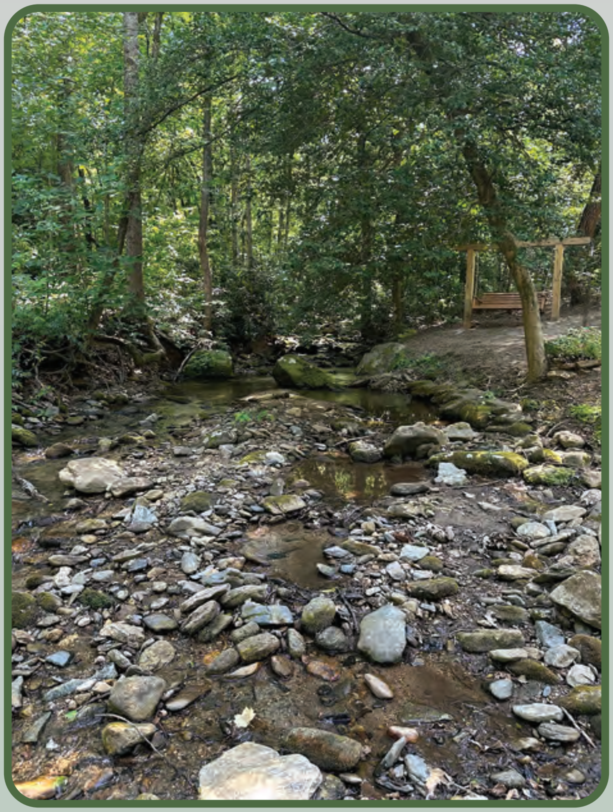
Groundwater and Streamflow Information Program

Prepared in cooperation with the Georgia Department of Natural Resources (Environmental Protection Division), North Carolina Department of Environmental Quality (Division of Water Resources), North Carolina Department of Public Safety (Office of Recovery and Resiliency), and South Carolina Department of Environmental Services

Methods for Estimating Selected Low-Flow Frequency and Mean Annual Flow Statistics at Gaged and Ungaged Locations on Streams in Georgia, North Carolina, and South Carolina



Scientific Investigations Report 2026–5021

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

Cover. Photograph showing Vaughn Creek in Greenville County, South Carolina, on July 8, 2024. Photograph by Toby D. Feaster, U.S. Geological Survey.

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U.S. Geological Survey, Reston, Virginia: 2026

Suggested citation:
Feaster, T.D., Harken, B.J., Aulenbach, B.T., Kolb, K.R., Mitchell, C.E., and Weaver, J.C., 2026, Methods for estimating selected low-flow frequency and mean annual flow statistics at gaged and ungaged locations on streams in Georgia, North Carolina, and South Carolina: U.S. Geological Survey Scientific Investigations Report 2026–5021, 48 p., https://doi.org/10.3133/sir20265021.

Associated data for this publication:
Kolb, K.R., Feaster, T.D., Harken, B.J., Mitchell, C.E., and Weaver, J.C., 2026, Methods for estimating selected low-flow frequency and mean annual flow statistics at gaged and ungaged locations on streams in Georgia, North Carolina, and South Carolina, 2022—Data: U.S. Geological Survey data release, https://doi.org/10.5066/P13BHRVE.

ISSN 2328-0328 (online)

Acknowledgments

The authors thank the State agencies in Georgia, North Carolina, and South Carolina for their cooperation with this project and the many other local, State, and Federal agencies that have helped and continue to help fund the operation and maintenance of the U.S. Geological Survey (USGS) streamgaging network. As senior author Toby Feaster likes to tell audiences, “The reason we need long-term records is because we have short-term memories.” Those long-term records have been made possible by the USGS and our partners since the late 1800s because of people who had the foresight to realize the importance of such records for future generations. As such, the authors would also like to recognize the important work of former and current USGS field-office staff in collecting, processing, and storing the streamflow data that are vital for investigations such as this one. The authors would also like to thank William H. Farmer, USGS, for making modifications to the R script used in the weighted left-censored low-flow frequency regression analyses, and USGS technical reviewers Gardner Bent and Thomas Suro, South Atlantic Water Science Center (SAWSC) Surface-Water Specialist Anthony Gotvald, SAWSC Report Specialist David (Chris) Leeth, supervisor Jimmy Clark, and USGS Science Publishing Network Editor Kimberly Waltenbaugh, who all provided thorough and thoughtful reviews that much improved this report.

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Plate

[Available for downloading from https://doi.org/10.3133/sir20265021.]

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows: °F = (1.8 × °C) + 32.

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C = (°F – 32) / 1.8.

Datums

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

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

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

Supplemental Information

A climate year is the 12-month period from April 1 through March 31 of the following year and is designated by the calendar year in which it begins.

A water year is the 12-month period from October 1 through September 30 of the following year and is designated by the calendar year in which it ends.

Abbreviations

1Q10	annual minimum 1-day average flow with a 10-year recurrence interval
7Q2	annual minimum 7-day average flow with a 2-year recurrence interval
7Q10	annual minimum 7-day average flow with a 10-year recurrence interval
30Q2	annual minimum 30-day average flow with a 2-year recurrence interval
30Q3	annual minimum 30-day average flow with a 3-year recurrence interval
AMLE	adjusted maximum-likelihood estimation
AVP	average variance of prediction
CR	continuous record
CY	climate year
EPA	U.S. Environmental Protection Agency
GAGES-II	Geospatial Attributes of Gages for Evaluating Streamflow, version II
GIS	geographic information system
HA	hydrologic area
IA	impervious area
LOESS	locally estimated scatterplot smoothing
LPIII	base 10 logarithm of Pearson Type III distribution
MLE	maximum-likelihood estimation
NOAA	National Oceanic and Atmospheric Administration
OLS	ordinary least squares
p-value	probability value
PR	partial record
R^2	coefficient of determination
S_p	standard error of prediction
SVI	streamflow-variability index
USGS	U.S. Geological Survey
VIF	variance inflation factor
V_p	variance of prediction
W7Q10	winter (November–March) minimum 7-day average flow with a 10-year recurrence interval

Methods for Estimating Selected Low-Flow Frequency and Mean Annual Flow Statistics at Gaged and Ungaged Locations on Streams in Georgia, North Carolina, and South Carolina

By Toby D. Feaster,[1] Bradley J. Harken,[1] Brent T. Aulenbach,[1] Katharine R. Kolb,[1] Caleb E. Mitchell,[2] and J. Curtis Weaver[1]

Abstract

The U.S. Geological Survey, in cooperation with the Georgia Department of Natural Resources (Environmental Protection Division), North Carolina Department of Environmental Quality (Division of Water Resources), North Carolina Department of Public Safety (Office of Recovery and Resiliency), and South Carolina Department of Environmental Services, updated low-flow frequency, mean annual flow, and flow-duration statistics at 843 streamgages in and near Georgia, North Carolina, and South Carolina. The low-flow frequency statistics are annual minimum 1-day average flow with a 10-year recurrence interval (1Q10), annual minimum 7-day average flow for 2- and 10-year recurrence intervals (7Q2 and 7Q10, respectively), and annual minimum 30-day average flow with 2- and 3-year recurrence intervals (30Q2 and 30Q3, respectively). Monthly 1Q10 and 7Q10, and W7Q10 flow statistics for the winter period (November–March) also are presented. By using data from 604 of the streamgages on streams with streamflows that are not substantially affected by regulation or diversion and are not tidally influenced, regional regression equations were developed to predict flow statistics with prediction intervals at ungaged locations on streams with those same criteria. The regional regression analysis included data from 132 streamgages from adjacent States Alabama, Florida, Tennessee, and Virginia. The final regional regression equations include variables such as drainage area, streamflow variability, precipitation, percentage of impervious area, and percentage of the basin in various ecoregions. The low-flow statistics for the streamgages analyzed and the regional regression equations will be integrated into the U.S. Geological Survey StreamStats application (https://www.usgs.gov/streamstats) for Georgia, North Carolina, and South Carolina. StreamStats generates basin characteristics needed to compute low-flow frequency statistics for ungaged locations.

A trend analysis of annual minimum 7-day average flows was done for 78 streamgages with at least 30 years of continuous record. Trends were evaluated for 30-, 50-, 70-, and 90-year periods, ending in climate year 2021, and independence and short- and long-term persistence assumptions were considered. For all trend analysis assumptions, most streamgages did not exhibit significant trends in annual minimum 7-day average flows. Trends in annual precipitation and air temperature were similarly evaluated for the period 1895–2021 to assess the variability of climate for Georgia, North Carolina, and South Carolina.

Plain Language Summary

Low flow is the sustained flow in a stream, supplied by groundwater. They are important to Federal, State, regional, and local agencies and municipalities making decisions related to water quality, supply planning, infrastructure design, and more.

In this study, the U.S. Geological Survey, in cooperation with several State agencies, calculated low flow statistics for select streamgages in and near Georgia, North Carolina, and South Carolina. A subset of those streamgages where streamflows were not substantially affected by water regulation (for example, by reservoirs and dams), diversion, or tides were used to develop regional regression equations to estimate mean annual flow and 30 low flow statistics.

Benefits of using the three-State region include having (1) a larger dataset for modeling regional regression equations, which typically improves statistical analyses, and (2) regional regression equations that are consistent across the three-State region and particularly beneficial for basins that cross State boundaries.

As a result of this study, low-flow statistics for the streamgages analyzed and regional regression equations will be integrated into the U.S. Geological Survey StreamStats online application for computing low-flow statistics, including at ungaged locations on streams not substantially affected by

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[1] U.S. Geological Survey.

[2] A. Morton Thomas and Associates, Inc.

regulation or diversion and not affected by tides. The low flow frequency regression equations and resulting statistics are important for processes such as state water plans, permitting, evaluating drought impacts, and more.

Introduction

Federal, State, regional, and local water-resource officials need low-flow data to effectively manage hydrologic resources. Low flows are not the same as drought. Low flows are an integral part of a stream's flow regime and are a seasonal phenomenon (Smakhtin, 2001). Low flow, also sometimes referred to as base flow, is the sustained flow in a stream from groundwater as opposed to runoff to a stream from rainfall or snow events (Langbein and Iseri, 1960). In Georgia, North Carolina, and South Carolina, annual minimum low-flow periods typically occur in late summer or early fall. Drought, on the other hand, results from below normal precipitation over a period; it can occur any time of year and can persist for a few months to several years.

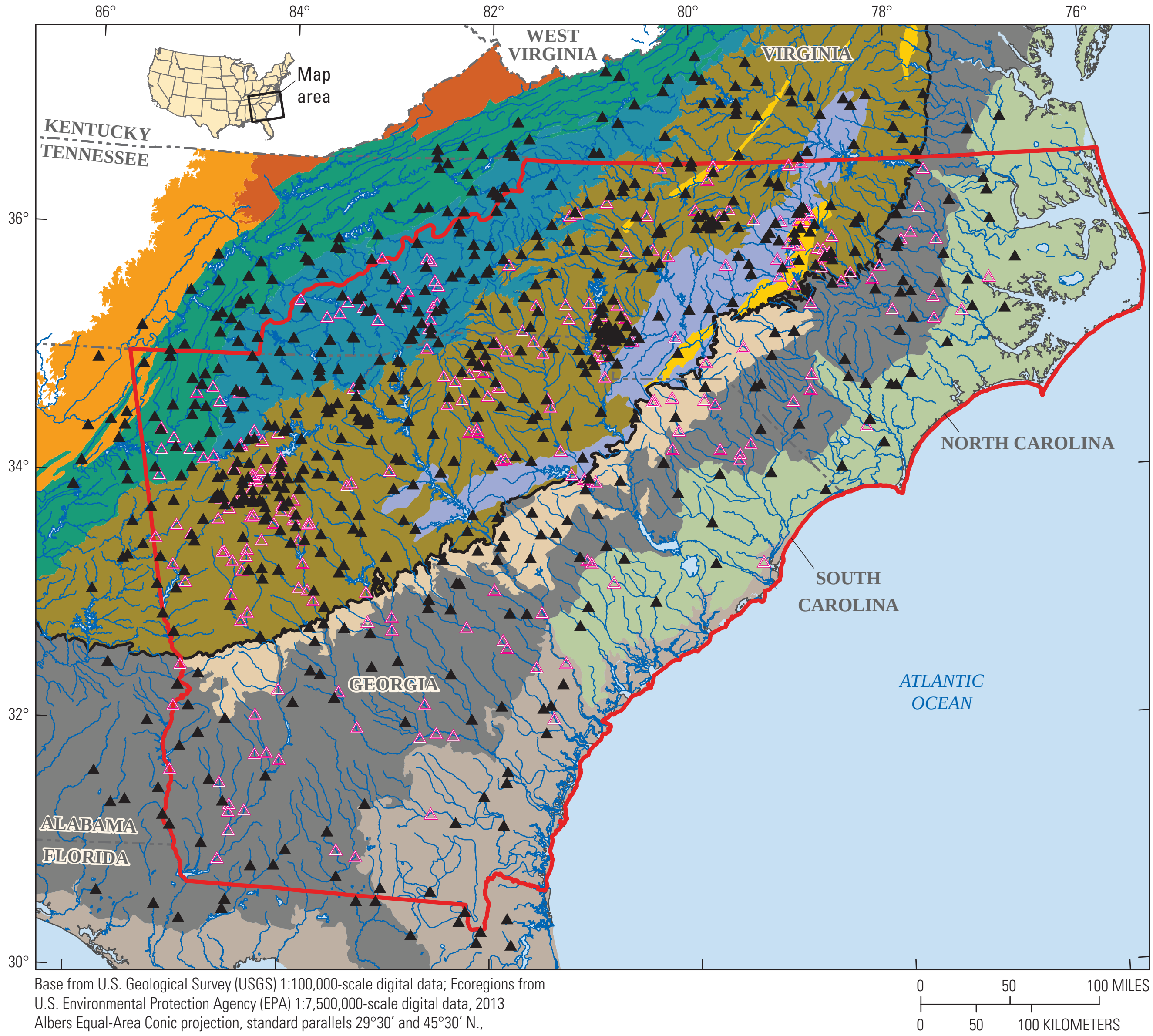
State agencies, such as the Georgia Department of Natural Resources (Environmental Protection Division), North Carolina Department of Environmental Quality (Division of Water Resources), and South Carolina Department of Environmental Services, use low-flow frequency and mean annual flow statistics for many applications, including determining wasteload allocations for National Pollutant Discharge Elimination System discharges, developing total maximum daily loads for streams, assessing minimum instream flow, informing public water supply availability and river-basin planning, restricting the quantity of water that can be transferred from one basin to another, and preparing the State Water Plan (Feaster and Cantrell, 2010; South Carolina Department of Natural Resources, 2019; State of South Carolina, 1981).

Historically, low-flow statistics, such as the annual minimum 7-day average flow that on average occurs once every 10 years (7Q10), have been used by water-resource managers and planners as threshold criteria for applications mentioned previously. In terms of probability of occurrence, there is a 10-percent probability in any given year that the annual minimum 7-day average flow at a specific streamgage will be at or below the 7Q10 value for that streamgage. For example, if a streamgage has 80 years of daily mean flows, it would be expected that for the 80 annual minimum 7-day flows computed at the streamgage, 8 of those (10 percent) would be at or below the 7Q10 value. However, annual minimum 7-day flows at or below the 7Q10 values would not be expected to occur at equal 10-year increments (once every 10 years). Because of the importance of these applications used by water-resource managers, it is critical to effectively measure and document low-flow data for use in updating low-flow frequency relations on a regular basis, typically about every 10 years (Benson and Carter, 1973).

Feaster and Cantrell (2010) provided a historical perspective on the use of the 7Q10 statistical flow in South Carolina water-quality management. As early as 1967, South Carolina adopted the 7Q10 statistic as the minimum streamflow for applying water-quality criteria (State of South Carolina, 1967, p. 2111). The 7Q10 statistic almost certainly predates its widespread adoption in water-quality laws and regulations across the United States; Matalas (1963) used 7-day minimum flows in probability distributions to remove flow variability from minor river regulations, based on statistical theory from Gumbel (1954). The 7Q10 statistic remains the applicable critical flow condition for most of the water-quality criteria for South Carolina and many other States.

At locations where no U.S. Geological Survey (USGS) streamgage is available, a process known as regionalization can be used to develop regional regression equations to estimate flow statistics at ungaged locations (Farmer and others, 2019; Feaster and others, 2020). Regionalization combines selected at-site streamflow statistics from a group of streamgages within a hydrologic region and selected basin characteristics to form the basis of predictions for ungaged locations on streams within that region. For this study, U.S. Environmental Protection Agency (EPA) Level III ecoregions and selected Level IV ecoregions were used as the basis for assessing potential regional hydrologic differences in low-flow statistics across Georgia, North Carolina, and South Carolina (EPA, 2013; Omernik and Griffith, 2014; fig. 1). Based on a geographic assessment of regression model residuals, the only three selected Level IV ecoregions were the Carolina Slate Belt and Triassic Basins, which are within the Piedmont Level III ecoregion, and Sand Hills, which is within the Southeastern Plains Level III ecoregion (fig. 1).

Although the USGS has done several flood-frequency investigations incorporating data from the three-State region of Georgia, North Carolina, and South Carolina (Feaster and others, 2009, 2014, 2023; Gotvald and others, 2009; Weaver and others, 2009), this low-flow study by the USGS, in cooperation with the Georgia Department of Natural Resources (Environmental Protection Division), the North Carolina Department of Environmental Quality (Division of Water Resources), the North Carolina Department of Public Safety (Office of Recovery and Resiliency), and the South Carolina Department of Environmental Services, is the first to be done concurrently across the three States. Benefits of using the three-State region are as follows: (1) consistent hydrologic regions across all three States; (2) larger dataset for modeling regional regression equations, which typically improves such statistical analyses; (3) consistency in basin characteristics included in the regression analysis; and (4) low-flow frequency and mean annual flow regression equations consistent across the three-State region—particularly beneficial for basins that cross State boundaries.



Base from U.S. Geological Survey (USGS) 1:100,000-scale digital data; Ecoregions from
U.S. Environmental Protection Agency (EPA) 1:7,500,000-scale digital data, 2013
Albers Equal-Area Conic projection, standard parallels 29°30′ and 45°30′ N.,
central meridian 81.5° W.; North American Datum of 1983

EXPLANATION

Level III ecoregion (EPA, 2013)

- ■ Southwestern Appalachians
- ■ Central Appalachians
- ■ Ridge and Valley
- ■ Blue Ridge
- ■ Piedmont
- ■ Southeastern Plains
- ■ Southern Coastal Plain
- ■ Middle Atlantic Coastal Plain

Selected Level IV ecoregion[1] (EPA, 2013)

- ■ Carolina Slate Belt
- ■ Triassic Basins
- ■ Sand Hills

▬ Fall Line (EPA, 2013)

▬ Study area boundary

USGS streamgage[2] (USGS, 2022; tables 1 and 2 in Kolb and others, 2026)

- ▲ Included in regional regression analysis
- △ Excluded from regional regression analysis

[1] Only showing Level IV ecoregions used for assessing potential regional hydrologic differences in low-flow statistics in this study. Carolina Slate Belt and Triassic Basins Level IV ecoregions are within the Piedmont Level III ecoregion, and Sand Hills Level IV ecoregion is within the Southeastern Plains Level III ecoregion.

[2] Streamgages had at least 10 climate years (CYs) of mean flow data through March 31, 2022 (the end of the 2021 CY).

Figure 1. Study area, Level III and selected Level IV ecoregions, and locations of U.S. Geological Survey streamgages included in and excluded from regional regression analysis in Georgia, North Carolina, South Carolina, and adjacent parts of Alabama, Florida, Tennessee, and Virginia.

Purpose and Scope

The purposes of this study were to update low-flow frequency and mean annual flow statistics at select USGS continuous-record (CR) streamgages, located mostly in Georgia, North Carolina, and South Carolina, and to develop regional regression equations to predict those streamflow statistics at ungaged locations in Georgia, North Carolina, and South Carolina on streams that streamflows are not substantially affected by regulation or diversion, and are not tidally influenced. This report documents the methods and regional regression equations used in the study with the resulting datasets provided in a companion data release by Kolb and others (2026). The report also includes trend analysis of low flows, to assess stationarity at streamgages with longer flow records, and of long-term climate data, for which trends may affect low flows. This trend analysis consists of minimum annual 7-day flows for the 78 streamgages with at least 30 years of continuous data for 30-, 50-, 70-, and 90-year periods ending in climate year (CY) 2021, and for precipitation (CYs 1896–2021) and air temperature (calendar years 1895–2021) for the three study States and their climate divisions.

Streamgage information—including State, counts of streamgages and their use, and the low-flow and streamflow statistics estimated in this report—is shown in table 1. Streamgages in the adjacent States of Alabama, Florida, Tennessee, and Virginia that were used in this study share river basins with Georgia, North Carolina, and South Carolina or are within about 50 miles of shared State borders (fig. 1; pl. 1; tables 1 and 2 in Kolb and others, 2026). The annual flow statistics estimated for these streamgages during this study are annual minimum 1-day average flow with a 10-year recurrence interval (1Q10), annual minimum 7-day average flow with 2- and 10-year recurrence intervals (7Q2 and 7Q10, respectively), and annual minimum 30-day average flow with 2- and 3-year recurrence intervals (30Q2 and 30Q3, respectively). Monthly statistics were estimated for the 1Q10 and 7Q10, and 7Q10 was predicted for the winter period (November–March, W7Q10). Mean annual flow (the average of the annual mean streamflows) and flow-duration (1st to 99th percentiles; computed from daily mean streamflows) statistics also were calculated for the period of record of each streamgage.

Regional regression equations were modeled from low-flow frequency and mean annual flow statistics computed from 604 USGS streamgages (at-site statistics) for which there were minimal to no effects of regulation, diversion, or irrigation groundwater withdrawals on streamflow, were not affected by tides, were not redundant, and were regionally consistent, hereinafter referred to as "unregulated streams." The modeled regional regression equations can be used to predict these flow statistics at ungaged locations at similarly unregulated streams. All streamflow statistics and geospatial datasets used to create the low-flow frequency and mean annual flow regression equations are available in a related data release (Kolb and others, 2026).

Table 1. U.S. Geological Survey streamgages used and annual statistics estimated in the updated low-flow frequency and mean annual flow statistics study for Georgia, North Carolina, and South Carolina.

[Annual statistics are in the format XQY, where X is the period used for the annual minimum average in days, Q is flow (also referred to as discharge), and Y is the recurrence interval in years. For example, 1Q10 is the annual minimum 1-day average flow with a 10-year recurrence interval. Detailed information about streamgages and annual statistics can be found in tables 1 and 2 in Kolb and others (2026) and U.S. Geological Survey (2022)]

State	Number of continuous-record streamgages used in study (pl. 1)	Streamgages included in regional regression analysis	Streamgages excluded from regional regression analysis	Low-flow and streamflow statistics
Georgia North Carolina South Carolina	711	[1]472	266	[2]1Q10 [2]7Q10 7Q2 30Q2 30Q3 [3]W7Q10 Mean annual flow[4] Flow duration[4]
Alabama Florida Tennessee Virginia	132	132	0	
Total	**843**	**[1]604**	**266**	

[1] Data from 27 of these streamgages were only used for the period when the streamgages were not substantially affected by regulation, diversion, or irrigation groundwater withdrawals.

