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West Virginia Department of Environmental Protection,
Division of Water and Waste Management

Estimation of Selected Seasonal Streamflow Statistics Representative of 1930–2002 in West Virginia

Scientific Investigations Report 2010–5185

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

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By Jeffrey B. Wiley and John T. Atkins, Jr.

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U.S. Geological Survey
Marcia K. McNutt, Director

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Conversion Factors, Acronyms, and Abbreviations

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Acronyms

LOESS	Locally weighted regression
MOVE.1	Maintenance of variance extension, type 1
NRAC	National Resource Analysis Center
USEPA	U.S. Environmental Protection Agency
USGS	U. S. Geological Survey
WCMS	Watershed Characterization Management System
WVDEP	West Virginia Department of Environmental Protection
WVDEP, DMR	West Virginia Department of Environmental Protection, Division of Mining and Reclamation
WVDEP, DWWM	West Virginia Department of Environmental Protection, Division of Water and Waste Management

Abbreviations

1Q10	1-day, 10-year hydrologically based low flow
7Q10	7-day, 10-year hydrologically based low flow
30Q5	30-day, 5-year hydrologically based low flow
A	Agriculture cover
A_U	Drainage area at the location of the unknown streamflow
A_K	Drainage area at the location of the known streamflow
A_{US}	Drainage area at the upstream location
A_{DS}	Drainage area at the downstream location
B	Barren land cover
BOr	Basin orientation
BP	Basin perimeter
BR	Basin relief
BS	Basin slope
BW	Basin width
CR	Compactness ratio
CL	Channel length
CM	Channel maintenance
CS	Channel slope
D50	50-percent-duration flow
DA	Drainage area
E	Mean basin elevation
ER	Elongation ratio
EX	Exponent for drainage-area ratios
F	Forest cover
G	Grassland cover
GLS	Generalized least squares
HM	Harmonic-mean flow
I	Impervious cover
I24-2	24-hour, 2-year rainfall
JANMIN	January minimum temperature
LAT_C	Latitude of the basin centroid
$LONG_C$	Longitude of the basin centroid

M_P	Mean of the log10-transformed streamflows at the partial-record station
M_G	Mean of the log10-transformed streamflows at the streamgage station
OLS	Ordinary least squares
P	Annual precipitation
Q_{DS}	Value of the streamflow statistic at the downstream location
Q_G	Log10-transformed value of the streamflow at the streamgage station
Q_K	Known value of the streamflow statistic
Q_{KE}	Regional equation evaluated at the location of the known value of the streamflow statistic
Q_P	Value of the streamflow statistic at the partial-record station
Q_U	Unknown value of the streamflow statistic
Q_{UE}	Regional equation evaluated at the location of the unknown value of the streamflow statistic
Q_{US}	Value of the streamflow statistic at the upstream location
RB	Rotundity of basin
R_{DS}	Downstream limit of the ratio of drainage areas
RN	Ruggedness number
RR	Relative relief
$R_{U/K}$	Ratio of the drainage area at the location of the unknown streamflow to the drainage area at the location of the known streamflow
R_{US}	Upstream limit of the ratio of drainage areas
S	Annual snow depth
SD	Stream density
SF	Shape factor
S_G	Standard deviation of the concurrent $\log_{10}$-transformed streamflows at the streamgage station
SIR	Sinuosity ratio
SL	Stream length
SLR	Slope ratio
SP	Slope proportion
S_P	Standard deviation of the concurrent $\log_{10}$-transformed streamflows at the partial-record station
U	Urban land cover
VL	Valley length
W	Wetland cover
Wa	Open-water cover
WLS	Weighted least squares

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Estimation of Selected Seasonal Streamflow Statistics Representative of 1930–2002 in West Virginia

By Jeffrey B. Wiley and John T. Atkins, Jr.

Abstract

Regional equations and procedures were developed for estimating seasonal 1-day 10-year, 7-day 10-year, and 30-day 5-year hydrologically based low-flow frequency values for unregulated streams in West Virginia. Regional equations and procedures also were developed for estimating the seasonal U.S. Environmental Protection Agency harmonic-mean flows and the 50-percent flow-duration values. The seasons were defined as winter (January 1–March 31), spring (April 1–June 30), summer (July 1–September 30), and fall (October 1–December 31).

Regional equations were developed using ordinary least squares regression using statistics from 117 U.S. Geological Survey continuous streamgage stations as dependent variables and basin characteristics as independent variables. Equations for three regions in West Virginia—North, South-Central, and Eastern Panhandle Regions—were determined. Drainage area, average annual precipitation, and longitude of the basin centroid are significant independent variables in one or more of the equations. The average standard error of estimates for the equations ranged from 12.6 to 299 percent.

Procedures developed to estimate the selected seasonal streamflow statistics in this study are applicable only to rural, unregulated streams within the boundaries of West Virginia that have independent variables within the limits of the stations used to develop the regional equations: drainage area from 16.3 to 1,516 square miles in the North Region, from 2.78 to 1,619 square miles in the South-Central Region, and from 8.83 to 3,041 square miles in the Eastern Panhandle Region; average annual precipitation from 42.3 to 61.4 inches in the South-Central Region and from 39.8 to 52.9 inches in the Eastern Panhandle Region; and longitude of the basin centroid from 79.618 to 82.023 decimal degrees in the North Region. All estimates of seasonal streamflow statistics are representative of the period from the 1930 to the 2002 climatic year.

Introduction

Streamflow statistics are used in the development and management of surface-water and groundwater resources in West Virginia, including assessing the availability of water for municipal, industrial, and irrigation supplies; recreation; aquatic-life and wildlife conservation; and disposal of liquid wastes. Streamflow statistics also are useful for forecasting low streamflows, are valuable as indicators of the amount of groundwater inflow to streams, and are helpful as legal indexes for maintaining water-quality standards. Industrial facilities whose effluent discharges may exceed those allowed on an annual basis might be within discharge standards seasonally. Some industries, such as tourism, are predominantly seasonal, and others may be able to coordinate activities with seasonal flows in order to meet regulatory guidelines. Therefore, the U.S. Geological Survey, in cooperation with the West Virginia Department of Environmental Protection, Division of Water and Waste Management, investigated the magnitude of selected seasonal streamflows.

This report documents the development of regional equations and estimating procedures for determining the seasonal 1-day 10-year (*1Q10*), 7-day 10-year (*7Q10*), and 30-day 5-year (*30Q5*) hydrologically based low-flow frequency values for unregulated streams in West Virginia. Equations and procedures are presented for estimating the seasonal U.S. Environmental Protection Agency (USEPA) harmonic mean flow (*HM*) and seasonal 50–percent duration flow (*D50*). Equations are applicable only to West Virginia for winter (January 1–March 31), spring (April 1–June 30), summer (July 1–September 30), and fall (October 1–December 31), representing the period April 1, 1930, through March 31, 2002 (1930–2002 climatic years).

Description of Study Area

West Virginia can be differentiated into three physiographic provinces, the Appalachian Plateaus, Valley and Ridge, and Blue Ridge (Fenneman, 1938) (fig. 1). The movement of air masses across the State allows identification of two climatic regions, separated by a line defined as the Climatic Divide (Wiley, 2008) (fig. 1).

Generally, the part of the State west of the Climatic Divide is in the Appalachian Plateaus Physiographic Province, where altitudes range from about 2,500 to 4,861 ft (NAVD 88) at Spruce Knob along the Climatic Divide to about 550 to 650 ft along the Ohio River. The part of West Virginia east of the Climatic Divide is in the Valley and Ridge Physiographic

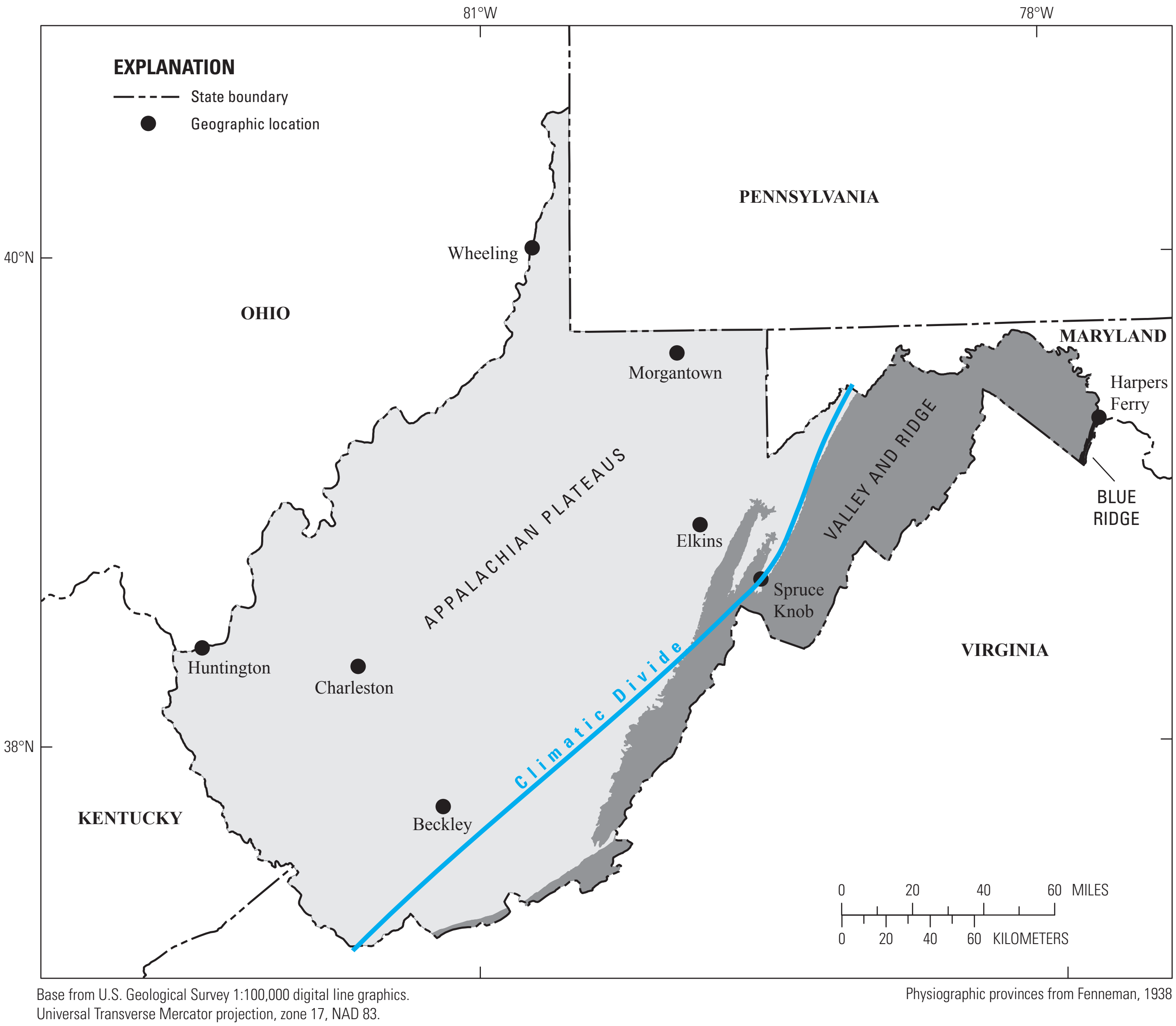


Figure 1. Appalachian Plateaus, Valley and Ridge, and Blue Ridge Physiographic Provinces, and Climatic Divide in West Virginia. (From Wiley and Atkins, 2010, fig. 2)

