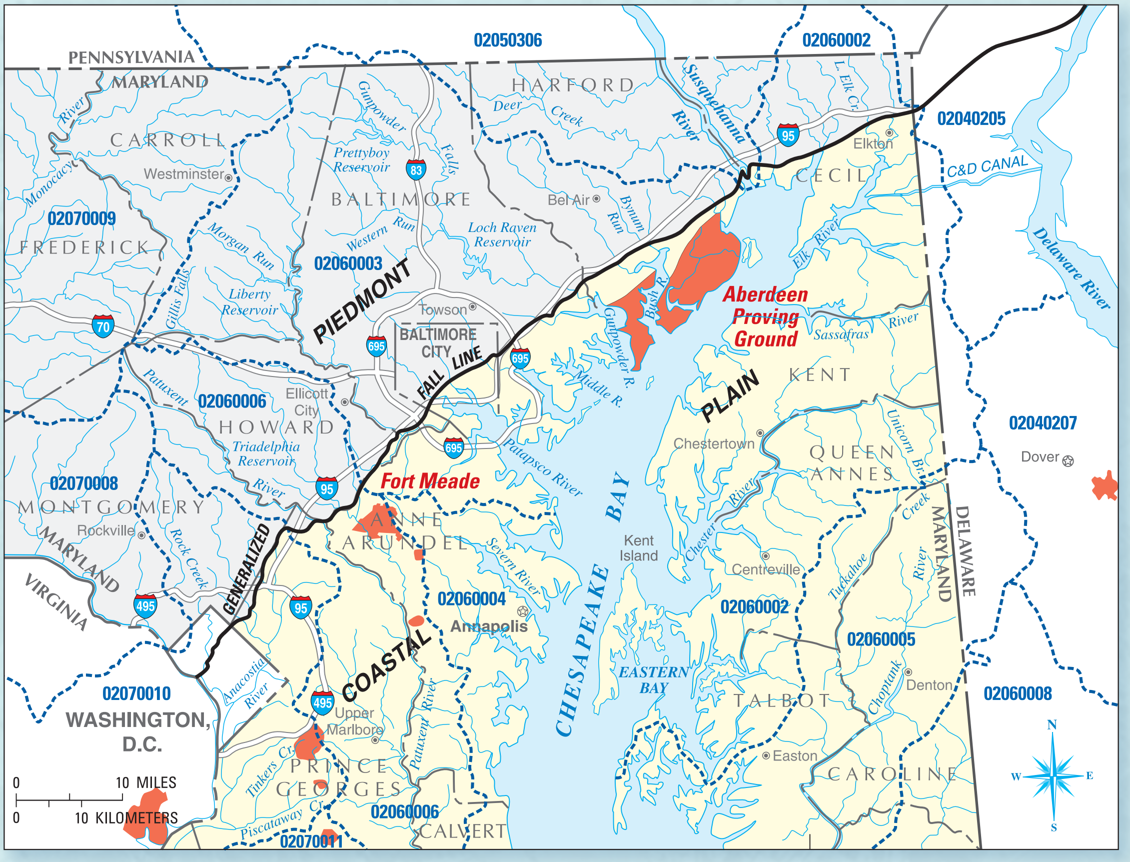
Prepared in cooperation with the
Maryland Department of the Environment

Estimation of Selected Streamflow Statistics for a Network of Low-Flow Partial-Record Stations in Areas Affected by Base Realignment and Closure (BRAC) in Maryland



Scientific Investigations Report 2010–5170

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

Cover. Map showing locations of areas to be affected by Base Realignment and Closure (BRAC) activities in Maryland, including Aberdeen Proving Ground and Fort Meade.

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By Kernell G. Ries III and Ken Eng

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Conversion Factors and Datum

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
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)

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

Abbreviations and Acronyms

7Q10	7-day, 10-year low flow
ADAPS	Automated Data Processing System
APG	Aberdeen Proving Ground
ASEE	average standard error of estimate
ASEP	average standard error of prediction
BRAC	Base Realignment and Closure
DoD	U.S. Department of Defense
HUC	8-digit hydrologic accounting units
LFPR	low-flow partial-record
MDE	Maryland Department of the Environment
MOVE1	Maintenance-of-Variance Extension type 1 record extension method
MOMENTS	Stedinger and Thomas (1985) record extension method
MSE	mean squared error
NSA	U.S. National Security Agency
R^2	coefficient of determination
R^2_{adj}	coefficient of determination adjusted for the number of stations and the number of explanatory variables used to develop the equation
USGS	U.S. Geological Survey
WMA	Maryland Department of the Environment Water Management Administration

Estimation of Selected Streamflow Statistics for a Network of Low-Flow Partial-Record Stations in Areas Affected by Base Realignment and Closure (BRAC) in Maryland

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Abstract

The U.S. Geological Survey, in cooperation with the Maryland Department of the Environment, operated a network of 20 low-flow partial-record stations during 2008 in a region that extends from southwest of Baltimore to the northeastern corner of Maryland to obtain estimates of selected streamflow statistics at the station locations. The study area is expected to face a substantial influx of new residents and businesses as a result of military and civilian personnel transfers associated with the Federal Base Realignment and Closure Act of 2005. The estimated streamflow statistics, which include monthly 85-percent duration flows, the 10-year recurrence-interval minimum base flow, and the 7-day, 10-year low flow, are needed to provide a better understanding of the availability of water resources in the area to be affected by base-realignment activities.

Streamflow measurements collected for this study at the low-flow partial-record stations and measurements collected previously for 8 of the 20 stations were related to concurrent daily flows at nearby index streamgages to estimate the streamflow statistics. Three methods were used to estimate the streamflow statistics and two methods were used to select the index streamgages. Of the three methods used to estimate the streamflow statistics, two of them—the Moments and MOVE1 methods—rely on correlating the streamflow measurements at the low-flow partial-record stations with concurrent streamflows at nearby, hydrologically similar index streamgages to determine the estimates. These methods, recommended for use by the U.S. Geological Survey, generally require about 10 streamflow measurements at the low-flow partial-record station. The third method transfers the streamflow statistics from the index streamgage to the partial-record station based on the average of the ratios of the measured streamflows at the partial-record station to the concurrent streamflows at the index streamgage. This method can be used with as few as one pair of streamflow measurements made on a single streamflow recession at the low-flow partial-record station, although additional pairs of measurements will increase the accuracy of the estimates. Errors associated with the two correlation methods generally were lower than the errors associated with the flow-ratio method, but the advantages of the flow-ratio method are that it can produce reasonably accurate estimates from streamflow measurements much faster and at lower cost than estimates obtained using the correlation methods.

The two index-streamgage selection methods were (1) selection based on the highest correlation coefficient between the low-flow partial-record station and the index streamgages, and (2) selection based on Euclidean distance, where the Euclidean distance was computed as a function of geographic proximity and the basin characteristics: drainage area, percentage of forested area, percentage of impervious area, and the base-flow recession time constant, τ. Method 1 generally selected index streamgages that were significantly closer to the low-flow partial-record stations than method 2. The errors associated with the estimated streamflow statistics generally were lower for method 1 than for method 2, but the differences were not statistically significant.

The flow-ratio method for estimating streamflow statistics at low-flow partial-record stations was shown to be independent from the two correlation-based estimation methods. As a result, final estimates were determined for eight low-flow partial-record stations by weighting estimates from the flow-ratio method with estimates from one of the two correlation methods according to the respective variances of the estimates. Average standard errors of estimate for the final estimates ranged from 90.0 to 7.0 percent, with an average value of 26.5 percent. Average standard errors of estimate for the weighted estimates were, on average, 4.3 percent less than the best average standard errors of estimate from the separate estimation methods.

Introduction

On May 13, 2005, the U.S. Department of Defense (DoD) issued a list of suggested military base realignments and closures planned to aid in military transformation and reduce costs. Subsequently, the U.S Congress appointed a Base Realignment and Closure (BRAC) Commission to provide an independent, non-partisan review of the DoD's recommendations and to ensure the integrity of the BRAC process. The goals of the BRAC recommendations were to support force transformation, address new threats and strategies, consolidate business functions, and provide significant cost savings. The Commission released its final report to the President of the United States on September 8, 2005. The President approved the recommendations on September 15, 2005, and forwarded them to Congress. The recommendations became law on November 9, 2005. The military realignments as a result of the BRAC process are expected to have a substantial impact on the State of Maryland, where the Aberdeen Proving Ground (APG) in Harford County, and Fort George G. Meade (Fort Meade) in Anne Arundel County are expected to grow larger in order to accommodate transferred Army personnel and consolidated operations.

The Maryland Department of Planning (2006) estimated that approximately 25,000 new households will be established in Maryland as a result of the BRAC. Of these, approximately 56 percent of them will be established due to new jobs at APG in Harford County, and approximately 42 percent of them will be established due to new jobs at Fort Meade in Anne Arundel County. The remaining 2 percent of new households will be established as a result of new jobs at Joint Base Andrews Naval Air Facility, Washington, (formerly Andrews Air Force Base) in Prince George's County. This influx of new residents will lead to greater demands for housing, schools, and infrastructure for water, wastewater, power, telecommunications, and transportation, particularly in Harford and Cecil Counties.

The increased demand for water and wastewater capacity resulting from the influx of new residents and businesses to BRAC-affected areas will likely necessitate new applications for water-withdrawal and wastewater-discharge permits. The Water Management Administration (WMA) of the Maryland Department of the Environment (MDE) is responsible for evaluating permit applications and issuing these permits (Maryland Department of the Environment, 2009). Making good permitting decisions will require the WMA to understand the natural availability of the affected water resources in relation to current and requested water withdrawals and return flows.

The U.S. Geological Survey (USGS) received funding through the MDE in January 2008 to begin a study of the potential water-resource impacts that could result from the BRAC process on areas in and around APG and Fort Meade. The study was funded through June 2009, and consisted of four coordinated investigations: (1) water-use activities, (2) groundwater simulation modeling, (3) estimation of low-flow statistics for streams that could be affected by new water withdrawals or pollutant discharges, and (4) hydrologic monitoring.

Areas in Maryland that will be affected by the BRAC are in the Coastal Plain and Piedmont Physiographic Provinces, which are separated by the Fall Line (fig. 1). The Coastal Plain, southeast of the Fall Line, is an area of low relief adjacent to the Chesapeake Bay. Streams in the Coastal Plain have relatively flat gradients, and often are affected by tides for substantial distances above their mouths. The Piedmont, northwest of the Fall Line, has a gently rolling landscape and streams with relatively high gradients, which drain to the Chesapeake Bay (Carpenter and Hayes, 1996). The Fall Line extends north and south along much of the eastern United States, and is named as such because numerous waterfalls occur along the line, where rivers transition from the higher Piedmont onto the lower Coastal Plain.

The investigation of BRAC water-resource needs was divided geographically into a Coastal Plain section that focused on Fort Meade, and a Piedmont section that focused on APG. Fort Meade is located in the upper part of the Coastal Plain near the Fall Line. Most of the anticipated water-resource impacts from this facility are expected to occur within the recharge areas of several important Coastal Plain aquifers, although some impacts also are likely to occur in Piedmont areas adjacent to the base. APG is located primarily within the Coastal Plain, but most of the increased water use from BRAC-related development is expected to occur in the surrounding counties, which are situated largely within the Piedmont.

The part of the overall BRAC investigation to estimate low-flow statistics for streams that could be affected by new water withdrawals or pollutant discharges was further separated into two major tasks. One task was to modify an existing Web-based decision-support system named StreamStats (Ries and others, 2008) to aid the WMA in evaluating permit applications for new water withdrawals and pollutant discharges in the BRAC area. The existing system, which previously was available for only part of the BRAC area, allows users to select ungaged sites anywhere within the BRAC area, determine drainage boundaries and other basin characteristics, and insert the basin characteristics as explanatory variables into regression equations to provide estimates of selected streamflow statistics for the ungaged sites. For the BRAC study, StreamStats was modified to allow its use for the entire BRAC area and to provide summaries of water withdrawals and return flows upstream from user-selected sites. A separate report has been prepared to describe this effort (Ries and others, 2010). The other task, which is addressed in this report, was to identify specific sites on streams that may be affected by development associated with BRAC and obtain streamflow measurements at selected sites that could be used to obtain estimates of streamflow statistics with greater accuracy than estimates that could be obtained for the sites from available regression equations.

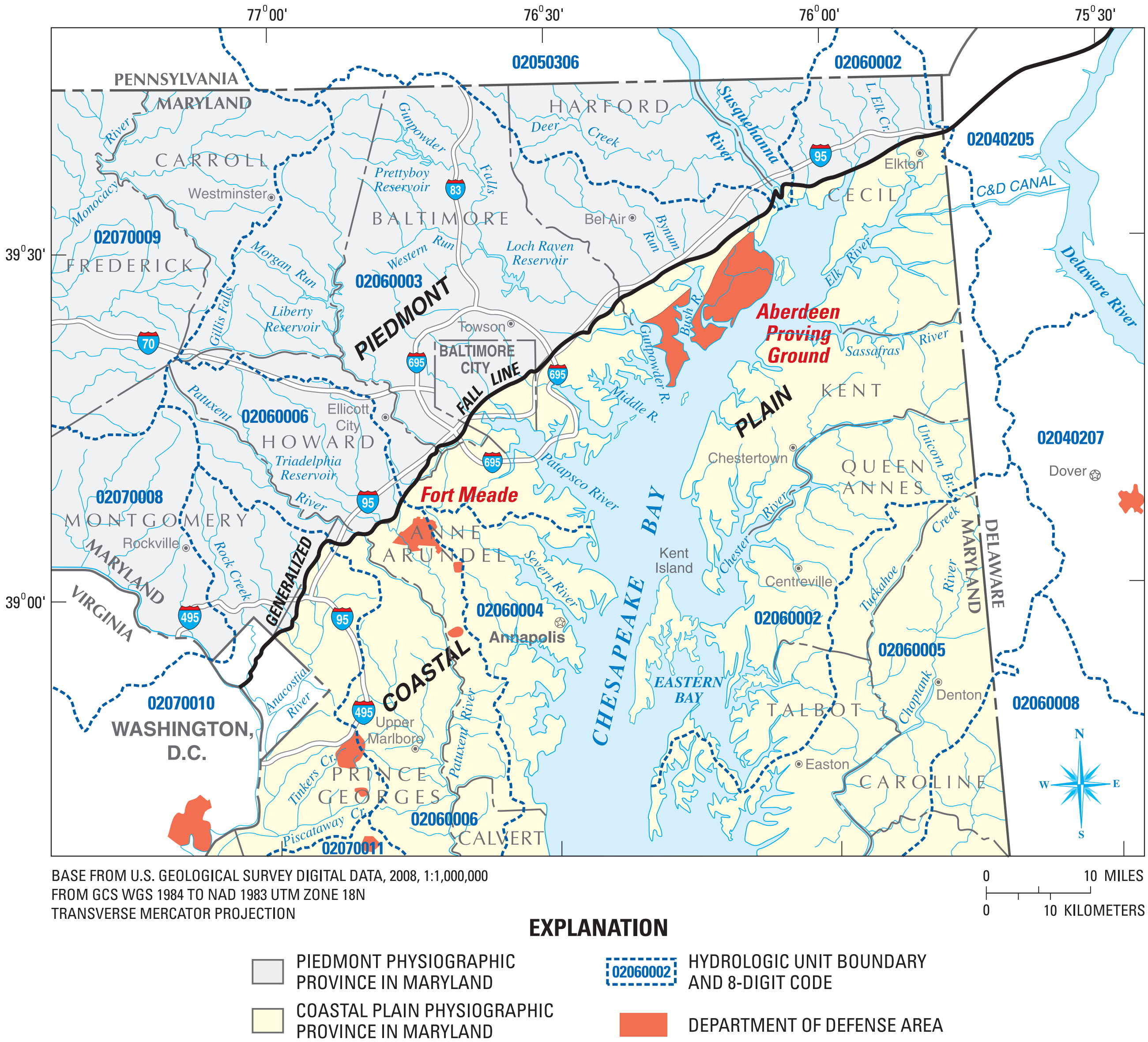

Figure 1. Location of areas to be affected by Base Realignment and Closure (BRAC) activities in Maryland, including Aberdeen Proving Ground and Fort Meade.