[2] Monthly statistics also included in this study.

[3] Winter (November to March).

[4] For streamgage period of record.

Previous Studies

The USGS has a long history of working with cooperators in Georgia, North Carolina, and South Carolina to continuously monitor streamflow and compute flow frequency statistics needed to support water-resource management across the three States. The following report sections provide summaries of previous low-flow investigations in each State; much of the information about these investigations can be obtained from Gotvald (2016), Weaver (2015), and Feaster and Guimaraes (2017).

Georgia

The earliest low-flow frequency study by the USGS in Georgia was completed by Thomson and Carter (1963), who assessed the impacts of the 1954 drought on streamflow and described graphical regression methods for estimating low-flow frequency statistics. Carter (1977) developed low-flow profiles for the upper stem of the Flint River Basin (Apalachicola subregion, fig. 2) by using streamflow data from seven CR streamgages and miscellaneous base-flow measurements made at various locations along the river. Carter and Putnam (1978) presented annual low-flow frequency statistics for 134 CR streamgages and 102 partial-record (PR) stations in Georgia. PR stations are sites that only have miscellaneous streamflow measurements and are not CR streamgages; many times, PR stations are measured only during low-flow conditions. Carter and Fanning (1982) presented monthly low-flow frequency statistics for 129 selected streamgages in Georgia. Carter (1983) assessed the effects of the 1980–81 drought on streamflow in Georgia. Carter and others (1986; 1988a, b, c, d; 1989a, b) developed 7Q10-flow profiles for selected streams in Georgia. These 7Q10-flow profiles incorporated low-flow data from previous USGS reports. Stamey (1996) presented low-flow characteristics for 12 selected streamgages in southwestern Georgia, southeastern Alabama, and northwestern Florida, which were updated in 2010 (Stamey, 2011). Stamey (2001) presented low-flow characteristics for four selected streamgages located in the Fort Gordon military base in Georgia. Gotvald (2016) presented annual and monthly 1Q10 and 7Q10 statistics for 197 CR streamgages in Georgia that had a minimum of 10 years of record. The study included 85 streamgages on unregulated streams with minimal upstream diversions, 69 streamgages that were known, or considered, to be affected by varying degrees of upstream diversions, and 43 streamgages on regulated streams. Using statistics from 56 streamgages in northern Georgia along with streamgages from Alabama, Tennessee, North Carolina, and South Carolina that were within 75 miles of the State's borders, Gotvald (2017) used weighted left-censored regression techniques to develop regional regression equations for annual 1Q10 and 7Q10, monthly 7Q10, and mean annual flow that can be used to predict these statistics at ungaged locations in north Georgia located above the Fall Line—the geographic boundary separating the higher elevations of the Southwestern Appalachians, Ridge and Valley, Blue Ridge, and Piedmont ecoregions from the low-lying Southeastern Plains, Middle Atlantic Coastal Plain, and Southern Coastal Plain ecoregions (Cooke, 1936; fig. 1).

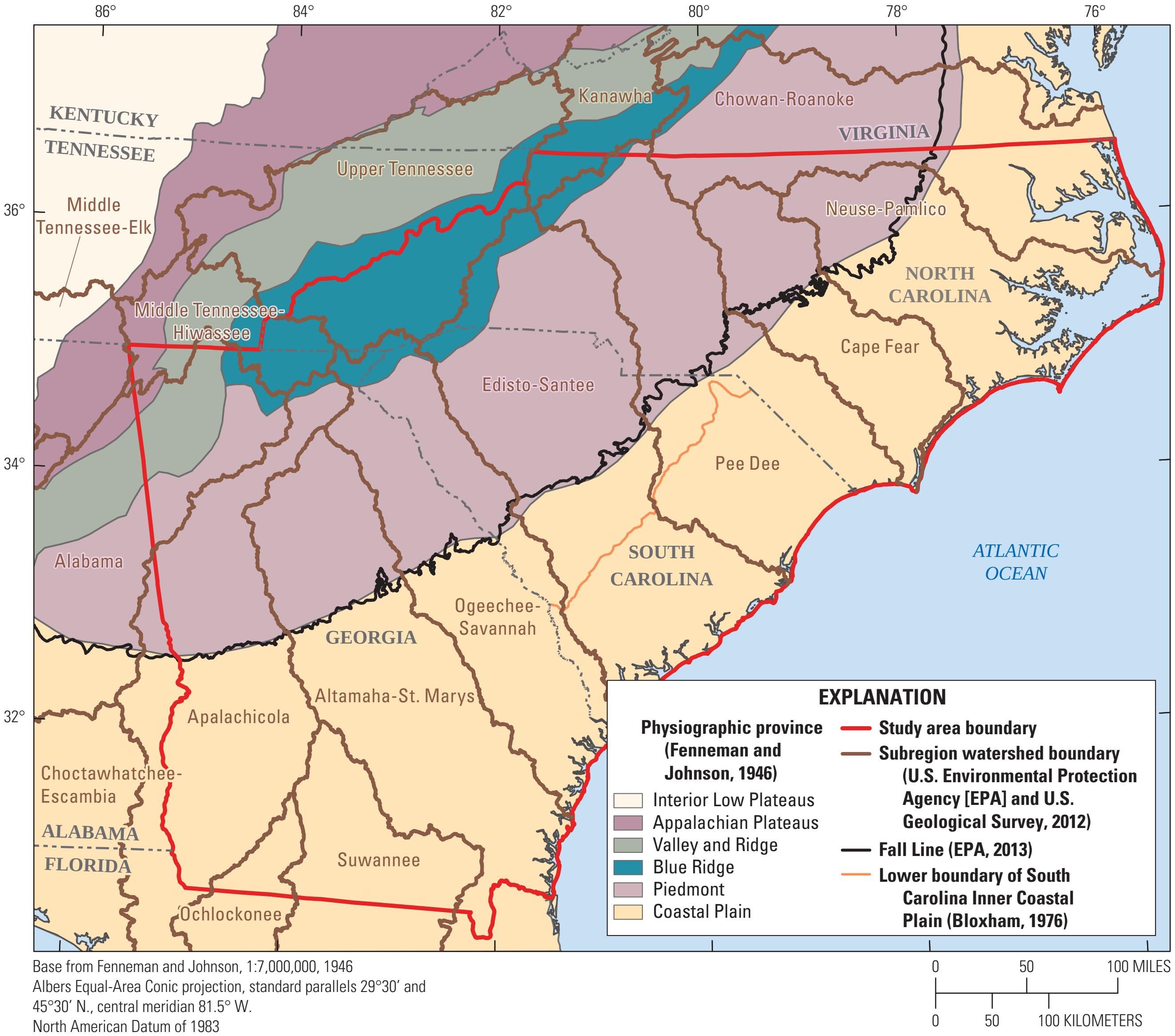
North Carolina

Prior to World War II, low-flow characteristics of North Carolina streams had been determined only for CR streamgages. The economic expansion that followed World War II caused an increasing need for hydrologic information at sites where no data had previously been collected (Yonts, 1971). Thus, the USGS expanded its data-collection program in the late-1940s to include PR stations where streamflow measurements were made on a periodic basis. Discharge measurements made under base-flow conditions, along with observations of zero flow, provided the data used in the initial assessments of low-flow characteristics of streams in North Carolina. With data available from the network of PR stations, the USGS began to respond to requests for low-flow characteristics on a site-specific basis, including for ungaged sites.

Several low-flow studies were completed in the 1960s and 1970s in North Carolina. Goddard (1963) presented low-flow characteristics for many CR streamgages in North Carolina, along with drainage area and 7Q10 discharge profiles developed for selected main-stem rivers. Yonts (1971) reported base-flow measurements made at more than 2,200 locations, including CR streamgages and PR stations throughout the State.

Giese and Mason (1993) evaluated low-flow characteristics at 122 CR streamgages and 396 PR stations having drainage areas ranging from 1 to 400 square miles (mi^2) and streamflow unaffected by regulation or diversions. Sites were characterized based on similarity in range of low flow and potential to sustain base flow. Ten hydrologic areas (HAs) were delineated in North Carolina, and regression equations relating low-flow characteristics to basin characteristics were developed for ungaged sites. Equations for 4 of the 10 hydrologic areas—HA10, representing the mountains and western Piedmont; HA3, representing the Sand Hills; HA5, representing the eastern Piedmont; and HA9, representing the central Piedmont—had standard errors considered small enough to permit use of regression equations to predict low-flow characteristics at ungaged sites.

Evett (1994) investigated effects of urbanization and land-use changes on low flows. Trends of decreasing low flows with increasing urbanization were detected in data from selected CR streamgages in the Asheville, Charlotte, Greensboro, and Raleigh metropolitan areas and from streamgages in nearby rural areas. Because of the downward trends noted at both urban and rural streamgages used in the analysis, Evett described the results as statistically inconclusive.



Base from Fenneman and Johnson, 1:7,000,000, 1946
Albers Equal-Area Conic projection, standard parallels 29°30′ and 45°30′ N., central meridian 81.5° W.
North American Datum of 1983

Figure 2. Study area, physiographic provinces, and 4-digit subregion hydrologic unit watersheds in Georgia, South Carolina, North Carolina, and adjacent States.

During 1996–2003, five reports about basin-wide low-flow investigations were published (Weaver, 1996, 1997, 1998; Weaver and Pope, 2001; Weaver and Fine, 2003) as part of the former North Carolina Division of Water Quality program of assessment and management of water quality in major river basins of North Carolina. These reports summarize low-flow characteristics of streamgages in the basins and present stream profiles of low-flow statistics and drainage areas for selected streams. The stream profiles are graphs of selected low-flow characteristics or drainage area (vertical axis) versus the stream's river mile (horizontal axis). These graphs provide a visual depiction of changes in at-site low-flow statistics and drainage area along the river length being analyzed, with contributions from major tributaries indicated. The stream profiles include the 7Q10, 30Q2, W7Q10, and 7Q2 low-flow statistics.

The Roanoke River Basin (Chowan-Roanoke subregion, fig. 2) low-flow investigation included 82 streamgages (79 sites in North Carolina and 3 sites in Virginia) and 10 stream profiles (Weaver, 1996). Drainage areas for profiled streams range from 22 mi^2 to about 9,700 mi^2.

The Deep River Basin (Cape Fear subregion, fig. 2) low-flow investigation included 7 CR streamgages, 23 PR stations, and stream profiles for the Deep River (Weaver, 1997). The Deep River Basin, in the central Piedmont Physiographic Province of North Carolina, drains slightly more than 1,440 mi^2 in parts of Chatham, Guilford, Moore, and Randolph Counties. The Deep River is a tributary to the Cape Fear River.

The Neuse River Basin (Neuse-Pamlico subregion, fig. 2) low-flow investigation included 50 CR streamgages, 113 PR stations, and 10 stream profiles (Weaver, 1998). Drainage areas for the profiled streams range from 9 to about 5,600 mi^2.

The Cape Fear River Basin (Cape Fear subregion, fig. 2) low-flow investigation included 67 CR streamgages, 121 PR stations, and 13 stream profiles (Weaver and Pope, 2001). Drainage areas for the profiled streams range from about 44 to almost 9,100 mi^2. Because the Deep River is part of the Cape Fear River Basin, the summary of low-flow characteristics at CR streamgages and PR stations in the Deep River Basin (Weaver, 1997) was republished in the Cape Fear River report (Weaver and Pope, 2001) but did not include the Deep River profiles or associated discussions of low-flow characteristics.

The Rocky River Basin (Pee Dee subregion, fig. 2) low-flow investigation included 12 CR streamgages, 44 PR stations, and stream profiles for Rocky River (Weaver and Fine, 2003). The Rocky River Basin, in the southern Piedmont Physiographic Province of North Carolina, drains slightly more than 1,410 mi^2 in parts of Anson, Cabarrus, Iredell, Mecklenburg, Rowan, Stanly, and Union Counties. The Rocky River is tributary to the Pee Dee River.

By using streamflow data through water year 2012, Weaver (2015) presented updated low-flow frequency and daily flow-duration statistics for 177 unregulated sites, 56 regulated sites, and 33 sites known or considered to be affected by varying degrees of minor regulation and (or) diversions upstream of streamgages. Low-flow frequency statistics included in the report were the 7Q10, W7Q10, 30Q2, and 7Q2 streamflow. At 63 unregulated streamgages in North Carolina that had at least 30 years of record as of CY 1998, the updated 7Q10 statistics were compared with previously computed values.

In addition to the previously referenced USGS reports about low-flow investigations for North Carolina streams, the USGS had traditionally provided a service of estimating low-flow statistics for ungaged locations in North Carolina in response to site-specific requests since the 1950s. With the release of updated techniques in 2026 for estimating low-flow statistics, as documented in this report and implemented within the USGS StreamStats application (USGS, 2019), users will be able to use StreamStats for estimating unregulated low-flow statistics at ungaged locations on streams in Georgia, North Carolina, and South Carolina. Because most requests for low-flow statistics have been for ungaged locations on streams known or considered to be unaffected by regulation and (or) major diversions, StreamStats application will be a suitable replacement for this service.

South Carolina

Stallings (1968) presented low-flow statistics for 61 CR streamgages and 83 PR stations where flow was measured during the 1954 drought (Thomson and Carter, 1963; Stallings, 1968). Johnson and others (1968) focused on low-flow statistics of streams in Pickens County. Streamflow measurements during low-flow conditions from 1945 through 1967 were presented for 32 PR stations. The PR stations were correlated with one of four potential index streamgages, which are CR streamgages suitable for correlation with selected PR stations, to estimate 7Q2 and 7Q10 streamflows.

Bloxham and others (1970) presented magnitude and frequency of low flows for nine CR streamgages in Spartanburg County (Edisto-Santee subregion, fig. 2), and streamflow measurements were presented for 63 sites. At 35 of the 63 sites, correlation techniques were used with index streamgages to estimate their 7Q2 and 7Q10. Bloxham (1976) used data from six index streamgages from the Inner (also referred to as Upper) Coastal Plain (defined as the portion of the Coastal Plain Physiographic Province [Fenneman, 1946] where elevations are about 200 feet [ft] or more above mean sea level [Bloxham, 1976]; fig. 2) to estimate the 7Q2 and 7Q10 at 54 PR stations. Bloxham (1979) used data through CY 1976 to compute low-flow frequency and flow-duration estimates at 71 CR streamgages in South Carolina.

Bloxham (1981) estimated the 7Q2 and 7Q10 at 113 PR stations in the Piedmont and lower (where elevations are below about 200 ft above mean sea level) Coastal Plain Physiographic Provinces of South Carolina (fig. 2). Barker (1986) described 361 PR stations and provided measurements that were made from August 1980 through July 1986. Zalants (1991a) provided estimates of the 7Q2 and 7Q10 at 564 PR stations and 27 CR streamgages on streams in the Blue Ridge and Piedmont Physiographic Provinces, and the Upper Coastal Plain in South Carolina and parts of North Carolina and Georgia. Zalants (1991b; fig. 2) provided estimates of annual minimum 1-, 3-, 7-, 14-, 30-, 60-, and 90-day average streamflow with recurrence intervals of 2 to 50 years (depending on length of record), for 55 CR streamgages in South Carolina when at least 5 years of unregulated daily mean streamflow data were available through CY 1986.

Feaster and Guimaraes (2009, 2012, 2014, and 2016) and Guimaraes and Feaster (2010) presented low-flow statistics in the Pee Dee (Pee Dee subregion, fig. 2); Saluda, Congaree, and Edisto (Edisto-Santee subregion); Catawba-Wateree and Santee (Edisto-Santee subregion); Savannah (Ogeechee-Savannah subregion) and Salkehatchie (Edisto-Santee subregion); and Broad (Edisto-Santee subregion) River Basins in South Carolina for 17, 25, 12, 28, and 24 CR streamgages, respectively. Low-flow estimates for the Pee Dee, Saluda-Congaree-Edisto, Catawba-Wateree and Santee, Savannah and Salkehatchie, and Broad River Basins were computed by using daily mean flow data through CYs 2006, 2008, 2011, 2013, and 2007, respectively. In addition, daily flow durations of the 5- to 95-percent probabilities of exceedance were presented for most of these streamgages. Feaster and Guimaraes (2017) summarized the findings from their five previously published USGS reports and provided a trend analysis for the annual minimum 7-day average flows as well as assessments of long-term annual precipitation. They also assessed the statewide variability in the annual minimum 7-day average flow at eight long-term streamgages.

Description of Study Area

The study area includes all of Georgia, South Carolina, and North Carolina, covering an area of about 142,500 mi^2 within seven EPA Level III ecoregions—Southwestern Appalachians, Ridge and Valley, Blue Ridge, Piedmont, Southeastern Plains, Middle Atlantic Coastal Plain, and Southern Coastal Plain (fig. 1; EPA, 2013; Omernik and Griffith, 2014). The ecoregions provide a spatial framework for the research, assessment, management, and monitoring of ecosystems and ecosystem components. Omernik (1987) and Griffith and others (2001, 2002) determined the ecoregions from an analysis of the spatial patterns and the composition of biotic and abiotic phenomena that include geology, physiography, vegetation, climate, soils, land use, wildlife, and hydrology. The Fall Line is a geologic and geographic boundary separating the higher elevation consolidated rocks of the Southwestern Appalachians, Ridge and Valley, Blue Ridge, and Piedmont ecoregions from low-lying, predominantly unconsolidated sediments of the Southeastern Plains, Middle Atlantic Coastal Plain, and Southern Coastal Plain ecoregions (fig. 1).

The Southwestern Appalachians ecoregion is composed of open, low mountains. The eastern boundary of this ecoregion, along the more abrupt escarpment where it meets the Ridge and Valley ecoregion, is relatively smooth and only slightly notched by small, eastward-flowing streams (Griffith and others, 2001, 2002). The Ridge and Valley ecoregion is composed of roughly parallel ridges and valleys with a variety of widths, heights, and geologic materials. Springs and caves are relatively numerous (as compared to other ecoregions), and present-day forests cover about 50 percent of the ecoregion (Griffith and others, 2001). The Blue Ridge ecoregion varies from narrow ridges to hilly plateaus to more mountainous areas. The mostly forested slopes; high-gradient, cool, clear streams; and rugged terrain overlie primarily metamorphic rocks, with minor areas of igneous and sedimentary rock. The Piedmont ecoregion is composed of a transitional area between the mostly mountainous ecoregions of the Appalachians to the northwest and the relatively flat Coastal Plain to the southeast. The Piedmont ecoregion is a complex mosaic of metamorphic and igneous Precambrian and Paleozoic rock, with moderately dissected irregular plains and some hills. Soils tend to be finer textured than in the Coastal Plain ecoregions to the south. Once largely cultivated, much of this ecoregion has reverted to pine and hardwood forests, with increasing conversion to urban and suburban land cover (Omernik, 1987).

The Southeastern Plains ecoregion is composed of irregular plains with a mixture of cropland, pasture, woodland, and forest (Griffith and others, 2001, 2002). The mostly unconsolidated sand, silt, and clay of this ecoregion contrast with the much older rocks of the Piedmont ecoregion. Elevations and relief are greater than in the Southern Coastal Plain ecoregion but generally are less than in much of the Piedmont ecoregion. Streams have relatively low gradient (as compared to the Piedmont ecoregion) with sandy bottoms. The Southern Coastal Plain ecoregion consists of mostly flat plains, but it is a heterogeneous ecoregion containing barrier islands, coastal lagoons, marshes, and swampy lowlands along the Atlantic and Gulf coasts. This ecoregion is lower in elevation with less relief and wetter soils than the Southeastern Plains ecoregion. The Middle Atlantic Coastal Plain ecoregion consists of low-elevation flat plains, with many swamps, marshes, and estuaries. Unconsolidated sediments underlie the low terraces, marshes, dunes, barrier islands, and beaches. Poorly drained soils are common, and the ecoregion has a mix of coarse and finer textured soils compared to the mostly coarse soils in most of the Southeastern Plains ecoregion. The Middle Atlantic Coastal Plain ecoregion typically is lower, flatter, and more poorly drained than the Southern Coastal Plain ecoregion (Omernik, 1987).

For most of the study area, the average annual precipitation generally ranged from 40 to 60 inches per year (in/yr) during 1991–2020 (PRISM Climate Group, 2023a). Average annual precipitation in the southern portion of the Blue Ridge ecoregion receives up to 80 in/yr or more. Precipitation in the study area is associated with the movement of warm and cold fronts from November through April and isolated summer thunderstorms from May through October. Occasionally, tropical storms or hurricanes that enter along the Atlantic and Gulf coasts produce unusually heavy amounts of rainfall. The mean annual air temperature for most of the study area ranged from 54 degrees Fahrenheit (°F) in northern North Carolina to 68 °F in southern Georgia during 1991–2020 (PRISM Climate Group, 2023b). However, temperatures varied, with means as low as 46 °F in some of the higher Blue Ridge elevations in western North Carolina.

Low-Flow Frequency and Flow-Duration Statistics at Gaged Locations

The low-flow frequency, mean annual flow, and flow-duration statistics were calculated during this study for streamgages that had at least 10 climate years (CYs) of daily mean flow data through March 31, 2022 (the end of CY 2021, see sidebar “Climate Year”). These statistics were computed by using the USGS Hydrologic Toolbox software (Barlow and others, 2022), a software package that provides statistical analyses of streamflow and groundwater-level time-series data from the USGS National Water Information System (USGS, 2022) and provides output text reports that describe those analyses. Statistically significant upward and downward trends in annual minimum 7-day average flows were identified for the period of record of each streamgage by using the Kendall’s tau trend test (Kendall, 1938; Helsel and Hirsch, 2002).

Climate Year

The climate (or climatic) year (CY) is a continuous 12-month period that contains a complete annual cycle and is arbitrarily selected for the presentation or analysis of data relative to hydrologic or meteorologic phenomena (Langbein and Iseri, 1960). The CY typically is designated by the calendar year during which most of the selected 12 months occur. For this investigation, the CY is the 12-month period April 1 through March 31, so the 2021 CY is the period April 1, 2021, through March 31, 2022. In Georgia, North Carolina, and South Carolina, minimum streamflow typically occurs in the fall months of September, October, and November and, therefore, use of the CY, as selected, prevents the annual low-flow cycle from being artificially placed in separate years.

Selection of Streamgages

Streamgages were selected, and low-flow frequency statistics were calculated for streamgages that had a minimum of 10 years of daily mean flows as of March 31, 2022 (end of CY 2021). The mean annual flow and flow-duration statistics were calculated for streamgages that had at least 10 water years of daily mean flow data through September 30, 2021. Streamgages that were considered tidally influenced at low flows were excluded from the study. These criteria resulted in 711 streamgages within the 3-State study area (table 1). For the purposes of regional regression analysis, 132 additional streamgages in Alabama, Florida, Tennessee, and Virginia were analyzed because they share basins with Georgia, North Carolina, and South Carolina or are within about 50 miles of these State boundaries (fig. 1; table 1). These criteria resulted in 843 streamgages for which low-flow frequency, mean annual flow, and flow-duration statistics were computed in this study. However, low-flow frequency and mean annual flow statistics needed for water-resources requirements in Alabama, Florida, Tennessee, and Virginia should be obtained from the most recent USGS streamflow statistics reports for those States. The daily mean flow data for these streamgages are available through web-based retrievals from the National Water Information System (USGS, 2022).