Province, except for the extreme eastern tip of the State, which is in the Blue Ridge Physiographic Province. Altitudes decrease eastward from the Climatic Divide to 274 ft at Harpers Ferry in the Eastern Panhandle (U.S. Geological Survey, 1990, 2006; National Oceanic and Atmospheric Administration, 2006a).

The Appalachian Plateaus Physiographic Province consists of consolidated, mostly noncarbonate sedimentary rocks that have a gentle slope from southeast to northwest near the Climatic Divide and are nearly flat-lying along the Ohio River. One exception is in the northeastern area of the province (west of the Climatic Divide), where the rocks are gently folded and some carbonate rock crops out (Fenneman, 1938). The rocks in the Appalachian Plateaus Physiographic Province have been eroded to form steep hills and deeply incised valleys. Drainage patterns are dendritic.

The Valley and Ridge Physiographic Province in West Virginia consists of consolidated carbonate and noncarbonate sedimentary rocks that are folded sharply and extensively faulted (Fenneman, 1938). Northeast-trending valleys and ridges parallel the Climatic Divide. Drainage patterns are trellis.

The Blue Ridge Physiographic Province within West Virginia consists predominantly of metamorphosed sandstone and shale (Fenneman, 1938). The province has high relief between mountains and wide valleys that parallel the Climatic Divide.

The climate of West Virginia is primarily continental, with mild summers and cold winters. Major weather systems generally approach from the west and southwest, although polar continental air masses of cold, dry air that approach from the north and northwest are not unusual. Air masses from the Atlantic Ocean sometimes affect the area east of the Climatic Divide and less frequently affect the area west of the Climatic Divide. Generally, tropical continental masses of hot, dry air from the southwest affect the climate west of the Climatic Divide. Tropical maritime masses of warm, moist air from the Gulf of Mexico affect the climate east of the Climatic Divide more than west of the Climatic Divide. Evaporation from local and upwind land surfaces, lakes, and reservoirs also provides a source of moisture that affects the climate of the State (U.S. Geological Survey, 1991; National Oceanic and Atmospheric Administration, 2006a).

Annual precipitation averages about 42 to 45 in. statewide with about 60 percent received from March through August. July is the wettest month, and September through November are the driest months. Annual average precipitation in the State generally decreases northwestward from about 50 to 60 in. along the Climatic Divide to about 40 in. along the Ohio River and increases from about 30 to 35 in. east of the Climatic Divide to about 40 in. in the extreme eastern tip of the State. Greater precipitation along and west of the Climatic Divide is a consequence of the higher elevations along the Divide and the general movement of weather systems approaching from the west and southwest. Annual average snowfall follows the general pattern of annual average precipitation, decreasing northwestward from about 36 to 100 in. along the Climatic Divide to about 20 to 30 in. along the Ohio River. East of the Climatic Divide, annual average snowfall ranges from 24 to 36 in. (U.S. Geological Survey, 1991; Natural Resources Conservation Service, 2006; National Oceanic and Atmospheric Administration, 2006a, 2006b).

Previous Studies

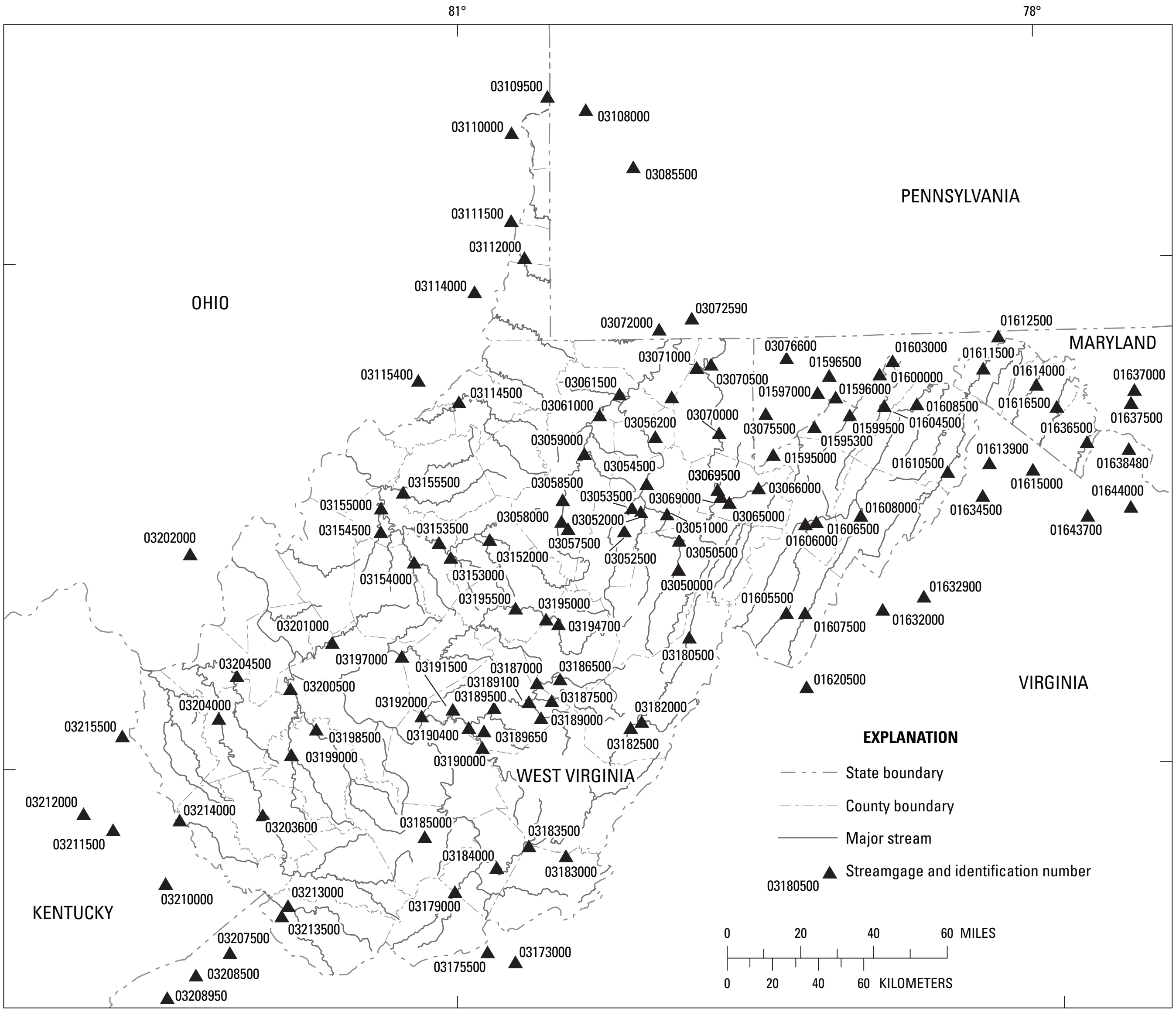
Selected statistics for U.S. Geological Survey (USGS) streamgage stations representative of conditions during 1930–2002 were determined by Wiley (2006). In that study, a criterion-based sample of the record period was used to determine statistics representative of the period rather than the entire record period and (or) record-extension techniques. The selected statistics included annual and seasonal hydrologically and biologically based low-flow frequency values, harmonic means, and flow-duration values (including variability index). The seasonal statistics published by Wiley (2006) were used in this current study to develop procedures for estimating seasonal statistics at ungaged locations in West Virginia.

Wiley (2008) developed estimating procedures for the annual 1-, 3-, 7-, 14-, and 30-day 2-year; 1-, 3-, 7-, 14-, and 30-day 5-year; and 1-, 3-, 7-, 14-, and 30-day 10-year hydrologically based low-flow frequency values for unregulated streams in West Virginia. Equations and procedures for the annual 1-day, 3-year and 4-day, 3-year biologically based low-flow frequency values; the annual USEPA harmonic-mean flows; and the annual 10-, 25-, 50-, 75-, and 90-percent flow-duration values also were developed. Regional equations were developed using ordinary least squares regression with flow statistics from streamgage stations as dependent variables and basin characteristics for these streamgage stations as independent variables.

Selected Seasonal Streamflow Statistics

Estimating procedures were developed for the following seasonal statistics: *1Q10*, *7Q10*, *30Q5*, *HM*, and *D50*. These seasonal statistics are available in Wiley (2006) for 77 streamgage stations in West Virginia and 40 streamgage stations in adjacent states (fig. 2).

Hydrologically based low-flow frequency values (*1Q10*, *7Q10*, and *30Q5*) were determined for each season using methods described by Riggs (1972). A series of the seasonal minimum n-day (number of consecutive days) daily mean low streamflows are fitted to a log-Pearson Type III probability curve. A plot of the probability curve and data is reviewed for fitness. Other probability distributions are considered or a smooth curve is constructed through the data if the data do not fit the log-Pearson Type III probability curve. The frequency of the n-day streamflow is computed from the fitted



Base from U.S. Geological Survey 1:100,00 Digital Line Graphics for state boundaries; 1:100,000 digital data for streams; and West Virginia Department of Enviromental Protection 1:24,000 digital data for county boundaries.
All data are in the Universal Tranverse Mercator projection, zone 17, NAD 83.