Purpose and Scope

The primary purpose of this report is to present streamflow statistics for a network of 20 low-flow partial-record (LFPR) stations that was established and operated during the summer and fall of 2008 in areas of Maryland that will be affected by an influx of new residents and businesses as a result of the BRAC process. The estimated streamflow statistics include monthly 85-percent duration flows, the 10-year recurrence interval minimum base flow (10-year base flow), and the 7-day, 10-year low flow (7Q10). These statistics were estimated because they are used by the MDE for making permitting decisions. The secondary purpose of this report is to present the results of an assessment done to determine the adequacy for potential future applications of a new method for collecting and analyzing data to obtain estimates of streamflow statistics at LFPR stations. The assessment was done by comparing the accuracy of estimates obtained by use of established methods for collecting and analyzing data to estimates obtained by use of the new method.

This report describes station selection and operation of the network, and methods used to estimate the streamflow statistics. Location information, streamflow measurements (including historical measurements), basin characteristics, and estimated streamflow statistics are provided in this report for each of the LFPR stations. Location information, periods of record, basin characteristics, and computed streamflow statistics also are presented for index streamgages used for estimating the streamflow statistics for the LFPR stations. A description of the study area also is provided.

Description of Study Area

The study area ranges from northeast to southwest of Baltimore, Maryland (fig. 1). The counties in Maryland that will be most affected by the BRAC are, from northeast to southwest, Cecil, Harford, Baltimore, Howard, Anne Arundel, Montgomery, and Prince George's. The City of Baltimore is located approximately centrally within the study area, and also is expected to be affected by BRAC. These areas are in the Piedmont and the Atlantic Coastal Plain Physiographic Provinces (Fenneman, 1938). The Fall Line, which roughly parallels U.S. Interstate 95 in the study area, separates the two physiographic provinces. The Piedmont, northwest of the Fall Line, has a gently rolling landscape and streams with relatively high gradients, which drain to the Chesapeake Bay (Carpenter and Hayes, 1996). The Coastal Plain, southeast of the Fall Line, is an area of low relief adjacent to the Chesapeake Bay. Streams in the Coastal Plain have relatively flat gradients, and often are affected by tides for substantial distances above their mouths. The Fall Line extends north and south along much of the eastern United States, and is named as such because numerous waterfalls occur along the line, where rivers transition from the higher Piedmont onto the lower Coastal Plain.

APG has been the U.S. Army's primary chemical warfare research and development center since World War I (Spencer and others, 2001). It is located in Harford County, primarily on land along the northwestern shore of Chesapeake Bay. BRAC-related development in Harford County is expected to occur primarily in an inverted "T" shape, running northeast to southwest along the U.S. Interstate 95 corridor, with a perpendicular axis to the northwest along Maryland Route 24 into Bel Air, although some development also is expected in more sparsely developed areas in Harford and Cecil Counties (Michelle Dobson, Harford County, oral commun., July 2008). From a water-supply perspective, the County is concerned that thousands of additional people could be tapping into the fractured-rock aquifers of the Piedmont in areas west and north of Bel Air. Production from the fractured rocks already is marginal in some locations (Bolton and others, 2009), and the impact of many additional wells could cause significant declines in areas where municipal water supplies are not yet available.

Fort Meade is a U.S. Army installation located in Anne Arundel County that primarily supports intelligence, knowledge capital, information management organizations, and installation operations for facilities and infrastructure in support of DoD activities (Anne Arundel County, 2008). The National Security Agency (NSA) is located near the western boundary of Fort Meade. The BRAC is anticipated to result in the addition of 5,695 direct new jobs at Fort Meade and NSA (Anne Arundel County, 2008). Development around the installation is expected to expand radially along major access roads and highways (Anne Arundel County, 2008). Substantial amounts of development also are anticipated to take place on the grounds of Fort Meade. Numerous row houses already have been constructed on the site of the former base golf course, and more are planned. From a water-resource perspective, Maryland State agencies are concerned that the Fort Meade water-supply system, which relies primarily on groundwater withdrawn from the Patuxent and Lower Patapsco aquifers, could further stress these aquifers. The Patuxent aquifer is used for municipal supply in nearby areas to the north and east of Fort Meade. At the start of BRAC in 2005, the potentiometric surface of the aquifer already had a drawdown equivalent to more than 40 ft (feet) in areas north of Fort Meade (Soeder and others, 2007). Withdrawals of groundwater from the Lower Patapsco aquifer, overlying the Patuxent, also are a concern. Fort Meade is within the recharge area of the Lower Patapsco, and pumpage, if excessive, could interfere with aquifer recharge.

Low-Flow Partial-Record Station Network Design and Operation

At least 10 years of record usually are required to estimate low-flow frequency statistics, such as the 7Q10, from continuous daily streamflow records at streamgages (Riggs, 1972). At current (2009) prices, the cost for the USGS to collect and analyze the 10 years of continuous data needed to estimate the 7Q10 at a streamgage in Maryland exceeds $140,000. This cost prohibits operating a streamgage everywhere this information is needed. In addition, regulators and planners often cannot wait for 10 years for the estimates.

LFPR stations often are established where information on low-streamflow conditions is needed, but (1) it is not physically or economically feasible to continuously monitor streamflows at the location, (2) the amount or accuracy of the needed streamflow information does not require continuous monitoring at the location, or (3) the information is needed sooner than the time that would be required to operate a streamgage at the location long enough to accurately compute the statistics from the continuous data that would be collected there. At LFPR stations, a series of streamflow measurements are made during low-flow periods when streamflow is primarily from groundwater discharge. These measurements are then related to daily mean streamflows on the same days at selected nearby streamgages, which are referred to as index streamgages. Streamflow statistics for the LFPR stations are then estimated from these relations.

Networks of LFPR stations have been operated intermittently by the USGS in Maryland since at least the mid-1950s. These networks have been operated following guidelines described by Riggs (1972) and provided in Technical Memorandums issued by the USGS Office of Surface Water, which can be found on the Web at *http://water.usgs.gov/osw/pubs/memo.summaries.html#LOW%20FLOW*. These guidelines suggest that streamflow measurements should be obtained several days after the most recent rainfall to assure that all streamflow is from groundwater discharge. Each measurement should be obtained on a separate recession to assure that the measured streamflows are independent. As a result, LFPR networks usually are operated with a goal of obtaining about 10 streamflow measurements at the sites over 3 years of operation.

Eng and Milly (2007) developed a new method for obtaining streamflow data and estimating streamflow statistics at LFPR stations. For this new method of data collection, pairs of streamflow measurements are obtained on the same recession. A single pair of measurements can be used to compute estimates of the base-flow recession time constant, τ, and streamflow statistics but multiple pairs of measurements can improve the accuracy of the estimates. As a result, reasonable estimates of streamflow statistics can be obtained after collecting data for only a single low-flow season, or less, thus decreasing the time and cost needed to obtain the estimates. This new method is further described below.

Twenty LFPR stations were operated in the BRAC study area during the summer and fall of 2008 (table 1, fig. 2). Streamflow measurements obtained for these stations were collected in the manner suggested by Eng and Milly (2007). LFPR stations were selected for inclusion in the network by the USGS in consultation with the MDE. In selecting the stations, priority was given to locations on streams that were (1) not already gaged, (2) most likely to be affected by the BRAC process, (3) minimally affected by water withdrawals and return flows, and (4) included in a previous LFPR network, and thus had previous streamflow measurements made at the locations. Inclusion of some stations with previous streamflow measurements allowed estimating and comparing streamflow statistics using traditional estimating techniques as well as using the new technique suggested by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008). All selected LFPR stations were located within the Piedmont areas of Cecil, Harford, Baltimore, Howard, and Montgomery Counties. Drainage areas for the LFPR stations ranged from 2.14 to 30.8 mi^2 (square miles). Forested land areas for the LFPR stations ranged from 21.3 to 48.1 percent, and impervious surfaces ranged from 0.42 to 28.5 percent. These basin characteristics were determined by use of the StreamStats Web application for Maryland, which is available on line at *http://streamstats.usgs.gov*.

Table 1. Descriptive information for low-flow partial-record stations.

[Latitudes and longitudes are in decimal degrees; drainage areas are in square miles; forest and impervious areas are in percent, determined from the National Land Cover Database 2001 (U.S. Geological Survey, 2008a)]

Station number	Station name	Latitude	Longitude	Drainage area	Forest area	Impervious area
01494995	Gramies Run near Elk Mills, MD	39.669722	75.830833	30.8	34.8	1.48
01495980	Northeast Creek near Calvert, MD	39.688889	76.008056	13.4	22.5	1.89
01496020	Little Northeast Creek near Pleasant Hill, MD	39.680278	75.929167	5.40	21.3	1.30
01496060	Stony Run near North East, MD	39.606667	75.959167	8.28	48.1	2.67
01496250	Mill Creek at Jackson, MD	39.574722	76.056111	3.55	47.4	3.87
01578150	Deep Creek at Susquehanna Hall Road near Flintville, MD	39.698889	76.263333	6.55	39.8	0.59
01578480	Stone Run at Rising Sun, MD	39.705833	76.077778	6.74	27.2	3.58
01579925	Little Deer Creek near Federal Hill, MD	39.661667	76.448611	13.9	33.6	0.60
01580170	Stout Bottle Branch near Ady, MD	39.620556	76.333611	7.33	23.7	1.81
01580510	Mill Brook near Noble Mill, MD	39.604722	76.240556	4.40	30.4	1.30
01580550	Rock Run at Quaker Bottom Road at Susquehanna State Park, MD	39.601667	76.150556	2.73	35.8	0.98
01581675	West Branch Winters Run near Pleasantville, MD	39.551389	76.446944	8.93	27.1	1.04
01581680	East Branch Winters Run near High Point, MD	39.563333	76.442778	9.57	37.8	1.50
01581985	Second Mine Branch at White Hall, MD	39.623056	76.630000	5.77	37.5	0.51
01583200	Blackrock Run at Coopersville, MD	39.543333	76.733333	9.78	40.8	0.53
01589015	Sucker Branch near Ellicott City, MD	39.278611	76.795000	2.46	25.3	18.00
01590996	Haights Branch near Unity, MD	39.249167	77.065833	2.78	29.5	0.42
01591690	Reddy Branch near Brookeville, MD	39.181944	77.066389	2.14	33.0	2.41
01593650	Middle Patuxent River tributary near Dayton, MD	39.236667	76.940833	4.23	23.0	1.99
01594400	Dorsey Run near Jessup, MD	39.120278	76.782222	11.9	34.0	28.50

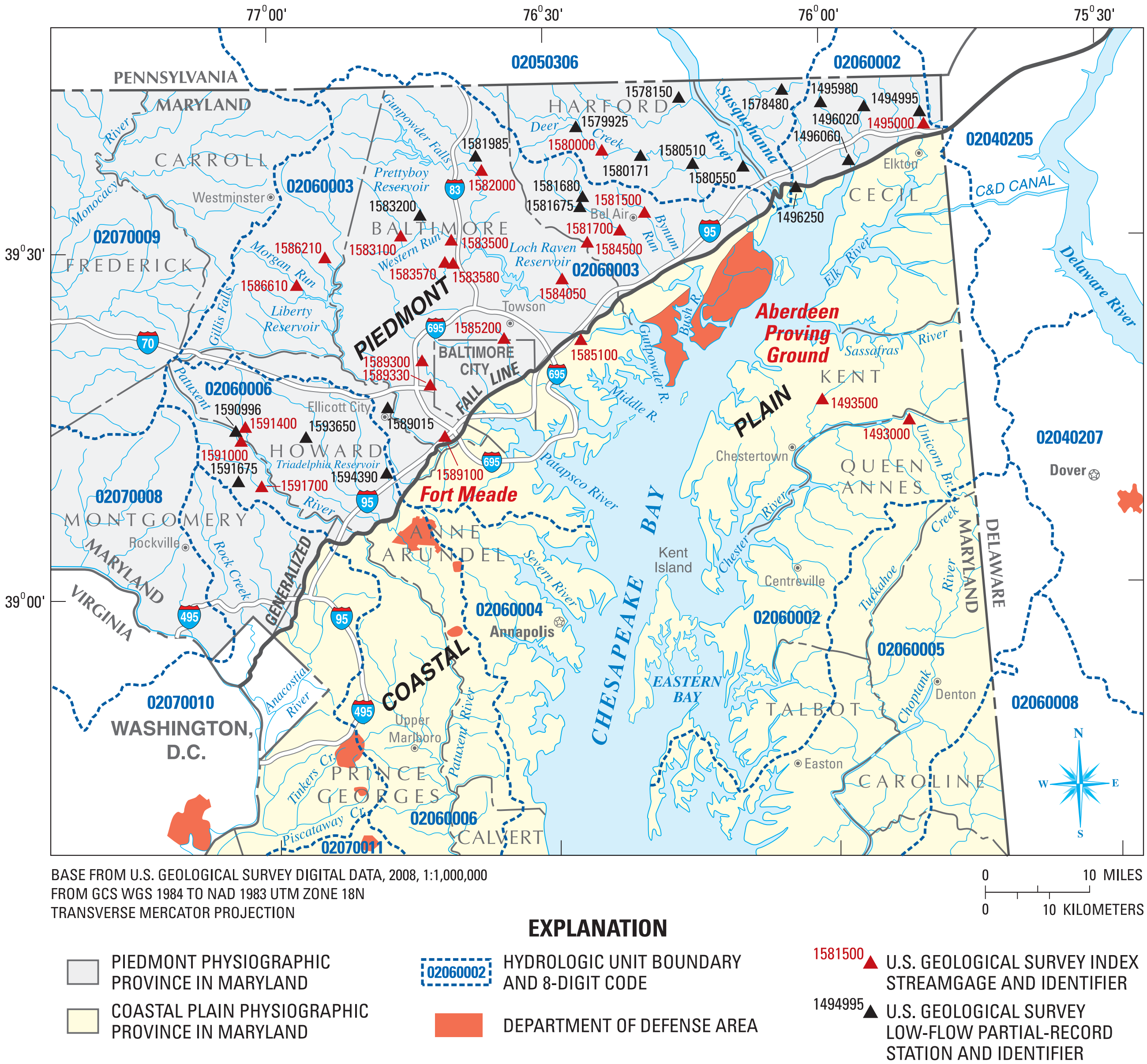

Figure 2. Locations of low-flow partial-record stations and index streamgages.