Quality Control and Assurance

Streamflow data were reviewed for quality control and quality assurance purposes and to assess potential effects from regulation or diversions. Plots of annual minimum *n*-day average flows and cumulative annual minimum *n*-day average flows against CY, known as a single-mass curve (Bohman and Patterson, 1993), were reviewed for each streamgage. Consistency in the slope of the single-mass curve indicates a consistency in the streamflow statistic being reviewed through time. Relatively wet or dry periods may cause a short-term change in the slope of the curve, but then the curve reverts to the previous slope when the streamflow regime returns to a more normal condition. However, a curve with a substantial change in the slope that persists and does not revert to the previous slope can indicate a change in the flow regime that could be related to changes in precipitation, land use, or other anthropogenic influences. See sidebar “Example of Single-Mass Curve Analysis” for an example.

Low-Flow Frequency Statistics

Low-flow frequency statistics, as defined in this report, are values of annual minimum daily mean streamflow averaged over designated periods (Riggs, 1972). Note that the use of “average” with respect to the low-flow statistics in this report refers to the arithmetic mean. For example, 7Q10 is one of the most used low-flow statistics and is defined as the annual minimum 7-day average flow with a 10-year recurrence interval. In terms of probability of occurrence, there is a 1 in 10 chance (or 10-percent probability) that the annual minimum 7-day average streamflow in any single year will be equal to or less than the estimated 7Q10 for a specific location (Riggs, 1968, 1972, 1985).

For this study, low-flow frequency statistics were computed by fitting a Pearson Type III distribution to the base 10 logarithms (LPIII) of the annual minimum *n*-day average streamflow and determining flow estimates for the recurrence intervals of interest (Riggs, 1972). Fitting the distribution required calculating the mean, standard deviation, and skew coefficient of the logarithms of the *n*-day streamflow. Estimates of the *n*-day non-exceedance flows for a specified recurrence interval *T* were computed by using the following equation:

$$Log\ Q_T = \overline{X} + K_T S, \tag{1}$$

where

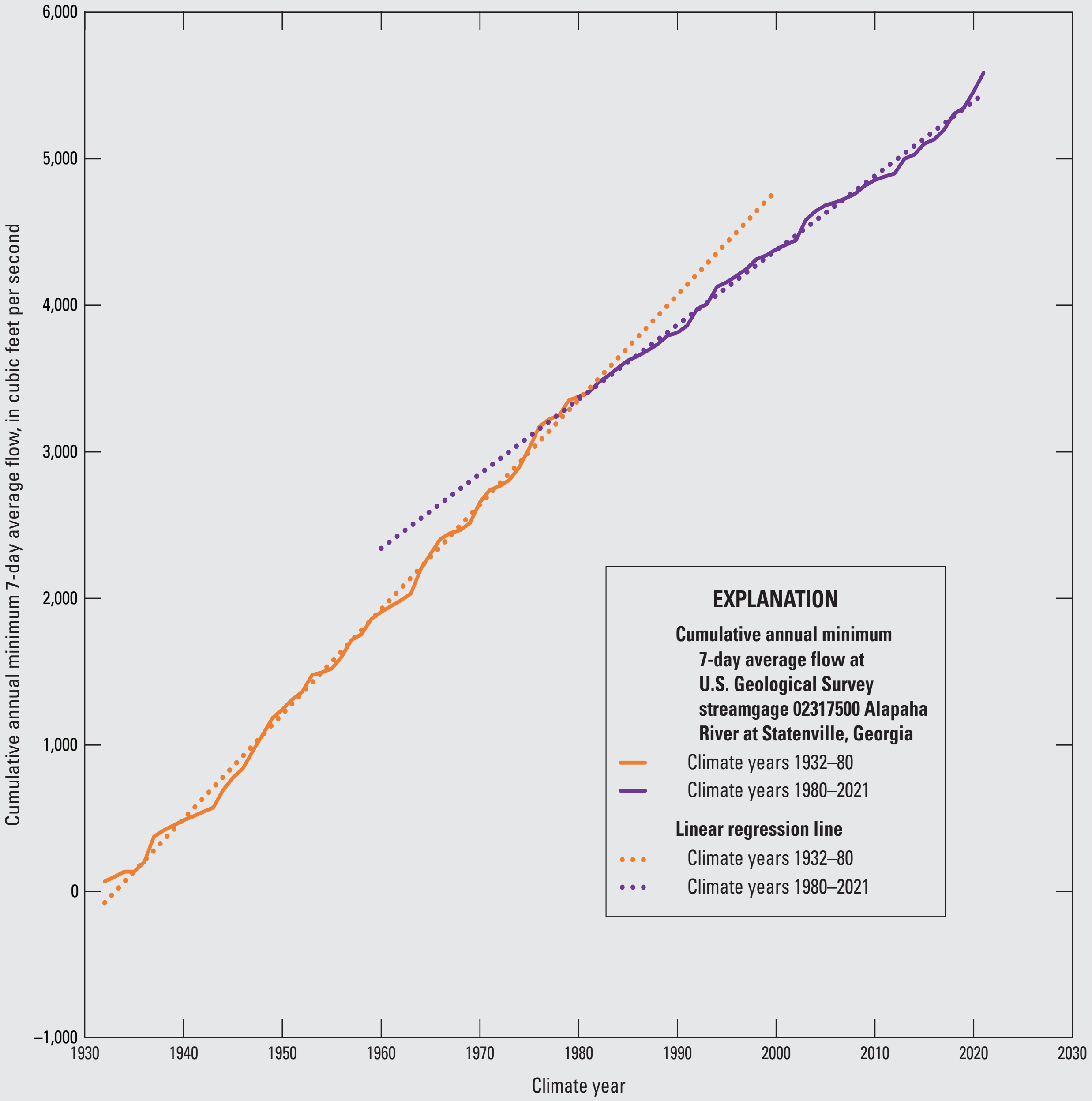
Q_T is the minimum *n*-day average flow for the *T*-year recurrence interval, in cubic feet per second;
$\overline{X}$ is the mean of the logarithms of the minimum *n*-day average flow;
K_T is a frequency factor that is a function of the recurrence interval and the coefficient of skew; and
S is the standard deviation of the logarithms of the minimum *n*-day average flows.

Zero flows cannot be included in an LPIII distribution because they cannot be transformed logarithmically. When zero flows are part of the *n*-day flows at a streamgage, a conditional probability adjustment can be made to estimate the low-flow characteristics (Jennings and Benson, 1969; Tasker, 1987). Additional information on the procedures

Example of Single-Mass Curve Analysis

An example of the single-mass curve analysis for which there is a change in the flow regime is shown for streamgage 02317500 Alapaha River at Statenville, Ga.

The slope of the single-mass curve was relatively consistent from 1932 to 1980, whereas the slope of the single-mass curve decreased around 1980 and remained relatively consistent through the end of climate year 2021. The Alapaha River in south-central Georgia, is part of the Suwannee River Basin (Suwannee subregion, fig. 2).



Single-mass curve of annual minimum 7-day average flows at U.S. Geological Survey streamgage 02317500 Alapaha River at Statenville, Georgia, for climate years 1932–2021. Linear regression reference lines of the annual minimum 7-day average flows for 1932–1980 and 1980–2021 intersect in about 1980.

and guidelines for the conditional probability adjustment can be found in the USGS Surface Water Branch Technical Memorandum No. 70.07 (Carter, 1969).

Active and discontinued USGS streamgages having at least 10 years of record were included in this study. Ten years of record is widely considered as the minimum period of record sufficient for this type of frequency analysis (Riggs, 1972). Frequency statistics were computed for the annual 1Q10, 7Q10, 7Q2, 30Q2, and 30Q3 streamflows; the W7Q10 (November–March) streamflow; and the monthly 1Q10 and 7Q10 streamflows (tables 1 and 2 in Kolb and others, 2026).

Flow-Duration Statistics

Flow-duration curves are cumulative frequency curves that show the percentage of time when specified flows were equaled or exceeded during the period analyzed (Searcy, 1959). Flow durations are computed by sorting the individual daily mean flows for the period of record being analyzed from the largest to the smallest value and assigning each value a rank, starting from 1 to the largest value. The frequencies of exceedance are then computed by using the Weibull formula for computing plotting positions (Helsel and others, 2020):

$$P = 100*[M/(n+1)], \tag{2}$$

where

P is the probability that a given flow will be equaled or exceeded (percentage of time),

M is the ranked position, and

n is the number of events for the period of record.

Streamgages included in the flow-duration analyses have a minimum of 10 years of daily mean flows as of September 30, 2021, which is the end of the water year 2021 (tables 1 and 2 in Kolb and others, 2026).

Trends in Annual Minimum 7-Day Average Flows

Trends for the annual minimum 7-day average flows were analyzed for all stations in the investigation by using a probability value (p-value) of 0.05 to determine significance (Kendall, 1938; Helsel and Hirsch, 2002). Kendall’s tau is a statistical test based on enumerating concordant (when both the x and y variables increase or decrease) and discordant (when x increases and y decreases or x decreases and y increases) pairs of x and y data (Kendall, 1938). Consequently, when stations have a substantial number of zero flows, causing ties in the pairs of x and y data, interpretation of the trend test can become tenuous at best. For hydrologic time-series data, Kendall’s tau is best suited for analysis of long-term datasets. Although it can be applied to short time series, Kendall’s tau may not provide information that is of practical importance, and care is needed to avoid misinterpreting results. Tests applied to short time series may (1) fail to detect a statistically significant trend even though a large increase or decrease in flow has been measured, or (2) detect a statistically significant trend even though the trend is of no practical importance (Oki, 2004). Thus, long-term streamgaging data are better suited for trend assessments. The USGS typically considers 30 years of streamflow record as a minimum requirement for assessing long-term trends (Lins, 2005). Nonetheless, results of the Kendall’s tau analysis are provided for all streamgages included in the study (tables 1 and 2 in Kolb and others, 2026). Additional trend analyses were completed for long-term streamgages and are discussed in later sections of this report.

Long-Term Trend Analyses for Annual Minimum 7-Day Average Flows, Precipitation, and Air Temperature in Georgia, North Carolina, and South Carolina

One of the assumptions of frequency analysis, as presented in this report, is stationarity over time. As such, trend tests, such as the Mann-Kendall test used herein (Kendall, 1938; Mann, 1945), often are used in reviewing frequency analysis flow data. Trend tests are best suited for long-term records because trends detected in a relatively short-term record may only be indicative of a short-term climatic condition and not long-term change in watershed characteristics or climate. This is particularly true for records that begin and (or) end in an extreme climatic condition. When such short-term extreme conditions are viewed in terms of a much longer timeframe, it may become clear that the short-term trend was not actually reflective of a long-term change in the system but may just be part of a much longer term oscillation (Lins and others, 2010).

To be included in trend analysis for this study, streamgages had to have at least 30 years of continuous record ending as of March 31, 2022, and a continuous record for the full period analyzed; they had to be in Georgia, North Carolina, or South Carolina; and they had to have been included in the regional regression analysis (table 1 in Kolb and others, 2026). Based on these criteria, 78 streamgages were included in the trend analysis. Streamgages were evaluated for trend records of 30, 50, 70, and 90 years, ending in CY 2021 and starting in CYs 1992, 1972, 1952, and 1932, respectively.

The dependency of low flow on the prior year’s low flow conditions can create autocorrelation and increase the Type I error rate, which is the detection of a trend when one is not present (Helsel and others, 2020). The long-term time-series structure of low-flow data is not well understood (Hodgkins and Dudley, 2011). Therefore, three dependence assumptions were tested to consider short- and long-term persistence along with the assumption of independence—which assumes the annual data are independent from each other and does not account for short- or long-term influences from impacts such as unusually wet or dry years.

Correlating the trends of the annual minimum 7-day average streamflow to other factors was outside the scope of this report. However, climatic variability, which may partially influence the lowest flows of the year, was assessed by trend analysis of long-term precipitation (climate years 1896–2021) and air temperature (calendar years 1895–2021) records.

Trend Methods for Long-Term Annual Minimum 7-Day Average Flows

Monotonic upward and downward trends were statistically assessed by using the Mann-Kendall test (Kendall, 1938; Mann, 1945) and the magnitude of trends was calculated by using the Theil-Sen estimator (Theil, 1950a, b; Sen, 1968). The Mann-Kendall test is a nonparametric test of trend based on the ranks of the observations. The Theil-Sen estimator is a robust, non-parametric method for simple linear regression and is calculated as the median of all possible pairwise slopes. The null hypothesis for the Mann-Kendall test was no monotonic trend (trend either upward or downward, without reversing direction). Statistically significant monotonic trends can be the result of a step change or another trend that may be best described as nonmonotonic. This analysis was limited to reporting the overall changes for the time periods tested.

In annual series data, short-term climatological variability could indicate serial correlation when assessed by using the Mann-Kendall test. For instance, the droughts of 1998 to 2002 and 2007 to 2008 in the southeastern United States spanned multiple CYs, setting record lows and likely causing the lowest flows each year (Weaver, 2015). By not accounting for persistence, such as a period of drought, the statistical significance of trends may be overstated (Cohn and Lins, 2005). Further, identification of a significant trend can be confounded by the presence of positive or negative autocorrelation in a time series. Thus, previous researchers have suggested statistical trend tests that modify the standard Mann-Kendall test to account for autocorrelated data (Hamed and Ramachandra Rao, 1998; Hamed, 2008). These modifications do not affect the power of the test to detect a trend and offer improved accuracy in significance levels (Hamed and Ramachandra Rao, 1998). The Type I error (that is, detecting a trend when none exists) is more prevalent due to the slow decay of the autocorrelation function when the time scale, the period of record, is greater than annual (Hamed, 2008). For this study, the shortest span analyzed was 30 years; thus, modified Mann-Kendall tests were used to account for autocorrelation.

Three dependence assumptions were tested: (1) independence (the standard Mann-Kendall test; Kendall, 1938; Mann, 1945), (2) short-term persistence (Hamed and Ramachandra Rao, 1998), and (3) long-term persistence (Hamed and Ramachandra Rao, 1998; Hamed, 2008). The three versions of the Mann-Kendall test all use the same test statistic, but the short-term persistence version inflates the variance computed by using the independence assumption by a factor related to the lag-1 autocorrelation coefficient, and the long-term persistence version inflates the variance based on the Hurst coefficient (Hurst, 1951). Data analysis was conducted in R version 4.4.0 (R Core Team, 2023). R scripts used to modify the Mann-Kendall test were obtained from the USGS New England Water Science Center. The scripts were originally written in 2014 by Benjamin Renard (IRSTEA, National Research Institute of Science and Technology for Environment and Agriculture, Lyon, France), for usage in USGS streamflow trend detection papers (Hodgkins and others, 2019; Dudley and others, 2020) and are available in a USGS data release (Dudley and others, 2018).

Graphical analysis of data was completed by using scatterplots and curve fitting. Temporal patterns in low-flow data were visualized with locally estimated scatterplot smoothing (LOESS) curves. Analogous to a moving average, the LOESS curve is a smoothing procedure for time-series data (Cleveland and Devlin, 1988). LOESS curves were fit to the data by using the “Exploration and Graphics for RivEr Trends” (EGRET) R package and the plotFlowTrend function (Hirsch and De Cicco, 2014; Hirsch and others, 2023). To aid in the visualization of long-term trends, the Theil-Sen estimator (also known as the Sen’s slope estimator or Kendall-Theil robust line) was used to fit patterns in low-flow data. The Theil-Sen estimator is a robust, nonparametric regression method for fitting a linear trend for data that may contain outliers or non-normal errors (Helsel and others, 2020). The slope is equal to the median of the slopes between all possible pairs of data. The Theil-Sen estimator was calculated with the “Median-Based Linear Models” R package by using the mblm function (Komsta, 2019). The method of computation for the statistical significance of the Theil-Sen estimator is identical to that of the Kendall’s τ coefficient (Helsel and others, 2020).

Trend Methods for Long-Term Precipitation and Air Temperature

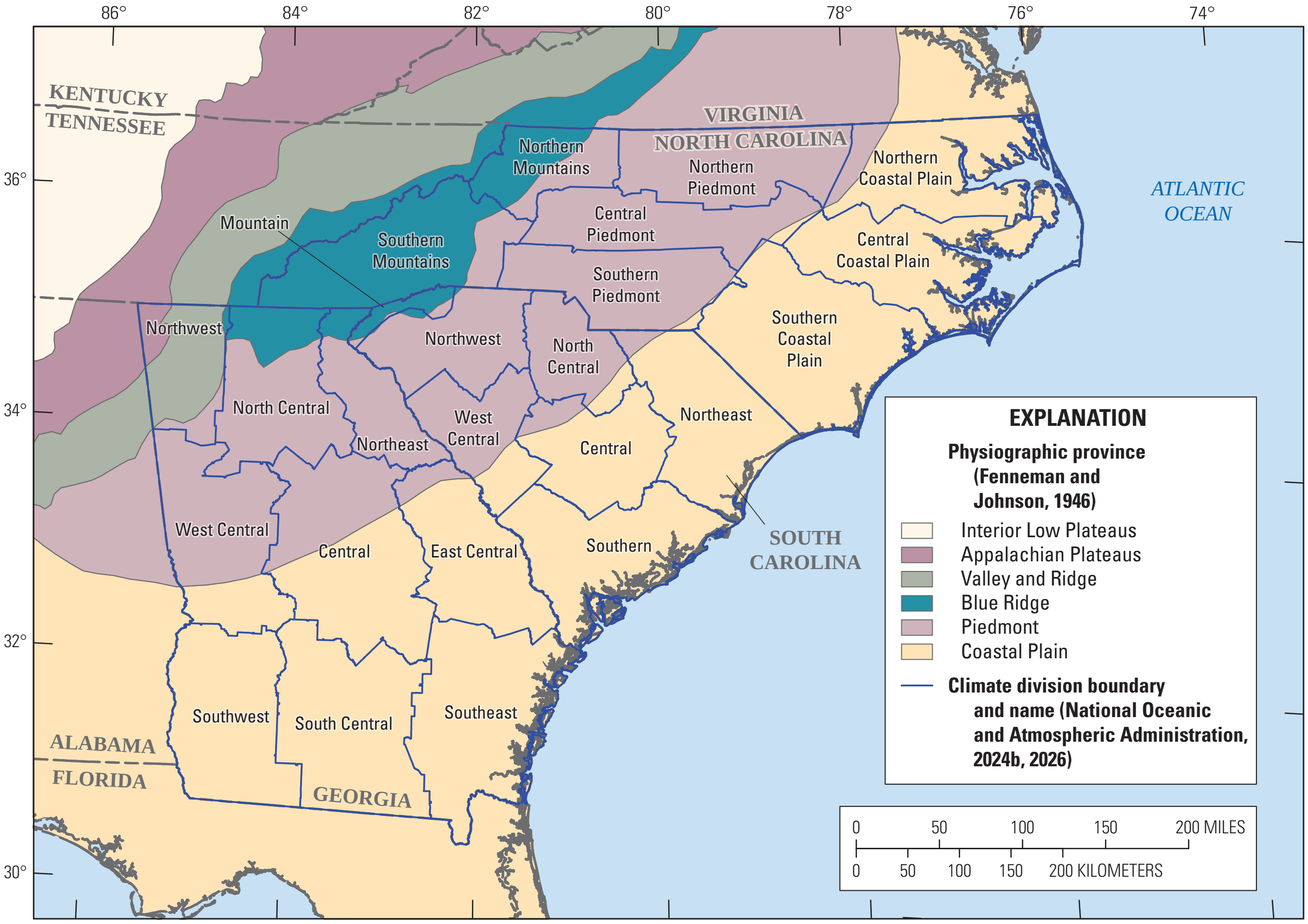
Two climatological influences on low flows are precipitation and air temperature. As such, trend analyses were completed for mean annual precipitation (CYs 1896–2021) and mean annual temperature (1895–2021) for Georgia, North Carolina, and South Carolina. Data for these analyses were obtained from the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information website (NOAA, 2024a). These analyses covered 24 climate divisions (NOAA, 2024b, 2026, 9 climate divisions in Georgia, 8 climate divisions in North Carolina, and 7 climate divisions in South Carolina) and statewide aggregates for the 3 States (fig. 3). Trend analysis was completed by using the same methods and three dependence assumptions (independence, short-term persistence, and long-term persistence) applied to the annual minimum 7-day average flows. Graphical assessments included LOESS curves to visualize patterns in the data and the Theil-Sen robust line to visualize trends.

Annual Minimum 7-Day Average Flow Trends

Examples of trends over time are shown in figure 4 for streamgages in Georgia, South Carolina, and North Carolina. Figure 4*A* shows no trend over time for USGS streamgage Oostanaula River at Resaca, Ga. (USGS site number 02387500; Alabama subregion, fig. 2), while figure 4*B* shows a downward trend over time at USGS streamgage North Pacolet River at Fingerville, S.C. (02154500; Edisto-Santee subregion), and figure 4*C* shows an upward trend over time at USGS streamgage Linville River near Nebo, N.C. (02138500; Edisto-Santee subregion).

For the 30-year climate period (CYs 1992–2021) for 78 streamgages, trend analysis in annual minimum 7-day average flows for the independence assumption (the standard Mann-Kendall test) indicated downward trends for 5 streamgages, an upward trend for 1 streamgage, and no statistically significant trends for 72 streamgages (table 2; table 3 in Kolb and others, 2026). Trend analysis using the short-term persistence assumption, indicated a downward trend for 1 streamgage, an upward trend for 1 streamgage, and no statistically significant trends for 76 streamgages. Trend analysis using the long-term persistence assumption indicated no statistically significant trends. Overall, this climate period is reflective of a largely stable pattern with minimal directional change.

For the 50-year climate period (CYs 1972–2021) trend analysis for 46 streamgages, there were downward trends in annual minimum 7-day average flows for 14, 10, and 1 streamgages for the independence, short-term



Base from Fenneman and Johnson, 1:7,000,000, 1946
Albers Equal-Area Conic projection, standard parallels 29°30′ and 45°30′ N., central meridian 81.5° W.
North American Datum of 1983

Figure 3. Physiographic provinces (Fenneman, 1946) in and near the study area and the 24 climate divisions for Georgia, North Carolina, and South Carolina from the National Oceanic and Atmospheric Administration (2026).