Figure 2. Location of the 117 U.S. Geological Survey streamgage stations in West Virginia and adjacent states considered in the estimation of selected seasonal statistics. (From Wiley, 2008, fig. 2)

probability curve or read from the smooth curve constructed through the data. In Wiley (2006), all data fit the log-Pearson Type III probability curve. For example, the value of *7Q10* would be the minimum average streamflow for 7 consecutive days expected on the average of once every 10 years.

The seasonal USEPA harmonic-mean flows (*HM*) were determined using methods described by Rossman (1990). The average of the reciprocals of the daily mean flows for each season is computed for a streamgage station record. The harmonic-mean flow is the reciprocal of that average. The USEPA harmonic-mean flow is the weighted average of the harmonic mean of the non-zero flows and the arithmetic mean of the zero flows (that is, zero). The harmonic mean of the non-zero flows is weighted by the number of non-zero values, and the arithmetic mean of the zero flows is weighted by the number of zero values.

The seasonal *D50* values were determined using methods described by Searcy (1959). A season of daily mean flows is divided into 20 to 30 classes of average streamflows. Every complete season of record for a streamgage station is divided into the same classes. The number of days in each class is computed for the entire record period and the percentage of the time a streamflow is in each class is determined. A particular flow-duration value is extrapolated from the class percentiles, and a log-probability plot of the class-percentile flow values is a flow-duration curve. For example, the flow for *D50* is equaled or exceeded 50 percent of the time.

Development of Equations for Estimating Selected Seasonal Streamflow Statistics

Ordinary least squares (OLS) regressions of the selected seasonal streamflow statistics (Wiley, 2006) with basin characteristics (Paybins, 2008) as independent variables were used to develop regional equations for estimating statistics at ungaged locations. Regression procedures were performed using the computer program S-PLUS 7.0 (Insightful Corporation, 2002), a commercially available statistical computing package. Dependent and independent variables were $\log_{10}$-transformed, and both transformed and untransformed independent variables were used in the regression procedures. A correlation matrix of independent variables was assessed to eliminate highly correlated independent variables from the equations, and data plots were assessed to ensure linearity between dependent and independent variables.

Generalized least squares (GLS) regression (Stedinger and Tasker, 1985; Tasker and Stedinger, 1989) was not used for this study. GLS regression requires time-series data and is more accurate than OLS regression for hydrologic purposes, primarily when record lengths vary between stations (Tasker and Stedinger, 1989, p. 363). Record lengths for the individual stations are all representative of 1930 to 2002 (73 years), regardless of the actual individual record lengths or actual years of record used to determine the statistics for this study (Wiley, 2006). GLS regression was not used because *HM* and *D50* are not determined from time-series data and because the representative record periods for all stations are identical.

Estimating procedures were not developed using a weighted least squares (WLS) regression because the results would likely be less accurate than those derived from the procedures developed using the criterion-based sample of data and OLS regression for the present study. The weights for each streamgage station could be based on a comparison between the average annual or seasonal minimum flows for the period of record at the streamgage station and the average annual or seasonal minimum flows for the region where the streamgage station is located, where the averages are normalized by either drainage area or standard deviations. The entire record period at a streamgage station could be used rather than the criterion-based sample of the record period. The time-sampling error would not relate to the length of the record but to the departure of low flows at a streamgage station from the 1930 to 2002 low flows in a region. The WLS regression could account for part of the time-sampling error, but the positive bias in flow data resulting from the operation of more streamgage stations during a wetter-than-average time period (Wiley, 2006, p. 22) would remain. WLS regression weights based simply on the record length are not appropriate because longer records do not necessarily provide more accurate low-flow estimates representative of 1930 to 2002; a 15-year record could include a wetter-than-average period and should be given less weight than a 10-year record that did not include a wetter-than-average period.

Basin Characteristics

Basin characteristics for 117 streamgage stations in West Virginia and adjacent states (Paybins, 2008) were available for use as independent variables for regression. The basin characteristics included the following: drainage area (*DA*), in square miles; latitude of the basin centroid (LAT_C), in decimal degrees; longitude of the basin centroid ($LONG_C$), in decimal degrees; basin perimeter (*BP*), in miles; basin slope (*BS*), in feet per mile; basin relief (*BR*), in feet; basin orientation (*BOr*), in degrees; channel length (*CL*), in miles; valley length (*VL*), in miles; channel slope (*CS*), in feet per mile; stream length (*SL*), in miles; mean basin elevation (*E*), in feet; 24-hour 2-year rainfall (I24-2), in inches; annual precipitation (*P*), in inches; January minimum temperature (*JANMIN*), in degrees Fahrenheit; annual snow depth (*S*), in inches; forest cover (*F*), in percent; grassland cover (*G*), in percent; barren land cover (*B*), in percent; urban land cover (U), in percent; wetland cover (*W*), in percent; open-water cover (*Wa*), in percent; agriculture cover (*A*), in percent; impervious cover (*I*), in percent; basin width (*BW*), in miles; shape factor (*SF*), dimensionless; elongation ratio (*ER*), dimensionless;

rotundity of basin (*RB*), dimensionless; compactness ratio (*CR*), dimensionless; relative relief (*RR*), in feet per mile; sinuosity ratio (*SIR*), dimensionless; stream density (*SD*), in miles per square mile; channel maintenance (*CM*), in square miles per mile; slope proportion (*SP*), dimensionless; ruggedness number (*RN*), in feet per mile; and slope ratio (*SLR*), dimensionless.

The base-flow recession time constant was not considered for use as an independent variable for regression. The base-flow recession time constant is the characteristic time constant of exponential decay of streamflow long after a storm and can be a significant dependent variable for regression of low-flow characteristics (Eng and Milly, 2007). The constant is estimated from at least one pair of base-flow measurements for a single recession. The constant was not computed because the USGS West Virginia Water Science Center does not operate a network of partial-record sites where paired base-flow measurements could be made, and available data from networks of partial-record sites measured by State agencies and private consultants do not include the necessary pair of base-flow measurements.

Data Correlation

The basin characteristics were $\log_{10}$-transformed, and both transformed and untransformed variables were evaluated for linear correlation among themselves by using a Pearson coefficient, or Pearson's *r* (Helsel and Hirsch, 2002). The integer 1 was added to values of *G*, *B*, *U*, *W*, *WA*, *A*, and *I* to ensure that values were greater than zero for $\log_{10}$ transformation. To decrease values for regression analysis, 77 was subtracted from $LONG_C$, and 37 was subtracted from LAT_C.

Variables were considered highly correlated where the absolute value of the Pearson coefficient was greater than or equal to 0.80. Untransformed and transformed variables except *DA*, *CS*, *CR*, *SP*, and *SLR* were highly correlated. Untransformed *DA*, *CS*, *CR*, *SP*, and *SLR* were not highly correlated with any transformed variables. Transformed *DA*, *CL*, *SL*, *CR*, *SP*, and variability index were highly correlated; transformed *VL* and *DA* were highly correlated with this group of variables but were not highly correlated themselves. Transformed *CS*, *SP*, and *SLR*; *BR* and *RN*; *CS* and *RR*; *F* and *I*; *U* and *I*; and *BW* and *SIR* were highly correlated.

In addition to being highly correlated, the absolute value of the Pearson coefficient was equal to 1 (singularity) for $\log_{10}$-transformed *SF*, *ER*, and *RB*; for transformed *SD* and *CM*; for transformed *DA*, *BW*, *SF*, and *RB*; and for transformed *SL*, *CR*, *RR*, *SD*, and *RN*. The variables *ER*, *RB*, *CM*, and *BW* were removed from consideration for regression because of singularity, and additional variables having singularity were removed if they became significant in the regression analysis.

On the basis of the correlation analysis, all $\log_{10}$-transformed variables except *ER*, *RB*, *CM*, and *BW*, and only untransformed *DA*, *CS*, *CR*, *SP*, and *SLR*, were considered for regression. Some $\log_{10}$-transformed variables that were not highly correlated on a statewide basis were highly correlated on a regional basis. *S* and *P,* and *S* and $LONG_C$ were highly correlated in the South-Central Region. *S* and $LONG_C$, and *U* and *I* were highly correlated in the North Region. All but one highly correlated value was eliminated from consideration when more than one highly correlated value became a significant independent variable in a regional regression equation.

Regional Regression Analysis

Wiley (2008) used multiple and simple regression techniques to determine regional boundaries for annual statistics. The selected annual statistics for 117 streamgage stations in West Virginia and adjacent states were $\log_{10}$-transformed and regressed with the basin characteristics as independent variables. Log_{10}-transformed *DA* was a significant independent variable for all regressions. Plots of residuals by latitude and longitude of basin centers from the simple regressions of selected statistics and $\log_{10}$-transformed *DA* indicated a regional boundary between the western part of the State and the Eastern Panhandle. A plot of residuals from regression of statistics and *DA* for the western part of the State indicated the presence of a regional boundary similar to that determined in the study by Friel and others (1989). This boundary in the western part of the State was described previously as approximately the outcrop of the base of the Upper Pennsylvanian (Conemaugh Group) rocks (Friel and others, 1989, p. 11), and delineated by Wiley (2008) following basin divides. Plots of residuals by latitude and longitude of basin centers from the simple regressions of selected annual statistics and *DA* did not indicate any additional regions. The following 14 stations in adjacent states were removed from the analysis because the absolute values of their residuals were greater than those of the residuals for stations within the State, indicating these stations were not representative of hydrologic conditions in West Virginia: 01612500, 01632000, 01643700, 01644000, 03085500, 03108000, 03109500, 03110000, 03111500, 03202000, 03210000, 03211500, 03212000, and 03215500 (fig. 2).