The LFPR network was designed for this study with the intention of obtaining two pairs of streamflow measurements at each station during the summer of 2008. A total of at least 5 days of dry weather after a rainfall event were needed to obtain a pair of measurements. The fist measurement was obtained at a minimum of 3 days after a rainfall event, and at least 2 days of dry weather were needed between measurements. Operation of this type of low-flow network was more difficult than for a traditional low-flow network because of the need to make pairs of measurements within a few days of each other and the need to rely on weather forecasts for at least 3 days in the future when deciding on any given day whether to make the first of a pair of measurements. These requirements became problematic because unusually frequent rains during 2008 presented very few opportunities for the collection of paired measurements until late summer. As a result, it was necessary to extend data collection into the fall. Also, most summertime rainfall events in Maryland are from thunderstorms of limited areal extent and duration, making it difficult to reliably determine if a rainfall event had occurred in a particular area.

In nine cases, initial streamflow measurements were made but it rained before the second measurement could be made. In five cases, second measurements were made during what was thought to be a continuous recession only to find after completing the measurements that the streamflow for the second measurement was greater than that for the first measurement, indicating that the local area had likely experienced an isolated rainfall event between measurements. Two usable pairs of measurements were obtained for only 4 of the 20 LFPR stations. The remaining 16 stations all had one pair of useable measurements except for one station, 01589015 (Sucker Branch near Ellicott City, MD), where no useable pairs were obtained. Historical measurements and measurements made during 2008 for the LFPR stations are listed in table 2. The number of measurements available at the LFPR stations ranged from 2 (stations 01580510, 01581675, and 01581680) to 20 (station 01593650), with an average of 7.1 available measurements per station.

Selection of Index Streamgages and Computation of Streamflow Statistics at the Streamgages

All active streamgages with predominantly natural-flow conditions and at least 10 years of streamflow record that were located within the five 8-digit hydrologic unit codes (HUCs) in the BRAC study area were used as index streamgages for this study. These included 23 streamgages in the Chester-Sassafras (02060002), the Lower Susquehanna (02050306), the Gunpowder-Patapsco (02060003), the Severn (02060004), and the Patuxent (02060006) HUCs (Seaber and others, 1987). The 8-digit HUCs are referred to as accounting units. Additional information about HUCs is available online at *http://water.usgs.gov/GIS/huc.html*. Station numbers, names, latitudes, longitudes, periods of record, and basin characteristics for the index streamgages are presented in table 3.

For each index streamgage, monthly 85-percent duration flows, the 10-year base flow, and the 7Q10 were computed. The monthly 85-percent duration flows are the streamflows that were exceeded 85 percent of the time for the given month during the period of record. The duration flows were computed by use of daily streamflow data from all complete water years, which begin on October 1 of the preceding year and end on September 30 of the stated year, using the daily streamflow values monthly and annual statistics routine of the USGS internal Automated Data Processing System (ADAPS) computer software (U.S. Geological Survey, 2003). This program computes the flow-duration statistics following methods described by Searcy (1959).

The 10-year base-flow values, defined as the minimum annual base flow that can be expected to occur, on average, once in 10 years, were computed for the index streamgages used in this study by the MDE. Base flow is the component of the total streamflow that is derived from groundwater discharge. The MDE determined annual base-flow time series using a computer program by Rutledge (1998) that separates out the groundwater component from the total streamflow for each day in the period of record and then sums the daily base-flow values to determine the total base flow for each year. The 10-year base-flow values were then computed from the annual base-flow time series. The 10-year base-flow values were computed by the MDE in units of inches per year to provide a direct comparison to annual rainfall. The values were converted to units of cubic feet per second (ft^3/s) for consistency with the units of the other streamflow statistics that were estimated for this study. The monthly 85-percent duration flows and the 10-year base flows for the index streamgages are provided in table 4. The 10-year base flows are provided in units of inches per year as well as in cubic feet per second.

The 7Q10 is the lowest 7-day mean streamflow that is expected to occur, on average, once in 10 years. The 7Q10 values for the index streamgages were determined by fitting a log-Pearson Type III distribution to annual series of minimum 7-day mean flows following methods described by Riggs (1972). The 7Q10 values were computed from all complete climatic years, which begin on April 1 of the stated year and end on March 31 of the following year. Climatic years normally are used instead of water years to compute 7Q10 because late March and early April are normally times of relatively high streamflow in most of North America, and thus it is unlikely that an annual minimum 7-day mean flow would occur at a time that spans two climatic years. The SWSTAT program (U.S. Geological Survey, 2008b) is available for computing these statistics. The 7Q10 flows for the index streamgages are provided in table 5, along with means, standard deviations, and skews of the logarithms of the annual 7-day low flows, the frequency factors, K, and the years of record that were used to compute the 7Q10 values from the log-Pearson Type III distribution.

Methods for Estimating the Selected Streamflow Statistics at the Low-Flow Partial-Record Stations

Three methods were used to estimate the streamflow statistics for the LFPR stations by relating measured streamflows at the LFPR stations to concurrent daily streamflows at index streamgages. These methods include the Maintenance-of-Variance Extension type 1 (MOVE1) method proposed by Hirsch (1982), a Moments approach (Moments) described by Stedinger and Thomas (1985), and a flow-ratio approach (Q-ratio) first proposed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008). Both the MOVE1 and Moments methods were recommended for use by the USGS Office of Surface Water in Technical Memorandum No. 86.02, Low- Flow Frequency Estimation at Partial-Record Sites, issued December 16, 1985 (available online at *http://water.usgs.gov/admin/memo/SW/sw86.02.html*.) Both methods assume a linear relation between the streamflows at the LFPR station and the index streamgage that remains constant with time, thus the relation between the same-day streamflows can be used to estimate streamflow statistics that represent long-term conditions. Both the MOVE1 and Moments methods are suggested for use with 10 or more measurements at the LFPR station, whereas the Q-ratio method can produce estimates from a single pair of measurements made on the same recession. Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008) indicated that two pairs of measurements produce optimal Q-ratio estimates, and additional pairs of measurements will reduce errors with diminishing returns. All three methods are further described in the following sections.

Table 2. Historical streamflow measurements and streamflow measurements made for this study at the low-flow partial-record stations.

[Streamflows are in cubic feet per second. Shaded streamflows were intended to be paired but second measured streamflow was higher than first streamflow.]

Station number	Year	Month	Day	Streamflow	Paired
01494995	1981	11	5	1.62	No
	1982	11	3	1.02	No
	1983	4	21	5.94	No
	1983	6	14	3.05	No
	1983	8	26	0.649	No
	2008	8	11	0.86	Yes
	2008	8	14	0.654	Yes
	2008	10	22	0.511	No
	2008	10	24	0.514	No
01495980	2008	8	11	4.19	No
	2008	9	3	2.09	Yes
	2008	9	5	1.28	Yes
01496020	2008	8	11	2.15	Yes
	2008	8	14	1.28	Yes
	2008	10	22	1.39	Yes
	2008	10	24	1.37	Yes
01496060	1981	11	14	2.17	No
	1982	8	18	1.58	No
	1983	4	21	17.8	No
	1983	5	13	6.67	No
	1983	6	13	4.98	No
	1983	8	17	1.27	No
	2008	8	11	1.12	Yes
	2008	8	14	0.848	Yes
	2008	10	22	0.741	No
	2008	10	24	0.79	No

Table 2. Historical streamflow measurements and streamflow measurements made for this study at the low-flow partial-record stations.

[Streamflows are in cubic feet per second. Shaded streamflows were intended to be paired but second measured streamflow was higher than first streamflow.]

Station number	Year	Month	Day	Streamflow	Paired
01496250	1981	11	4	1.61	No
	1982	4	13	3.78	No
	1982	8	16	1.86	No
	1983	4	21	8.68	No
	1983	5	13	5.36	No
	1983	6	15	4.43	No
	2008	8	14	1.22	Yes
	2008	8	18	0.815	Yes
	2008	10	22	1.19	Yes
	2008	10	24	0.786	Yes
01578150	2008	8	11	3.14	No
	2008	9	3	2.4	Yes
	2008	9	5	2.16	Yes
01578480	1981	11	3	2.35	No
	1982	3	30	2.75	No
	1982	8	17	1.7	No
	1983	4	21	10.7	No
	1983	6	16	4.39	No
	2008	8	11	2.04	No
	2008	9	3	0.817	Yes
	2008	9	5	0.614	Yes
01579925	1974	10	24	7.45	No
	1975	11	17	20.9	No
	1975	11	17	20.9	No
	1976	3	8	16.7	No
	1976	6	8	13.6	No
	1976	7	27	8.28	No
	1976	8	25	6.89	No
	1977	8	4	6.43	No
	1977	9	21	5.34	No
	1978	9	12	8.81	No
	1978	11	3	6.79	No
	1979	5	2	18.9	No
	2002	9	19	1.39	No
	2008	8	12	4.06	No
	2008	9	3	3.95	Yes
	2008	9	5	3.46	Yes

Table 2. Historical streamflow measurements and streamflow measurements made for this study at the low-flow partial-record stations.

[Streamflows are in cubic feet per second. Shaded streamflows were intended to be paired but second measured streamflow was higher than first streamflow.]

Station number	Year	Month	Day	Streamflow	Paired
01580170	1980	5	15	11.3	No
	1980	6	23	8.76	No
	1980	7	17	5.99	No
	1980	9	4	3.94	No
	1981	3	27	4.46	No
	1981	8	28	2.3	No
	1982	5	18	4.79	No
	1982	9	15	2.72	No
	2002	9	19	1.04	No
	2008	8	11	3.77	Yes
	2008	8	13	3.16	Yes
01580510	2008	8	11	1.16	Yes
	2008	8	13	1.06	Yes
01580550	2008	8	11	0.75	No
	2008	9	3	0.419	Yes
	2008	9	5	0.373	Yes
01581675	2008	8	11	3.49	Yes
	2008	8	13	3.1	Yes
01581680	2008	8	11	3.5	Yes
	2008	8	13	3.24	Yes
01581985	2008	8	14	2.85	No
	2008	9	3	2.45	No
	2008	9	16	2.63	Yes
	2008	9	19	2.54	Yes
01583200	1956	05	26	10.4	No
	1957	05	07	10.6	No
	1957	08	22	2.68	No
	1958	06	06	13.8	No
	1958	09	09	4.96	No
	1959	05	12	5.33	No
	1959	09	28	1.5	No
	1962	07	30	4.59	No
	1962	08	30	2.9	No
	1963	07	30	3.44	No
	1963	09	26	2.1	No
	1966	07	21	1.26	No
	2002	09	19	0.95	No
	2008	09	03	3.09	No
	2008	09	16	3.83	Yes
	2008	09	19	3.63	Yes

Table 2. Historical streamflow measurements and streamflow measurements made for this study at the low-flow partial-record stations.

[Streamflows are in cubic feet per second. Shaded streamflows were intended to be paired but second measured streamflow was higher than first streamflow.]

Station number	Year	Month	Day	Streamflow	Paired
01589015	2008	9	3	0.131	No
	2008	9	17	0.285	No
	2008	9	19	0.46	No
	2008	10	20	0.282	No
	2008	10	24	0.293	No
01590996	2008	8	7	0.562	Yes
	2008	8	14	0.43	Yes
	2008	10	20	0.592	Yes
	2008	10	24	0.568	Yes
01591690	2008	8	12	0.175	No
	2008	9	16	0.321	Yes
	2008	9	23	0.249	Yes
	2008	10	20	0.324	Yes
	2008	10	24	0.317	Yes
01593650	1977	5	31	2.18	No
	1977	8	4	1.15	No
	1977	9	15	0.692	No
	1978	9	21	1.72	No
	1978	11	6	1.72	No
	1979	5	3	3.86	No
	1980	5	15	4.6	No
	1980	6	24	3.41	No
	1980	9	2	1.22	No
	1981	3	27	2.39	No
	1981	8	27	0.84	No
	1982	5	17	2.08	No
	1982	9	14	0.342	No
	1990	4	27	4.12	No
	1990	9	10	2.07	No
	2002	9	20	0.108	No
	2008	8	7	0.84	Yes
	2008	8	14	0.653	Yes
	2008	10	20	0.967	No
	2008	10	24	1.08	No
01594400	2008	9	17	2.77	No
	2008	9	23	3.3	No
	2008	10	20	2.96	Yes
	2008	10	24	2.56	Yes

Table 3. Descriptive information for index streamgages used to estimate streamflow statistics at the low-flow partial-record stations.

[Latitudes and longitudes are in decimal degrees; drainage areas are in square miles; forest and impervious areas are in percent, determined from the National Land Cover Database 2001 (U.S. Geological Survey, 2008a); τ (base-flow recession constant) is in days; --, not available]

Streamgage number	Streamgage name	Latitude	Longitude	Period of record	Drainage area	Forest area	Impervious area	τ
01493000	Unicorn Branch near Millington, MD	39.24969	75.86131	1948–2004, 2007	19.7	--	1.01	33.4
01493500	Morgan Creek near Kennedyville, MD	39.28003	76.01456	1952–2007	12.5	--	1.39	46.2
01495000	Big Elk Creek at Elk Mills, MD	39.65706	75.82236	1932–2006	53.3	27.7	1.58	47.2
01580000	Deer Creek at Rocks, MD	39.62997	76.40331	1927–2007	94.3	35.8	1.36	51.4
01581500	Bynum Run at Bel Air, MD	39.54147	76.33011	1945–1969, 2000–2007	8.38	--	13.8	32.0
01581700	Winters Run near Benson, MD	39.51994	76.37297	1968–2007	34.6	--	2.28	50.9
01582000	Little Falls at Blue Mount, MD	39.60408	76.62047	1945–2007	53.8	42.1	0.89	46.6
01583100	Piney Run at Dover, MD	39.52061	76.76689	1983–1987, 1997–2008	12.5	33.5	1.71	50.1
01583500	Western Run at Western Run, MD	39.51078	76.67650	1945–2007	60.3	36.3	0.86	49.9
01583570	Pond Branch at Oregon Ridge, MD	39.48031	76.68750	1983–1985, 1999–2007	0.13	100	0.00	43.5
01583580	Baisman Run at Broadmoor, MD	39.47947	76.67803	1965–1968, 2000–2008	1.49	71.8	0.41	45.6
01584050	Long Green Creek at Glen Arm, MD	39.45469	76.47889	1976–2007	9.3	22.9	1.53	55.1
01584500	Little Gunpowder Falls at Laurel Brook, MD	39.50536	76.43178	1927–1969, 1999–2008	36.1	34.6	0.83	58.6
01585100	Whitemarsh Run at White Marsh, MD	39.37053	76.44592	195–1988, 1992–2007	7.56	--	30.9	25.1
01585200	West Branch Herring Run at Idlewylde, MD	39.37364	76.58433	1958–1986, 1997–2007	2.18	1.53	28.5	32.9
01586210	Beaver Run near Finksburg, MD.	39.48944	76.90294	1983–2007	14.1	23.1	4.10	39.7
01586610	Morgan Run near Louisville, MD	39.45189	76.95531	1983-2008	28.1	35.0	1.56	36.9
01589100	East Branch Herbert Run at Arbutus, MD	39.24000	76.69219	1958–1988, 1999–2007	2.43	6.08	45.7	36.2
01589300	Gwynns Falls at Villa Nova, MD	39.34589	76.73319	1957–1987, 1997–2007	32.6	18.9	21.1	39.0
01589330	Dead Run at Franklintown, MD	39.31122	76.71664	1960–1986, 1999–2007	5.47	4.05	45.3	28.7
01591000	Patuxent River near Unity, MD	39.23825	77.05572	1945–2008	35.0	42.6	0.93	32.1
01591400	Cattail Creek near Glenwood, MD	39.25597	77.05106	1979–2008	22.8	24.5	1.88	41.2
01591700	Hawlings River near Sandy Spring, MD	39.17467	77.02158	1979–2007	27.2	32.3	3.86	35.9

Table 4. Flow-duration and base-flow statistics for index streamgages used to estimate streamflow statistics at the low-flow partial-record stations.