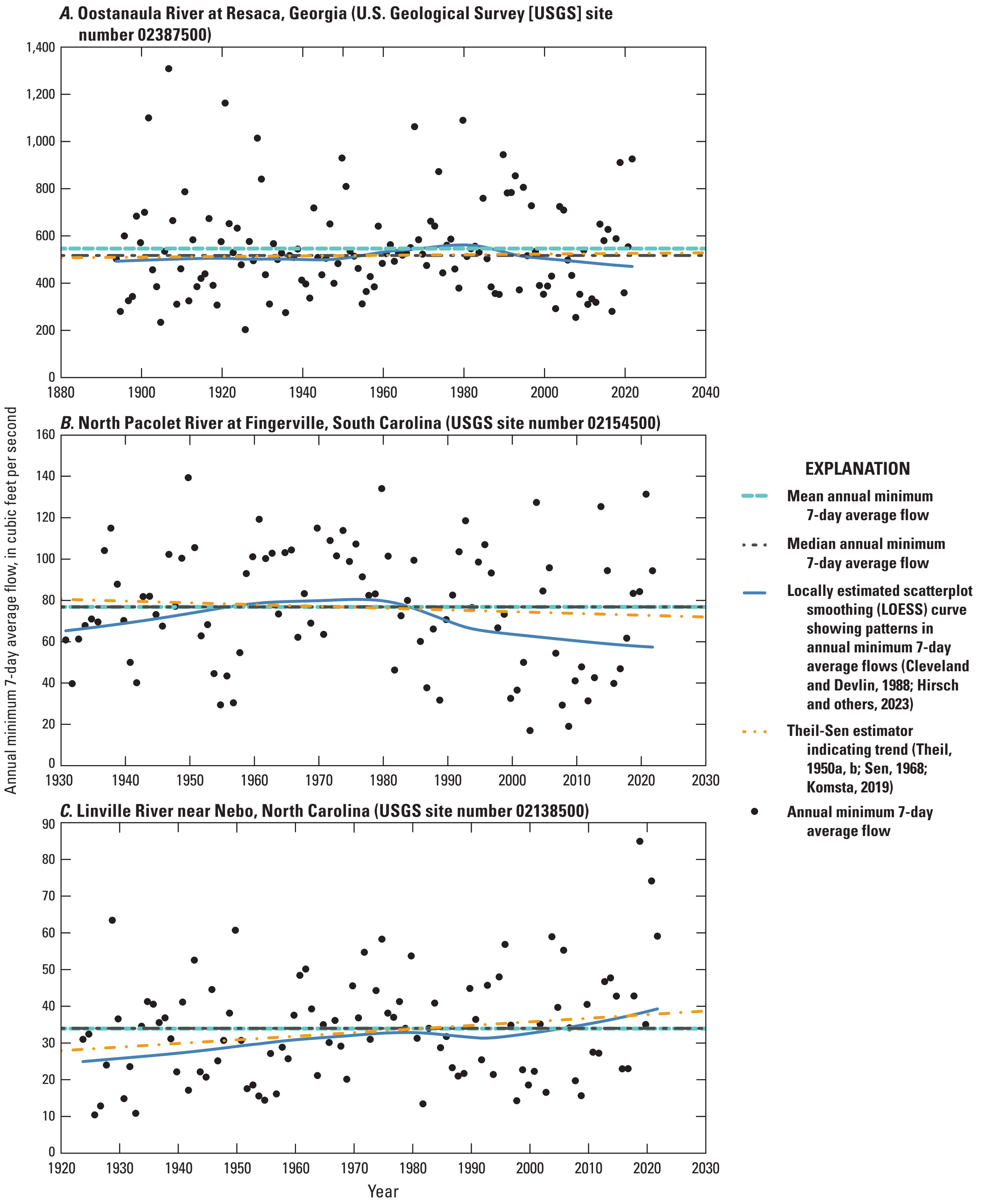


Figure 4. Examples of scatterplots and curve-fitting lines of annual minimum 7-day average flows for U.S. Geological Survey (USGS) streamgages *A*, Oostanaula River at Resaca, Ga. (USGS site number 02387500), *B*, North Pacolet River at Fingerville, S.C. (02154500), and *C*, Linville River near Nebo, N.C. (02138500).

Table 2. Results of trend analysis for annual minimum 7-day average flows obtained by using the Mann-Kendall test (Kendall, 1938; Mann, 1945) and three dependence assumptions for 30-, 50-, 70-, and 90-year periods (climate years 1992–2021, 1972–2021, 1952–2021, and 1932–2021, respectively) for streamgages with minimal to no regulation in Georgia, North Carolina, and South Carolina.

[climate year, April 1–March 31, with year at the beginning of the period; NSS, not statistically significant. Detailed information can be found in tables 3–6 in Kolb and others (2026)]

Climate years (and periods)	Total number of streamgages analyzed	Trend direction	Dependence assumption		
			Independence[1]	Short-term persistence[2]	Long-term persistence[3]
			Number of streamgages		
1992–2021 (30 year)	78	Downward	5	1	0
		Upward	1	1	0
		NSS	72	76	78
1972–2021 (50 year)	46	Downward	14	10	1
		Upward	0	0	0
		NSS	32	36	45
1952–2021 (70 year)	27	Downward	7	6	0
		Upward	1	0	0
		NSS	20	21	27
1932–2021 (90 year)	6	Downward	2	2	1
		Upward	0	0	0
		NSS	4	4	5

[1] Kendall (1938); Mann (1945).

[2] Hamed and Ramachandra Rao (1998).

[3] Hamed and Ramachandra Rao (1998); Hamed (2008).

persistence, and long-term persistence analyses, respectively; no statistically significant trends were indicated for the remaining streamgages (table 2; table 4 in Kolb and others, 2026). Assessing this trend data overall, the argument could be made that downward trends were a prominent feature of streamgage data during this period. However, during the 1960–70s, the southeastern United States was relatively wetter and cooler than the long-term normal (NOAA, 2024a). During 1998–2002, many areas in the southeastern United States experienced historic droughts (Weaver, 2005). As previously noted, in situations where a trend analysis begins and (or) ends in a relatively extreme condition, the trend test may indicate a statistically significant trend that may not actually be indicative of a longer term condition. This is likely the reason that the trend analysis considering long-term persistence for the period 1972–2021 indicates far fewer streamgages with statistically significant trends than the independence and short-term persistence analyses.

For the 70-year climate period (CYs 1952–2021) trend analysis for 27 streamgages, there were downward trends in annual minimum 7-day average flows for 7 and 6 streamgages for the independence and short-term persistence analyses, respectively, an upward trend in flows for 1 streamgage for the independence analysis, and no statistically significant trends for the remaining analyses (table 2; table 5 in Kolb and others, 2026). The lack of downward trends for the long-term persistence analysis as opposed to several downward trends for the independence and short-term persistence analyses, indicates that downward trends are not likely the result of longer term conditions—similar to the results from the 50-year climate period trend analysis.

For the 90-year climate period (CYs 1932–2021) trend analysis for six streamgages, there were downward trends in annual minimum 7-day average flows for two, two, and one streamgages for the independence, short-term persistence, and long-term persistence analyses, respectively; no statistically significant trends were indicated for the remaining analyses (table 2; table 6 in Kolb and others, 2026). Only a few streamgages were used in this analysis, and the majority indicated no statistically significant trend. All downward trends occurred within tests for two streamgages, indicating that minimum flows were decreasing at these sites.

Mean Annual Precipitation Trends for Climate Years 1896 to 2021

Trend analysis indicated no statistically significant trends in mean annual precipitation for CYs 1896 to 2021 in either the statewide analysis or analysis by climate division for the independence, short-term persistence, or long-term persistence assumptions (table 3). Although not statistically significant, the Theil-Sen slope for the statewide analyses did indicate a slight total increase of 1.31, 1.74, and 1.74 inches of precipitation for Georgia, North Carolina, and South Carolina, respectively (fig. 5). With respect to the climate divisions, the Theil-Sen slope varied substantially. For example, the Central climate division in Georgia had a small total decrease of 0.14 inch, whereas the other climate divisions in Georgia had increases ranging from 0.13 inch in the Northeast to 3.67 inches in the Northwest (table 3).

Mean Annual Air Temperature Trends for Calendar Years 1895 to 2021

Trend analysis for statewide mean annual air temperature for calendar years 1895 to 2021 that were done by using the dependence assumptions indicated upward trends for all three States (table 4; fig. 6). The independence trend analysis indicated upward trends for four climate divisions in Georgia, with total change from the Theil-Sen slope ranging from 0.81 to 1.14 °F; the remaining five divisions had no statistically significant trends. For North Carolina, seven climate divisions had statistically significant upward trends in air temperature, with total change ranging from 1.22 to 1.65 °F, whereas the Southern Mountains climate division had no statistically significant trend. All seven climate divisions in South Carolina had statistically significant upward trends in air temperature, with total change ranging from 0.83 to 1.20 °F. The long-term persistence analysis indicated that air temperature increases were not statistically significant.

Table 3. Trend statistics for mean annual precipitation for National Oceanic and Atmospheric Administration (NOAA) climate divisions (NOAA, 2026) and statewide in Georgia, North Carolina, and South Carolina for climate years 1896 to 2021 (NOAA, 2024a) obtained by using the Mann-Kendall test (Kendall, 1938; Mann, 1945), Theil-Sen estimator (Theil, 1950a, b; Sen, 1968), and three dependence assumptions.

[Ga., Georgia; N.C., North Carolina; S.C., South Carolina; *p*-value, probability value; NSS, not statistically significant]

State	Climate division number	Climate division name[1]	Theil-Sen estimator[2] magnitude (inches per year)	Total change in mean annual precipitation (inches)	Dependence assumption: Independence[3] *p*-value	Independence[3] Trend	Short-term persistence[4] *p*-value	Short-term persistence[4] Trend	Long-term persistence[5] *p*-value	Long-term persistence[5] Trend
Ga.	1	Northwest	0.029	3.67	0.15	NSS	0.16	NSS	0.22	NSS
Ga.	2	North Central	0.029	3.62	0.23	NSS	0.22	NSS	0.31	NSS
Ga.	3	Northeast	0.001	0.13	0.97	NSS	0.97	NSS	0.98	NSS
Ga.	4	West Central	0.010	1.29	0.65	NSS	0.63	NSS	0.70	NSS
Ga.	5	Central	−0.001	−0.14	0.95	NSS	0.95	NSS	0.96	NSS
Ga.	6	East Central	0.006	0.81	0.77	NSS	0.78	NSS	0.81	NSS
Ga.	7	Southwest	0.009	1.19	0.65	NSS	0.65	NSS	0.70	NSS
Ga.	8	South Central	0.011	1.43	0.58	NSS	0.58	NSS	0.64	NSS
Ga.	9	Southeast	0.010	1.31	0.59	NSS	0.56	NSS	0.64	NSS
Ga.		Statewide	0.010	1.31	0.55	NSS	0.54	NSS	0.61	NSS
N.C.	1	Southern Mountains	0.019	2.39	0.46	NSS	0.48	NSS	0.53	NSS
N.C.	2	Northern Mountains	0.011	1.37	0.62	NSS	0.60	NSS	0.67	NSS
N.C.	3	Northern Piedmont	0.010	1.22	0.52	NSS	0.51	NSS	0.59	NSS
N.C.	4	Central Piedmont	−0.004	−0.50	0.76	NSS	0.76	NSS	0.80	NSS
N.C.	5	Southern Piedmont	−0.009	−1.15	0.63	NSS	0.63	NSS	0.68	NSS
N.C.	6	Southern Coastal Plain	0.032	4.03	0.052	NSS	0.058	NSS	0.10	NSS
N.C.	7	Central Coastal Plain	0.021	2.59	0.19	NSS	0.20	NSS	0.27	NSS
N.C.	8	Northern Coastal Plain	0.014	1.78	0.29	NSS	0.26	NSS	0.37	NSS
N.C.		Statewide	0.014	1.74	0.30	NSS	0.30	NSS	0.38	NSS
S.C.	1	Mountain	0.008	0.96	0.80	NSS	0.80	NSS	0.83	NSS
S.C.	2	Northwest	−0.011	−1.33	0.65	NSS	0.65	NSS	0.70	NSS
S.C.	3	North Central	−0.007	−0.89	0.70	NSS	0.71	NSS	0.75	NSS
S.C.	4	Northeast	0.030	3.78	0.07	NSS	0.07	NSS	0.12	NSS
S.C.	5	West Central	0.014	1.71	0.50	NSS	0.52	NSS	0.56	NSS
S.C.	6	Central	0.015	1.95	0.36	NSS	0.37	NSS	0.44	NSS
S.C.	7	Southern	0.028	3.49	0.12	NSS	0.12	NSS	0.19	NSS
S.C.		Statewide	0.014	1.74	0.34	NSS	0.35	NSS	0.42	NSS

[1] NOAA (2024a); figure 3.

[2] Theil (1950a, b); Sen (1968).

[3] Kendall (1938); Mann (1945).

[4] Hamed and Ramachandra Rao (1998).

[5] Hamed and Ramachandra Rao (1998); Hamed (2008).

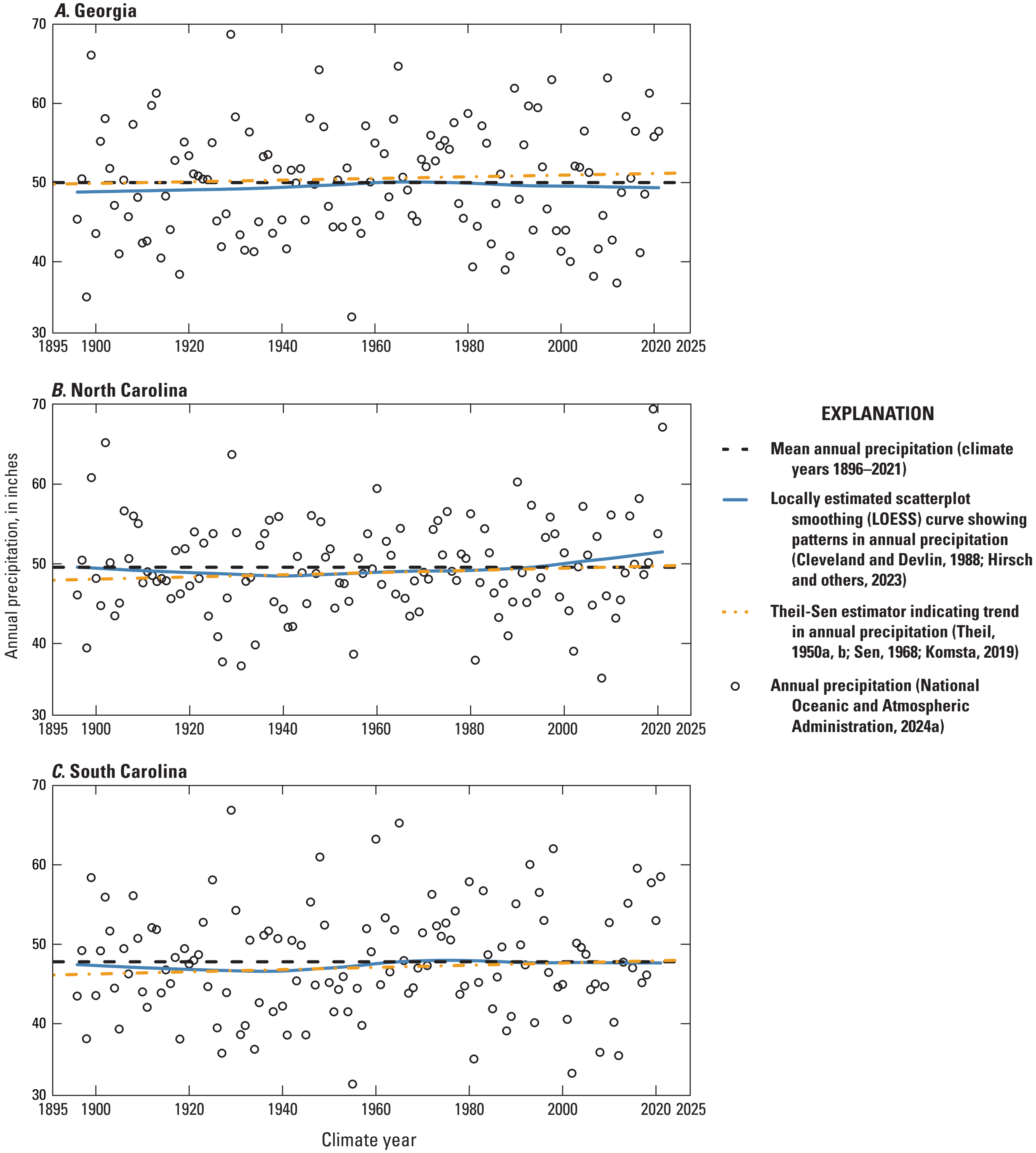


Figure 5. Annual precipitation and mean annual, curve-fitting, and trend lines for precipitation for *A*, Georgia, *B*, North Carolina, and *C*, South Carolina, for climate years 1896 to 2021.

Table 4. Trend statistics for mean annual air temperature for National Oceanic and Atmospheric Administration (NOAA) climate divisions (NOAA, 2026) and statewide in Georgia, North Carolina, and South Carolina for calendar years 1895 to 2021 (NOAA, 2024a) obtained by using the Mann-Kendall test (Kendall, 1938; Mann, 1945), Theil-Sen estimator (Theil, 1950a, b; Sen, 1968), and three dependence assumptions.

[°F, degrees Fahrenheit; Ga., Georgia; N.C., North Carolina; S.C., South Carolina; *p*-value, probability value; NSS, not statistically significant]

State	Climate division number	Climate division name[1]	Theil-Sen estimator[2] magnitude (°F per year)	Total change in mean annual temperature (°F)	Dependence assumption					
					Independence[3]		Short-term persistence[4]		Long-term persistence[5]	
					p-value	Trend	*p*-value	Trend	*p*-value	Trend
Ga.	1	Northwest	0.0016	0.20	0.63	NSS	0.71	NSS	0.83	NSS
Ga.	2	North Central	0.0010	0.13	0.70	NSS	0.77	NSS	0.87	NSS
Ga.	3	Northeast	0.0014	0.18	0.53	NSS	0.65	NSS	0.79	NSS
Ga.	4	West Central	0.0039	0.50	0.16	NSS	0.30	NSS	0.55	NSS
Ga.	5	Central	0.0053	0.68	0.052	NSS	0.15	NSS	0.37	NSS
Ga.	6	East Central	0.0078	0.99	0.006	Upward	0.054	NSS	0.27	NSS
Ga.	7	Southwest	0.0064	0.81	0.014	Upward	0.050	NSS	0.21	NSS
Ga.	8	South Central	0.0067	0.85	0.006	Upward	0.038	Upward	0.18	NSS
Ga.	9	Southeast	0.0090	1.14	0.001	Upward	0.016	Upward	0.14	NSS
Ga.		Statewide	0.0051	0.65	0.048	Upward	0.14	Upward	0.38	NSS
N.C.	1	Southern Mountains	0.0047	0.60	0.093	NSS	0.21	NSS	0.46	NSS
N.C.	2	Northern Mountains	0.0116	1.48	0.000	Upward	0.004	Upward	0.061	NSS
N.C.	3	Northern Piedmont	0.0130	1.65	0.000	Upward	0.005	Upward	0.072	NSS
N.C.	4	Central Piedmont	0.0104	1.32	0.000	Upward	0.017	Upward	0.16	NSS
N.C.	5	Southern Piedmont	0.0098	1.24	0.001	Upward	0.032	Upward	0.22	NSS
N.C.	6	Southern Coastal Plain	0.0107	1.36	0.000	Upward	0.011	Upward	0.12	NSS
N.C.	7	Central Coastal Plain	0.0105	1.34	0.000	Upward	0.016	Upward	0.14	NSS
N.C.	8	Northern Coastal Plain	0.0096	1.22	0.001	Upward	0.025	Upward	0.18	NSS
N.C.		Statewide	0.0100	1.27	0.001	Upward	0.018	Upward	0.15	NSS
S.C.	1	Mountain	0.0069	0.88	0.014	Upward	0.075	NSS	0.27	NSS
S.C.	2	Northwest	0.0095	1.20	0.001	Upward	0.014	Upward	0.098	NSS
S.C.	3	North Central	0.0074	0.94	0.009	Upward	0.061	NSS	0.27	NSS
S.C.	4	Northeast	0.0087	1.10	0.003	Upward	0.045	Upward	0.23	NSS
S.C.	5	West Central	0.0071	0.91	0.010	Upward	0.058	NSS	0.26	NSS
S.C.	6	Central	0.0065	0.83	0.026	Upward	0.12	NSS	0.37	NSS
S.C.	7	Southern	0.0089	1.13	0.001	Upward	0.036	Upward	0.23	NSS
S.C.		Statewide	0.0078	0.99	0.005	Upward	0.052	NSS	0.25	NSS

[1] NOAA (2024a); figure 3.

[2] Theil (1950a, b); Sen (1968).

[3] Kendall (1938); Mann (1945).

[4] Hamed and Ramachandra Rao (1998).

[5] Hamed and Ramachandra Rao (1998); Hamed (2008).

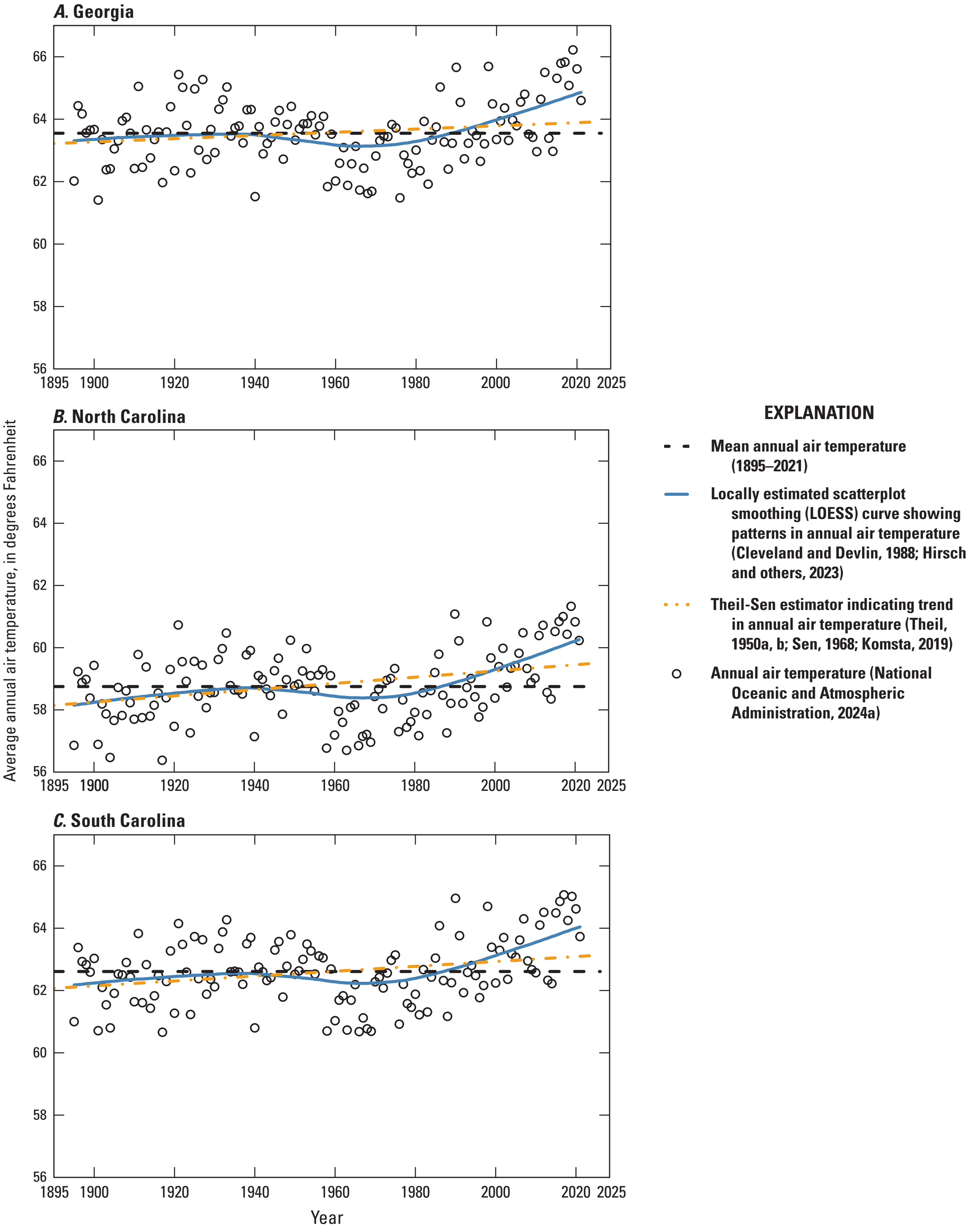


Figure 6. Average annual air temperature and mean annual, curve-fitting, and trend lines for air temperature for *A*, Georgia, *B*, North Carolina, and *C*, South Carolina, for calendar years 1895 to 2021.