In this study, the regions and stations representative of hydrologic conditions in West Virginia determined by Wiley (2008) were used to develop equations for estimating seasonal values of *1Q10*, *7Q10*, *30Q5*, *HM*, and *D50*. The hydrologic assumption that the regional boundaries for determining seasonal statistics were equivalent to the regional boundaries for determining annual statistics was tested by plotting residuals by latitude and longitude of basin centroids from the simple regressions of selected seasonal statistics and $\log_{10}$-transformed *DA* for each region. These plots provided some confidence that the regional boundaries for determining seasonal and annual statistics were equivalent because the residuals were well distributed across the regions.

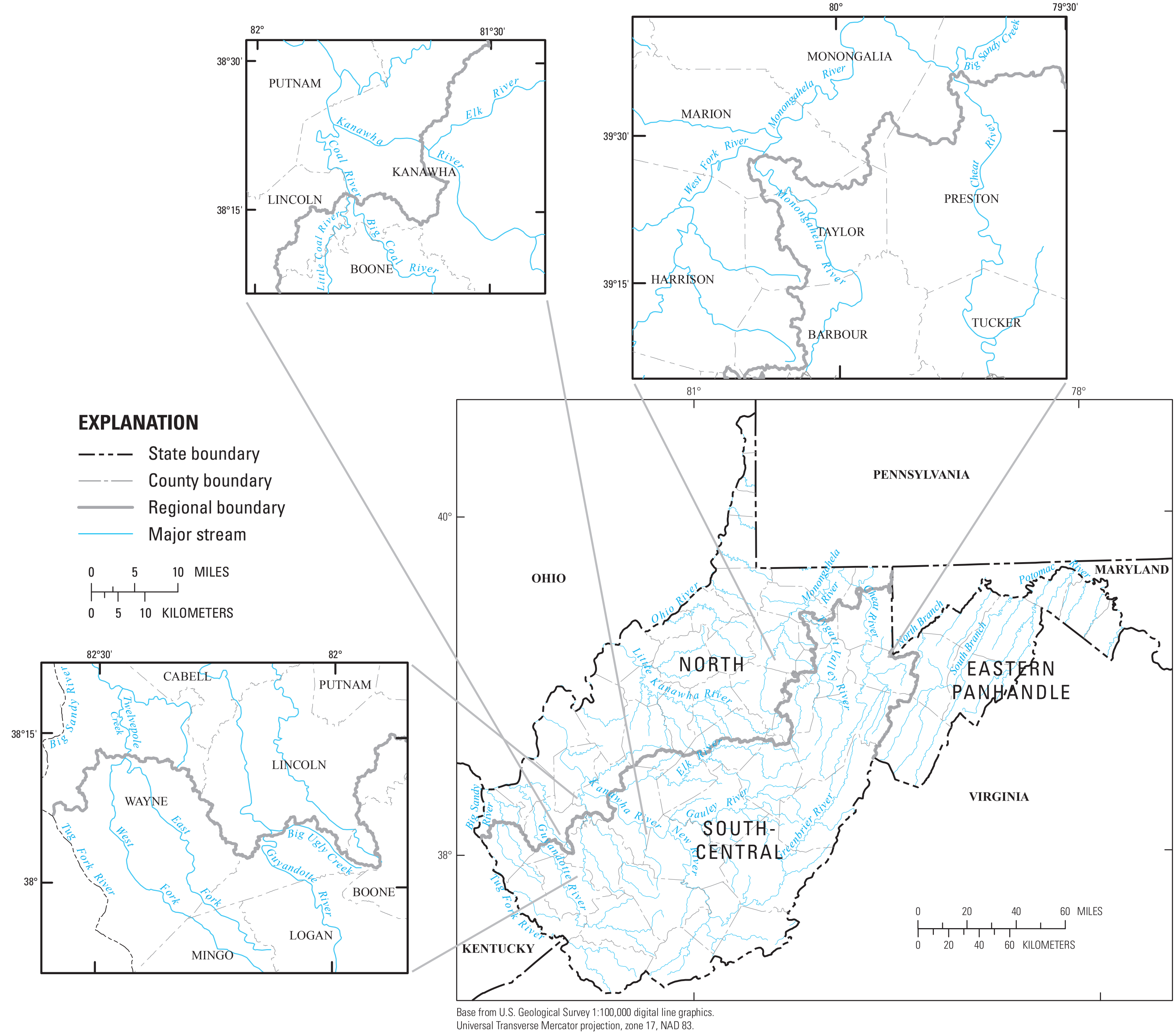


Figure 3. Location of the North, South-Central, and Eastern Panhandle Regions of West Virginia for which equations for estimation of selected seasonal streamflow statistics were developed in this study. (Insets provided to clarify location of the regional boundary.)

The three regions—North, South-Central, and Eastern Panhandle (fig. 3)—are separated by topographic features. The boundary between the Eastern Panhandle and South-Central Regions follows the Potomac River Basin boundary. The South-Central Region (from northeast to southwest) is the area upstream from the confluence of Big Sandy Creek (excluding Big Sandy Creek) on the Cheat River, upstream from the confluence of West Fork River (excluding West Fork River) on the Monongahela River, upstream from the confluence of the Elk and Kanawha Rivers, upstream from the confluence of the Big and Little Coal Rivers, upstream from the confluence of Big Ugly Creek and Guyandotte River, upstream from the confluence of East and West Forks of Twelvepole Creek, and upstream from the confluence of Tug Fork on the Big Sandy River. The main stems (excluding tributaries) of the Cheat, Monongahela, Kanawha, Coal, Guyandotte, and Big Sandy Rivers and Twelvepole Creek downstream from the regional boundary (visually in the North Region in fig. 3) are included in the South-Central Region. The North Region consists of the remainder of the State.

The regional equations were evaluated subjectively. Generally, equations were developed by limiting the inclusion of independent variables when additional independent variables did not increase the coefficient of determination (r^2) by at least 0.05 or decrease the standard error of the estimate by at least 5 percent. Wiley (2008) found it necessary to require that the inclusion of additional independent variables did not result in unreasonable solutions, such as higher recurrence interval flows greater than lower recurrence interval flows. Although the range of flows investigated in this study is not as large as that investigated by Wiley (2008), consideration was given to the likelihood that unreasonable solutions would be found with the inclusion of additional independent variables if more flows were investigated.

Three independent variables, *DA*, $LONG_C$, and *P*, were significant in equations for determining the selected seasonal statistics for the three regions in West Virginia (table 1). *DA* ranged from 16.3 to 1, 516 mi^2 in the North Region, 2.78 to 1,619 mi^2 in the South-Central Region, and 8.83 to 3,041 mi^2 in the Eastern Panhandle Region. $LONG_C$ ranged from 79.618 to 82.023 decimal degrees in the North Region. *P* ranged from 42.3 to 61.4 inches in the South-Central Region and 39.8 to 52.9 inches the Eastern Panhandle Region. *DA*, $LONG_C$, and *P* also were the significant independent variables for the selected annual statistics determined by Wiley (2008).

The average standard error of estimates for the regional equations ranged from 12.6 to 299 percent (table 1). The average standard error of estimates for some equations could be reduced by considering additional independent variables that increase the r^2 by at least 0.05 or decrease the standard error of the estimate by at least 5 percent. Reduction of the average standard errors of equations by including additional independent variables was not done because the resulting equations would likely lead to higher recurrence interval flows greater than lower recurrence interval flows, particularly if the range of flows investigated in this study was as large as that investigated by Wiley (2008).

The number of observations used to develop equations within a region is not equal (table 1) because streamgages with streamflow statistics equal to zero were eliminated from consideration. The $\log_{10}$ transformation of zero is negative infinity.

Table 1. Equations for estimating selected seasonal streamflow statistics for the North, South-Central, and Eastern Panhandle Regions of West Virginia.

[*xQy*, *x*-day, *y*-year hydrologically based flow, in cubic feet per second; *HM*, U.S. Environmental Protection Agency harmonic-mean flow, in cubic feet per second; *Dn*, *n*-percent-duration flow, in cubic feet per second; *DA*, drainage area, in square miles; $LONG_C$, longitude of basin centroid, in decimal degrees from North American Datum of 1983; *P*, average annual precipitation, in inches]

Equation	Coefficient of determination (r^2), unitless	Average standard error of estimate, in percent	Number of observations used to develop equation
North Region (range in *DA* from 16.3 to 1,516; range in $LONG_C$ from 79.618 to 82.023)			
Winter (January 1–March 31)			
$1Q10 = 2.34\ DA^{1.14} / (LONG_C - 77)^{3.03}$	0.93	33.4	22
$7Q10 = 2.65\ DA^{1.12} / (LONG_C - 77)^{2.84}$	.94	29.3	22
$30Q5 = 1.95\ DA^{1.08} / (LONG_C - 77)^{1.31}$	.92	33.6	22
$HM = 10.1\ DA^{1.11} / (LONG_C - 77)^{2.71}$	.94	30.1	22
$D50 = 2.81\ DA^{1.08} / (LONG_C - 77)^{0.854}$	.99	12.7	22
Spring (April 1–June 30)			
$1Q10 = 3.03 \text{ X } 10^{-1}\ DA^{1.32} / (LONG_C - 77)^{3.68}$	.80	78.8	22
$7Q10 = 4.88 \text{ X } 10^{-1}\ DA^{1.21} / (LONG_C - 77)^{3.25}$	.82	65.3	22
$30Q5 = 1.14\ DA^{1.19} / (LONG_C - 77)^{2.54}$	.94	33.1	22
$HM = 2.76\ DA^{1.10} / (LONG_C - 77)^{1.92}$	.88	44.5	22
$D50 = 4.04\ DA^{1.08} / (LONG_C - 77)^{1.83}$	.97	19.5	22
Summer (July 1–September 30)			
$1Q10 = 2.03 \text{ X } 10^{-1}\ DA^{2.05} / (LONG_C - 77)^{8.55}$	.62	299	16
$7Q10 = 3.10\ DA^{1.48} / (LONG_C - 77)^{7.60}$	.64	179	17
$30Q5 = 3.88 \text{ X } 10^{-1}\ DA^{1.51} / (LONG_C - 77)^{4.69}$	.89	61.3	22
$HM = 2.63\ DA^{1.23} / (LONG_C - 77)^{4.56}$	.78	79.7	22
$D50 = 5.54 \text{ X } 10^{-1}\ DA^{1.27} / (LONG_C - 77)^{2.49}$	.96	28.4	22
Fall (October 1–December 31)			
$1Q10 = 8.94 \text{ X } 10^{-1}\ DA^{1.42} / (LONG_C - 77)^{6.15}$	.80	91.3	20
$7Q10 = 3.05\ DA^{1.19} / (LONG_C - 77)^{5.73}$	.87	55.5	20
$30Q5 = 7.01 \text{ X } 10^{-1}\ DA^{1.36} / (LONG_C - 77)^{3.94}$	.91	46.8	22
$HM = 6.96\ DA^{1.16} / (LONG_C - 77)^{5.08}$	.85	60.2	22
$D50 = 3.38\ DA^{1.14} / (LONG_C - 77)^{2.46}$	.96	25.4	22
South-Central Region (range in *DA* from 2.78 to 1,619; range in *P* from 42.3 to 61.4)			
Winter (January 1–March 31)			
$1Q10 = 1.04 \text{ X } 10^{-9}\ DA^{1.15}\ P^{4.63}$	0.94	41.7	52
$7Q10 = 8.48 \text{ X } 10^{-9}\ DA^{1.14}\ P^{4.15}$	.94	39.6	52
$30Q5 = 2.69 \text{ X } 10^{-6}\ DA^{1.01}\ P^{3.18}$	.98	20.5	52
$HM = 5.44 \text{ X } 10^{-8}\ DA^{1.11}\ P^{4.08}$	.96	30.3	52
$D50 = 9.04 \text{ X } 10^{-5}\ DA^{1.02}\ P^{2.50}$	.99	12.6	52
Spring (April 1–June 30)			
$1Q10 = 1.74 \text{ X } 10^{-2}\ DA^{1.29}$	.91	55.7	52
$7Q10 = 3.20 \text{ X } 10^{-2}\ DA^{1.23}$	.92	49.5	52
$30Q5 = 1.88 \text{ X } 10\text{-}1\ DA^{1.12}$	.93	41.7	52
$HM = 5.04 \text{ X } 10^{-1}\ DA^{1.12}$	.94	36.4	52
$D50 = 1.70 \text{ X } 10^{-5}\ DA^{1.05}\ P^{2.74}$	.98	17.5	52