[All streamflow statistics are in units of cubic feet per second except for 10-year base flows, which also are provided in units of inches; --, not available]

Streamgage Number	October 85-percent flow	November 85-percent flow	December 85-percent flow	January 85-percent flow	February 85-percent flow	March 85-percent flow	April 85-percent flow	May 85-percent flow	June 85-percent flow	July 85-percent flow	August 85-percent flow	September 85-percent flow	10-year base flow	10-year base flow (inches)
01493000	6.77	8.16	10.2	12.7	16.1	19.3	18.0	12.5	8.74	6.88	6.46	6.35	10.2	7.0
01493500	3.24	4.29	4.81	4.79	5.51	5.88	5.35	4.32	3.56	2.85	2.67	2.71	4.42	4.8
01495000	18.4	24.2	28.2	33.4	39.7	47.9	44.7	36.2	27.1	19.4	16.8	15.9	29.4	7.5
01580000	38.1	46.6	53.3	62.8	72.1	90.2	89	78.4	62.7	47.8	39.3	35	56.9	8.2
01581500	1.51	2.33	2.95	4.23	4.94	6.06	5.09	3.62	2.35	1.27	0.92	0.83	3.08	5.0
01581700	14.3	18.4	22.6	24.9	30.1	33.5	34.4	28.5	21.8	15.4	12.5	11.5	21.4	8.4
01582000	22.6	27.9	31.1	34.4	42.1	50.4	49	42.5	34.2	25.9	21.3	19.3	30.9	7.8
01583100	5.00	6.60	7.10	7.12	9.70	11.0	11.0	8.82	6.37	4.74	4.80	4.40	--	--
01583500	21.1	26.2	30.8	35.3	43.5	52.8	48.7	41.4	31.9	22.8	18.9	17.3	31.5	7.1
01583570	0.050	0.060	0.070	0.070	0.080	0.090	0.090	0.070	0.050	0.030	0.020	0.030	0.053	5.5
01583580	0.38	0.45	0.56	0.63	0.78	0.99	1.00	0.90	0.56	0.29	0.21	0.22	0.483	4.4
01584050	2.89	3.76	4.47	5.26	6.80	7.75	7.59	6.06	4.80	3.48	2.76	2.51	4.86	7.1
01584500	13.5	17.2	20.5	23.4	26.6	32.6	30.5	26.1	19.2	14.4	13.1	11.4	18.1	6.8
01585100	1.38	2.08	2.59	2.64	3.46	3.68	3.52	2.63	1.68	1.19	0.93	0.95	2.56	4.6
01585200	0.31	0.43	0.60	0.65	0.91	0.93	0.93	0.76	0.6	0.37	0.28	0.26	0.642	4.0
01586210	4.38	5.79	7.06	8.2	10.9	13.4	13.0	9.69	6.65	4.59	3.67	3.22	8.51	8.2
01586610	7.94	10.9	13.6	15.8	21.2	25.9	26.1	20.1	14.4	9.26	6.95	5.91	16.1	7.8
01589100	0.56	0.67	0.79	0.89	1.22	1.29	1.22	0.91	0.78	0.65	0.53	0.52	0.877	4.9
01589300	9.06	12.6	15.0	16.7	19.4	22.0	22.2	17.3	12.7	9.07	7.63	6.54	13.9	5.8
01589330	0.55	0.80	1.12	1.31	1.54	1.92	1.72	1.29	0.93	0.68	0.51	0.51	1.25	3.1
01591000	7.42	10.9	14.8	17.8	22.3	29.1	27.1	20.7	13.2	7.9	6.04	5.47	15.7	6.1
01591400	5.50	8.06	11.0	12.1	16.6	17.4	16.5	13.0	9.14	6.08	4.27	3.92	10.7	6.4
01591700	4.41	7.83	11.8	13.6	17.4	20.7	19.5	15.0	8.72	5.15	3.21	3.16	11.6	5.8

Table 5. Estimated 7-day, 10-year low-flow statistics and parameters of the log-Pearson Type III distribution for index streamgages used to estimate streamflow statistics at the low-flow partial-record stations.

[7-day, 10-year low flows are in units of cubic feet per second; means, standard deviations, skews, and K factors are in log-base 10 units]

Station number	7-day, 10-year low flow	Mean	Standard deviation	Skew	K factor	Years of record
01493000	3.22	0.816	0.288	-3.469	-1.071	58
01493500	1.71	0.508	0.206	-0.665	-1.329	54
01495000	8.73	1.252	0.233	-1.019	-1.335	75
01580000	22.9	1.634	0.208	-1.453	-1.324	81
01581500	0.258	-0.018	0.430	-1.386	-1.327	28
01581700	5.59	1.139	0.312	-2.239	-1.256	40
01582000	12.5	1.375	0.209	-0.666	-1.329	63
01583100	2.51	0.707	0.231	-1.229	-1.332	17
01583500	10.7	1.348	0.238	-0.851	-1.334	63
01583570	0.016	-1.354	0.325	-0.437	-1.318	12
01583580	0.168	-0.392	0.289	-0.542	-1.324	13
01584050	1.59	0.508	0.237	-0.164	-1.298	32
01584500	6.59	1.139	0.246	-1.797	-1.301	53
01585100	0.452	-0.022	0.247	-0.265	-1.306	45
01585200	0.092	-0.564	0.468	-3.846	-1.012	39
01586210	1.54	0.584	0.298	-1.396	-1.326	25
01586610	2.98	0.869	0.297	-0.823	-1.333	26
01589100	0.346	-0.222	0.186	-0.037	-1.285	40
01589300	3.75	0.890	0.239	-0.498	-1.322	42
01589330	0.276	-0.261	0.231	-0.100	-1.292	36
01591000	1.85	0.811	0.413	-1.594	-1.316	64
01591400	1.24	0.666	0.432	-1.392	-1.326	30
01591700	0.972	0.574	0.440	-1.210	-1.332	29

Maintenance-of-Variance Extension (MOVE1) Method

Before the MOVE1 method is applied, a graph of the logarithms-base 10 of the streamflow measurements for the LFPR station (Y_i) and the logarithms-base 10 of the same-day mean streamflows for the index streamgage (X_i) is constructed to ascertain the linearity of the relation. The correlation coefficient, r, also is computed as an indicator of linearity using:

$$r_{X_iY_i} = \frac{\sum (X_i - \overline{X})(Y_i - \overline{Y})}{(n-1)s_x s_y} \quad (1)$$

where $\overline{X}$ and $\overline{Y}$ are the means, s_x and s_y are the standard deviations of X_i and Y_i, and n is the number of concurrent streamflows (Iman and Conover, 1983). If the relation appears linear, then estimates of the logarithms-base 10 of the streamflow statistics (Y_j) for the LFPR station are obtained by use of the MOVE1 equation:

$$\hat{Y}_j = \overline{Y} + \frac{s_y}{s_x}(X_j - \overline{X}) \quad (2)$$

where X_j are the logarithms-base 10 of the streamflow statistics computed from available data at the index streamgage, and all other variables are as previously defined (Hirsch, 1982). The estimates are then retransformed by exponentiation ($10^{\hat{Y}_j}$) to convert the estimates into their original units of measurement, cubic feet per second.

The MOVE1 relation between LFPR station 01583200, Blackrock Run at Coopersville, and index streamgage 01583500, Western Run at Western Run, MD, is shown in figure 3. The line through the data points was determined by inserting the same-day streamflows for the index streamgage (X_i) into the MOVE1 equation in place of the streamflow statistics for the index streamgage (X_j) shown in equation 2 to obtain estimated same-day streamflows for the LFPR station ($\hat{Y}_l$), and then connecting the points to illustrate how the MOVE1 estimates fit the original data.

An indicator of the errors associated with the MOVE1 estimates can be obtained by computing the mean-squared error (MSE) of the estimates of instantaneous streamflow ($\hat{Y}_l$) at the LFPR determined from the MOVE1 relation. The MSE is computed as:

$$MSE_M = \sum_{i=1}^{n} (\hat{Y}_l - Y_i)^2 / (n-2) \quad (3)$$

The MSE_M is a sample estimate of the model variance of the MOVE1 relation. Estimates of streamflow statistics determined from the MOVE1 relations will have somewhat greater errors than the indicated MSE values because the values do not account for sampling errors associated with the limited data available to establish the relation and to compute the streamflow statistics for the index streamgages. The MSE

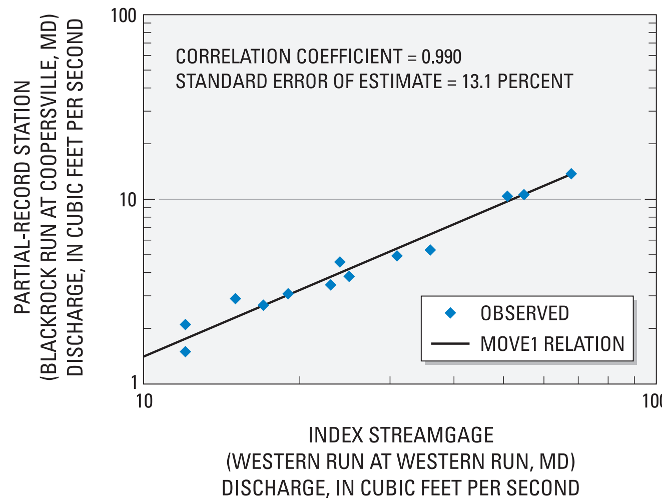

Figure 3. MOVE1 relation between low-flow partial-record station 01583200, Blackrock Run at Coopersville, MD, and index streamgage 01583500, Western Run at Western Run, MD.

also does not account for errors associated with obtaining the streamflow measurements at the LFPR stations.

Moments Method

The Moments method developed by Stedinger and Thomas (1985) is applicable only for estimating low-flow-frequency statistics. As a result, it was useful only to estimate 7-day, 10-year low-flow frequency statistics for this study. In this method, ordinary-least-squares regression analysis is used to fit a line of relation between the base-10 logarithms of the streamflow measurements at a LFPR station and the base-10 logarithms of the same-day streamflows at an index streamgage. This linear relation is then used to obtain sample estimates of base-10 logarithms of the mean (μ) and standard deviation (σ) of the annual minimum N-day low flows at the LFPR station. Stedinger and Thomas (1985) provided equations that can be used to adjust the sample estimates to obtain unbiased estimates of the parameters. Estimates of base-10 logarithms of the low-flow-frequency statistics can be computed by inserting the unbiased parameter estimates into the equation:

$$Y_T = \mu + K_T\sigma \quad (4)$$

where Y_T is the base-10 logarithm of the annual minimum N-day mean flow that is exceeded, on average, once in T years, and K_T is a frequency factor for the log-Pearson Type III distribution that depends on the skew of the annual minimum N-day low flows and the recurrence interval to be estimated. Stedinger and Thomas (1985) showed that it is reasonable to assume that the K_T for the LFPR station is the same as the K_T for the index streamgage, and they provide an equation for computing the variance of the Y_T estimate. Estimates from equation 4 can be retransformed by exponentiation (10^{Y_T}) to obtain estimates in units of cubic feet per second.

Q-Ratio Method

Potter (2001) developed a method by which a base-flow statistic is estimated as the product of the base-10 logarithm of the computed statistic at the index streamgage and the geometric mean of the base-10 logarithms of the ratios of the measured base-flow discharges and the concurrent discharges at the index streamgage. Potter (2001) assumed a bivariate normal distribution for the flows at the assumed LFPR station and the index streamgage. The method was used to estimate the median daily discharge, the 0.90 quantile of daily streamflow, and the mean base flow for two watershed pairs in Wisconsin. Potter (2001) obtained estimates with low standard error and low bias when the log-transformed streamflows for the stations were highly correlated and had nearly equal variances, but results were not as good when these conditions did not exist.

The modified Q-ratio approach by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008) was applied in this study. This method does not assume a bivariate normal distribution. As a result, logarithmic transformations are not done on the computed streamflow statistic at the index streamgage or on the ratios of the concurrent streamflows, thus allowing application of the method at locations with zero-flow values. Estimates obtained by use of the Q-ratio approach are determined by

$$\hat{Y}_j = WX_j \tag{5}$$

where W is calculated as

$$W = \frac{1}{n}\sum_{i=1}^{n}\frac{Y_i}{X_i} \tag{6}$$

and n is the total number of concurrent measurements between the LFPR and index streamgage. The MSE was calculated by

$$MSE_Q = \sum\nolimits_{i=1}^{n}(\hat{Y}_i - Y_i)^2 \,/\, (n-2) \tag{7}$$

where MSE_Q is a sample estimate of the model variance of the Q-ratio method estimates.

Index-Streamgage Selection

The USGS provides no official guidance on selecting index streamgages to estimate low-flow statistics for LFPR stations, and various researchers have used different selection methods. For example, Stedinger and Thomas (1985) based selection on similar drainage areas and base-flow recession characteristics. Riggs (1972) suggested selecting an index streamgage with concurrent streamflows that are directly proportional to those at the LFPR station. Potter (2001) suggested that selection of an index streamgage should be based on the similarity of the variances determined from the logarithms of the continuous base-flow records at the index streamgage and LFPR station, but this guidance is useful only if some continuous streamflow record is available for the LFPR station. Reilly and Kroll (2003) estimated 7Q10s and the associated variances for LFPR stations using multiple index streamgages that were selected on the basis of geographic proximity and similarity of basin characteristics. The estimates for the LFPR stations with the lowest variances were then used as the final estimates for the LFPR stations. Ries and Friesz (2000) also estimated 7Q10s, as well as other low-flow statistics, and their associated variances for multiple index streamgages selected on the basis of having correlation coefficients of at least 0.80, and obtained final estimates by weighting the estimates obtained from the relations with each index streamgage according to the variances of the estimates. Eng and Milly (2007) suggested that, as an alternative to either matching or minimizing statistical properties, a better method for selecting a single index streamgage would be based on variables derived from base-flow analysis, such as the base-flow-recession time constant, τ, that can be calculated at LFPR stations.