Streamflow Record Selection for Regional Regression Analysis

USGS streamgages were selected for use in the regional regression analysis based on their records being minimally affected by regulation, by diversion, and, for those in the Coastal Plain Physiographic Province in Georgia (fig. 2), by irrigation groundwater withdrawals. This is because regression analysis is used to predict natural flow statistics for ungaged sites. Of the 843 streamgages analyzed for flow statistics, 140 streamgages were excluded for regulations, 74 were excluded for diversions, and 2 were excluded for a combination of regulations/diversions. Streamflow statistics from another 27 streamgage records that were affected by regulation, diversion, or groundwater withdrawals, but had a substantial portion of their early record considered unregulated, were included in the regression analysis based on statistics from their unaffected/unregulated periods. Of those 27 streamgages, 11 were affected by regulation, 14 were affected by diversion (of which 13 likely were influenced by irrigation groundwater withdrawals), and 2 were affected by a combination of regulations/diversions. In addition, 21 streamgages were excluded because they were considered redundant, 2 were excluded because their statistics did not fit regional regression relations, and 1 was excluded because its flow statistics were considered an outlier. This resulted in 604 streamgages with unregulated flow in the regional regression analysis (fig. 1; table 1; table 1 in Kolb and others, 2026). The 239 excluded streamgages and 27 streamgages where streamflows were affected later in their records are listed in table 2 in Kolb and others (2026).

Station description information was reviewed for insight into potential regulation and diversions. Station descriptions contain a regulation and diversion section that describes basin anthropogenic influences, such as dams, reservoirs, and water intakes and returns, and the effects of regulation on streamflow. Those descriptions and other assessments and information, like the presence and effects of dams, reservoirs, canals, retention and detention ponds, sewers, power plants, water intakes, wastewater returns, and National Pollutant Discharge Elimination System permit facilities, were used to determine streamgages that were considered as minimally affected by regulation or diversions and, therefore, suitable to include in the regional regression analysis. In some cases, part of a streamgage period of record represented a more natural condition, but another part reflected anthropogenic influences. In such cases, the streamgage record was analyzed for the two periods separately, with low-flow frequency statistics from the period representing natural condition included in regression analysis (table 1 in Kolb and others, 2026) and low-flow frequency statistics from the period reflecting anthropogenic influences published but not included in regression analysis (table 2 in Kolb and others, 2026).

Another resource used to help assess suitability of streamgages for inclusion in the regional regression analysis was the Geospatial Attributes of Gages for Evaluating Streamflow, version II (GAGES-II) dataset (Falcone, 2011). The GAGES-II dataset provides geospatial data classifications for 9,322 streamgages maintained by the USGS and consists of streamgages that have 20 or more years of record (since 1950) or are currently (2023) active. The GAGES-II dataset classifies streamgages considered “near natural” as “reference” gages. GAGES-II also has a disturbance index to help assess if a gage is a reference or non-reference streamgage. For many of the streamgages in the GAGES-II dataset, screening comments are included to provide some insight into the classification. The GAGES-II documentation notes that the classifications presented are not intended to be definitive and, as such, were considered another resource to assist in determining whether to include a streamgage in the regional regression analysis. Additional information on regulation, diversion, irrigation groundwater withdrawals, and streamgage redundancy, along with details about how unregulated streamgages for regional regression analysis were selected, is provided in the following subsections.

Regulation

Streams are impounded for a variety of reasons such as flood control, water supply, irrigation, and hydroelectric power generation (Ruddy and Hitt, 1990). The effect of the regulation from those various impoundments on downstream flows also varies widely (Feaster and Musser, 2023). For example, a water-supply reservoir may have little to no storage capacity for flood control and, consequently, not appreciably change the characteristics of downstream flood flows. Reservoirs where the main function is hydroelectric power generation or flood control will tend to decrease flood flows but may increase low flows (Graf, 2006). With respect to frequency analyses of regulated streams, a frequency analysis can be deemed reasonable if the period of record being analyzed has been determined to be a period when regulation patterns have been relatively stable and the statistical distribution used in the frequency analysis provides a reasonable fit to the data (Feaster and others, 2023). For regulated streamgages included in this report—for which low-flow frequency statistics are provided—graphical analysis of data, including scatterplots, LOESS curves, and single-mass curves, and trend analysis, as previously discussed, were used to assess the relative stability of regulation patterns, and low-flow frequency curves were reviewed to determine that the statistical distribution was reasonable for the analysis used here.

Diversion

Determining a true natural condition in a stream or accurately accounting for all diversions in a basin is generally difficult. Diversions from natural flow can occur for many reasons (Ries, 1994; Feaster and Lee, 2017). Some diversions result from water-supply withdrawals, manufacturing processes, point-source discharges, and irrigation. In some cases, streamflow diversions may only affect flows for a short distance along the stream. For instance, water might be removed from a river, passed through a manufacturing plant for use in processing, cooling, or dilution of wastes, and then returned to the river. Under such conditions, consumptive losses from the diversion may be negligible. Subsequently, the effects of diversions on the streamflow regime of a river are variable and depend on the location of the diversion with respect to where streamflow is being monitored, the use (consumptive or not), and the return location of diverted water.

Water diverted from a stream or adjacent aquifer for municipal supplies often is returned to the same basin as effluent from individual septic systems or wastewater-treatment plants, which generally causes little loss of water to the basin; however, such diversions may affect the temporal pattern of streamflow (Ries, 1994). Diversions from one basin to another reduce streamflow in the donor basin and increase streamflow in the receiving basin. Diversions between subbasins of a larger basin may substantially affect streamflow in the subbasins, but if consumptive losses are negligible, streamflow in the larger basin may be nearly unaffected. These various diversion scenarios indicate that an accurate accounting of all diversions in a basin is generally problematic; therefore, most USGS low-flow studies, including this study, are based on the flow data as measured at the streamgage without adjustments for diversions.

Irrigation Groundwater Withdrawals in the Coastal Plain Physiographic Province of Georgia

Some of the long-term streamgages in the Coastal Plain Physiographic Province of Georgia (Georgia Coastal Plain; fig. 2) indicated a change in the pattern in annual minimum 7-day average flows around 1980, based on single-mass curve assessment of those minimum flows over time (see sidebar “Example of Single-Mass Curve Analysis”). Much of the decrease in annual minimum 7-day average flows likely resulted from increases in irrigation groundwater withdrawals that began in this region around 1980; although, determining all factors influencing the decrease in minimum flows was beyond the scope of this investigation. In the Georgia Coastal Plain, a substantial amount of water is used for agricultural irrigation (Painter, 2019), mostly from groundwater withdrawals (Henley, 2023; Hicks and others, 1987), and has contributed to long-term groundwater-level declines that have affected streamflows (Hicks and others, 1981, 1987; USGS, 2026). Williams and others (2017) documented large increases in irrigated acres in the Georgia Coastal Plain beginning between 1980 and 1984 and continuing through the end of their study, based on center pivot irrigation systems identified from Landsat images between 1976 and 2013. Based on this study, irrigated areas represented 4.1 percent of the Georgia Coastal Plain in 2013 and were concentrated in southwest Georgia.

For the 13 Georgia Coastal Plain streamgages for which change in flow was detected around 1980, the streamflow prior to 1980 was assumed to represent more natural conditions; therefore, streamflow frequency statistics from that period were included in regional regression analysis (Kolb and others, 2026, table 1). Streamflow frequency statistics also were calculated for these streamgages for the period after 1980 through CY 2021, but these data were not included in regression analysis (Kolb and others, 2026, table 2). These 13 streamgages are identified as having a flow condition of diversions, a remark indicating the partial period was excluded due to anthropogenic influences, and a period starting around CY 1980 in table 2 in Kolb and others (2026).

Streamgage Redundancy

For streams with multiple streamgages, an assessment was made to determine potential redundancy of streamgages to be included in the regional regression analysis. Redundancy occurs when the drainage basins of two streamgages are nested, where one basin is inside another basin, and most or all streamflow records at the two streamgages represent concurrent periods of time (Gruber and Stedinger, 2008). For this investigation, a streamgage was considered redundant if it was on the same stream as another streamgage and the drainage area of one streamgage contained more than 50 percent of the drainage area of the second streamgage, unless there was an insignificant overlap in the period of record for the two streamgages.

Estimating Low-Flow Frequency and Mean Annual Flow Statistics at Ungaged Locations

The USGS operates a multipurpose streamgaging network in Georgia, North Carolina, and South Carolina in cooperation with many Federal, State, and local agencies and organizations for which multiple streamflow statistics are computed. However, streamflow statistics are often needed at ungaged locations. In such cases, regional regression equations may be developed by relating the streamflow statistics of interest computed at USGS streamgages to basin characteristics that can be readily determined by using the USGS StreamStats application (Ries and others, 2017; USGS, 2019). For this study, regional regression equations (Farmer and others, 2019) were developed to estimate annual 1Q10, 7Q10, 7Q2, 30Q2, and 30Q3 streamflow, winter (November–March) 7Q10 streamflow, monthly 1Q10 and 7Q10 streamflow, and the mean annual flow.

Physical and Climatic Basin Characteristics

Streamflow statistics can be estimated at ungaged sites by using multiple linear regression techniques that relate streamflow characteristics computed at gaged sites (such as the 7Q10 flow) to selected basin characteristics (hydrography, elevation, ecoregion, land use, soil, surficial geology, and climate) computed for the gaged drainage basins (table 5). Delineating basin boundaries at the USGS streamgage locations is the first step in generating potential basin characteristics for the regional regression analyses. Drainage-basin boundaries for this study were generated by using the USGS StreamStats application (Ries and others, 2017, 2024; USGS, 2019). Basin characteristics chosen for testing as potential explanatory variables were selected based on their potential theoretical relation to low flows, results of previous studies of low-flow regionalization, and the ability to quantify the basin characteristics by using a geographic information system (GIS). The use of GIS enables automation of the determination of basin characteristics and solution of the regional regression equations when using the USGS StreamStats application.

Streamflow-Variability Index

The streamflow-variability index (SVI) was introduced by Lane and Lei (1950) as a useful index in analyzing hydraulic-engineering projects and producing synthetic flow-duration curves. Areas with similar surface geology can be expected to correspond to similar SVI values, suggesting SVI would be a beneficial characteristic for regionalizing low flows based on geology (Ruhl and Martin, 1991). Given that low flows are considered a groundwater phenomenon, aquifer characteristics would be expected to influence low flows. Aquifer characteristics are diverse, and the interaction of aquifers and streamflow is complex; therefore, the flow in many streams is likely to be affected by several aquifers (Friel and others, 1989). Consequently, along with incorporating a variable related to surficial geology that may have a regional aspect, the SVI also incorporates the integrated effects of multiple aquifers on low flows within a given basin. As such, a generalized SVI has been successfully used in many USGS low-flow regionalization studies (Friel and others, 1989; Martin and Ruhl, 1993; Koltun and Whitehead, 2002; Martin and Arihood, 2010; Eash and Barnes, 2012; Koltun and Kula, 2013; Southard, 2013; Feaster and others, 2020; VonIns and Koltun, 2024).

The SVI is the standard deviation of the logarithms of the 19 streamflow values at 5-percent class intervals from 5 to 95 percent on the flow-duration curve of daily mean flows for the analysis period (fig. 7; Searcy, 1959; Koltun and Whitehead, 2002; Southard, 2013). The magnitude of the SVI is inversely related to the capacity of a basin to sustain base flow in a stream; for example, smaller SVI values are indicative of a higher sustained base flow. Figure 7 shows two different examples of the flow-duration curves and associated SVI values. USGS streamgage Upper Three Runs near New Ellenton, S.C. (USGS site number 02197300; south-central South Carolina; Ogeechee-Savannah subregion, fig. 2) has an SVI value of 0.09 (relatively flat slope to the flow-duration curve) with a high base-flow component of streamflow. USGS streamgage Little Ocmulgee River at Ga. 149, at Scotland, Ga. (USGS site number 02215900; central Georgia; Altamaha-St. Marys subregion) has an SVI value of 1.19 (relatively steep slope to the flow-duration curve) and a lower base-flow component of streamflow. The SVI is computed as follows:

$$SVI = \sqrt{\frac{\sum_{i=5,5}^{95}\left(log_{10}(D_i) - \overline{log_{10}(D)}\right)^2}{n-1}}, \tag{3}$$

where

SVI is the streamflow-variability index (unitless),

D_i is the *i*th percent duration streamflow (i=5, 10, 15, …95),

$\overline{log_{10}(D)}$ is the mean of the base 10 logarithms of the 19 streamflow values at 5-percent class intervals from 5 to 95 percent from the flow-duration curve of the daily mean flow, and

n equals 19 and is the number of 5-percent class intervals from 5 to 95 percent.

For the few cases in which the 95-percent flow value at a streamgage was zero, the value was set to 0.01 for the SVI computation because the logarithm of zero is undefined.

To estimate SVI at ungaged locations, an SVI raster was developed for Georgia, North Carolina, and South Carolina by using ordinary kriging. Ordinary kriging is a spatial interpolation method used to estimate unknown values at desired locations based on a set of known data points (Rubin, 2003). To quantify the spatial variability of SVI data, ordinary kriging uses a variogram, which is a model that describes the pattern of spatial autocorrelation. An exponential variogram model with two parameters—the range and sill—was used for this study. The range determines the length scale where spatial autocorrelation approaches zero, and the sill is a measure of total variability of the data.

For this study, SVI values were computed for 625 streamgages and used as conditioning points for the kriging model. Of 625 streamgages, 604 were used in regression analysis. The 21 SVI values not used in the regression analysis were excluded because of statistical redundancy. The 625 SVI values had a mean of 0.40 and a variance of 0.034. The minimum and maximum values were 0.09 and 1.47, respectively.

Ordinary kriging was completed by using an exponential variogram model. Variogram fitting and kriging estimation were done by using the gstat library (Pebesma, 2004; Gräler and others, 2016). The resulting variogram had a sum of squared errors of 5.44×10^{-11}. A comparison between the experimental variogram and the exponential model fit is shown in figure 8. The resulting gridded SVI values are shown in figure 9.

For raster generation, each SVI point value was located at the centroid of the drainage basin of the streamgage. As such, determining the SVI value for an ungaged location from the grid should be done at the centroid of the ungaged basin.

Table 5. Basin characteristics, units of measure, and sources considered for inclusion in regional regression analysis for Georgia, North Carolina, and South Carolina.

[USGS, U.S. Geological Survey; DEM, digital elevation model; m, meter; ft, foot; SCDNR, South Carolina Department of Natural Resources; EPA, U.S. Environmental Protection Agency; km, kilometer; SSURGO, Soil Survey Geographic Database]

Basin characteristic	Unit of measure	Source
Drainage area	Square miles	USGS StreamStats application,[1] based on USGS National Elevation Dataset DEM at 10-m and 30-ft resolution,[2] conditioned to conform with National Hydrography Dataset streams, 1:24,000 scale.[3] USGS StreamStats application,[1] based on SCDNR DEM at 30-ft resolution,[4] conditioned to conform with SCDNR lidar-derived streamlines. NHDPlus Medium resolution (30-m) version 2.1.[3]
Mean basin elevation	Feet	DEM data used to create the watershed boundaries as defined in the drainage area source data section of this table.
Minimum basin elevation	Feet	DEM data used to create the watershed boundaries as defined in the drainage area source data section of this table.
Maximum basin elevation	Feet	DEM data used to create the watershed boundaries as defined in the drainage area source data section of this table.
Relief (maximum elevation − minimum elevation)	Feet	DEM data used to create the watershed boundaries as defined in the drainage area source data section of this table.
Relief ratio (mean elevation − minimum elevation)/(maximum elevation − minimum elevation)	Unitless	DEM data used to create the watershed boundaries as defined in the drainage area source data section of this table.
Basin perimeter	Feet	Watershed boundaries as defined in the drainage area source data section of this table.
Percentage of basin in each Level III ecoregion for the Central Appalachians, Southwestern Appalachians, Ridge and Valley, Blue Ridge, Piedmont, Southeastern Plains, Middle Atlantic Coastal Plain, and Southern Coastal Plain	Percent	EPA Level III and IV ecoregions of the continental United States.[5]
Percentage of basin in each Level IV ecoregions for the Sand Hills, Triassic Basins, Carolina Slate Belt, Northern and Southern Inner Piedmont, and Northern and Southern Outer Piedmont	Percent	EPA Level III and IV ecoregions of the continental United States.[5]
Percentage of developed land (low, medium, and high intensity)	Percent	National Land Cover Database 2019, 30-m resolution.[6]
Percentage of impervious area	Percent	National Land Cover Database 2019, Percent Developed Imperviousness, 30-m resolution.[6]
Percentage of forest land (deciduous and evergreen)	Percent	National Land Cover Database 2019, 30-m resolution.[6]
Percentage of pasture/hay	Percent	National Land Cover Database 2019, 30-m resolution.[6]
Percentage of cultivated crops	Percent	National Land Cover Database 2019, 30-m resolution.[6]
Percentage of pasture/hay/cultivated crops	Percent	National Land Cover Database 2019, 30-m resolution.[6]
Percentage of woody wetlands	Percent	National Land Cover Database 2019, 30-m resolution.[6]
Percentage of herbaceous wetlands	Percent	National Land Cover Database 2019, 30-m resolution.[6]
Percent storage (woody wetlands + herbaceous wetlands + open water)	Percent	National Land Cover Database 2019, 30-m resolution.[6]

Table 5. Basin characteristics, units of measure, and sources considered for inclusion in regional regression analysis for Georgia, North Carolina, and South Carolina.—Continued

[USGS, U.S. Geological Survey; DEM, digital elevation model; m, meter; ft, foot; SCDNR, South Carolina Department of Natural Resources; EPA, U.S. Environmental Protection Agency; km, kilometer; SSURGO, Soil Survey Geographic Database]

Basin characteristic	Unit of measure	Source
Basin centroid streamflow-variability index	Unitless	Calculated from ordinary kriging of streamflow-variability index calculated from streamgage daily mean streamflows for the analysis period.[7]
Base-flow index	Unitless	Base-flow index grid for the conterminous United States, 1-km resolution.[8]
Groundwater head	Feet	National Map 3D Elevation Program.[2]
Soil saturated hydraulic conductivity (K-sat)	Inches per hour	SSURGO vector data.[9]
Percent SSURGO Hydrologic Soil Groups (A, B, C, D)	Percent	Hydrologic Group - Dominant Conditions from SSURGO.[9]
Mean annual precipitation	Inches	PRISM 1991–2020 30-year normals, 800-m resolution.[10]
Mean monthly precipitation (January–December)	Inches	PRISM 1991–2020 30-year normals, 800-m resolution.[10]
Groundwater recharge	Inches per year	Estimated mean annual natural groundwater recharge in the conterminous United States, 1-km resolution.[11]
Basin outlet latitude and longitude	Decimal degrees	DEM data used to create the watershed boundaries as defined in the drainage area source data section of this table.
Basin centroid latitude and longitude	Decimal degrees	DEM data used to create the watershed boundaries as defined in the drainage area source data section of this table.

[1] USGS (2019); https://www.usgs.gov/streamstats.

[2] USGS (2023); https://www.usgs.gov/3d-elevation-program.

[3] EPA and USGS (2012); https://www.epa.gov/waterdata/nhdplus-national-hydrography-dataset-plus.

[4] SCDNR (2023); https://www.dnr.sc.gov/GIS/lidar.html.

[5] EPA (2013); https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states.

[6] Dewitz (2021); https://doi.org/10.5066/P9KZCM54.

[7] Lane and Lei (1950).

[8] Wolock (2003a); https://doi.org/10.3133/ofr03263.

[9] Natural Resources Conservation Service (2023); https://www.nrcs.usda.gov/resources/data-and-reports/soil-survey-geographic-database-ssurgo.

[10] PRISM Climate Group (2023a); https://www.prism.oregonstate.edu/normals/.

[11] Wolock (2003b); https://doi.org/10.3133/ofr03311.

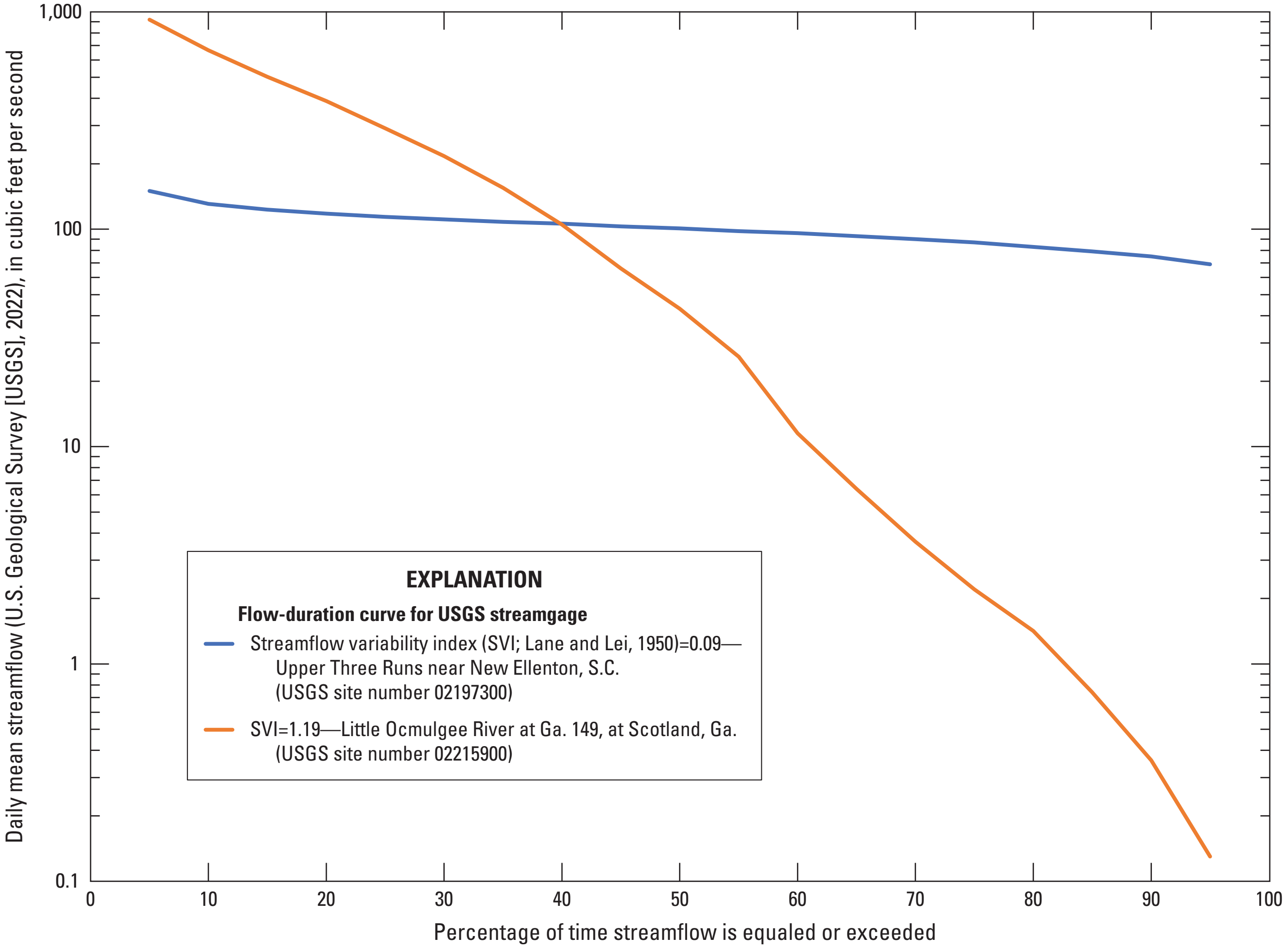


Figure 7. Flow-duration curves for U.S. Geological Survey streamgages Upper Three Runs near New Ellenton, S.C. (USGS site number 02197300), and Little Ocmulgee River at Ga. 149, at Scotland, Ga. (02215900).