Table 1. Equations for estimating selected seasonal streamflow statistics for the North, South-Central, and Eastern Panhandle Regions of West Virginia.—Continued

[*xQy*, *x*-day, *y*-year hydrologically based flow, in cubic feet per second; *HM*, U.S. Environmental Protection Agency harmonic-mean flow, in cubic feet per second; *Dn*, *n*-percent-duration flow, in cubic feet per second; *DA*, drainage area, in square miles; $LONG_C$, longitude of basin centroid, in decimal degrees from North American Datum of 1983; *P*, average annual precipitation, in inches]

Equation	Coefficient of determination (r^2), unitless	Average standard error of estimate, in percent	Number of observations used to develop equation
Summer (July 1–September 30)			
$1Q10 = 4.30 \text{ X } 10^{-3} DA^{1.26}$	.69	106	50
$7Q10 = 3.56 \text{ X } 10\text{-}3 \; DA^{1.33}$	.75	104	51
$30Q5 = 3.44 \text{ X } 10^{-2} DA^{1.14}$	.89	53.8	52
$HM = 4.31 \text{ X } 10^{-2} DA^{1.23}$	.90	57.4	52
$D50 = 6.19 \text{ X } 10^{-7} DA^{1.10} P^{3.14}$	.96	29.9	52
Fall (October 1–December 31)			
$1Q10 = 8.57 \text{ X } 10^{-3} DA^{1.18}$	.74	109	52
$7Q10 = 1.54 \text{ X } 10^{-2} DA^{1.12}$	.75	99.3	52
$30Q5 = 9.52 \text{ X } 10^{-2} DA^{1.02}$	.78	78.2	52
$HM = 6.63 \text{ X } 10^{-2} DA^{1.12}$	.80	80.4	52
$D50 = 2.30 \text{ X } 10^{-9} DA^{0.951} P^{4.95}$	.94	35.4	52
Eastern Panhandle Region (range in *DA* from 8.83 to 3,041; range in *P* from 39.8 to 52.9)			
Winter (January 1–March 31)			
$1Q10 = 5.80 \text{ X } 10^{-11} DA^{1.11} P^{5.57}$	0.98	22.9	29
$7Q10 = 1.27 \text{ X } 10^{-10} DA^{1.09} P^{5.44}$	.98	23.8	29
$30Q5 = 5.30 \text{ X } 10^{-10} DA^{1.04} P^{5.36}$	.99	15.1	29
$HM = 5.32 \text{ X } 10^{-10} DA^{1.06} P^{5.44}$	.99	16.9	29
$D50 = 3.23 \text{ X } 10^{-9} DA^{1.01} P^{5.20}$	.99	16.2	29
Spring (April 1–June 30)			
$1Q10 = 5.69 \text{ X } 10^{-8} DA^{1.17} P^{3.62}$	.95	39.3	29
$7Q10 = 2.85 \text{ X } 10^{-8} DA^{1.16} P^{3.87}$	.96	34.4	29
$30Q5 = 1.53 \text{ X } 10^{-9} DA^{1.12} P^{4.91}$	.98	21.2	29
$HM = 1.52 \text{ X } 10^{-9} DA^{1.04} P^{5.25}$	.99	15.1	29
$D50 = 5.61 \text{ X } 10^{-10} DA^{1.03} P^{5.54}$	.99	15.4	29
Summer (July 1–September 30)			
$1Q10 = 8.83 \text{ X } 10^{-3} DA^{1.28}$	.85	90.4	29
$7Q10 = 1.23 \text{ X } 10^{-2} DA^{1.24}$	.86	84.1	29
$30Q5 = 3.88 \text{ X } 10^{-2} DA^{1.14}$	.91	56.6	29
$HM = 8.82 \text{ X } 10^{-2} DA^{1.12}$	.93	47.5	29
$D50 = 3.90 \text{ X } 10^{-9} DA^{1.13} P^{4.50}$	.97	31.0	29
Fall (October 1–December 31)			
$1Q10 = 1.85 \text{ X } 10^{-6} DA^{1.23} P^{2.39}$	.89	66.0	29
$7Q10 = 9.44 \text{ X } 10^{-7} DA^{1.20} P^{2.65}$	.90	63.0	29
$30Q5 = 1.66 \text{ X } 10^{-8} DA^{1.11} P^{4.00}$	.94	40.4	29
$HM = 5.42 \text{ X } 10^{-8} DA^{1.15} P^{3.75}$	.94	41.1	29
$D50 = 3.48 \text{ X } 10^{-11} DA^{1.04} P^{6.03}$	.98	21.4	29

Procedures for Estimating Selected Seasonal Streamflow Statistics

Estimating procedures were developed for streamflow statistics at a streamgage, at a partial-record station, and at an ungaged location. For streamgage stations with records of less than 10 years or not representative of the period 1930 to 2002, a partial record can be developed from base-flow measurements made at the streamgage stations (or published daily mean streamflows during base-flow conditions as surrogates for measurements).

At a Streamgage

Streamflow statistics for streamgage stations were published in Wiley (2006, table 11). Not all the published statistics were selected for developing estimating procedures in this current study. All streamgage stations with a minimum of 10 years of record included in Wiley (2006, table 11) are representative of 1930 to 2002.

At a Partial-Record Station

Eight or more base-flow measurements at a partial-record station made across a wide range of base flows in more than 1 year are compared to concurrent streamflows at a nearby streamgage station to develop a relation to transfer the selected flow statistics from the streamgage station to the partial-record station (Riggs, 1972). The streamgage station used for comparison should be within the same basin and have similar geology to meet the assumptions that the base flows are sufficiently correlated and the relation is linear. The mean daily streamflow can be used as the concurrent streamflow at the streamgage station under base-flow conditions by considering the change in streamflow over the day as an additional error. A log-log plot of flow data should be viewed to ensure the relation is linear. The “maintenance of variance extension, type 1” (MOVE.1), also referred to as “line of organic correlation,” is developed between the measurements at the partial-record station and the concurrent streamflows at the streamgage station using methods described by Hirsch (1982), Hirsch and Gilroy (1984), and Helsel and Hirsch (2002). MOVE.1 was developed for extending streamflow records but is used in the current study for transferring flow statistics according to the procedures described by Riggs (1972). The means and standard deviations of the concurrent $\log_{10}$-transformed streamflows at the partial-record station and the streamgage station are determined. The value of the streamflow statistic at the partial-record station is computed by evaluating MOVE.1 at the flow value for the statistic at the streamgage station, by using the following equation:

$$Q_P = 10^{\left[M_P + (S_P / S_G)(Q_G - M_G)\right]}, \quad (1)$$

where

Q_P is the value of the streamflow statistic at the partial-record station, in ft^3/s;

M_P is the mean of the concurrent $\log_{10}$-transformed streamflows at the partial-record station, in ft^3/s;

S_P is the standard deviation of the concurrent $\log_{10}$-transformed streamflows at the partial-record station, in ft^3/s;

S_G is the standard deviation of the concurrent $\log_{10}$-transformed streamflows at the streamgage station, in ft^3/s;

Q_G is the $\log_{10}$-transformed streamflow of the statistic at the streamgage station, in ft^3/s; and

M_G is the mean of the concurrent $\log_{10}$-transformed streamflows at the streamgage station, in ft^3/s.

A graphical procedure is used to estimate statistics if the relation between base-flow measurements at a partial-record station and concurrent streamflows at a nearby streamgage station is not linear (Riggs, 1972). The untransformed streamflows are plotted on log-log graph paper with streamflows for the streamgage station plotted on the x-axis, streamflows for the partial-record station plotted on the y-axis, and a smooth line constructed through the streamflow points. The streamflow for the statistic of interest for the streamgage station is projected parallel to the y-axis from the value on the x-axis to the smooth line, and then projected parallel to the x-axis from the smooth line to the corresponding partial-record streamflow on the y-axis. The extrapolated streamflow on the y-axis is the estimated value for the statistic of interest at the partial-record station.