Eng and Milly (2007) defined τ as the long-term recession rate of streamflow from groundwater discharge. Streamflows during base-flow periods will decline more slowly in streams with large τ values compared to streams with small τ values. Streams with similar τ values can be expected to decline at similar rates. Eng and Milly (2007) explain in detail the physical basis for τ and provide the following equation for computing τ, in units of days:

$$\tau = \frac{J\Delta t}{ln\,Q_j - ln\,Q_{j+J}} \tag{8}$$

where Q_j is the daily streamflow on day j, Q_{j+J} is the streamflow on day $j + J$, J is the number of days between two streamflow measurements made on a single recession, and Δt is the length of 1 day. This equation is used to compute τ from each pair of measurements made on the same recession at the LFPR stations, and the values from the individual recessions are averaged to obtain the final τ values for the LFPR stations.

A computer program developed by Ken Eng (U.S. Geological Survey, written commun., 2009) was used in this study to select index streamgages by either maximizing the correlation coefficient or minimizing the Euclidean distance metric, R_i, from the LFPR station to index streamgage i, where R_i is a function of geographic proximity, τ, and other basin characteristics (Eng, Milly, Tasker, and Gruber-Veilleux, U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008). R_i is computed by

$$R_i = \Big[\sum_{k=1}^{p}\Big(\frac{\log\omega_k - \log\omega_{ki}}{\sigma_{\log\omega_k}}\Big)^2\Big]^{1/2} \quad (9)$$

where k is a basin characteristic from 1 to p, p is the total number of basin characteristics, ω is a selected basin characteristic, and $\sigma_{\log\omega_k}$ is the regional standard deviation of the k^{th} basin characteristic. The geographic proximity is included as a basin characteristic in equation 9. The selection process first established a subset of all available index streamgages whose geographic proximity was within the specified limit of 140 km (kilometers). From this subset, R_i values were calculated between the LFPR site and each candidate index site, and the candidate index site associated with the lowest R_i value was selected.

The program allows specification of a maximum geographic proximity, and whether or not to include any of up to four basin characteristics in the selection process. A maximum physiographic proximity of 140 km was used for this study to avoid spurious index-station selections. The basin characteristics used for this study were drainage area, percentage of forested area, percentage of impervious surfaces, and τ.

The program first establishes the subset of all available index streamgages whose geographic proximity is within the specified limit and then calculates the R_i values between the LFPR station and each candidate index streamgage. The candidate index streamgage associated with the lowest R_i value is then used to estimate the low-flow statistics for the LFPR station using all three estimation methods described above. The program also computes the estimators of the model variances of the estimated low-flow statistics. Program runs were made for each LFPR station using both station-selection methods and the results were compared to determine the best estimates for each LFPR station. The τ values used for the index streamgages in equation 9 were the averages of τ values computed from the daily mean streamflows at the index streamgages on the same days that were used to compute the average τ values for the LFPR stations. This differs from the approach that Eng and Milly (2007) used, which is to use the average of τ values calculated from 400 independent recessions made at random from the daily mean streamflows at the index streamgage. The average index-streamgage τ values computed from the days of concurrent streamflows provides a more direct comparison of τ under the conditions when the measurements were made than comparing the LFPR station τ to the average index streamgage τ computed from 400 random recessions.

Regression analyses were run to determine whether the basin characteristics chosen for use in the index-station selection process were actually important in explaining the variation in the streamflow statistics of interest for this study. Streamflow statistics and the basin characteristics—drainage area, percent forested land area, percent impervious surfaces, and τ—for each index streamgage were used to develop a regression equation for each streamflow statistic. The equations were in the form of:

$$Q = aDA^b F^c (I+1)^d \tau^e \quad (10)$$

where Q is the streamflow statistic, a is the regression constant, DA is the drainage area, in square miles, F is the percentage of forested area in the basin, I is the percentage of impervious surfaces in the basin, τ is as previously defined, and b, c, d, and e are regression coefficients. Results from the regression analyses are shown in table 6.

P-values were used to determine if the regression constants and exponents in the equations were statistically significant. The p-values are shown for each equation in table 6 on the line below the listing of the equation. The p-values indicate the probability that there is no real relation between the streamflow statistic and the regression-equation parameter. Statistical significance was assumed at a maximum p-value of 0.05, which indicates a 5-percent probability of erroneously accepting the variable as statistically significant. The regression constant and drainage area were statistically significant in each of the regression equations. The percentage area of forest was statistically significant for the October through January 85-percent duration flows. The percentage of impervious area was statistically significant for the February through May 85-percent duration flows and the 10-year base flow. τ was statistically significant for the October through January and May through September 85-percent duration flows, as well as for the 7Q10.

The equations in table 6 were developed only as a means of determining which variables to include in the index-station selection process. As all of the variables were statistically significant for at least some of the statistics, all of the variables were used as criteria for selecting index streamgages. The equations could potentially be used to estimate the streamflow statistics for ungaged sites in the study area, except that τ cannot be computed for ungaged sites. Only the equations for the February through April 85-percent duration flows and the 10-year base flow do not include the τ variable.

The R^2_{adj} values in table 6 are the adjusted coefficients of determination, which state the percentage of the variation in the streamflow statistics used as the dependent variables in the equations that is explained by the variation in the basin characteristics used as the explanatory variables. The R^2_{adj} values are adjusted for the number of streamgages and the number of explanatory variables used to develop the equations. These values were all were very high, ranging from 95.8 for the 7Q10 to 99.6 for the January 85-percent duration flow.

In addition to the R^2_{adj} values, other indicators of the accuracy of the equations provided in table 6 are the average standard errors of estimate (ASEE) and prediction (ASEP), both given in percent. The ASEE is an indication of the model error, and is determined from the differences between the observed values of the streamflow statistics for the streamgages and the values estimated from the regression equations. Approximately two-thirds of the estimates had errors that were within the given average ASEE, which ranged from 40.2 percent for the 7Q10 to 11.9 percent for the January 85-percent duration flow. The ASEP is an indicator of the error

Table 6. Regression constants and basin-characteristic exponents for equations for estimating monthly 85-percent duration flows, 10-year recurrence interval minimum base flows, and 7-day, 10-year low flows, with indicators of the accuracy of the equations.

[All streamflow statistics are in units of cubic feet per second; regression constants (a) and exponents (b), (c), (d), and (e) are unitless; red values on second lines are p-values associated with the regression coefficients; adjusted R^2 is the proportion of the variation in the dependent variable that is explained by the explanatory variables, adjusted for the number of stations used in the analysis and the number of explanatory variables; t is the base-flow recession constant; ASEE is the average standard error of estimate; ASEP is the average standard error of prediction.]

Statistic	(a) Constant	(b) Drainage area (square miles)	(c) Forest Area (percent)	(d) Impervious area (percent + 1)	(e) τ (days)	Adjusted R^2 (percent)	ASEE (percent)	ASEP (percent)
October 85-percent flow	-2.837	1.009	0.131		1.28	98.68	20.9	29.5
	0.000	0.000	0.044		0.001			
November 85-percent flow	-2.182	1.034	0.142		0.93	99.27	17.2	26.1
	0.000	0.000	0.012		0.003			
December 85-percent flow	-1.556	1.039	0.141		0.600	99.53	13.6	22.1
	0.000	0.000	0.003		0.011			
January 85-percent flow	-1.412	1.059	0.139		0.53	99.58	11.9	18.8
	0.000	0.000	0.001		0.010			
February 85-percent flow	-0.179	1.064		-0.145		99.19	16.4	21.8
	0.000	0.000		0.000				
March 85-percent flow	-0.110	1.077		-0.166		99.47	13.6	17.4
	0.008	0.000		0.000				
April 85-percent flow	-0.113	1.07		-0.173		99.37	15.6	19.7
	0.011	0.000		0.000				
May 85-percent flow	-0.986	1.067		-0.149	0.47	99.47	13.5	17.7
	0.050	0.000		0.001	0.049			
June 85-percent flow	-2.396	1.065			1.2	99.08	17.9	23.9
	0.000	0.000			0.000			
July 85-percent flow	-2.788	1.089			1.32	99.07	19.8	24.8
	0.000	0.000			0.000			
August 85-percent flow	-3.299	1.109			1.56	98.46	24.8	28.9
	0.000	0.000			0.000			
September 85-percent flow	-3.380	1.045			1.64	98.38	24.1	30.6
	0.000	0.000			0.000			
10-year base flow	-0.368	1.083		-0.117		99.16	17.5	21.1
	0.000	0.000		0.005				
7-day, 10-year low flow	-4.952	1.007			2.46	95.84	40.2	46.5
	0.000	0.000			0.000			

associated with estimating the streamflow statistics for locations other than the streamgages used to develop the equations, including the locations of LFPR stations. Approximately two-thirds of the estimates for these ungaged locations will have errors that are within the given ASEP, which ranged from 46.5 percent for the 7Q10 to 17.4 percent for the March 85-percent duration flow.

Weighting of Independent Estimates

The Interagency Advisory Committee on Water Data (IACWD) (1982) showed that if two independent flood-frequency estimates are available for a streamgage, then an improved estimate can be obtained for the streamgage by computing the weighted average of the independent estimates using the equation:

$$z = \frac{xV_y + yV_x}{V_y + V_x} \quad (11)$$

where z is the logarithm of the weighted flood-frequency estimate, x and y are the logarithms of the two independent flood-frequency estimates, and V_x and V_y are the variances of those estimates, in units of squared logarithms. The variance of the resulting improved estimate will be less than the variance for either of the independent estimates, and is computed using the equation:

$$V_z = \frac{V_x V_y}{V_x + V_y} \quad (12)$$

where V_z is the variance of the weighted estimate. The above equations are applicable not just to flood-frequency estimates for streamgages, but also to independent estimates of any streamflow statistic for a LFPR station.

An analysis was done to investigate the potential independence of the MOVE1, Moments, and Q-ratio methods used for estimating streamflow statistics for this study. The analysis was done using resampling techniques on the daily time series for the 23 index streamgages and treating them as LFPR stations. This method was first applied by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008), and is summarized here. All independent recessions of at least 8 days or longer were identified from daily time-series for the index streamgages. The first 5 days of each recession were truncated and then daily mean streamflows for a pair of days were randomly selected as simulated LFPR streamflow measurements. The truncation was done to avoid selection of daily mean streamflows that may be affected by channel storage and direct runoff contributions. The sensitivity of performance to the number of measurements, n, was explored by varying n across the values 2, 3, 4, 5, 6, 7, 8, 10, 15, and 18, which are the values of n at the LFPR stations in this study (see tables 1 and 2). The sampling of the time series described above was repeated 500 times for each value of n to obtain robust error statistics. Maximum correlation among concurrent streamflow measurements and hybrid space of geographic proximity and basin characteristics were used to select index streamgages. For each value of n, the Moments method, MOVE1, and the Q-ratio methods were applied to calculate estimates of the 7Q10. This process was repeated using the remaining 499 datasets. For each LFPR station, 500 residuals were computed by subtracting the estimated 7Q10 (log-base 10) from the computed 7Q10 (log-base 10) at the station that is treated as a LFPR station.

As an example, the averages of the 500 squared errors across the 23 simulated LFPR stations (actual index streamgages) using the MOVE1 method ranged from 0.0011 to 0.22, with an arithmetic regional average of 0.048 for n equal to 18. This regional average variance reflects the errors that can be expected when applying the MOVE1, Moments, and (or) Q-ratio methods at a real LFPR station with 18 streamflow measurements. The simulated LFPR stations with large average squared errors relative to the regional average of 0.048 were stations that did not have index streamgages with hydrologically similar basins nearby, as defined by the hybrid space or by maximum correlation of concurrent streamflows of less than 0.75. In this study, all actual LFPR stations had a hydrologically similar basin nearby (average correlation coefficient equal to 0.968).

Graphs of the relations between the residuals from each estimation method, shown in figure 4, were used to evaluate independence among them. Regression equations and coefficients of determination (R^2) are included in the graphs in figure 4 to explain the relations, where y is the dependent variable shown on the y axis of the graphs and x is the explanatory variable shown on the x axis. The R^2 values are a measure of the proportion of the variation in y that is explained by the variation in x. Results showed that the Moments and MOVE methods produce highly correlated estimates, indicating that the methods are not independent. Estimates from the Q-ratio method are independent from both the Moments and MOVE methods, however. The correlation between the Moments and MOVE methods is not unexpected, as both methods use the same streamflow data and a line-fitting technique to determine the estimates. The Q-ratio method uses different streamflow data and does not rely on a line-fitting technique to determine the estimates. As a result, it also is not unexpected that the Q-ratio method would give estimates that are independent from the Moments and MOVE estimates.

In application of the weighting method, the variances for the Q-ratio estimates from index-streamgage selection based on geographical proximity and similarity of basin characteristics were compared to the variances for the estimates from index-station selection based on correlation coefficients. The Q-ratio estimates with the lower variances were used in the weighting process along with the MOVE1 or Moments estimates for the LFPR station that had the lowest variance.

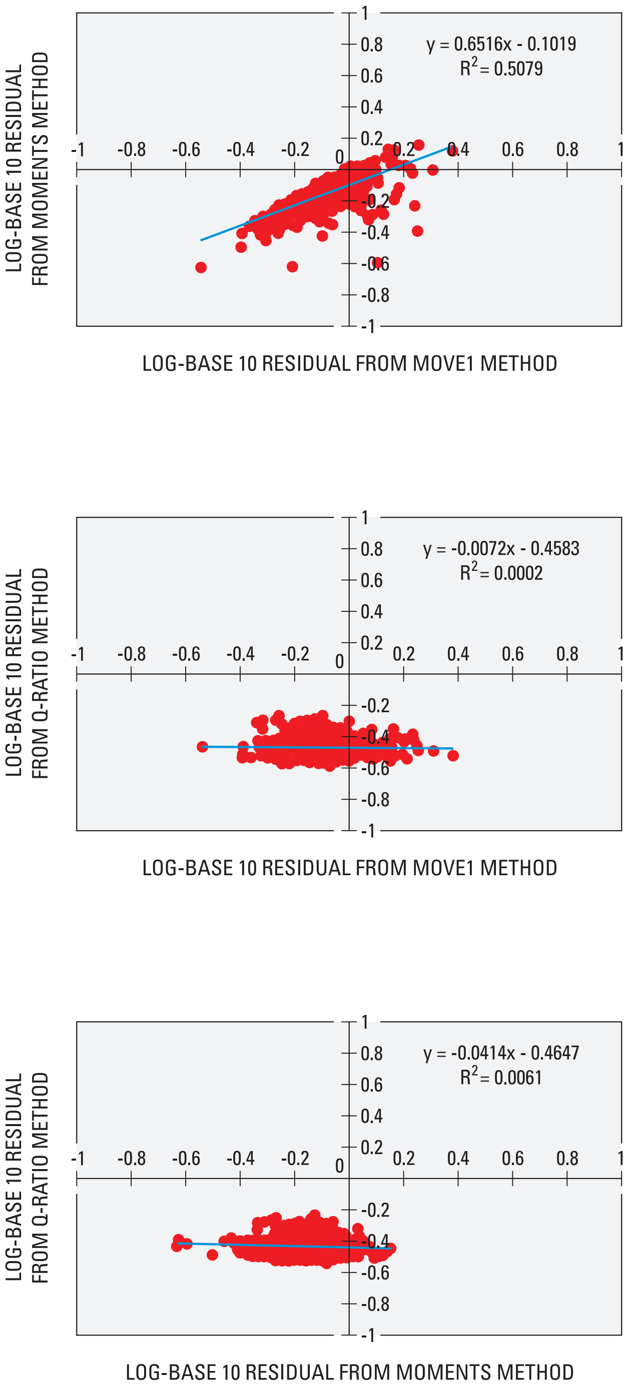

Figure 4. Relations between log-base 10 residuals from the Moments, MOVE1, and Q-ratio methods for estimating 7-day, 10-year flows for index streamgages in the study area. [Equations relate the dependent variables on the y axis to the explanatory variables on the x axis. R^2 is the coefficient of determination, a measure of the proportion of the variation in the dependent variable that is explained by the explanatory variable.]