Using the basin centroid as locations for estimation of the SVI at ungaged locations was decided upon following a comparative analysis with the same methodology but using the basin outlet location's SVI. This comparison to determine the most appropriate SVI value for an ungaged site was done by using *k*-fold cross-validation (Kohavi, 1995), where the validation included the two-step process of fitting the variogram parameters by using the training data and then computing kriging estimates at the testing locations. In each of the 100 folds of cross validation, 25 percent of data were randomly selected for testing data. The average root mean square error resulting from using the basin centroid location as the SVI value was 0.109, compared to an average root mean square error of 0.134 when using outlet location SVI values.

Exploratory Regression Analysis

A regional regression analysis is an iterative process (Farmer and others, 2019; Feaster and others, 2020). The initial step involves computing streamflow statistics of interest along with potential basin characteristics (hydrography, elevation, ecoregion, land use, soil, surficial geology, and climate; table 5). Model development involves exploratory data analysis to get a general understanding of relations among the variables that are to be predicted, which can be referred to as the dependent or response variable (for example, the 7Q10 streamflow statistic), and certain basin characteristics, which can be referred to as the independent or explanatory variables (for example, drainage area). Often the estimation step begins with assessing the complete study area by testing all potential independent variables with a dependent variable of choice such as the 7Q10, which is referred to as an all-possible-subsets regression analysis. The results are then evaluated based on statistical significance of the independent variables, adherence to the assumptions of the regression techniques being applied, which are typically assessed based on the residuals computed from the difference in the observed and predicted dependent variable, and the geographical distribution of those residuals. Mapping the geographical distribution of the residuals provides information on potential subregions

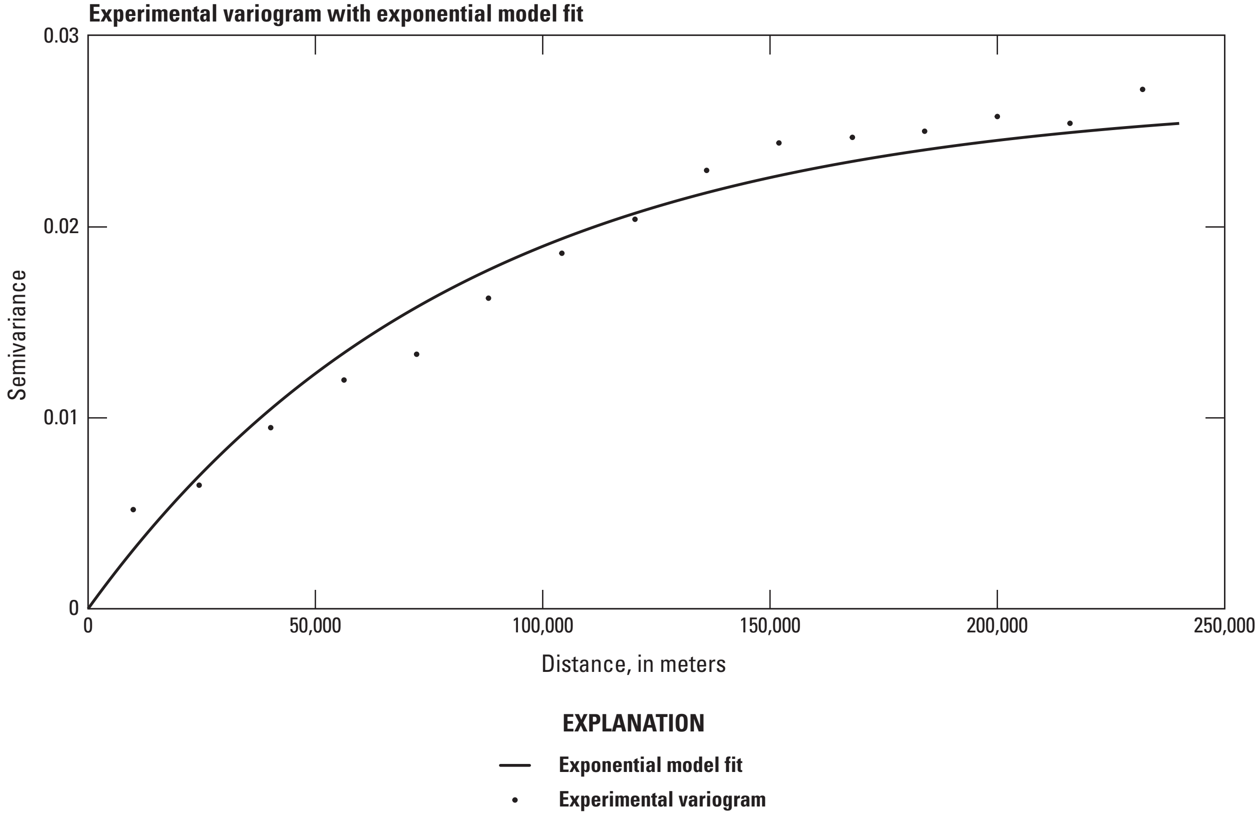


Figure 8. Experimental variogram with exponential model fit for ordinary kriging of streamflow-variability index values at 625 U.S. Geological Survey streamgages in and near Georgia, North Carolina, and South Carolina.

that might be warranted to improve the uncertainty in the predictions. Once a set of regional regression equations has been determined, the final step is to document the process with ample detail such that users of the equations have a general understanding of the proper application of the equations.

For an exploratory regression analysis, it is best to start with the largest reasonable region, which is often the complete study area (Farmer and others, 2019). The initial regression analysis for this investigation included the complete study area, and from there, several potential subregions were tested. The exploratory regression analysis was done by using ordinary least squares (OLS) regression techniques (SAS Institute, 2024). The general model for an OLS regression analysis is of the form:

$$Q_T = a \times A^b \times B^c \times C^d, \qquad (4)$$

where

Q_T is a low-flow frequency statistic, such as the 7Q10;

A, B, C are explanatory (independent) variables, such as drainage area and other basin characteristics; and

$a, b, c,$ and d are regression coefficients.

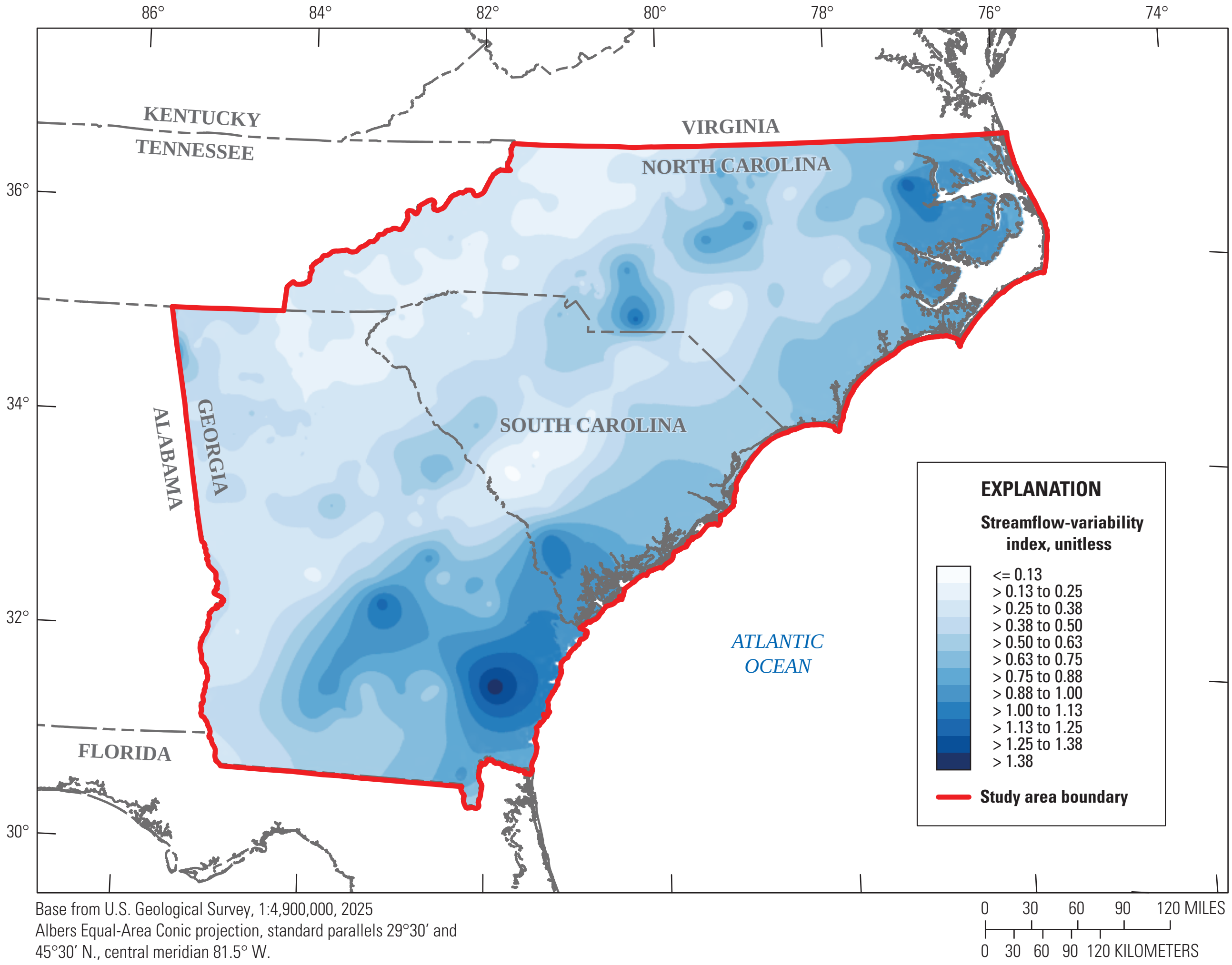
One of the assumptions of multiple linear regression is that the residuals are homoscedastic, meaning that they are equally dispersed throughout the range of the explanatory variables (Helsel and others, 2020). To obtain homoscedasticity, it is often necessary to transform the response variable and one or more of the explanatory variables. If the response and explanatory variables are logarithmically transformed, which is often the case with streamflow statistics, the regression model has the following form:

$$\log Q_T = \log a + b(\log A) + c(\log B) + d(\log C) + \ldots, \qquad (5)$$

where the variables are as previously defined in equation 4. Both logarithmic and arithmetic relations were used in this investigation because the logarithmic transformation of some variables did not improve the linear relation with Q_T.

Left-Censored Regression

At some of the streamgages included in this study, the low-flow frequency statistics were zero. When logarithmic transformation is used in a regression analyses, having response variables with a zero value is problematic because



Base from U.S. Geological Survey, 1:4,900,000, 2025
Albers Equal-Area Conic projection, standard parallels 29°30′ and 45°30′ N., central meridian 81.5° W.
North American Datum of 1983

Figure 9. Streamflow-variability index values for Georgia, North Carolina, and South Carolina.

the logarithm of zero is undefined. In such cases where a relatively small percentage of the response variables is zero, left-censored regression, also referred to as Tobit regression (Tobin, 1958), can be used to overcome this issue. Helsel and Hirsch (2002) suggested that censored regression is appropriate for small to moderate amounts of censoring. Hirsch and others (1993) suggested censored regression is appropriate if censoring does not exceed 50 percent of observations.

Censored regression includes the uncensored and censored data and is similar to multiple linear regression, except regression coefficients are fit by maximum-likelihood estimation (MLE; Helsel and Hirsch, 2002; Eash and Barnes, 2012). MLE is comparable to a curve-matching process, in which a probability distribution is best matched to the observed data. MLE assumes that residuals are normally distributed around the regression line for the estimation of the slope and intercept and that the range of predicted values has constant variance. Cohn (1988) has shown that censored regression estimates are slightly biased, and an adjustment for first-order bias in these estimates is made by an adjusted maximum-likelihood estimation (AMLE) computation. An AMLE procedure implemented in the USGS-R/smwrQW package (Lorenz, 2014), which is available at https://rdrr.io/github/USGS-R/smwrQW/, was used to develop the left-censored regression equations in this study.

Final Regional Regression Equations

For the final regional regression equations developed in this study, weighted left-censored regression techniques were used, with weights based on the number of climate or water years of record (Lorenz, 2014; Ziegeweid and others, 2015; Gotvald, 2017). For datasets that do not contain censored values, weighted left-censored regression provides the same results as weighted least squares regression (Helsel and Hirsch, 2002). In censored regression for low-flow studies, the selected censoring level is typically a low streamflow value, such as 0.01, 0.05, or 0.1 cubic foot per second (ft^3/s).

For example, a censoring level of 0.1 ft^3/s has been used in low-flow studies by Eash and Barnes (2012), Gotvald (2017), Feaster and others (2020), and Lukasz (2021). For this study, a censoring level of 0.05 ft^3/s was used for consistency with the flow design criteria from the North Carolina Department of Environmental Quality, Division of Water Resources, for developing water-quality-based effluent limitations (North Carolina Department of Environment and Natural Resources, 2006).

Final selection of the independent variables to include in the regression models was based on several factors such as statistical significance, standard error, coefficient of determination, and ease of measurement of the explanatory variables. Correlation among the explanatory variables (multicollinearity) was assessed by using the variance inflation factor (VIF). If one or more VIF values exceed 5, the regression coefficients are likely poorly estimated due to multicollinearity (Montgomery and others, 2012). In such a case, one of the explanatory variables should be removed and the regressions reanalyzed to assess the remaining variables. All independent variables were considered statistically significant with a p-value of ≤ 0.05, and the VIF for all independent variables indicated no issues of multicollinearity among the variables.

For the OLS and left-censored regression analyses, multiple regression diagnostics were generated and used to identify possible problems with the streamgage data or basin characteristics. Along with reviews to ensure that the regression residuals were randomly distributed around zero and that they were reasonably distributed geographically, other regression diagnostics were reviewed to determine streamgages that had high leverage and (or) high influence (Eng and others, 2009). The leverage metric is used to measure how unusual the values of independent variables at one streamgage are compared to the values of the same variables at all other streamgages. The influence metric indicates whether the data at a streamgage had a high influence on the estimated regression metric values. A streamgage may have a high leverage metric indicating that its independent variables are substantially different from those at all other streamgages, but the same streamgage may not have a high influence on the regression metrics. Conversely, a streamgage with a high influence may not have a high leverage metric. Sometimes, measurement or transposing errors in reported values of some independent variables can produce high leverage or influence metrics. Streamgages with high influence or leverage were given additional review to determine if such errors had been made or if the streamgage should be excluded for other reasons.

For this study, regional regression equations were developed for 30 low-flow statistics and the mean annual flow. The 30 low-flow statistics were the annual 1Q10, 7Q2, 7Q10, 30Q2, and 30Q3, the W7Q10, and monthly (January–December) 1Q10 and 7Q10 statistics (table 6). The regression analyses included 604 streamgages from 7 States (table 7). For those 604 streamgages, the distribution of the systematic record lengths included in the regression analyses is shown on figure 10.

For low-flow frequency regression equations, the dominant independent variables were base 10 logarithm of drainage area (logDA), SVI, and mean annual precipitation (MeanAP). In 25 of 31 regression equations, percentage of impervious area (IA) was statistically significant, indicating that the regression equations are suitable for urban basins. The six equations for which IA was tested but was not statistically significant were Jan1Q10, May1Q10, Dec1Q10, Jan7Q10, May7Q10, and Dec7Q10. Because IA was tested but was not statistically significant, those equations also are considered applicable for use in urban basins.

Mean annual precipitation and SVI are regional variables in the regression equations. To account for additional regional differences, percentages of drainage basins in Level III and IV ecoregions also were tested as independent variables. All final regression equations include one or more independent variables that represent the percentage of basin in Level III and (or) Level IV ecoregions (fig. 1; EPA, 2013; Omernik and Griffith, 2014). When regression equations are applied in basins for which independent variables for the Level III or IV ecoregions are zero, those variables drop out, and the regression equation is just a function of the remaining variables. For example, if the Jan7Q10 equation is applied at an ungaged location that drains 100 percent from the Piedmont ecoregion, the percentage of basin draining from the Southwestern Appalachians, Sand Hills, and Southern Coastal Plain ecoregions is zero, and the equation then becomes a function of just logDA, SVI, and MeanAP.

Figure 11 provides an example of plots of the observed and predicted mean annual flow (fig. 11*A*), 1Q10 (fig. 11*B*), 7Q2 (fig. 11*C*), and 7Q10 (fig. 11*D*), along with the line of equality. The plots indicate a reasonable scatter distribution around the line of equality throughout the range of flows. Similar plots also were reviewed for all the other frequency statistics.

Accuracy and Limitations

The accuracy (or uncertainty) in a regression model is evaluated based on the residuals (or error)—the differences between the predicted and observed values. Regression equations are statistical models that should be interpreted and applied within the limits of the data and understanding that results are best-fit predictions with an associated scatter or variance about the regression curve (Farmer and others, 2019; Feaster and others, 2023).

Table 6. Selected mean annual flow and low-flow frequency regional regression equations and regression diagnostics for streams in Georgia, North Carolina, and South Carolina.

[R^2, coefficient of determination; MAF, mean annual flow, in cubic feet per second (ft^3/s); logDA, is base 10 logarithm of drainage area, in square miles[1,2]; MeanAP, mean annual precipitation, in inches[3]; IA, percentage of impervious area[4]; BR, percentage of basin in the Blue Ridge ecoregion[5]; A1Q10, annual minimum 1-day average flow with a 10-year recurrence interval (RI), in ft^3/s; SVI, streamflow-variability index, unitless[6]; RV, percentage of basin in the Ridge and Valley ecoregion[5]; LR1 (low-flow region 1), percentage of basin in the Piedmont ecoregion minus the percentage of basin in the Triassic Basins and the Carolina Slate Belt ecoregions[5]; LR2 (low-flow region 2), the percentage of basin in the Triassic Basins and the Carolina Slate Belt ecoregions[5]; SH, percentage of basin in the Sand Hills ecoregion[5]; SCP, percentage of basin in the Southern Coastal Plain ecoregion[5]; A7Q2, annual minimum 7-day average flow with 2-year RI, in ft^3/s; A7Q10, annual minimum 7-day average flow with 10-year RI, in ft^3/s; A30Q2, annual minimum 30-day average flow with 2-year RI, in ft^3/s; A30Q3, annual minimum 30-day average flow with 3-year RI, in ft^3/s; W7Q10, winter (November–March) minimum 7-day average flow with a 10-year RI, in ft^3/s; SWApp, percentage of basin in the Southwestern Appalachians ecoregion[5]; Jan1Q10, January minimum 1-day average flow with a 10-year RI, in ft^3/s; Feb1Q10, February minimum 1-day average flow with a 10-year RI, in ft^3/s; Mar1Q10, March minimum 1-day average flow with a 10-year RI, in ft^3/s; Apr1Q10, April minimum 1-day average flow with a 10-year RI, in ft^3/s; SEP, percentage of basin in the Southeastern Plains ecoregion[5]; May1Q10, May minimum 1-day average flow with a 10-year RI, in ft^3/s; Jun1Q10, June minimum 1-day average flow with a 10-year RI, in ft^3/s; Sto (storage), percentage of wetlands and water[4]; Jul1Q10, July minimum 1-day average flow with a 10-year RI, in ft^3/s; Aug1Q10, August minimum 1-day average flow with a 10-year RI, in ft^3/s; Sep1Q10, September minimum 1-day average flow with a 10-year RI, in ft^3/s; Oct1Q10, October minimum 1-day average flow with a 10-year RI, in ft^3/s; Nov1Q10, November minimum 1-day average flow with a 10-year RI, in ft^3/s; Dec1Q10, December minimum 1-day average flow with a 10-year RI, in ft^3/s; Jan7Q10, January minimum 7-day average flow with a 10-year RI, in ft^3/s; Feb7Q10, February minimum 7-day average flow with a 10-year RI, in ft^3/s; Mar7Q10, March minimum 7-day average flow with a 10-year RI, in ft^3/s; Apr7Q10, April minimum 7-day average flow with a 10-year RI, in ft^3/s; May7Q10, May minimum 7-day average flow with a 10-year RI, in ft^3/s; Jun7Q10, June minimum 7-day average flow with a 10-year RI, in ft^3/s; Jul7Q10, July minimum 7-day average flow with a 10-year RI, in ft^3/s; Aug7Q10, August minimum 7-day average flow with a 10-year RI, in ft^3/s; Sep7Q10, September minimum 7-day average flow with a 10-year RI, in ft^3/s; Oct7Q10, October minimum 7-day average flow with a 10-year RI, in ft^3/s; Nov7Q10, November minimum 7-day average flow with a 10-year RI, in ft^3/s; Dec7Q10, December minimum 7-day average flow with a 10-year RI, in ft^3/s]