Statistics at partial-record stations are limited to estimates at and below the streamflow of 50-percent duration (median) because concurrent streamflows for the streamgage station and partial-record station are generally at the same base-flow condition (same flow duration). Concurrent streamflows for the streamgage station and partial-record station above the streamflow of 50-percent duration typically change rapidly and are not under base-flow conditions at one or both locations.

The USGS West Virginia Water Science Center does not operate a network of partial-record stations. However, measurements at partial-record networks have been made by State agencies and private consultants in West Virginia in the recent past. A private consultant made monthly streamflow measurements for the West Virginia Department of Environmental Protection (WVDEP), Division of Mining and Reclamation (DMR), at a network of about 240 locations in the coal-mining region of the State. WVDEP, Division of Water and Waste Management (DWWM), measures streamflow at a network of partial-record stations as part of a 5-year cycle of hydrologic assessment of basins in the State. Streamflow statistics for partial-record stations in these two networks are estimated by WVDEP, DWWM, using base-flow measurements and extrapolating statistics from nearby streamgage stations.

At an Ungaged Location

Four different procedures are used to determine streamflow statistics at an ungaged location (1) when the ungaged location is upstream from a streamgage station or partial-record station, (2) when the ungaged location is downstream from a streamgage station or partial-record station, (3) when the ungaged location is between two streamgage stations and (or) partial-record stations on the same stream, and (4) when the ungaged location is not on the same stream as a streamgage station or partial-record station. Two locations were considered to be on the same stream when the stream path from the downstream location to the basin divide followed the stream segment with the largest drainage area at each stream confluence and passed through the upstream location.

It is necessary to determine whether the ungaged location is near a streamgage station or partial-record station, and arithmetic methods are used to quantify the definition of “near.” A drainage-area-ratio method for estimating statistics at ungaged locations has been used by several researchers, including Hayes (1991), Ries and Friesz (2000), Flynn (2003), and Wiley (2008). Ratio of the drainage areas ($R_{U/K}$) is defined as the ratio of the drainage area where the value of the statistic is unknown (A_U) to the drainage area where the value of the statistic is known (A_K). These researchers use arithmetic methods for determining the upstream and downstream limits of the range of drainage-area ratios over which streamflow statistics can be accurately estimated from those at a streamgage station using an equation similar to the following:

$$Q_U = Q_K \, (R_{U/K})^{EX} \,, \qquad (2)$$

where

Q_U is the value of the unknown streamflow statistic, in ft^3/s;

Q_K is the value of the known streamflow statistic, in ft^3/s;

$R_{U/K}$ is the ratio of the drainage area at the location of the unknown streamflow (A_U) to the drainage area at the location of the known streamflow (A_K), unitless; and

EX is the exponent for the particular statistic, unitless.

The seasonal *1Q10*, *7Q10*, *30Q5*, *HM*, and *D50* at 25 pairs of streamgage stations located on the same stream in West Virginia and adjacent states (table 2) were evaluated to quantify the definition of “near” for application of the drainage-area-ratio method in this study. Two computations, one upstream and one downstream, were made for each pair of stations. Seasonal ratios of the drainage areas for the 50 computations ranged from 0.21 to 4.76. Equation 2 was solved for the exponent *EX* as the dependent variable:

$$\log_{10} (Q_U \,/\, Q_K) = EX \,(\log_{10} (R_{U/K}))\ . \qquad (3)$$

The exponent was evaluated for the 25 pairs of streamgage stations for each seasonal statistic using simple linear regression with no intercept (regression line goes through the graph origin). The values of the exponent (*EX*) ranged from 0.93 to 1.56 (table 3).

The upstream and downstream limits for application of drainage-area ratios used to quantify the definition of “near” were determined by plotting the drainage-area ratio against the absolute percent difference between the value of the flow statistic at the streamgage station determined from the station record and the value of the statistic estimated by applying (1) the regional equations and (2) the drainage-area-ratio method. S-PLUS 7.0 (Insightful Corporation, 2002), a commercially available statistical computing package, was used to construct locally weighted regression (LOESS) curves (a data-smoothing technique) through differences between flow statistics computed from streamgage-station records and the estimated values (selected LOESS parameters were “span = 0.5; degree = one, locally-linear fitted; family = Symmetric, no feature for handling outlier distortions, strictly applying locally-linear fitting”). For example, the absolute percent differences for estimates of the selected winter statistics made by applying the drainage-area-ratio method are lower than the estimates made by applying the regional equation at drainage-area ratios less than about 2 (fig. 4). The absolute percent differences for estimates of the selected winter statistics made by applying the regional equation are lower than the estimates made by applying the drainage-area-ratio method at drainage-area ratios greater than about 2. The downstream limit for using the drainage-area ratios is 2 and the upstream limit is set to the minimum ratio studied, 0.21 (table 3). Similar analyses were made for all the selected seasonal statistics, and some downstream limits were set to the maximum ratio studied, 4.76 (table 3).

Upstream From a Streamgage Station or Partial-Record Station

This procedure is used when there is a streamgage station or partial-record station downstream from the ungaged location but none upstream on the same stream.

Table 2. Description of the 25 pairs of U.S. Geological Survey streamgage stations in West Virginia and adjacent states that were evaluated to quantify the definition of "near" for application of the drainage-area-ratio method in this study.

[MD, Maryland; WV, West Virginia; VA, Virginia; KY, Kentucky]

Pair number	Upstream station			Downstream station		
	Station number	Station name	State	Station number	Station name	State
1	01600000	North Branch Potomac River at Pinto	MD	01603000	North Branch Potomac River near Cumberland	MD
2	01607500	South Fork South Branch Potomac River at Brandywine	WV	01608000	South Fork South Branch Potomac River near Moorefield	WV
3	01606500	South Branch Potomac River near Petersburg	WV	01608500	South Branch Potomac River near Springfield	WV
4	01615000	Opequon Creek near Berryville	VA	01616500	Opequon Creek near Martinsburg	WV
5	01643700	Goose Creek near Middleburg	VA	01644000	Goose Creek near Leesburg	VA
6	03050000	Tygart Valley River near Dailey	WV	03050500	Tygart Valley River near Elkins	WV
7	03050500	Tygart Valley River near Elkins	WV	03051000	Tygart Valley River at Belington	WV
8	03058500	West Fork River at Butcherville	WV	03059000	West Fork River at Clarksburg	WV
9	03059000	West Fork River at Clarksburg	WV	03061000	West Fork River at Enterprise	WV
10	03069500	Cheat River near Parsons	WV	03070000	Cheat River at Rowlesburg	WV
11	03070000	Cheat River at Rowlesburg	WV	03071000	Cheat River near Pisgah	WV
12	03152000	Little Kanawha River at Glenville	WV	03153500	Little Kanawha River at Grantsville	WV
13	03153500	Little Kanawha River at Grantsville	WV	03155000	Little Kanawha River at Palestine	WV
14	03180500	Greenbrier River at Durbin	WV	03182500	Greenbrier River at Buckeye	WV
15	03182500	Greenbrier River at Buckeye	WV	03183500	Greenbrier River at Alderson	WV
16	03183500	Greenbrier River at Alderson	WV	03184000	Greenbrier River at Hilldale	WV
17	03187000	Gauley River at Camden on Gauley	WV	03189100	Gauley River near Craigsville	WV
18	03189100	Gauley River near Craigsville	WV	03189500	Gauley River near Summersville	WV
19	03190000	Meadow River at Nallen	WV	03190400	Meadow River near Mount Lookout	WV
20	03189500	Gauley River near Summersville	WV	03192000	Gauley River above Belva	WV
21	03194700	Elk River below Webster Springs	WV	03195000	Elk River at Centralia	WV
22	03195500	Elk River at Sutton	WV	03197000	Elk River at Queen Shoals	WV
23	03203600	Guyandotte River at Logan	WV	03204000	Guyandotte River at Branchland	WV
24	03210000	Johns Crek near Meta	KY	03211500	Johns Creek near Van Lear	KY
25	03213000	Tug Fork at Litwar	WV	03214000	Tug Fork near Kermit	WV

Table 3. Values of the exponent and upstream and downstream limits of the drainage-area ratios used to quantify the definition of "near" for estimating selected seasonal streamflow statistics at ungaged locations in West Virginia.

[*EX*, exponent; R_{US}, upstream limit of the drainage-area ratios; R_{DS}, downstream limit of the drainage-area ratios: *x*Q*y*, *x*-day, *y*-year hydrologically based flow; *HM*, U.S. Environmental Protection Agency harmonic-mean flow; *Dn*, *n*-percent-duration flow; all values are unitless]

Streamflow statistic	*EX*	R_{US}	R_{DS}
Winter (January 1–March 31)			
1Q10	1.03	0.21	2
7Q10	1.02	.21	2
30Q5	.94	.21	2
HM	.99	.21	2
D50	.97	.21	2
Spring (April 1–June 30)			
1Q10	1.14	.21	2
7Q10	1.13	.21	2
30Q5	1.01	.21	2
HM	.98	.21	2
D50	.96	.21	2
Summer (July 1–September 30)			
1Q10	1.34	.4	2
7Q10	1.47	.4	2
30Q5	1.29	.4	2
HM	1.21	.4	4.76
D50	1.05	.21	2
Fall (October 1–December 31)			
1Q10	1.56	.4	2
7Q10	1.32	.4	2
30Q5	1.08	.4	2
HM	1.29	.4	4.76
D50	.93	.21	4.76

The hydrologic assumption for this circumstance is that the conditions affecting streamflow, such as lithology, structure of rock formations, and evapotranspiration, are unchanged upstream from the streamgage station or partial-record station. Mathematically, the value of a statistic is proportioned by drainage area. It is suggested to establish a partial-record station at the ungaged location when $R_{U/K}$ is less than or equal to the upstream limit of the ratio of drainage areas (R_{US}) (table 3). The following equation is used to estimate the value of a statistic:

$$Q_U = Q_K \, (R_{U/K})^{EX} , \quad (4)$$

where

Q_U is the value of the unknown streamflow statistic, in ft^3/s;

Q_K is the value of the known streamflow statistic, in ft^3/s;

$R_{U/K}$ is the ratio of the drainage area at the location of the unknown streamflow (A_U) to the drainage area at the location of the known streamflow (A_K), unitless; and

EX is the exponent for the particular statistic (table 3), unitless.