Estimates of the Selected Streamflow Statistics and Comparison of Estimates from Different Methods

Estimates of the selected streamflow statistics determined from the three different estimation methods and the two different index-streamgage selection methods are provided in tables 7 and 8. Ideally, tables 7 and 8 would be combined to facilitate comparisons of estimates across all methods, but it was not possible to fit the combined table on the width of a single landscaped page. Estimates for the LFPR stations determined based on relations developed with index streamgages that were selected on the basis of geographic proximity and similarity of basin characteristics are provided in table 7. For each LFPR station listed in the table, the following are included: the total number of streamflow measurements and the number of pairs of measurements that were available for the analyses, the average τ value computed from the paired measurements, the selected index streamgage, the straight-line distance from the LFPR station to the index streamgage, the distance ranking of the index streamgage, estimates of the 14 streamflow statistics—monthly 85-percent duration flows, the 10-year base flow, and the 7Q10—determined from the three estimation methods, and the respective ASEEs. The ASEEs displayed in tables 7 and 8, in units of percent, were converted from variances (for the Moments method) and MSEs (for the MOVE1 method), in units of squared base-10 logarithms, to be more easily understood by use of the equation:

$$ASEE = 100 \times \sqrt{\exp(5.3018V) - 1} \qquad (13)$$

where V is the variance or MSE computed for the estimate (Stedinger and Thomas, 1985). All statistics determined from each estimation method for an individual station have the same ASEE. MOVE1 estimates were provided only when six or more measurements were available for computation. The Moments method could be used only to obtain estimates of the 7Q10, and only when eight or more measurements were available for computation.

Estimates of the streamflow statistics for the LFPR stations determined from relations developed with index streamgages that were selected on the basis of maximum correlation coefficient are provided in table 8. For each LFPR station listed in the table, the following are included: the selected index streamgage, its distance, distance rank, the correlation coefficient, the estimated streamflow statistics determined from the three estimation methods (where applicable), the weighted estimates, and the respective ASEEs. Where available, the weighted estimates are the best estimates available for the stations. The weighted estimates of the streamflow statistics were determined by combining the best Q-ratio estimates from either of the two index-station selection approaches with the best estimates from either of the other two estimation methods, based on the minimum variance of the estimates. The weighted estimates and their variances were computed using equations 11 and 12, and the estimated streamflow statistics that are shaded in gray for each LFPR station in either table 7 or table 8. The estimates used to determine the final weighted estimates are sometimes listed in different tables. For example, the weighted estimates determined for LFPR station 01579925 (Little Deer Creek near Federal Hill, MD) were determined by weighting the Q-ratio estimates from table 7 with the MOVE1 estimates from table 8, with the exception of the weighted estimate for the 7Q10, which was determined by weighting the Q-ratio estimate from table 7 with the Moments estimate from table 8. The variances of the weighted estimates that are shown in tables 7 and 8 were converted to ASEEs using equation 13. The maximum correlation index-station selection method was used only when at least six concurrent streamflows were available from which to compute the correlations. As a result, weighted estimates were not available for 12 of the 20 LFPR stations.

The number of streamflow measurements used to estimate the streamflow statistics often was less than the total number of measurements that were available at the LFPR stations because the index streamgages were not always in operation during times when measurements were made at the LFPR stations. In addition, when paired measurements were made, only the first of the two measurements was used to estimate streamflow statistics with the MOVE1 and Moments methods because an assumption for those methods is that the measurements are not correlated. Only estimates from the Q-ratio method were available for the new LFPR stations that were established for this study, as a maximum of five measurements were made at those stations. All concurrent measurements were used to compute the Q-ratio estimates, as an assumption of independence of the measurements is not required for that method. An estimate of the 10-year base flow is not available for LFPR station 01581985 (Second Mine Branch at White Hall, MD) because this statistic was not computed by MDE for the selected index streamgage, station 01583100 (Piney Run at Dover, MD).

Estimates were determined using the Q-ratio method for all 20 LFPR stations when station selection was based on geographic proximity and similarity of basin characteristics. As a minimum of six concurrent streamflow measurements were required for index-streamgage selection based on the maximum correlation coefficient, estimates were obtained for only eight LFPR stations using that selection method. An average of 4.4 measurements was available when selection was based on geographic proximity and similarity of basin characteristics, whereas an average of 10.8 measurements was available when selection was based on the correlation coefficient.

Moments estimates were available for only two LFPR stations and MOVE1 estimates were available for only three LFPR stations when selection was based on geographic proximity and similarity of basin characteristics because the number of concurrent streamflow measurements available was less than the minimum number required. Averages of the ASEE values for all available estimates from this index-streamgage selection method were 22.9 percent for the Moments method, 33.3 percent for the MOVE1 method, and 41.2 percent for the Q-ratio method. The average of the ASEE values for the Q-ratio method is based on 17 LFPR stations because only two measurements were available for 3 of the 20 LFPR stations, making computation of the ASEEs for those LFPR stations impossible. Estimates were available from all three estimation methods for only two stations when this index-station selection method was used. The averages of the ASEE values for these two stations were 22.9 percent for the Moments, 13.0 percent for the MOVE1, and 25.8 percent for the Q-ratio methods.

Moments estimates were available for five LFPR stations and MOVE1 and Q-ratio estimates were available for eight LFPR stations when selection was based on the correlation coefficient. Averages of the ASEE values for all available estimates from this index-streamgage selection method, were 14.2 percent for the Moments, 23.6 percent for the MOVE1, and 32.1 percent for the Q-ratio methods. Estimates were available from all three estimation methods for five stations when this index-streamgage selection method was used. The averages of the ASEE values for these five stations were 14.2 percent for the Moments, 17.4 percent for the MOVE1, and 26.5 percent for the Q-ratio methods.

When the estimates from all three estimation methods are combined for the two index-station selection methods, a total of seven comparisons between the estimation methods are available. The averages of the ASEE values for these five stations are 16.7 percent for the Moments method, 16.2 percent for the MOVE1 method, and 26.3 percent for the Q-ratio method.

Weighted estimates were computed for eight LFPR stations in the manner described above. The estimates from the Moments, MOVE1, or Q-ratio methods that were used to compute the weighted estimates are shaded gray in tables 7 and 8. The average of the ASEE values for the weighted estimates is 15.5 percent. In comparison, the average of the ASEE values for the best individual estimate for these eight LFPR stations is 19.8 percent, indicating that ASEEs were reduced an average of 4.3 percent as a result of weighting. The average of the ASEE values for the best estimates available for all 20 LFPR stations ranged from 90.0 percent to 7.0 percent, with an average ASEE of 26.5 percent. This does not include the three LFPR stations for which errors from the Q-ratio method could not be computed because too few measurements were available.

Direct comparisons were not possible between the errors associated with the estimates obtained for the LFPR stations for this study and the errors associated with estimates obtained from the regression equations published by Carpenter and Hayes (1996). It was possible to compute only ASEEs for the estimation methods used in this study, whereas Carpenter and Hayes (1996) published only ASEPs for their regression equations. Usually, ASEPs are a few percentage points higher than ASEEs. The ASEPs that apply to the four hydrologic regions (Eastern Piedmont region, subregions A to D) from Carpenter and Hayes (1996) that are within the study area for this study range from 20 to 44 percent.

An examination of differences in the performance of the index-streamgage selection methods was made using a limited dataset of 20 sets of estimates from selection of index streamgages based on geographic proximity and basin characteristics and 8 sets of estimates from selection of index-stations based on the correlation coefficient. Average distances between the LFPR station and the selected index streamgage were 16.1 miles when index-streamgage selection was based on the correlation coefficient, and 39.9 miles when index-streamgage selection was based on geographic proximity and similarity of basin characteristics. When the 23 potential index streamgages were ranked according to distance from the LFPR station, the average distance ranking was 5.0 for index streamgages selected based on the correlation coefficient, whereas the average distance ranking was 13.0 for index streamgages selected based on geographic proximity and basin characteristics. The closest station was never selected when selection was based on geographic proximity and similarity of basin characteristics, but the closest station was selected four of eight times when station selection was based on the correlation coefficient.

When comparisons were made using only the eight LFPR stations that had estimates available from both index-streamgage selection methods, the average distances between the LFPR station and the selected index streamgage were 16.1 miles when station selection was based on the correlation coefficient, and 44.6 miles when station selection was based on geographic proximity and similarity of basin characteristics. The average distance rankings between the LFPR station and the selected index streamgage were 5.0 when station selection was based on the correlation coefficient and 14.0 when station selection was based on geographic proximity and similarity of basin characteristics. Paired, one-sided t-tests of the direct comparisons of distance and distance rankings indicated distances were significantly closer ($p = 0.013$) and distance rankings were significantly higher ($p = 0.007$) for the correlation-coefficient selection method than for the geographic proximity and basin-characteristics selection method. Probability plots were used to assure that the assumption of normality of the data required for use of the t-tests was valid. These results should be qualified by the very small sample size of eight observations. It is possible that different results could be obtained with more index streamgages for comparison or with index streamgages located in areas that are hydrologically different from the study area. Future studies could attempt to improve the results by modifying equation 9 to give more weight to the geographic proximity or by reducing the maximum distance allowed for selection from 87 miles (140 kilometers) to a smaller value. Currently, all parameters are weighted equally in equation 9.

The fact that one index-streamgage selection method generally selects index streamgages that are closer to the LFPR station than another method does not necessarily indicate that the estimates for the method that selects closer index streamgages are more accurate than the estimates for the other method. For example, an index streamgage on a nearby tributary stream with basin characteristics similar to those for a LFPR station also on a tributary stream is likely to be a better match for the LFPR station than an index streamgage that is geographically closer but on the much larger main stream. In Maryland, a nearby index streamgage that is located in the Piedmont physiographic region is likely to be a better match for a LFPR station that is also in the Piedmont physiographic region than a geographically closer index streamgage that is in the Coastal Plain physiographic region because the hydrology of the two physiographic regions is different.

A comparison of the errors in the estimates obtained from the two index-station selection methods is a better way to examine the relative performance of the methods, but direct comparisons of the errors could only be made for 7Q10 estimates obtained from the Q-ratio method. Direct comparisons of the errors could not be made for the other two flow-estimation methods because different index streamgages were chosen by the two station-selection methods and the numbers of streamflow measurements that were available at the different index streamgages were not the same. In the eight direct comparisons between Q-ratio estimates obtained from the two different station-selection methods, the ASEE was 32.1 percent for the Q-ratio estimates obtained when index-station selection was based on the correlation coefficient, whereas the ASEE was 46.6 percent when index-station selection was based on geographic proximity and basin characteristics. Although this 14.5-percent difference in ASEE between the methods is fairly large, a t-test indicated the difference is not statistically significant ($p = 0.158$).

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measure-ments	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 esti-mate	MOVE1 ASEE	Q-ratio esti-mate	Q-ratio ASEE
01494995	9	1	11.0	Oct. 85%	01591700	89.1	22	7			0.663	73.7	0.625	63.7
				Nov. 85%							1.13	73.7	1.11	63.7
				Dec. 85%							1.65	73.7	1.67	63.7
				Jan. 85%							1.88	73.7	1.93	63.7
				Feb. 85%							2.36	73.7	2.47	63.7
				Mar. 85%							2.77	73.7	2.94	63.7
				Apr. 85%							2.62	73.7	2.77	63.7
				May 85%							2.05	73.7	2.13	63.7
				June 85%							1.24	73.7	1.24	63.7
				July 85%							0.765	73.7	0.73	63.7
				Aug. 85%							0.494	73.7	0.455	63.7
				Sept. 85%							0.487	73.7	0.448	63.7
				BaseFlow10yr							1.62	73.7	1.65	63.7
				7Q10							0.164	73.7	0.138	63.7
01495980	3	1	4.1	Oct. 85%	01583570	49.0	14	3					7.39	51.3
				Nov. 85%									8.87	51.3
				Dec. 85%									10.3	51.3
				Jan. 85%									10.3	51.3
				Feb. 85%									11.8	51.3
				Mar. 85%									13.3	51.3
				Apr. 85%									13.3	51.3
				May 85%									10.3	51.3
				June 85%									7.39	51.3
				July 85%									4.44	51.3
				Aug. 85%									2.96	51.3
				Sept. 85%									4.44	51.3
				BaseFlow10yr									7.84	51.3
				7Q10									2.37	51.3

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measure-ments	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 esti-mate	MOVE1 ASEE	Q-ratio esti-mate	Q-ratio ASEE
01496020	4	2	5.8	Oct. 85%	01583580	53.5	13	4					1.00	90.0
				Nov. 85%									1.19	90.0
				Dec. 85%									1.48	90.0
				Jan. 85%									1.67	90.0
				Feb. 85%									2.06	90.0
				Mar. 85%									2.62	90.0
				Apr. 85%									2.64	90.0
				May 85%									2.38	90.0
				June 85%									1.48	90.0
				July 85%									0.767	90.0
				Aug. 85%									0.555	90.0
				Sept. 85%									0.582	90.0
				BaseFlow10yr									1.28	90.0
				7Q10									0.444	90.0
01496060	10	1	10.8	Oct. 85%	01583580	50.4	13	4					0.598	107
				Nov. 85%									0.708	107
				Dec. 85%									0.881	107
				Jan. 85%									0.991	107
				Feb. 85%									1.23	107
				Mar. 85%									1.56	107
				Apr. 85%									1.57	107
				May 85%									1.42	107
				June 85%									0.881	107
				July 85%									0.456	107
				Aug. 85%									0.330	107
				Sept. 85%									0.346	107
				BaseFlow10yr									0.760	107
				7Q10									0.264	107