Statistic	Equation	[7]*Pseudo R*^{2}	Average variance of prediction (log units)	Average standard error of prediction (percent)	Number of left-censored streamgages
MAF	$10^{[-0.7641 + 0.9913\mathrm{logDA} + 0.01629\mathrm{MeanAP} + 0.004066\mathrm{IA} + 0.001131\mathrm{BR}]}$	0.99	0.00497	16.3	0
A1Q10	$10^{[-0.6825 + 1.111\mathrm{logDA} - 4.773\mathrm{SVI} + 0.02034\mathrm{MeanAP} + 0.01260\mathrm{IA} + 0.003310\mathrm{RV} - 0.003790\mathrm{LR1} - 0.005412\mathrm{LR2} - 0.002322\mathrm{SH} + 0.001929\mathrm{SCP}]}$	0.97	0.0618	62.2	74
A7Q2	$10^{[-0.4705 + 1.030\mathrm{logDA} - 3.212\mathrm{SVI} + 0.01687\mathrm{MeanAP} + 0.004525\mathrm{IA} + 0.001019\mathrm{RV} - 0.001074\mathrm{LR1} - 0.001547\mathrm{LR2} - 0.001073\mathrm{SH}]}$	0.99	0.0107	24.2	11
A7Q10	$10^{[-0.5976 + 1.093\mathrm{logDA} - 4.515\mathrm{SVI} + 0.01908\mathrm{MeanAP} + 0.01280\mathrm{IA} + 0.002936\mathrm{RV} - 0.003459\mathrm{LR1} - 0.004981\mathrm{LR2} - 0.001873\mathrm{SH}]}$	0.97	0.0475	53.5	52
A30Q2	$10^{[-0.6860 + 1.009\mathrm{logDA} - 2.532\mathrm{SVI} + 0.01885\mathrm{MeanAP} + 0.005569\mathrm{IA} - 0.001005\mathrm{SCP}]}$	0.99	0.0101	23.4	1
A30Q3	$10^{[-0.7244 + 1.018\mathrm{logDA} - 2.960\mathrm{SVI} + 0.01963\mathrm{MeanAP} + 0.007073\mathrm{IA} + 0.001475\mathrm{RV} - 0.001074\mathrm{LR2}]}$	0.99	0.0114	25.0	4
W7Q10	$10^{[-0.2963 + 0.9765\mathrm{logDA} - 3.236\mathrm{SVI} + 0.01419\mathrm{MeanAP} + 0.001559\mathrm{IA} + 0.001351\mathrm{SWApp} + 0.001084\mathrm{RV} + 0.001117\mathrm{SH}]}$	0.98	0.0203	33.7	9
Jan1Q10	$10^{[-1.143 + 1.012\mathrm{logDA} - 1.354\mathrm{SVI} + 0.02151\mathrm{MeanAP} + 0.003557\mathrm{SWApp} + 0.002541\mathrm{SH} - 0.005713\mathrm{SCP}]}$	0.97	0.0223	35.4	1
Feb1Q10	$10^{[-1.098 + 1.006\mathrm{logDA} - 0.9049\mathrm{SVI} + 0.02049\mathrm{MeanAP} - 0.002503\mathrm{IA} + 0.002474\mathrm{SWApp} - 0.001222\mathrm{LR2} + 0.001701\mathrm{SH} - 0.006022\mathrm{SCP}]}$	0.98	0.0154	29.2	1
Mar1Q10	$10^{[-1.027 + 1.020\mathrm{logDA} - 0.9383\mathrm{SVI} + 0.02051\mathrm{MeanAP} - 0.003385\mathrm{IA} + 0.002321\mathrm{SWApp} - 0.006693\mathrm{SCP}]}$	0.98	0.0160	29.7	1
Apr1Q10	$10^{[-0.7289 + 1.019\mathrm{logDA} - 1.685\mathrm{SVI} + 0.01908\mathrm{MeanAP} - 0.003337\mathrm{IA} + 0.003790\mathrm{SWApp} - 0.008692\mathrm{SCP} - 0.001918\mathrm{SEP}]}$	0.98	0.0199	33.4	2
May1Q10	$10^{[-0.4402 + 1.011\mathrm{logDA} - 2.765\mathrm{SVI} + 0.01574\mathrm{MeanAP} + 0.005114\mathrm{SWApp} + 0.002109\mathrm{RV} + 0.001348\mathrm{BR} + 0.002296\mathrm{LR2} - 0.007204\mathrm{SCP} - 0.001774\mathrm{SEP}]}$	0.97	0.0284	40.3	7
Jun1Q10	$10^{[-0.9228 + 1.077\mathrm{logDA} - 3.213\mathrm{SVI} + 0.02229\mathrm{MeanAP} + 0.001661\mathrm{IA} + 0.002839\mathrm{SWApp} + 0.002432\mathrm{RV} - 0.01013\mathrm{Sto}]}$	0.98	0.0226	35.7	20
Jul1Q10	$10^{[-0.8151 + 1.102\mathrm{logDA} - 3.766\mathrm{SVI} + 0.02108\mathrm{MeanAP} + 0.009146\mathrm{IA} + 0.002556\mathrm{SWApp} + 0.002243\mathrm{RV} - 0.002265\mathrm{LR1} - 0.001976\mathrm{LR2} - 0.002092\mathrm{SH} - 0.004498\mathrm{Sto}]}$	0.98	0.0281	40.1	34

Table 6. Selected mean annual flow and low-flow frequency regional regression equations and regression diagnostics for streams in Georgia, North Carolina, and South Carolina.—Continued

[R^2, coefficient of determination; MAF, mean annual flow, in cubic feet per second (ft^3/s); logDA, is base 10 logarithm of drainage area, in square miles[1,2]; MeanAP, mean annual precipitation, in inches[3]; IA, percentage of impervious area[4]; BR, percentage of basin in the Blue Ridge ecoregion[5]; A1Q10, annual minimum 1-day average flow with a 10-year recurrence interval (RI), in ft^3/s; SVI, streamflow-variability index, unitless[6]; RV, percentage of basin in the Ridge and Valley ecoregion[5]; LR1 (low-flow region 1), percentage of basin in the Piedmont ecoregion minus the percentage of basin in the Triassic Basins and the Carolina Slate Belt ecoregions[5]; LR2 (low-flow region 2), the percentage of basin in the Triassic Basins and the Carolina Slate Belt ecoregions[5]; SH, percentage of basin in the Sand Hills ecoregion[5]; SCP, percentage of basin in the Southern Coastal Plain ecoregion[5]; A7Q2, annual minimum 7-day average flow with 2-year RI, in ft^3/s; A7Q10, annual minimum 7-day average flow with 10-year RI, in ft^3/s; A30Q2, annual minimum 30-day average flow with 2-year RI, in ft^3/s; A30Q3, annual minimum 30-day average flow with 3-year RI, in ft^3/s; W7Q10, winter (November–March) minimum 7-day average flow with a 10-year RI, in ft^3/s; SWApp, percentage of basin in the Southwestern Appalachians ecoregion[5]; Jan1Q10, January minimum 1-day average flow with a 10-year RI, in ft^3/s; Feb1Q10, February minimum 1-day average flow with a 10-year RI, in ft^3/s; Mar1Q10, March minimum 1-day average flow with a 10-year RI, in ft^3/s; Apr1Q10, April minimum 1-day average flow with a 10-year RI, in ft^3/s; SEP, percentage of basin in the Southeastern Plains ecoregion[5]; May1Q10, May minimum 1-day average flow with a 10-year RI, in ft^3/s; Jun1Q10, June minimum 1-day average flow with a 10-year RI, in ft^3/s; Sto (storage), percentage of wetlands and water[4]; Jul1Q10, July minimum 1-day average flow with a 10-year RI, in ft^3/s; Aug1Q10, August minimum 1-day average flow with a 10-year RI, in ft^3/s; Sep1Q10, September minimum 1-day average flow with a 10-year RI, in ft^3/s; Oct1Q10, October minimum 1-day average flow with a 10-year RI, in ft^3/s; Nov1Q10, November minimum 1-day average flow with a 10-year RI, in ft^3/s; Dec1Q10, December minimum 1-day average flow with a 10-year RI, in ft^3/s; Jan7Q10, January minimum 7-day average flow with a 10-year RI, in ft^3/s; Feb7Q10, February minimum 7-day average flow with a 10-year RI, in ft^3/s; Mar7Q10, March minimum 7-day average flow with a 10-year RI, in ft^3/s; Apr7Q10, April minimum 7-day average flow with a 10-year RI, in ft^3/s; May7Q10, May minimum 7-day average flow with a 10-year RI, in ft^3/s; Jun7Q10, June minimum 7-day average flow with a 10-year RI, in ft^3/s; Jul7Q10, July minimum 7-day average flow with a 10-year RI, in ft^3/s; Aug7Q10, August minimum 7-day average flow with a 10-year RI, in ft^3/s; Sep7Q10, September minimum 7-day average flow with a 10-year RI, in ft^3/s; Oct7Q10, October minimum 7-day average flow with a 10-year RI, in ft^3/s; Nov7Q10, November minimum 7-day average flow with a 10-year RI, in ft^3/s; Dec7Q10, December minimum 7-day average flow with a 10-year RI, in ft^3/s]

Statistic	Equation	[7]*Pseudo* R^2	Average variance of prediction (log units)	Average standard error of prediction (percent)	Number of left-censored streamgages
Aug1Q10	$10^{[-0.9001 + 1.105\text{logDA} - 4.015\text{SVI} + 0.02211\text{MeanAP} + 0.01073\text{IA} + 0.002793\text{RV} - 0.002944\text{LR1} - 0.003448\text{LR2} - 0.001388\text{SH} + 0.004044\text{SCP}]}$	0.98	0.0357	45.7	44
Sep1Q10	$10^{[-0.6383 + 1.082\text{logDA} - 4.233\text{SVI} + 0.01895\text{MeanAP} + 0.01079\text{IA} + 0.002610\text{RV} - 0.003200\text{LR1} - 0.004777\text{LR2} + 0.004078\text{SCP}]}$	0.97	0.0405	48.9	51
Oct1Q10	$10^{[-0.3118 + 1.039\text{logDA} - 4.246\text{SVI} + 0.01564\text{MeanAP} + 0.009171\text{IA} + 0.002089\text{RV} - 0.002655\text{LR1} - 0.004268\text{LR2} + 0.003055\text{SCP}]}$	0.98	0.0307	42.1	36
Nov1Q10	$10^{[-0.1980 + 0.9797\text{logDA} - 3.574\text{SVI} + 0.01360\text{MeanAP} + 0.001317\text{IA} + 0.001456\text{RV} + 0.001990\text{SWApp}]}$	0.98	0.0235	36.4	14
Dec1Q10	$10^{[-0.6498 + 0.9788\text{logDA} - 2.315\text{SVI} + 0.01702\text{MeanAP} + 0.002810\text{SWApp} - 0.001306\text{LR2} + 0.001971\text{SH} - 0.004133\text{SCP}]}$	0.97	0.0302	41.6	4
Jan7Q10	$10^{[-1.116 + 1.007\text{logDA} - 1.173\text{SVI} + 0.02139\text{MeanAP} + 0.003375\text{SWApp} + 0.002335\text{SH} - 0.006103\text{SCP}]}$	0.97	0.0207	34.1	1
Feb7Q10	$10^{[-1.047 + 1.004\text{logDA} - 0.8277\text{SVI} + 0.02044\text{MeanAP} - 0.002489\text{IA} + 0.002605\text{SWApp} - 0.001069\text{LR2} + 0.001381\text{SH} - 0.006298\text{SCP}]}$	0.98	0.0144	28.1	1
Mar7Q10	$10^{[-1.024 + 1.019\text{logDA} - 0.7972\text{SVI} + 0.02072\text{MeanAP} - 0.002393\text{IA} + 0.002192\text{SWApp} - 0.006465\text{SCP}]}$	0.98	0.0138	27.5	1
Apr7Q10	$10^{[-0.7453 + 1.019\text{logDA} - 1.518\text{SVI} + 0.01926\text{MeanAP} - 0.002752\text{IA} + 0.003465\text{SWApp} - 0.008654\text{SCP} - 0.001772\text{SEP}]}$	0.98	0.0168	30.5	1
May7Q10	$10^{[-0.4178 + 1.002\text{logDA} - 2.543\text{SVI} + 0.01549\text{MeanAP} + 0.004759\text{SWApp} + 0.001826\text{RV} + 0.001272\text{BR} + 0.002161\text{LR2} - 0.008024\text{SCP} - 0.001831\text{SEP}]}$	0.97	0.0264	38.8	5
Jun7Q10	$10^{[-0.8224 + 1.065\text{logDA} - 2.978\text{SVI} + 0.02097\text{MeanAP} + 0.002338\text{IA} + 0.002315\text{SWApp} + 0.001899\text{RV} - 0.01114\text{Sto}]}$	0.98	0.0166	30.4	11
Ju17Q10	$10^{[-0.7906 + 1.095\text{logDA} - 3.428\text{SVI} + 0.02040\text{MeanAP} + 0.01018\text{IA} + 0.001714\text{SWApp} + 0.001628\text{RV} - 0.002025\text{LR1} - 0.001903\text{LR2} - 0.001512\text{SH} - 0.006265\text{Sto}]}$	0.98	0.0221	35.2	19
Aug7Q10	$10^{[-0.8529 + 1.092\text{logDA} - 3.757\text{SVI} + 0.02146\text{MeanAP} + 0.01187\text{IA} + 0.002305\text{RV} - 0.002660\text{LR1} - 0.002941\text{LR2} - 0.001316\text{SH} + 0.003757\text{SCP}]}$	0.98	0.0293	41.0	33
Sep7Q10	$10^{[-0.6485 + 1.068\text{logDA} - 3.925\text{SVI} + 0.01888\text{MeanAP} + 0.01006\text{IA} + 0.002286\text{RV} - 0.002718\text{LR1} - 0.004256\text{LR2} + 0.004521\text{SCP}]}$	0.98	0.0290	40.7	37

Table 6. Selected mean annual flow and low-flow frequency regional regression equations and regression diagnostics for streams in Georgia, North Carolina, and South Carolina.—Continued

[R^2, coefficient of determination; MAF, mean annual flow, in cubic feet per second (ft^3/s); logDA, is base 10 logarithm of drainage area, in square miles[1,2]; MeanAP, mean annual precipitation, in inches[3]; IA, percentage of impervious area[4]; BR, percentage of basin in the Blue Ridge ecoregion[5]; A1Q10, annual minimum 1-day average flow with a 10-year recurrence interval (RI), in ft^3/s; SVI, streamflow-variability index, unitless[6]; RV, percentage of basin in the Ridge and Valley ecoregion[5]; LR1 (low-flow region 1), percentage of basin in the Piedmont ecoregion minus the percentage of basin in the Triassic Basins and the Carolina Slate Belt ecoregions[5]; LR2 (low-flow region 2), the percentage of basin in the Triassic Basins and the Carolina Slate Belt ecoregions[5]; SH, percentage of basin in the Sand Hills ecoregion[5]; SCP, percentage of basin in the Southern Coastal Plain ecoregion[5]; A7Q2, annual minimum 7-day average flow with 2-year RI, in ft^3/s; A7Q10, annual minimum 7-day average flow with 10-year RI, in ft^3/s; A30Q2, annual minimum 30-day average flow with 2-year RI, in ft^3/s; A30Q3, annual minimum 30-day average flow with 3-year RI, in ft^3/s; W7Q10, winter (November–March) minimum 7-day average flow with a 10-year RI, in ft^3/s; SWApp, percentage of basin in the Southwestern Appalachians ecoregion[5]; Jan1Q10, January minimum 1-day average flow with a 10-year RI, in ft^3/s; Feb1Q10, February minimum 1-day average flow with a 10-year RI, in ft^3/s; Mar1Q10, March minimum 1-day average flow with a 10-year RI, in ft^3/s; Apr1Q10, April minimum 1-day average flow with a 10-year RI, in ft^3/s; SEP, percentage of basin in the Southeastern Plains ecoregion[5]; May1Q10, May minimum 1-day average flow with a 10-year RI, in ft^3/s; Jun1Q10, June minimum 1-day average flow with a 10-year RI, in ft^3/s; Sto (storage), percentage of wetlands and water[4]; Jul1Q10, July minimum 1-day average flow with a 10-year RI, in ft^3/s; Aug1Q10, August minimum 1-day average flow with a 10-year RI, in ft^3/s; Sep1Q10, September minimum 1-day average flow with a 10-year RI, in ft^3/s; Oct1Q10, October minimum 1-day average flow with a 10-year RI, in ft^3/s; Nov1Q10, November minimum 1-day average flow with a 10-year RI, in ft^3/s; Dec1Q10, December minimum 1-day average flow with a 10-year RI, in ft^3/s; Jan7Q10, January minimum 7-day average flow with a 10-year RI, in ft^3/s; Feb7Q10, February minimum 7-day average flow with a 10-year RI, in ft^3/s; Mar7Q10, March minimum 7-day average flow with a 10-year RI, in ft^3/s; Apr7Q10, April minimum 7-day average flow with a 10-year RI, in ft^3/s; May7Q10, May minimum 7-day average flow with a 10-year RI, in ft^3/s; Jun7Q10, June minimum 7-day average flow with a 10-year RI, in ft^3/s; Jul7Q10, July minimum 7-day average flow with a 10-year RI, in ft^3/s; Aug7Q10, August minimum 7-day average flow with a 10-year RI, in ft^3/s; Sep7Q10, September minimum 7-day average flow with a 10-year RI, in ft^3/s; Oct7Q10, October minimum 7-day average flow with a 10-year RI, in ft^3/s; Nov7Q10, November minimum 7-day average flow with a 10-year RI, in ft^3/s; Dec7Q10, December minimum 7-day average flow with a 10-year RI, in ft^3/s]

Statistic	Equation	[7]*Pseudo* R^2	Average variance of prediction (log units)	Average standard error of prediction (percent)	Number of left-censored streamgages
Oct7Q10	$10^{[-0.2665 + 1.023\mathrm{logDA} - 4.060\mathrm{SVI} + 0.01510\mathrm{MeanAP} + 0.01016\mathrm{IA} + 0.001913\mathrm{RV} - 0.002392\mathrm{LR1} - 0.003504\mathrm{LR2} + 0.002876\mathrm{SCP}]}$	0.98	0.0263	38.7	29
Nov7Q10	$10^{[-0.2015 + 0.9686\mathrm{logDA} - 3.291\mathrm{SVI} + 0.01333\mathrm{MeanAP} + 0.001452\mathrm{IA} + 0.001452\mathrm{SWApp} + 0.001087\mathrm{RV}]}$	0.98	0.0184	32.1	10
Dec7Q10	$10^{[-0.6367 + 0.9756\mathrm{logDA} - 2.176\mathrm{SVI} + 0.01716\mathrm{MeanAP} + 0.003564\mathrm{SWApp} - 0.001049\mathrm{LR2} + 0.001761\mathrm{SH} - 0.004593\mathrm{SCP}]}$	0.97	0.0258	38.3	2

[1] U.S. Geological Survey (2019); https://www.usgs.gov/streamstats.

[2] U.S. Environmental Protection Agency (EPA; 2012); http://nhd.usgs.gov/.

[3] PRISM Climate Group (2023a); https://www.prism.oregonstate.edu/normals/.

[4] Dewitz (2021); https://doi.org/10.5066/P9KZCM54.

[5] EPA (2013); https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states.

[6] Koltun and Whitehead (2002).

[7] Griffis and Stedinger (2007).

Table 7. Distribution, by State, of 604 streamgages included in regional regression equations for Georgia, North Carolina, and South Carolina, including supplemental streamgages in Alabama, Florida, Tennessee, and Virginia.

State	Alabama	Florida	Georgia	North Carolina	South Carolina	Tennessee	Virginia	Total
Number of streamgages used in regression equations	23	14	197	200	75	44	51	604

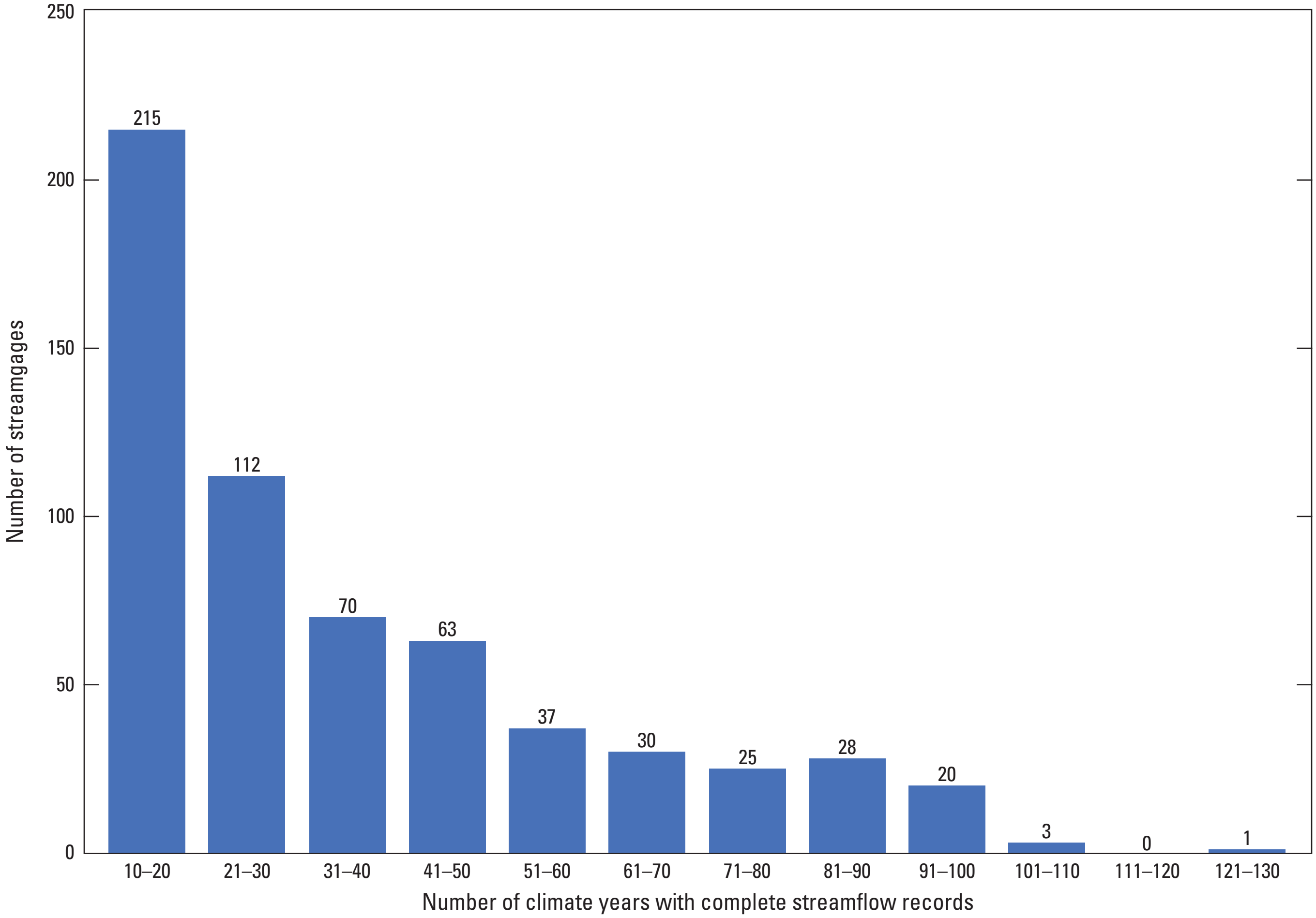
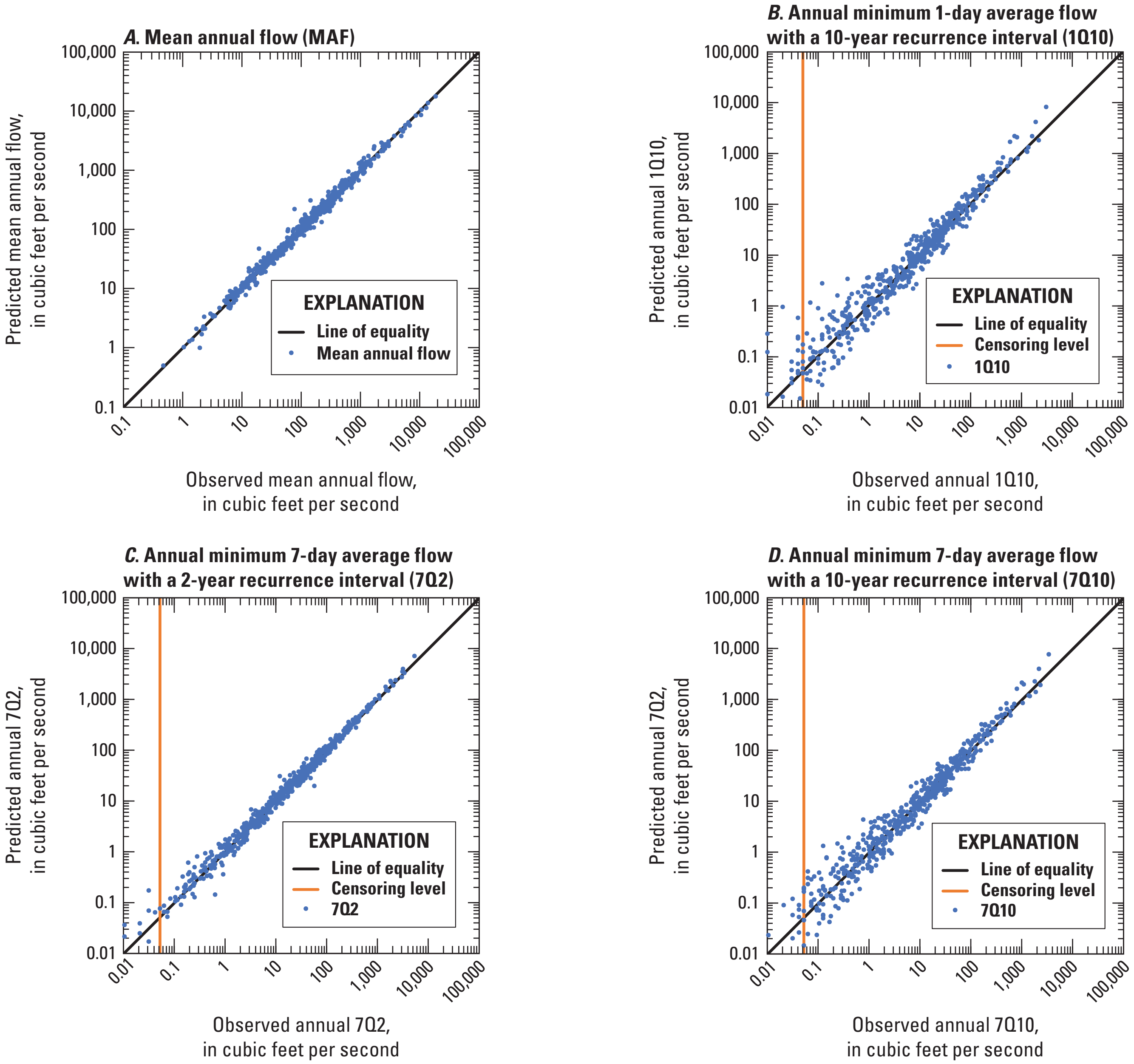


Figure 10. Distribution of number of climate years with complete streamflow records, April 1, 1884–March 31, 2022 (climate years 1884–2021), for the 604 U.S. Geological Survey streamgages used in the regional low-flow regression analysis for Georgia, North Carolina, and South Carolina, including supplemental streamgages in Alabama, Florida, Tennessee, and Virginia.