In this method, it is not assumed that the conditions affecting streamflow change toward the regional tendency in the upstream direction. The critical situation for the assumption of streamflow changing to the regional tendency in the upstream direction (this assumption) is where the unknown location approaches the headwaters of a stream. This assumption might be acceptable if the streamflow at the known location is greater than that estimated by applying the regional equation at the known location because the upstream estimate of streamflow would be lower and, therefore, more conservative from an availability or regulatory perspective than that determined using the method presented. However, this assumption would be unacceptable if the streamflow at the known location is less than that estimated by applying the regional equation because the upstream estimate of streamflow would be greater than that determined using the method presented, thus requiring an assumption of additional unit inflow. The method presented would require establishing a partial-record station at the unknown location in order to increase unit inflow when the known streamflow is less than that estimated using the regional equation.

Downstream From a Streamgage Station or Partial-Record Station

This procedure is used when there is a streamgage station or partial-record station upstream from the ungaged location but none downstream on the same stream. The hydrologic assumption for this circumstance is that the conditions

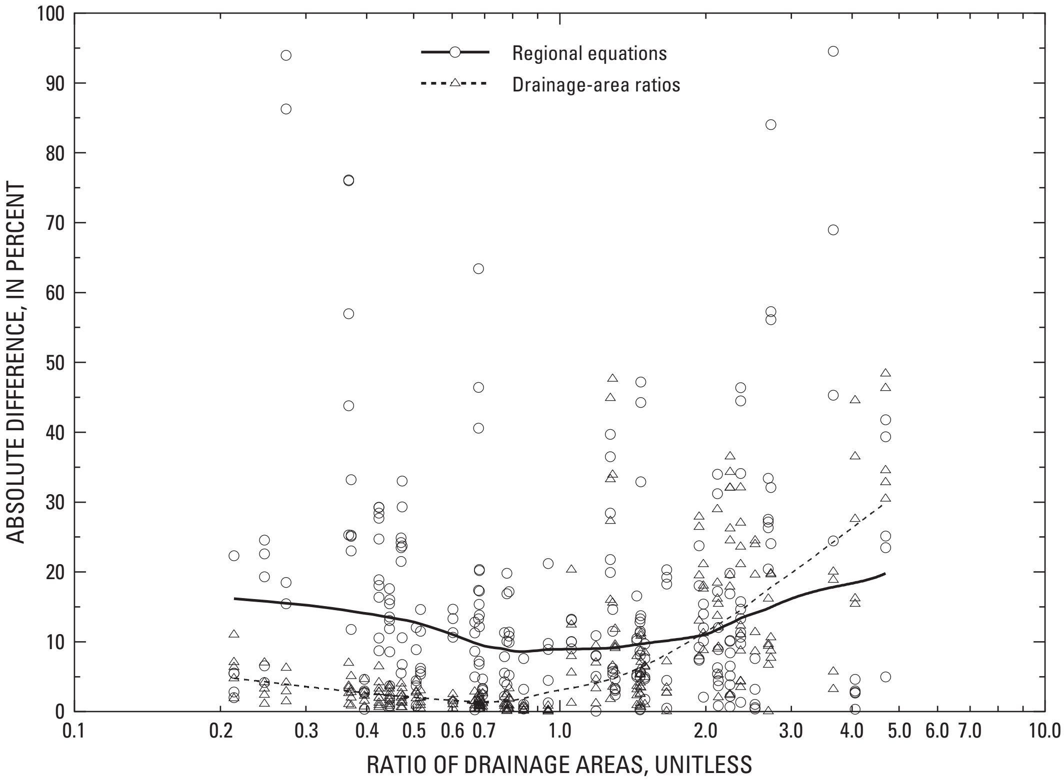


Figure 4. LOESS curves of the absolute differences between the selected winter statistics determined at streamgage stations and values determined from (1) regional equations and (2) drainage-area ratios, in relation to the ratio of drainage areas. (Some values greater than 100 percent are not shown.)

affecting streamflow at the streamgage station or partial-record station changed, in the downstream direction, toward that of the regional tendency. The conditions affecting streamflow in the vicinity of the streamgage station or partial-record station could be an aquifer, land use, or diversion that likely would not significantly affect streamflow if the drainage area were larger and, therefore, conditions were more similar to the regional tendency. Mathematically, the value of a statistic is changed to that estimated by applying the regional equation as $R_{U/K}$ approaches the downstream limit of the ratio of drainage areas (R_{DS}) (table 3). It is suggested to establish a partial-record station at the ungaged location when $R_{U/K}$ is greater than or equal to R_{DS}. The value of the statistic is estimated by applying the regional equation when $R_{U/K}$ is greater than or equal to R_{DS}, and the following equation is used to estimate the value of a statistic when $R_{U/K}$ is less than R_{DS}:

$$Q_U = Q_{UE} + (Q_K - Q_{KE})(R_{DS} - R_{U/K}) / (R_{DS} - 1), \qquad (5)$$

when

$R_{U/K} < R_{DS}$ and

where

Q_U is the value of the unknown streamflow statistic, in ft^3/s;

Q_{UE} is the regional equation evaluated at the location of the unknown value of the streamflow statistic, in ft^3/s;

Q_K is the value of the known streamflow statistic, in ft^3/s;

Q_{KE} is the regional equation evaluated at the location of the known value of the streamflow statistic, in ft^3/s;

R_{DS} is the downstream limit of the ratio of drainage areas (table 3), unitless; and

$R_{U/K}$ is the ratio of the drainage area at the location of the unknown streamflow (A_U) to the drainage area at the location of the known streamflow (A_K), unitless.

Between Streamgage Stations and (or) Partial-Record Stations

This procedure is used when there are streamgage stations or partial-record stations both upstream and downstream from the ungaged location on the same stream. The hydrologic assumption for this circumstance is that the conditions affecting streamflow are changing on the basis of the relation between the streamflows at the streamgage stations or partial-record stations, the ratios of the drainage areas, and differences between regional hydrologic conditions and those that affect streamflows at the station. It is suggested to establish a partial-record station at the ungaged location when $R_{U/K}$ is greater than R_{DS} and less than R_{US}, and when one of the values of the streamflow statistic at the upstream and downstream locations is greater than and one of the values is less than that estimated by applying the regional equation. Two alternative hydrologic assumptions are described in detail below.

Hydrologic Conditions Change Linearly Between Streamgage Stations and (or) Partial-Record Stations

This hydrologic assumption is that the conditions affecting streamflow at the upstream streamgage station or partial-record station change linearly with drainage area to those at the downstream location when (1) both streamgage stations or partial-record stations are near the ungaged location, or (2) both streamgage stations or partial-record stations are not near the ungaged location, but the hydrologic conditions affecting streamflow at the stations and ungaged location are consistent. The conditions affecting streamflow between the upstream and downstream locations are well defined by streamgage stations or partial-record stations when both are near the ungaged location; the conditions affecting streamflow are consistent from the upstream to the downstream location when neither is near the ungaged location and the conditions at both stations are more similar to each other than to the regional hydrologic conditions. Mathematically, the value of a statistic changes linearly with respect to drainage area from the upstream to the downstream value when (1) $R_{U/K}$ is less than R_{DS} at the upstream location and $R_{U/K}$ is greater than R_{US} at the downstream location, or (2) $R_{U/K}$ is greater than or equal to R_{DS} at the upstream location, $R_{U/K}$ is less than or equal to R_{US} at the downstream location, and the values of the statistic at the upstream and downstream locations are both greater than or both less than those estimated by applying the regional equation. The following equation is used to estimate the value of a statistic under the limitations described above:

$$Q_U = [Q_{US}(A_{DS} - A_U) + Q_{DS}(A_U - A_{US})] / (A_{DS} - A_{US}) , \quad (6)$$

when

$R_{U/K} < R_{DS}$ at the upstream location and
$R_{U/K} > R_{US}$ at the downstream location,

or when

$R_{U/K} \geq R_{DS}$ at the upstream location and
$R_{U/K} \leq R_{US}$ at the downstream location; and
Q_{KE} at the upstream location > Q_{US} and
Q_{KE} at the downstream location > Q_{DS} or
Q_{KE} at the upstream location < Q_{US} and
Q_{KE} at the downstream location < Q_{DS}; and

where

- Q_U is the value of the unknown streamflow statistic, in ft^3/s;
- Q_{US} is the value of the streamflow statistic at the upstream location, in ft^3/s;
- Q_{DS} is the value of the streamflow statistic at the downstream location, in ft^3/s;
- Q_{KE} is the regional equation evaluated at the location of the value of the known streamflow statistic, in ft^3/s;
- A_U is the drainage area at the location of the unknown value of the streamflow statistic, in mi^2;
- A_{US} is the drainage area at the upstream location, in mi^2;
- A_{DS} is the drainage area at the downstream location, in mi^2;
- R_{US} is the upstream limit of the ratio of drainage areas (table 3), unitless; and
- R_{DS} is the downstream limit of the ratio of drainage areas (table 3), unitless.