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measurements	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 estimate	MOVE1 ASEE	Q-ratio estimate	Q-ratio ASEE
01496250	10	2	9.9	Oct. 85%	01591400	69.5	22	8			1.330	11.6	1.16	15.0
				Nov. 85%							1.870	11.6	1.70	15.0
				Dec. 85%							2.470	11.6	2.32	15.0
				Jan. 85%							2.690	11.6	2.55	15.0
				Feb. 85%							3.570	11.6	3.49	15.0
				Mar. 85%							3.720	11.6	3.66	15.0
				Apr. 85%							3.550	11.6	3.47	15.0
				May 85%							2.870	11.6	2.74	15.0
				June 85%							2.090	11.6	1.92	15.0
				July 85%							1.450	11.6	1.28	15.0
				Aug. 85%							1.060	11.6	0.899	15.0
				Sept. 85%							0.979	11.6	0.825	15.0
				BaseFlow10yr							2.410	11.6	2.25	15.0
				7Q10					0.352	25.6	0.349	11.6	0.261	15.0
01578150	3	1	19.0	Oct. 85%	01591400	62.4	21	3					3.94	10.6
				Nov. 85%									5.77	10.6
				Dec. 85%									7.88	10.6
				Jan. 85%									8.67	10.6
				Feb. 85%									11.9	10.6
				Mar. 85%									12.5	10.6
				Apr. 85%									11.8	10.6
				May 85%									9.31	10.6
				June 85%									6.55	10.6
				July 85%									4.35	10.6
				Aug. 85%									3.06	10.6
				Sept. 85%									2.81	10.6
				BaseFlow10yr									7.66	10.6
				7Q10									0.888	10.6

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measure-ments	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 esti-mate	MOVE1 ASEE	Q-ratio esti-mate	Q-ratio ASEE
01578480	8	1	7.0	Oct. 85%	01583570	44.9	14	5					1.44	72.7
				Nov. 85%									1.73	72.7
				Dec. 85%									2.01	72.7
				Jan. 85%									2.01	72.7
				Feb. 85%									2.30	72.7
				Mar. 85%									2.59	72.7
				Apr. 85%									2.59	72.7
				May 85%									2.01	72.7
				June 85%									1.44	72.7
				July 85%									0.863	72.7
				Aug. 85%									0.575	72.7
				Sept. 85%									0.863	72.7
				BaseFlow10yr									1.52	72.7
				7Q10									0.460	72.7
01579925	16	1	15.1	Oct. 85%	01583580	20.2	9	4					7.52	10.3
				Nov. 85%									8.91	10.3
				Dec. 85%									11.1	10.3
				Jan. 85%									12.5	10.3
				Feb. 85%									15.4	10.3
				Mar. 85%									19.6	10.3
				Apr. 85%									19.8	10.3
				May 85%									17.8	10.3
				June 85%									11.1	10.3
				July 85%									5.74	10.3
				Aug. 85%									4.16	10.3
				Sept. 85%									4.36	10.3
				BaseFlow10yr									9.56	10.3
				7Q10									3.33	10.3

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measurements	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 estimate	MOVE1 ASEE	Q-ratio estimate	Q-ratio ASEE
01580170	11	1	11.3	Oct. 85%	01591400	55.6	21	10			3.26	14.4	2.54	36.6
				Nov. 85%							4.27	14.4	3.72	36.6
				Dec. 85%							5.31	14.4	5.07	36.6
				Jan. 85%							5.68	14.4	5.58	36.6
				Feb. 85%							7.10	14.4	7.65	36.6
				Mar. 85%							7.34	14.4	8.02	36.6
				Apr. 85%							7.07	14.4	7.61	36.6
				May 85%							5.98	14.4	5.99	36.6
				June 85%							4.66	14.4	4.21	36.6
				July 85%							3.50	14.4	2.80	36.6
				Aug. 85%							2.73	14.4	1.97	36.6
				Sept. 85%							2.57	14.4	1.81	36.6
				BaseFlow10yr							5.21	14.4	4.93	36.6
				7Q10					1.150	20.1	1.14	14.4	0.572	36.6
01580510	2	1	22.2	Oct. 85%	01583580	31.4	12	2					0.069	--
				Nov. 85%									0.082	--
				Dec. 85%									0.102	--
				Jan. 85%									0.115	--
				Feb. 85%									0.143	--
				Mar. 85%									0.181	--
				Apr. 85%									0.183	--
				May 85%									0.164	--
				June 85%									0.102	--
				July 85%									0.053	--
				Aug. 85%									0.038	--
				Sept. 85%									0.040	--
				BaseFlow10yr									0.804	--
				7Q10									0.031	--

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measure-ments	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 esti-mate	MOVE1 ASEE	Q-ratio esti-mate	Q-ratio ASEE
01580550	3	1	17.2	Oct. 85%	01583580	37.4	13	3					1.02	26.4
				Nov. 85%									1.20	26.4
				Dec. 85%									1.50	26.4
				Jan. 85%									1.68	26.4
				Feb. 85%									2.09	26.4
				Mar. 85%									2.65	26.4
				Apr. 85%									2.67	26.4
				May 85%									2.41	26.4
				June 85%									1.50	26.4
				July 85%									0.775	26.4
				Aug. 85%									0.562	26.4
				Sept. 85%									0.588	26.4
				BaseFlow10yr									1.29	26.4
				7Q10									0.449	26.4
01581675	2	1	16.9	Oct. 85%	01591400	37.4	13	2					2.94	--
				Nov. 85%									4.31	--
				Dec. 85%									5.88	--
				Jan. 85%									6.47	--
				Feb. 85%									8.87	--
				Mar. 85%									9.30	--
				Apr. 85%									8.82	--
				May 85%									6.95	--
				June 85%									4.89	--
				July 85%									3.25	--
				Aug. 85%									2.28	--
				Sept. 85%									2.10	--
				BaseFlow10yr									3.42	--
				7Q10									0.663	--

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measure-ments	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 esti-mate	MOVE1 ASEE	Q-ratio esti-mate	Q-ratio ASEE
01581680	2	1	25.9	Oct. 85%	01583580	17.2	10	2					0.212	--
				Nov. 85%									0.251	--
				Dec. 85%									0.313	--
				Jan. 85%									0.352	--
				Feb. 85%									0.436	--
				Mar. 85%									0.553	--
				Apr. 85%									0.559	--
				May 85%									0.503	--
				June 85%									0.313	--
				July 85%									0.162	--
				Aug. 85%									0.117	--
				Sept. 85%									0.123	--
				BaseFlow10yr									2.46	--
				7Q10									0.094	--
01581985	4	1	86.2	Oct. 85%	01583100	11.8	5	4					2.19	5.4
				Nov. 85%									2.89	5.4
				Dec. 85%									3.11	5.4
				Jan. 85%									3.12	5.4
				Feb. 85%									4.25	5.4
				Mar. 85%									4.82	5.4
				Apr. 85%									4.82	5.4
				May 85%									3.86	5.4
				June 85%									2.79	5.4
				July 85%									2.08	5.4
				Aug. 85%									2.10	5.4
				Sept. 85%									1.93	5.4
				BaseFlow10yr									NA	
				7Q10									1.10	5.4

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measure-ments	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 esti-mate	MOVE1 ASEE	Q-ratio esti-mate	Q-ratio ASEE
01583200	16	1	55.9	Oct. 85%	01583100	2.8	1	4					2.76	32.0
				Nov. 85%									3.64	32.0
				Dec. 85%									3.92	32.0
				Jan. 85%									3.93	32.0
				Feb. 85%									5.35	32.0
				Mar. 85%									6.07	32.0
				Apr. 85%									6.07	32.0
				May 85%									4.87	32.0
				June 85%									3.51	32.0
				July 85%									2.62	32.0
				Aug. 85%									2.65	32.0
				Sept. 85%									2.43	32.0
				BaseFlow10yr									NA	
				7Q10									1.380	32.0
01589015	5	0	NA	Oct. 85%	01585200	16.0	5	5					0.330	49.1
				Nov. 85%									0.458	49.1
				Dec. 85%									0.639	49.1
				Jan. 85%									0.692	49.1
				Feb. 85%									0.969	49.1
				Mar. 85%									0.990	49.1
				Apr. 85%									0.990	49.1
				May 85%									0.809	49.1
				June 85%									0.639	49.1
				July 85%									0.394	49.1
				Aug. 85%									0.298	49.1
				Sept. 85%									0.277	49.1
				BaseFlow10yr									0.683	49.1
				7Q10									0.149	49.1

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measure-ments	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 esti-mate	MOVE1 ASEE	Q-ratio esti-mate	Q-ratio ASEE
01590996	4	2	26.1	Oct. 85%	01583570	30.6	10	4					0.639	47.2
				Nov. 85%									0.766	47.2
				Dec. 85%									0.894	47.2
				Jan. 85%									0.894	47.2
				Feb. 85%									1.02	47.2
				Mar. 85%									1.15	47.2
				Apr. 85%									1.15	47.2
				May 85%									0.894	47.2
				June 85%									0.639	47.2
				July 85%									0.383	47.2
				Aug. 85%									0.256	47.2
				Sept. 85%									0.383	47.2
				BaseFlow10yr									0.677	47.2
				7Q10									0.204	47.2
01591690	5	2	27.6	Oct. 85%	01586210	30.6	10	5					0.214	18.3
				Nov. 85%									0.283	18.3
				Dec. 85%									0.345	18.3
				Jan. 85%									0.401	18.3
				Feb. 85%									0.533	18.3
				Mar. 85%									0.655	18.3
				Apr. 85%									0.636	18.3
				May 85%									0.474	18.3
				June 85%									0.325	18.3
				July 85%									0.224	18.3
				Aug. 85%									0.179	18.3
				Sept. 85%									0.157	18.3
				BaseFlow10yr									0.416	18.3
				7Q10									0.075	18.3

Table 7. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index streamgage selection based on physical proximity, basin characteristics and τ.—Continued

[τ is the base-flow recession constant, in days; all estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates in table 8; --, not available]

Partial-record station number	Total measure-ments	Pairs	Average τ	Statistic	Index-streamgage selection based on physical proximity, basin characteristics, and τ									
					Index streamgage	Distance	Distance rank	Concurrent streamflows	Moments estimate	Moments ASEE	MOVE1 esti-mate	MOVE1 ASEE	Q-ratio esti-mate	Q-ratio ASEE
01593650	20	1	27.8	Oct. 85%	01583570	24.3	10	5					1.00	35.5
				Nov. 85%									1.21	35.5
				Dec. 85%									1.41	35.5
				Jan. 85%									1.41	35.5
				Feb. 85%									1.61	35.5
				Mar. 85%									1.81	35.5
				Apr. 85%									1.81	35.5
				May 85%									1.41	35.5
				June 85%									1.00	35.5
				July 85%									0.603	35.5
				Aug. 85%									0.402	35.5
				Sept. 85%									0.603	35.5
				BaseFlow10yr									1.06	35.5
				7Q10									0.322	35.5
01594400	4	1	27.6	Oct. 85%	01493000	64.2	22	4					3.28	28.7
				Nov. 85%									3.96	28.7
				Dec. 85%									4.95	28.7
				Jan. 85%									6.16	28.7
				Feb. 85%									7.81	28.7
				Mar. 85%									9.36	28.7
				Apr. 85%									8.73	28.7
				May 85%									6.06	28.7
				June 85%									4.24	28.7
				July 85%									3.34	28.7
				Aug. 85%									3.13	28.7
				Sept. 85%									3.08	28.7
				BaseFlow10yr									4.95	28.7
				7Q10									1.56	28.7

Table 8. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index-streamgage selection based on correlation coefficient and weighted estimates.

[All estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates]

Partial-record station number	Statistic	Index-streamgage selection based on correlation coefficient											Weighted	
		Index streamgage	Distance	Distance rank	Concurrent streamflows	Correlation coefficient	Moments estimate	Moments ASEE	MOVE1 estimate	MOVE1 ASEE	Q-ratio estimate	Q-ratio ASEE	Estimate	ASEE
01494995	Oct. 85%	01591000	1.1	1	7	0.987			0.645	37.0	0.555	36.0	0.599	25.4
	Nov. 85%								0.924	37.0	0.815	36.0	0.868	25.4
	Dec. 85%								1.23	37.0	1.11	36.0	1.17	25.4
	Jan. 85%								1.46	37.0	1.33	36.0	1.39	25.4
	Feb. 85%								1.80	37.0	1.67	36.0	1.73	25.4
	Mar. 85%								2.31	37.0	2.18	36.0	2.24	25.4
	Apr. 85%								2.16	37.0	2.03	36.0	2.09	25.4
	May 85%								1.68	37.0	1.55	36.0	1.61	25.4
	June 85%								1.11	37.0	0.987	36.0	1.04	25.4
	July 85%								0.684	37.0	0.591	36.0	0.636	25.4
	Aug. 85%								0.532	37.0	0.451	36.0	0.491	25.4
	Sept. 85%								0.485	37.0	0.409	36.0	0.446	25.4
	BaseFlow10yr								0.537	37.0	1.17	36.0	0.864	25.4
	7Q10								0.191	37.0	0.138	36.0	0.164	25.4
01495980		Insufficient measurements available for use of this index-streamgage selection method												
01496020		Insufficient measurements available for use of this index-streamgage selection method												
01496060	Oct. 85%	01586210	10.1	1	6	0.987			0.777	23.0	1.64	57.0	0.912	21.1
	Nov. 85%								1.18	23.0	2.17	57.0	1.33	21.1
	Dec. 85%								1.58	23.0	2.65	57.0	1.75	21.1
	Jan. 85%								1.98	23.0	3.08	57.0	2.15	21.1
	Feb. 85%								3.02	23.0	4.09	57.0	3.18	21.1
	Mar. 85%								4.10	23.0	5.03	57.0	4.25	21.1
	Apr. 85%								3.92	23.0	4.88	57.0	4.07	21.1
	May 85%								2.53	23.0	3.64	57.0	2.70	21.1
	June 85%								1.45	23.0	2.50	57.0	1.61	21.1
	July 85%								0.833	23.0	1.72	57.0	0.972	21.1
	Aug. 85%								0.598	23.0	1.38	57.0	0.719	21.1
	Sept. 85%								0.492	23.0	1.21	57.0	0.603	21.1
	BaseFlow10yr								2.09	23.0	3.19	57.0	2.26	21.1
	7Q10								0.165	23.0	0.579	57.0	0.229	21.1

Table 8. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index-streamgage selection based on correlation coefficient and weighted estimates.—Continued

[All estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates]

