed from unregulated periods at currently regulated sites are used only for determining regression equations and accuracy of values at ungaged sites.

So far, discussion of errors has involved the collection of flow data. Reliability and limitations of low-flow characteristics due to the use of the Pearson Type III distribution are not analyzed in this report but are discussed in Hardison (1969), Hardison (1971), Kite (1977), and Rao (1980).

Short-Term Continuous-Record Sites and Partial-Record Sites

The reliability of calculated low-flow values at short-term continuous-record sites and partial-record sites depends on the reliability of the flow data collected at the short-term or partial-record site, the flow data and frequency analysis for the index sites, and the relation line between the related sites. In addition to problems for long-term continuous-record sites already mentioned, other time-sampling errors may arise from low-flow data at short-term continuous-record sites and partial-record sites.

Selection of daily mean base-flow discharges at short-term continuous-record sites sampled the full range of base-flow discharges over the entire period of discharge record, so that a representative low-flow value could be computed. Only one daily mean base-flow discharge for a single streamflow recession was selected. The discharge was selected so that the related station was also at base-flow conditions. A relation line was developed using a linear least-squares regression method on the logarithms of the concurrent daily mean discharges. The linear-regression line was plotted with the data and was visually adjusted at lower discharges when necessary. The coefficient of determination, which indicates how well the regression line explains the observed values, was computed for each pair of related sites and is given in appendix 3. There was no method for determining the reliability or error associated with extension of the relation line below the observed values to estimate the *T*-year event; however, the short-term continuous-record sites were related to several index sites when available. Analysis of the variation of the computed values from separate correlations indicates the reliability of the relation between the sites (app. 3) and reduces the possibility of chance correlations. Accuracy of low-flow characteristics estimated from correlation of daily mean base-flow discharges is discussed in Hardison and Moss (1972).

The timing and distribution of base-flow discharge measurements at partial-record sites can influence the accuracy of the predicted low-flow values. By distributing the discharge measurements over several years and selecting the discharge so an adequate range of flows is sampled, a representative low-flow value can be computed. Analyses of measurement notes, climatological data, and hydrographs of the index sites were used to determine if the partial-record site and the index site were at base-flow conditions. Less weight was given to those points that may have been influenced by runoff. Logarithms of the discharge measurement values at the partial-record site were plotted with logarithms of the concurrent daily mean discharge values at the index site. A relation line was visually fitted through the points. Because of the limited number of discharge measurements and the nonlinearity of the relation lines, a statistically based relation line and the associated coefficient of determination were not computed. Like the short-term continuous-record sites, there was no method for determining the reliability or error associated with extension of the relation line below the measured values to estimate the *T*-year event; however, the partial-record sites were related to several index sites when available. Analysis of the variation of the computed values from separate correlations indicates the reliability of the relation between the sites (app. 4) and reduces the possibility of chance correlations. The accuracy of low-flow characteristics estimated from correlation of base-flow measurements is discussed in Hardison and Moss (1972).

Ungaged Sites on Gaged Streams

The flow-routing method predicts low-flow values fairly well along gaged streams when the basin characteristics between the gaged site and ungaged site are homogeneous. Tests were performed on the continuous-record data to determine the maximum distance that data from a gaged site can be reliably transferred to an ungaged site.

The drainage-area ratio range was determined for the flow-routing equation by analyzing predictions at the 77 paired continuous-record sites described in the section "Methods for Determining Low-Flow Characteristics." The paired sites were rank ordered, from maximum to minimum, according to drainage-area ratio. The standard error of estimate, as a percentage of the mean, was calculated for both the 7Q2 and 7Q10 data sets. The pair of sites having the largest drainage-area ratio was excluded from the group, and the standard errors of estimate recalculated. Fifty paired