Hydrologic Conditions Change Linearly to the Regional Hydrologic Conditions Between Streamgage Stations and (or) Partial-Record Stations

This hydrologic assumption is that the conditions affecting streamflow at the streamgage station or partial-record station change linearly with drainage area to those represented by the regional equation when neither the streamgage station nor the partial-record station is near the ungaged location and the hydrologic conditions affecting streamflow are inconsistent. The conditions affecting streamflow are significantly different as a result of factors such as input from a productive aquifer, input from a tributary stream that is hydrologically different from the stream on which the station is located or from regional hydrologic conditions, water withdrawal for domestic or industrial use, an outcrop of impervious rock strata, transfer of water to deeper rock strata, or transfer of water to or from an underground mine (possibly into or out of the basin). Mathematically, the hydrologic conditions are inconsistent if one of the values of the statistic at the upstream and downstream locations is greater than, and one of the values is less than, those estimated by applying the regional equation—that is, the streamflow changes from a value greater than the value estimated by applying the regional equation at the upstream location to a value equal to the value estimated from the regional equation, and then to a value less than the value estimated from the regional equation at the downstream location, or the reverse. The regional equation (table 1) is applied to estimate the value of a statistic if $R_{U/K}$ is greater than or equal to R_{DS} at the upstream location and $R_{U/K}$ is less than or equal to R_{US} at the downstream location. Equation 5, presented in the section "Downstream from a Streamgage Station or Partial-Record Station," is used to estimate the value of a statistic if $R_{U/K}$ is less than R_{DS} at the upstream location and $R_{U/K}$ is less than or equal to R_{US} at the downstream location. The following equation is used to estimate the value of a statistic if $R_{U/K}$ is greater than or equal to R_{DS} at the upstream location and $R_{U/K}$ is greater than R_{US} at the downstream location:

$$Q_U = Q_{UE} + (Q_K - Q_{KE})(R_{US} - R_{U/K}) / (1 - R_{US}) , \qquad (7)$$

when

$R_{U/K} \geq R_{DS}$ at the upstream location and $R_{U/K} > R_{US}$ at the downstream location, and

where

Q_U is the value of the unknown streamflow statistic, in ft^3/s;

Q_{UE} is the regional equation evaluated at the location of the value of the unknown streamflow statistic, in ft^3/s;

Q_K is the value of the known streamflow statistic, in ft^3/s;

Q_{KE} is the regional equation evaluated at the location of the value of the known streamflow statistic, in ft^3/s;

R_{DS} is the downstream limit of the ratio of drainage areas (table 3), unitless;

R_{US} is the upstream limit of the ratio of drainage areas (table 3), unitless; and

$R_{U/K}$ is the ratio of the drainage area at the location of the unknown streamflow (A_U) to the drainage area at the location of the known streamflow (A_K), unitless.

Not on the Same Stream as a Streamgage Station or Partial-Record Station

This procedure is used when there is no streamgage station or partial-record station on the same stream as the ungaged location. The hydrologic assumption for this circumstance is that the conditions affecting streamflow are those represented by the regional equation. A partial-record station could be established when there is no streamgage station or partial-record station on the same stream as the ungaged location. Mathematically, the value of a statistic is estimated by applying the regional equation.

Example Applications of Procedures for Estimating Selected Seasonal Streamflow Statistics

The example applications of the estimating procedures are presented for manual computations of statistics at theoretical locations considering only the statistics from the streamgage stations. The USGS West Virginia Water Science Center, National Resource Analysis Center (NRAC), and WVDEP are incorporating the estimating procedures into the Watershed Characterization Management System (WCMS) for electronic computation of statistics for all streams in West Virginia. This system will incorporate the statistics from streamgage stations and partial-record stations, and will encompass statistics available from various sources for regulated streams. WCMS is a map-based Web applications system developed by the NRAC (associated with West Virginia University) for the WVDEP. WCMS will allow WVDEP to add and revise partial-record and regulated locations and statistics. WCMS is similar to the USGS "StreamStats" program (Ries and others, 2004) and is used by government agencies in managing the natural resources of West Virginia.

- **Example 1:** The winter *30Q5* at an ungaged location with a drainage area of 84.2 mi^2 (A_U) upstream from the streamgage station 01607500, South Fork South Branch Potomac River at Brandywine, can be estimated using equation 4. This equation can be used because there are no additional streamgage stations upstream on the same stream (fig. 2) and the size of the drainage area is within the limits for which the estimate can be made using drainage-area ratios. The winter *30Q5* at the streamgage station is 27.0 ft^3/s (Q_K) (Wiley, 2006, p. 73), and the drainage area at the streamgage stations is 103 mi^2 (A_K) (Paybins, 2008). The ratio of drainage areas ($R_{U/K}$) is A_U divided by A_K, or 84.2 mi^2 divided by 103 mi^2, which is 0.817. The exponent (E) for winter *30Q5* is 0.94 (table 3). Substituting into equation 4, the winter *30Q5* at the ungaged location (Q_U) is 22.3 ft^3/s. The value of $R_{U/K}$ of 0.817 is greater than the upstream limit (R_{US}) of 0.21 (table 3), indicating the establishment of a partial-record station at the ungaged location is not suggested.

- **Example 2:** The fall *D50* at an ungaged location with a drainage area of 1,450 mi^2 (A_U) downstream from the streamgage station 03183500, Greenbrier River at Alderson, with a drainage area of 1,364 mi^2 (Paybins, 2008) (A_{US}) and upstream from the streamgage station 03184000, Greenbrier River at Hilldale, with a drainage area of 1,619 mi^2 (Paybins, 2008) (A_{DS}) can be estimated using equation 6. This equation can be used because the ratio of drainage areas ($R_{U/K}$, or A_U divided by A_K) is equal to 1,450 mi^2 divided by 1,364 mi^2, or 1.06, which is less than the R_{DS} of 4.76 (table 3) at the upstream location, and the $R_{U/K}$ (A_U divided by A_K, or 1,450 mi^2 divided by 1,619 mi^2) of 0.896 is greater than the R_{US} of 0.21 (table 3) at the downstream location (fig. 2). The fall *D50* at Alderson (Q_{US}) is 549 ft^3/s (Wiley, 2006, p. 116) and at Hilldale (Q_{DS}) is 625 ft^3/s (Wiley, 2006, p. 117). By substituting these values into equation 6, the fall *D50* at the ungaged location (Q_U) is 575 ft^3/s.

Additional examples using identical procedures for estimating annual streamflow statistics are presented by Wiley (2008) and for estimating flood-frequency discharges are presented by Wiley and Atkins (2010).

Limitations of Procedures for Estimating Selected Seasonal Streamflow Statistics

The estimating procedures presented in this report are applicable only to unregulated streams in West Virginia, and estimates are representative of the period 1930–2002. The procedures are not applicable to streams regulated by large lakes, ponds, or navigation dams. Equations are applicable only within the specified limits of dependent variables (table 1). The statistics for streamgage stations from surrounding states used in this study do not supersede values determined for the particular state.

Caution should be used when applying the estimating procedures in areas of underground mining and karst terrain, where water can be transferred between basins and streams can lose water. A partial-record station can be established where there is some streamflow for estimating statistics, but estimating procedures for ungaged locations should not be applied without first determining that the streams involved are not losing or gaining water to or from underground mines or karst geology.

Estimating procedures for ungaged locations are applicable only to perennial streams. The median drainage area upstream from the location where an intermittent stream becomes perennial was determined to be 40.8 acres (0.064 mi^2). This value ranged from 10.2 to 150.1 acres (0.016 to 0.235 mi^2) in a limited study of 36 sites conducted in the southern coal fields of West Virginia (Paybins, 2003), and differed by region, with a median of 66.1 acres (0.103 mi^2) in the northeastern part of the southern coal fields and 34.8 acres (0.054 mi^2) in the southwestern part. Estimating procedures are not used for drainage areas less than 0.05 mi^2 because the streams are likely not perennial, and procedures are applied to drainage areas less than 0.25 mi^2 only when there is some determination (such as a field observation at low streamflow) that the stream is perennial.

The estimating procedures presented in this report, unlike the methods developed by Hayes (1991), are not conservative at the confluence of streams. The value of the statistic estimated downstream from the confluence of two streams will not equal the summation of the values of the statistic estimated upstream from the confluence. Low streamflows can be affected by mining (Hobba, 1981; Puente and Atkins, 1989; Borchers and others, 1991; Wiley and others, 2001), which can result in differences in timing and magnitude of base-flow conditions between nearby locations. Streamflows may be reduced in streams that are "dewatered" by underlying underground mines or can be increased in streams that are downdip (where the elevation is lower and where the rock strata slope toward the stream) from flooded underground mines. Water also can be transferred between basins by drainage through coal mines, and low streamflows can be increased by drainage from valley-fill deposits. Streamflow at outflow points of large basins that are stratigraphically below mined coal beds likely would be increased from the pre-mining condition, except where large interbasin transfer of water occurs. The variability of the effects caused by mining and other conditions is accounted for within the accuracy of the non-conservative estimating procedures developed in this study.

Summary

The U.S. Geological Survey, in cooperation with the West Virginia Department of Environmental Protection, Division of Water and Waste Management, developed procedures for estimating selected seasonal streamflow statistics on unregulated streams in West Virginia. The seasons were defined as winter (January 1–March 31), spring (April 1–June 30), summer (July 1–September 30), and fall (October 1–December 31).

Regional equations were developed for estimating the seasonal 1-day 10-year, 7-day 10-year, and 30-day 5-year hydrologically based low-flow frequency values for unregulated streams in West Virginia. Equations and procedures for estimating the seasonal U.S. Environmental Protection Agency (USEPA) harmonic-mean flow and the seasonal 50-percent flow-duration values also were developed. Regional equations were developed using ordinary least squares regression using flow statistics from 117 streamgage stations as dependent variables with basin characteristics for these streamgage stations as independent variables. Generalized least squares regression was not used because USEPA harmonic-mean flows and flow durations do not have annual time series and because the record periods for all stations represent equal periods of 73 years (1930–2002).

The three hydrologic regions for this study were determined in a previous study—North, South-Central, and Eastern Panhandle Regions. Drainage area, average annual precipitation, and longitude of the basin centroid were significant independent variables in one or more of the regional regression equations. The average standard error of estimates for the equations ranged from 12.6 to 299 percent.

Estimating procedures are presented for determining statistics at streamgage stations, partial-record stations, and ungaged locations, including (1) an ungaged location upstream from a streamgage station or partial-record station, (2) an ungaged location downstream from a streamgage station or partial-record station, (3) an ungaged location on a stream other than the one on which the streamgage station or partial-record station is located, and (4) an ungaged location between two streamgage stations and (or) partial-record stations. The procedures are based on a comparison of estimates made at 25 pairs of streamgage stations by using drainage-area ratios and estimates made using the regional regression equations.

Procedures developed to estimate the selected seasonal streamflow statistics in this study are applicable only to rural, unregulated streams within the boundaries of West Virginia that have independent variables within the limits of the stations used to develop the regional equations: drainage area from 16.3 to 1,516 square miles in the North Region, from 2.78 to 1,619 square miles in the South-Central Region, and from 8.83 to 3,041 square miles in the Eastern Panhandle Region; average annual precipitation from 42.3 to 61.4 inches in the South-Central Region and from 39.8 to 52.9 inches in the Eastern Panhandle Region; and longitude of the basin centroid from 79.618 to 82.023 decimal degrees in the North Region.

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