Partial-record station number	Statistic	Index-streamgage selection based on correlation coefficient											Weighted	
		Index streamgage	Distance	Distance rank	Concurrent streamflows	Correlation coefficient	Moments estimate	Moments ASEE	MOVE1 estimate	MOVE1 ASEE	Q-ratio estimate	Q-ratio ASEE	Estimate	ASEE
01496250	Oct. 85%	01591000	45.4	15	8	0.995			1.30	9.8	0.821	36.7	1.25	8.2
	Nov. 85%								1.72	9.8	1.21	36.7	1.71	8.2
	Dec. 85%								2.16	9.8	1.64	36.7	2.20	8.2
	Jan. 85%								2.47	9.8	1.97	36.7	2.49	8.2
	Feb. 85%								2.92	9.8	2.47	36.7	3.09	8.2
	Mar. 85%								3.55	9.8	3.22	36.7	3.58	8.2
	Apr. 85%								3.37	9.8	3.00	36.7	3.40	8.2
	May 85%								2.76	9.8	2.29	36.7	2.75	8.2
	June 85%								1.98	9.8	1.46	36.7	1.96	8.2
	July 85%								1.36	9.8	0.874	36.7	1.33	8.2
	Aug. 85%								1.11	9.8	0.668	36.7	1.05	8.2
	Sept. 85%								1.04	9.8	0.605	36.7	0.972	8.2
	BaseFlow10yr								2.25	9.8	1.74	36.7	2.25	8.2
	7Q10						0.467	14.8	0.466	9.8	0.205	36.7	0.466	8.2
01578150		Insufficient measurements available for use of this index-streamgage selection method												
01578480	Oct. 85%	01582000	18.0	1	7	0.990			1.40	41.3	1.57	34.2	1.50	25.9
	Nov. 85%								1.78	41.3	1.94	34.2	1.88	25.9
	Dec. 85%								2.02	41.3	2.16	34.2	2.10	25.9
	Jan. 85%								2.27	41.3	2.39	34.2	2.34	25.9
	Feb. 85%								2.86	41.3	2.93	34.2	2.90	25.9
	Mar. 85%								3.52	41.3	3.50	34.2	3.51	25.9
	Apr. 85%								3.41	41.3	3.41	34.2	3.41	25.9
	May 85%								2.90	41.3	2.96	34.2	2.93	25.9
	June 85%								2.25	41.3	2.38	34.2	2.33	25.9
	July 85%								1.64	41.3	1.80	34.2	1.73	25.9
	Aug. 85%								1.31	41.3	1.48	34.2	1.41	25.9
	Sept. 85%								1.17	41.3	1.34	34.2	1.27	25.9
	BaseFlow10yr								2.01	41.3	2.15	34.2	2.09	25.9
	7Q10								0.707	41.3	0.869	34.2	0.802	25.9

Table 8. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index-streamgage selection based on correlation coefficient and weighted estimates.—Continued

[All estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates]

Partial-record station number	Statistic	Index-streamgage selection based on correlation coefficient											Weighted	
		Index streamgage	Distance	Distance rank	Concurrent streamflows	Correlation coefficient	Moments estimate	Moments ASEE	MOVE1 estimate	MOVE1 ASEE	Q-ratio estimate	Q-ratio ASEE	Estimate	ASEE
01579925	Oct. 85%	01580000	3.8	1	15	0.986			4.54	15.3	4.90	15.4	6.59	8.5
	Nov. 85%								5.67	15.3	5.99	15.4	7.89	8.5
	Dec. 85%								6.57	15.3	6.85	15.4	9.67	8.5
	Jan. 85%								7.86	15.3	8.07	15.4	11.03	8.5
	Feb. 85%								9.15	15.3	9.27	15.4	13.47	8.5
	Mar. 85%								11.7	15.3	11.6	15.4	17.13	8.5
	Apr. 85%								11.5	15.3	11.4	15.4	17.21	8.5
	May 85%								10.0	15.3	10.1	15.4	15.38	8.5
	June 85%								7.85	15.3	8.06	15.4	10.07	8.5
	July 85%								5.83	15.3	6.15	15.4	5.77	8.5
	Aug. 85%								4.70	15.3	5.05	15.4	4.33	8.5
	Sept. 85%								4.14	15.3	4.50	15.4	4.29	8.5
	BaseFlow10yr								7.06	15.3	7.32	15.4	8.78	8.5
	7Q10						2.577	10.6	2.59	15.3	2.94	15.4	2.96	7.4
01580170	Oct. 85%	01582000	19.8	7	10	0.998			2.98	10.3	3.05	9.5	3.02	7.0
	Nov. 85%								3.72	10.3	3.77	9.5	3.74	7.0
	Dec. 85%								4.17	10.3	4.20	9.5	4.18	7.0
	Jan. 85%								4.63	10.3	4.64	9.5	4.64	7.0
	Feb. 85%								5.73	10.3	5.68	9.5	5.71	7.0
	Mar. 85%								6.93	10.3	6.81	9.5	6.86	7.0
	Apr. 85%								6.73	10.3	6.62	9.5	6.67	7.0
	May 85%								5.79	10.3	5.74	9.5	5.76	7.0
	June 85%								4.61	10.3	4.62	9.5	4.61	7.0
	July 85%								3.44	10.3	3.50	9.5	3.47	7.0
	Aug. 85%								2.80	10.3	2.88	9.5	2.84	7.0
	Sept. 85%								2.52	10.3	2.61	9.5	2.57	7.0
	BaseFlow10yr								4.14	10.3	4.17	9.5	4.16	7.0
	7Q10						1.588	10.3	1.59	10.3	1.69	9.5	1.64	7.0

Table 8. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index-streamgage selection based on correlation coefficient and weighted estimates.—Continued

[All estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates]

Partial-record station number	Statistic	Index-streamgage selection based on correlation coefficient											Weighted	
		Index streamgage	Distance	Distance rank	Concurrent streamflows	Correlation coefficient	Moments estimate	Moments ASEE	MOVE1 estimate	MOVE1 ASEE	Q-ratio estimate	Q-ratio ASEE	Estimate	ASEE
01580510		Insufficient measurements available for use of this index-streamgage selection method												
01580550		Insufficient measurements available for use of this index-streamgage selection method												
01581675		Insufficient measurements available for use of this index-streamgage selection method												
01581680		Insufficient measurements available for use of this index-streamgage selection method												
01581985		Insufficient measurements available for use of this index-streamgage selection method												
01583200	Oct. 85%	01583500	4.5	2	15	0.99			3.43	13.1	3.73	18.1	3.54	10.6
	Nov. 85%								4.43	13.1	4.64	18.1	4.50	10.6
	Dec. 85%								5.37	13.1	5.45	18.1	5.40	10.6
	Jan. 85%								6.30	13.1	6.25	18.1	6.28	10.6
	Feb. 85%								8.07	13.1	7.70	18.1	7.94	10.6
	Mar. 85%								10.1	13.1	9.34	18.1	9.87	10.6
	Apr. 85%								9.22	13.1	8.62	18.1	9.01	10.6
	May 85%								7.61	13.1	7.33	18.1	7.51	10.6
	June 85%								5.59	13.1	5.65	18.1	5.61	10.6
	July 85%								3.76	13.1	4.03	18.1	3.86	10.6
	Aug. 85%								3.01	13.1	3.34	18.1	3.13	10.6
	Sept. 85%								2.71	13.1	3.06	18.1	2.83	10.6
	BaseFlow10yr								5.51	13.1	5.57	18.1	5.53	10.6
	7Q10						1.533	12.3	1.54	13.1	1.90	18.1	1.65	10.1

Table 8. Estimates of the selected streamflow statistics for the low-flow partial-record stations determined from index-streamgage selection based on correlation coefficient and weighted estimates.—Continued

[All estimated streamflow statistics are in cubic feet per second; distances are in miles; %, percent; Moments is the method developed by Stedinger and Thomas (1985); MOVE1 is the method developed by Hirsch (1982); Q-ratio is the method developed by Potter (2001) and modified by Eng, Milly, Tasker, and Gruber-Veilleux (U.S. Geological Survey, U.S. Geological Survey, U.S. Geological Survey (retired), and Cornell University, respectively, written commun., 2008); ASEE is the average standard error of estimate, in percent; shaded values were used to compute weighted estimates]

Partial-record station number	Statistic	Index-streamgage selection based on correlation coefficient											Weighted	
		Index streamgage	Distance	Distance rank	Concurrent streamflows	Correlation coefficient	Moments estimate	Moments ASEE	MOVE1 estimate	MOVE1 ASEE	Q-ratio estimate	Q-ratio ASEE	Estimate	ASEE
01589015		Insufficient measurements available for use of this index-streamgage selection method												
01590996		Insufficient measurements available for use of this index-streamgage selection method												
01591690		Insufficient measurements available for use of this index-streamgage selection method												
01593650	Oct. 85%	01591700	26.3	12	18	0.809			0.712	38.4	1.07	50.1		25.7
	Nov. 85%								1.01	38.4	1.33	50.1		25.7
	Dec. 85%								1.31	38.4	1.57	50.1		25.7
	Jan. 85%								1.63	38.4	1.80	50.1		25.7
	Feb. 85%								2.27	38.4	2.21	50.1		25.7
	Mar. 85%								3.10	38.4	2.69	50.1		25.7
	Apr. 85%								2.72	38.4	2.48	50.1		25.7
	May 85%								2.10	38.4	2.11	50.1		25.7
	June 85%								1.38	38.4	1.62	50.1		25.7
	July 85%								0.806	38.4	1.16	50.1		25.7
	Aug. 85%								0.597	38.4	0.962	50.1		25.7
	Sept. 85%								0.518	38.4	0.881	50.1		25.7
	BaseFlow10yr								1.35	38.4	1.60	50.1		25.7
	7Q10						0.247	22.9	0.241	38.4	0.547	50.1		19.0
01594400		Insufficient measurements available for use of this index-streamgage selection method												

Summary and Conclusions

The U.S. Geological Survey (USGS), in cooperation with the Maryland Department of the Environment (MDE), operated a network of 20 low-flow partial-record (LFPR) stations during 2008 in central and northeastern Maryland to obtain estimates of selected streamflow statistics at the station locations. The study area is expected to face a substantial influx of new residents and businesses as a result of military and civilian personnel transfers associated with the Base Realignment and Closure Act of 2005 (BRAC). The estimated streamflow statistics are needed to provide a better understanding of water availability in the BRAC-affected areas in anticipation of increased requests to the MDE for new water-withdrawal and wastewater-discharge permits. The estimated streamflow statistics include monthly 85-percent duration flows, the 10-year base flow, and the 7-day, 10-year low flow.

Three methods were used to estimate the streamflow statistics for the LFPR stations by relating the streamflow measurements made at the LFPR stations to concurrent daily streamflows at nearby, hydrologically similar index streamgages, and two methods were used to select the index streamgages. The LFPR-station network was designed with the intention of obtaining two pairs of streamflow measurements at each LFPR station so that the recently developed Q-ratio approach could be used to estimate the streamflow statistics. The Q-ratio approach requires as few as one pair of measurements made on a single streamflow recession, but accuracy of the estimates improves with more pairs of measurements. The MOVE1 and Moments methods also were used to estimate the streamflow statistics at 8 of the 20 LFPR stations by making use of additional measurements made previously at those stations. The MOVE1 and the Moments approaches normally require the collection of approximately 10 streamflow measurements at the LFPR stations on independent recessions over a period of about 3 years.

The two methods for selecting the index streamgages included (1) maximizing the correlation coefficient, and (2) minimizing the Euclidean distance between the LFPR station and the candidate index streamgage, where the Euclidean distance was computed as a function of geographic proximity and the basin characteristics: drainage area, percentage of forested area, percentage of impervious area, and the base-flow recession time constant, τ. The τ values were determined for the LFPR stations from the rates of change in flow between the pairs of streamflow measurements made on the same recession. Corresponding τ values for the index streamgages were computed from the daily streamflows on the same days as measurements were made at the LFPR stations.

An analysis of estimated 7-day, 10-year low flows determined by use of the three different flow-estimation methods on resampled daily streamflow data for the index streamgages indicated that there was no correlation between the estimates obtained from the Q-ratio method and the estimates obtained from either of the other two methods. As a result, when estimates were available from two or more methods for a LFPR station, final estimates for the station were determined by weighting the Q-ratio estimate with the best estimate from the other methods on the basis of the variance of the estimates. Average standard errors of estimate (ASEEs) for the final estimates for 17 of the 20 LFPR stations ranged from 90.0 to 7.0 percent, with an average value of ASEE of 26.5 percent. ASEEs for three LFPR stations could not be computed because only two measurements were available at the stations.

Sample sizes generally were too small to test for significant differences in the accuracy of the three estimation methods. Direct comparisons between all three methods were available only for seven LFPR stations. From these comparisons, the average values of the ASEEs for the MOVE1 and Moments methods were comparable, at 16.7 and 16.2 percent, respectively. The average value of the ASEE for the Q-ratio method was 26.3 percent. Although the ASEEs for the Q-ratio method generally were higher than the ASEEs for the other two estimation methods, the ASEEs for the Q-ratio method still are reasonable given the reduced time and cost needed to obtain the estimates. The value of weighting independent estimates was illustrated by the fact that the weighted estimates had ASEEs that were, on average, 4.3 percent lower than the best ASEE from the separate estimation methods.

Index streamgages that were selected based on the correlation coefficient were, on average, significantly closer in distance to the LFPR station and had significantly higher distance rankings than index streamgages selected based on geographic proximity and similarity of basin characteristics. Closer proximities between the LFPR stations and the selected index streamgages for the correlation-coefficient station-selection method do not necessarily indicate that errors associated with estimates of streamflow statistics from that station-selection method are less than the errors associated with the estimates from the geographic-proximity and basin-characteristics station-selection method, however. Direct comparisons of the ASEEs obtained for estimates of the 7-day, 10-year low flow from the Q-ratio method for eight LFPR stations indicated that the average value of the ASEE when index-streamgage selection was based on the correlation coefficient was 14.5 percent lower than when index-streamgage selection was based on geographic proximity and basin characteristics, but this difference was not statistically significant. As a result, it cannot be concluded that one index-streamgage selection method is superior to the other.

Future studies could attempt to improve the results for the geographic proximity and basin characteristics index-streamgage selection method by giving more weight to the geographic proximity or by reducing the maximum distance allowed for selection from 87 miles (140 kilometers) to a smaller value. Possible improvements also could be made by use of different basin characteristics in the selection process that better describe the variation in streamflow statistics. The basin characteristics used in this analysis were limited to those that could be computed at the time by the StreamStats

Web application. Also, more paired streamflow measurements available at the LFPR stations could lead to better estimates of average τ at the stations.

Operation of the low-flow network in the manner required for use of the Q-ratio approach was more difficult than for a traditional low-flow network because of the need to make pairs of measurements within a few days of each other and the need to rely on weather forecasts for at least 3 days in the future when deciding on any given day whether to make the first of a pair of measurements. This manner of operation was especially difficult during a summer of above-average precipitation. Two useable pairs of streamflow measurements were obtained at only four of the LFPR stations. Frequent summer thunderstorms gave few opportunities of at least 5 days of dry weather needed to obtain a pair of measurements on the same recession. In addition, the often localized extent of the thunderstorms made it difficult to determine with confidence when the drainage basins for the LFPR stations had received rain. Second measurements were obtained nine times when available weather information indicated dry conditions had prevailed since the previous measurement, but the computed streamflow was higher for the second measurement than for the first measurement. It is likely that ASEEs for the estimated streamflow statistics at the LFPR stations where only one pair of measurements was obtained would have been lower if a second pair of measurements had been made.

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