Notes: Zero flow is not shown on the plots because a log-log scale is used.
The censoring level of 0.05 cubic foot per second is shown where left-censored regression was used.

Figure 11. Relation between the observed and predicted (using the regional regression equations, table 6) *A*, mean annual flow (MAF); *B*, annual minimum 1-day average flow with a 10-year recurrence interval (1Q10); *C*, annual minimum 7-day average flow with a 2-year recurrence interval (7Q2); and *D*, annual minimum 7-day average flow with a 10-year recurrence interval (7Q10) at 604 U.S. Geological Survey streamgages in Georgia, North Carolina, and South Carolina, including supplemental streamgages in Alabama, Florida, Tennessee, and Virginia.

Accuracy

Model accuracy depends on model and sampling error (Eng and others, 2009). Model error measures the capacity of a set of explanatory variables to predict the values of the streamflow statistics calculated from streamgage records and used to develop a regression equation. Model error depends on the number and predictive power of the explanatory variables in a regression equation. Sampling error measures the capacity of a finite number of streamgages with a finite number of recorded streamflows to describe the true characteristics of the entire streamflow record for a streamgage. Sampling error depends on the number and record length of streamgages used in analysis and decreases as the number of streamgages and record lengths increase. A measure of the uncertainty in a regression-equation prediction for a site, *i*, is the variance of prediction, $V_{p,i}$. The $V_{p,i}$ is the sum of the model-error variance and sampling-error variance and is computed by using the following equation:

$$V_{p,i} = \gamma^2 + MSE_{s,i}, \tag{6}$$

where

$V_{p,i}$ is the variance of prediction for site *i*;

γ^2 is the model-error variance, in log units; and

$MSE_{s,i}$ is the time-sampling mean square error for site *i*, in log units.

Assuming the explanatory variables for the streamgages in a regression analysis are representative of all streamgages in the region, the average accuracy of prediction for a regression equation can be determined by computing the average variance of prediction, *AVP*, for *n* number of streamgages:

$$AVP = \gamma^2 + \left(\frac{1}{n}\right) \sum_{i=1}^{n} MSE_{s,i}, \tag{7}$$

where the remaining variables are as previously defined in equation 6.

A more traditional measure of accuracy of streamflow regression equations is the standard error of prediction, S_p, which is the square root of the variance of prediction. The average standard error of prediction for a regression equation can be computed in percent by using *AVP*, in log units, and the following transformation formula:

$$S_{p,ave} = 100\left[10^{2.3026(AVP)} - 1\right]^{0.5}, \tag{8}$$

where

$S_{p,ave}$ is the average standard error of prediction, in percent.

The average standard error of prediction ($S_{p,ave}$) is a measure of the average uncertainty of the regression equations when predicting streamflow estimates for ungaged sites—the most common application of the regression equations. There is about a 68-percent probability that the true streamflow at an ungaged location will be within plus or minus the $S_{p,ave}$ of the regression estimate (Hodgkins, 1999).

A measure of the proportion of the variation in the response variable explained by the explanatory variables in OLS regressions is the coefficient of determination, R^2 (Montgomery and others, 2012). A more appropriate performance metric than R^2 is *pseudo* R^2 described by Griffis and Stedinger (2007). Unlike the R^2 metric, *pseudo* R^2 is based on the variability in the response variable explained by the regression after removing the effect of time-sampling error. The *pseudo* R^2 is computed by using the following formula:

$$pseudo\ R^2 = 1 - \frac{\gamma^2(k)}{\gamma^2(0)}, \tag{9}$$

where

$\gamma^2(k)$ is the model-error variance from a regression with *k* explanatory variables, and

$\gamma^2(0)$ is the model-error variance from a regression with no explanatory variables.

When *pseudo* R^2 is closer to 1, the regression equation better explains variation in the response variable. The *pseudo* R^2, *AVP*, and $S_{p,ave}$ for the final set of regional regression equations are listed in table 6.

Users of the regression models may be interested in a measure of uncertainty at a particular ungaged site as opposed to the uncertainty statistics based on streamgage data used to generate the regression models. One such measure of uncertainty at a particular ungaged site is the confidence interval of a prediction, or prediction interval. The prediction interval is the likely range that contains the streamflow characteristic for a new observation not included in the development of the regression equations. Tasker and Driver (1988) determined that a 100(1–α) prediction interval for the true value of a streamflow characteristic for an ungaged site from the regression equation can be computed as follows:

$$Q/C < Q < Q \times C, \tag{10}$$

where

Q is the streamflow characteristic for the ungaged site, and

C is the confidence or prediction interval computed as

$$C = 10^{Z_{\left(\frac{\alpha}{2}\right)} S_{p,i}}, \tag{11}$$

where

$Z_{(\alpha/2)}$ is the normal critical value at a particular alpha level α, which equals 0.05 for a 95-percent prediction interval, divided by 2 and is equal to 1.96 for an α of 0.05; and

$S_{p,i}$ is the standard error of prediction computed as

$$S_{p,i} = [\gamma^2 + x_i U x_i']^{0.5}, \qquad (12)$$

where

γ^2 is the model-error variance;

x_i is a row vector of the independent variables for site *i*, augmented by a 1 as the first element;

U is the covariance matrix for the regression coefficients; and

x_i' is the transpose of $\boldsymbol{x_i}$ (Ludwig and Tasker, 1993).

The values for γ^2 and U are presented in table 8 in Kolb and others (2026).

Limitations for Applying the Regional Regression Equations

The following limitations should be considered when using regional regression equations for predicting low-flow frequency and mean annual flow for Georgia, North Carolina, and South Carolina:

1. Regional regression equations are applicable to rural and urban streams in Georgia, North Carolina, and South Carolina but should not be applied to streams that are known to be substantially affected by regulation, diversion, or tides. The user of the USGS StreamStats application (USGS, 2019) will need to know the stream condition when using predicted low-flow statistics for an ungaged location on a stream.
2. Ranges of basin characteristics as explanatory variables used to develop regression equations are listed in table 8. Because regression analysis included percentage of ecoregions as an independent variable, accuracy estimates and use of the relations are considered appropriate for basins contained within a single ecoregion or draining from multiple ecoregions. Applying the equations at locations on a stream having explanatory variables outside the range of those used in developing the regression equations may result in prediction errors greater than those listed in table 6.
3. Regional regression equations were developed by using left-censoring techniques with a censoring level of 0.05 ft^3/s. Consequently, a regression analysis at an ungaged location that results in a predicted value of less than 0.05 ft^3/s should be reported as less than 0.05 ft^3/s.

Table 8. Ranges of basin characteristics that were explanatory variables in the low-flow frequency and mean annual flow regression equations for Georgia, North Carolina, and South Carolina.

Basin characteristic	Minimum	Maximum
Drainage area (DA, square miles)[1,2]	0.3	13,560
Streamflow-variability index (SVI, unitless)[3]	0.09	1.47
Mean annual precipitation (MeanAP, inches)[4]	42.3	82.6
Percentage of impervious area (IA)[5]	0.01	62.5
Percentage of storage (Sto)[5]	0	76.9
Percentage of drainage basin within: Blue Ridge ecoregion (BR), Ridge and Valley ecoregion (RV), low-flow region 1 (LR1), low-flow region 2 (LR2), Sand Hills ecoregion (SH), Southern Coastal Plain ecoregion (SCP), Southwestern Appalachians ecoregion (SWApp), Southeastern Plains ecoregion (SEP), and Piedmont ecoregion (Pied)[6]	0	100

[1] U.S. Geological Survey (2019); https://www.usgs.gov/streamstats.

[2] U.S. Environmental Protection Agency (EPA; 2012); http://nhd.usgs.gov/.

[3] Koltun and Whitehead (2002).

[4] PRISM Climate Group (2023a); https://www.prism.oregonstate.edu/normals/.

[5] Dewitz (2021); https://doi.org/10.5066/P9KZCM54.

[6] EPA (2013); https://www.epa.gov/eco-research/level-iii-and-iv-ecoregions-continental-united-states.

Application of Low-Flow Frequency Methods

Uncertainty of frequency statistics at a streamgage can be reduced by combining the at-site estimate, based on the streamgage record, with the prediction from the regionalization equations to obtain a weighted estimate (Tasker, 1975; USGS, 2010; England and others, 2018). This can be particularly beneficial for at-site estimates based on short records. The following sections describe the weighting process for an estimate at a USGS streamgage. Procedures are also described for weighting an estimate at an ungaged site on the same stream with an estimate from a nearby streamgage. The regional regression models developed herein have been incorporated into the StreamStats application, which can be used to delineate drainage areas, generate basin characteristics, and compute estimates of streamflow statistics for user-selected sites (USGS, 2019).

As previously discussed, when zero flows are part of the *n*-day flows at a streamgage, a conditional probability adjustment can be made to estimate the low-flow statistics (Jennings and Benson, 1969; Tasker, 1987). However, because the uncertainty statistics also are computed in log space, and zero is undefined in log space, those uncertainty statistics are not computed at streamgages that have *n*-day flows equal to zero (Kiang and others, 2018). For such streamgages, the weighting procedures are not applicable.

Weighted Low-Flow Frequency Estimation at a Streamgage

At-site low-flow frequency estimates at a USGS streamgage can be weighted with the regression prediction at the streamgage by using the weighting procedures outlined in USGS (2010) and England and others (2018). The weighting procedure for the low-flow frequency statistics is done by using the at-site variance from the LPIII analysis and the variance from the regression model as shown in equation 13. A weighted variance for the weighted low-flow prediction can be computed by using equation 14. Note that the weighted low-flow frequency prediction is computed by using base 10 logarithms and then transformed back to arithmetic units (eq. 15). To weight an at-site estimate that was not included in the regression analyses, replace the variance from the regression estimate with the average variance of prediction from table 6.

$$\log Q_{w(s)} = \frac{V_{r(s)} \log Q_s + V_s \log Q_{r(s)}}{V_s + V_{r(s)}}, \qquad (13)$$

where

$Q_{w(s)}$ is the weighted low-flow frequency estimate at a streamgage, in cubic feet per second;

$V_{r(s)}$ is the variance of prediction at the streamgage derived from the applicable low-flow frequency regression equation (table 9 in Kolb and others, 2026), in log units, which is obtained from the left-censored regression output. If the weighting is being done for a streamgage that was not included in the low-flow frequency regression analyses, the average variance of prediction from table 6 can be used;

Q_s is the low-flow frequency estimate at the streamgage from the LPIII analysis, in cubic feet per second;

V_s is the variance of the streamgage estimate from the LPIII analysis (table 9 in Kolb and others, 2026), in log units; and

$Q_{r(s)}$ is the low-flow frequency estimate at the streamgage derived from the applicable regional regression equations in table 6, in cubic feet per second.

The variance of prediction associated with the weighted estimate, $V_{w(s)}$, is computed by using the following equation:

$$V_{w(s)} = \frac{V_s V_{r(s)}}{V_s + V_{r(s)}}, \qquad (14)$$

where all variables are as previously defined.

Transformation of the low-flow frequency estimate back to arithmetic units, in cubic feet per second, is shown in equation 15:

$$Q_{w(s)} = 10^{\log Qw(s)}. \qquad (15)$$

Confidence intervals for the weighted estimate also can be computed. The upper and lower 95-percent confidence intervals (95%CI) on the weighted low-flow frequency estimate can be computed as

$$95\%CI = [10^{\left(\log Q_{w(s)} - 1.96\sqrt{V_{w(s)}}\right)},\ 10^{\left(\log Q_{w(s)} + 1.96\sqrt{V_{w(s)}}\right)}, \qquad (16)$$

where all variables are as previously defined.

Low-Flow Frequency Estimate for an Ungaged Site Near a Streamgage

Sauer (1974) presented a method to transpose a weighted frequency estimate from a streamgage to a nearby ungaged site on the same stream when the drainage area of the ungaged site is within plus or minus 50 percent of the drainage area at the gaged site. Many USGS flood-frequency reports have presented the method as a two-step process, with the first step being to transfer the weighted flow estimate at the streamgage to the ungaged location by using the following equation:

$$Q_u = \left(A_u / A_g\right)^b \times Q_{w(s)}, \qquad (17)$$

where

Q_u is the flow estimate at the ungaged site transferred from the gaged site, in cubic feet per second;

A_u is the drainage area at the ungaged site, in square miles;

A_g is the drainage area at the gaged site, in square miles;

b is the exponent of the drainage area term for a single-variable regional regression equation that is just a function of drainage area; and

$Q_{w(s)}$ is the weighted low-flow frequency estimate at the gaged location, in cubic feet per second, as previously defined in equation 13 (Guimaraes and Bohman, 1992; Stamey and Hess, 1993; Atkins, 1996).

Before simplifying, the ratio in equation 17 represents the ratio of the regression flow estimate at the ungaged and gaged locations when the regression equation is just a function of drainage area and when the two locations are in the same hydrologic region. As such, and before simplifying, equation 17 could be written as $Q_u = (CA_u{}^b/CA_g{}^b) \times Q_{w(s)}$, where C is the regression constant, and the other variables are as previously defined. Thus, in a case where the regression equation is a multivariable equation, such as the low-flow frequency equations from this report, the equation for Q_u would be as follows:

$$Q_u = \left(Q_{r(u)} / Q_{r(s)}\right) \times Q_{w(s)}, \qquad (18)$$

where $Q_{r(u)}$ is the low-flow frequency estimate from the regression equation at the ungaged site and the other variables are as previously defined.

The final step in the procedure for transferring the weighted at-site estimate to an ungaged location is shown in equation 19:

$$Q_{w(u)} = \left(\frac{2|\Delta A|}{A_g}\right) Q_{r_{(u)}} + \left(1 - \frac{2|\Delta A|}{A_g}\right) Q_u, \qquad (19)$$

The farther away the ungaged location is from the gaged location, equation 18 gives more weight to the regression prediction, $Q_{r(u)}$. When the ungaged location is 0.5 or 1.5 times the drainage area of the gaged location, equation 19 gives full weight to $Q_{r(u)}$. The two-step process can be done in a single step by combining equations 18 and 19, which results in equation 20:

$$Q_{w(u)} = \left[\left(\frac{2|\Delta A|}{A_{(s)}}\right) + \left(1 - \frac{2|\Delta A|}{A_{(s)}}\right)\left(\frac{Q_{w(s)}}{Q_{r(s)}}\right)\right] Q_{r(u)}, \qquad (20)$$

where

$Q_{w(u)}$ is the weighted low-flow frequency estimate at the ungaged site, in cubic feet per second;

$|\Delta A|$ is the absolute value of the difference between the drainage areas of the streamgage and the ungaged site, in square miles;

$A_{(s)}$ is the drainage area for the streamgage, in square miles;

$Q_{r(u)}$ is the low-flow frequency estimate from the applicable regional equations in table 6 at the ungaged site, in cubic feet per second; and

$Q_{w(s)}$ and $Q_{r(s)}$ are as previously defined in equation 13.

StreamStats

The low-flow frequency and mean annual flow regression equations developed during this study will be incorporated into the USGS StreamStats application (https://www.usgs.gov/streamstats; USGS, 2019) for Georgia, North Carolina, and South Carolina. USGS StreamStats is a web-based GIS application that provides a range of analytical tools for water-resource managers, planners, and engineers (Weaver and others, 2012; Ries and others, 2017; Feaster and others, 2018). The StreamStats application can be used to delineate drainage areas, generate basin characteristics, and compute estimates of streamflow statistics for user-selected sites through consistent and repeatable methods.

Summary

The U.S. Geological Survey (USGS), in cooperation with the Georgia Department of Natural Resources (Environmental Protection Division), the North Carolina Department of Environmental Quality (Division of Water Resources), the North Carolina Department of Public Safety (Office of Recovery and Resiliency), and the South Carolina Department of Environmental Services, completed a regional low-flow study concurrently across the three-State region. Benefits of using the three-State region are as follows: (1) consistent hydrologic regions across all three States; (2) a larger dataset for developing the regional regression equations—typically improving results from such equations; (3) consistency in basin characteristics included in the regression analysis; and (4) low-flow frequency and mean annual flow regression equations that are consistent across the three-State region and particularly beneficial for basins that cross State boundaries.

Selected low-flow frequency and mean annual flow statistics were updated at 843 USGS streamgages. Of those 843 streamgages, 712 are in Georgia, North Carolina, and South Carolina, and the remaining 132 streamgages are in adjacent States of Alabama, Florida, Tennessee, and Virginia. Regional regression analysis was done by using 604 streamgages considered to have minimal to no effects from regulation, diversion, or tides. At some of the streamgages included in this study, the low-flow frequency statistics were zero. When logarithmic transformation is used in a regression analysis, having response variables with a zero value is problematic because the logarithm of zero is undefined. As such, weighted left-censored regression techniques were used to develop 31 regression equations to estimate mean annual flow and the following low-flow frequency statistics: annual minimum 1-day average flow with a 10-year recurrence interval (1Q10), annual minimum 7-day average flow with 2- and 10-year recurrence intervals (7Q2 and 7Q10, respectively), and annual minimum 30-day average flow with 2- and 3-year recurrence intervals (30Q2 and 30Q3, respectively). The 1Q10 and 7Q10 statistics were also presented monthly, and 7Q10 was predicted for the winter period (November–March, W7Q10).

The main independent variables for the regression equations were drainage area, streamflow-variability index, mean annual precipitation, and percentage of impervious area. Because percentage of impervious area was included in 25 of 31 equations, these regional regression equations can be applied for rural and urban basins. Streamflow-variability index and mean annual precipitation provide regional variables in the regression equations to account for some of the regional differences across the three States. To account for other regional differences, percentages of drainage basins in U.S. Environmental Protection Agency Level III and Level IV ecoregions also were statistically significant variables in some of the regression equations. Average standard error of prediction for the low-flow frequency equations ranged from 23.3 to 61.6 percent. Mean annual flow was predicted as a function of drainage area, mean annual precipitation, percentage of impervious area, and percentage of basin in the Blue Ridge ecoregion. Average standard error of prediction for the mean annual flow equation is 16.3 percent.

Trends were calculated for annual minimum 7-day average flows for 78 streamgages in Georgia, North Carolina, and South Carolina that were included in the regression analysis and had at least 30 years of continuous record ending as of March 31, 2022. Three dependence assumptions were tested: independence, short-term persistence, and long-term persistence. Trend analyses were done for streamgages with streamflow records of 30-, 50-, 70-, and 90-year time periods (climate years 1992–2021, 1972–2021, 1952–2021, and 1932–2021, respectively). For all three trend analysis assumptions, the majority of streamgages had no statistically significant trend in annual minimum 7-day average flows. During the four climate-year periods (periods) for the three trend analysis assumptions either zero or only one streamgage had an upward trend. For each of the four periods, a small number of streamgages had downward trends. The only period and trend test that was notable for downward trends was for the 50-year period (climate years 1972–2021), where the independence assumption test found 14 of 46 streamgages to have a statistically significant downward trend. Because the beginning of this period represented a relatively wet period and the later part of the period included historic drought years, that is likely why the independence analysis indicated 14 streamgages with downward trends. When long-term persistence was considered, only 1 of the 46 streamgages indicated a statistically significant trend.

Trends of mean annual precipitation by climate division and statewide for Georgia, South Carolina, and North Carolina were calculated for climate years 1896 to 2021. For mean annual precipitation, no statistically significant trends were indicated by the independence and short-term and long-term persistence analyses for all climate divisions across the three States and statewide analyses. For mean annual air temperature for calendar years 1895 to 2021, all three statewide independence trend analyses indicated statistically significant upward trends. These upward trends were also indicated for several climate divisions within Georgia and North Carolina, and all seven climate divisions in South Carolina had statistically significant upward trends in air temperature, with total change ranging from 0.81 to 1.65 degrees Fahrenheit. The long-term persistence analysis, however, indicated no statistically significant trends in air temperature.

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For additional information, visit
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Publishing support provided by
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Lafayette Publishing Service Center

Feaster and others—**Estimating Low-Flow Frequency and Mean Annual Flow Statistics, Ga., N.C., and S.C.**—SIR 2026–5021

ISSN 2328-0328 (online)
https://doi.org/10.3133/sir20265021