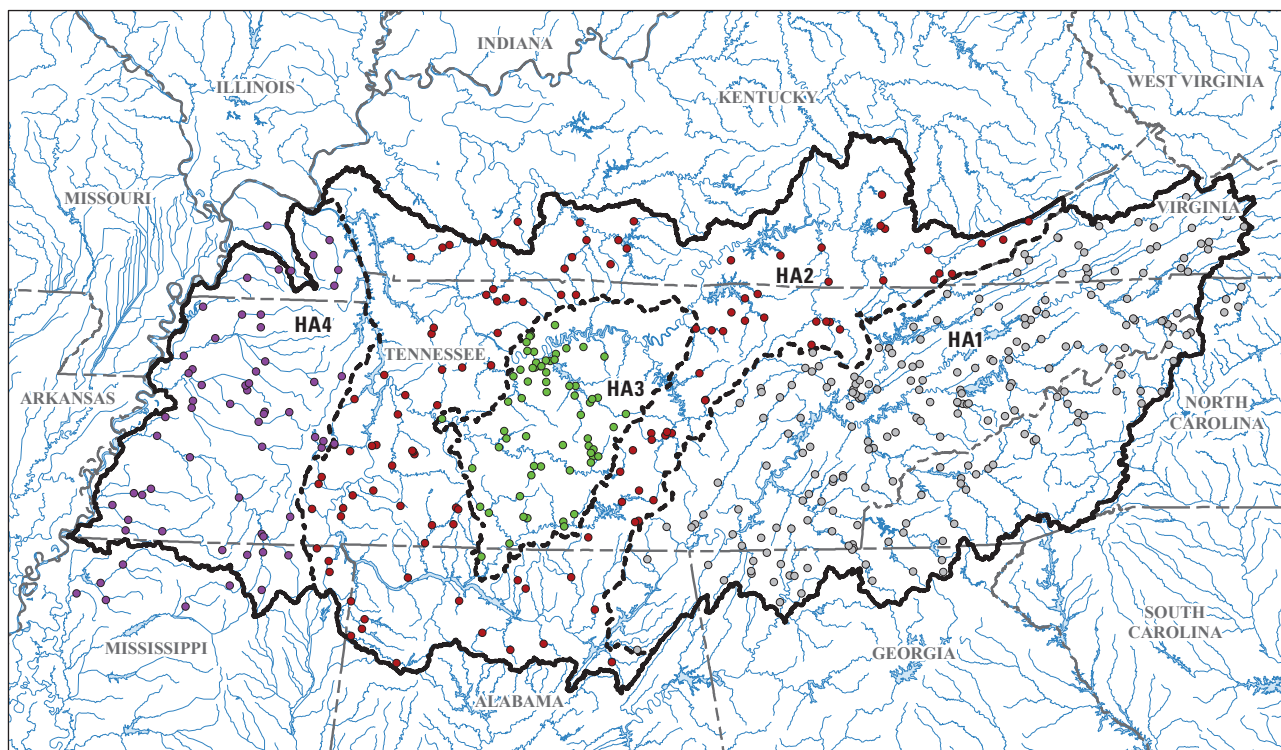


Prepared in cooperation with the Tennessee Department of Transportation

Estimating the Magnitude and Frequency of Floods at Ungaged Locations on Streams in Tennessee Through the 2013 Water Year



Scientific Investigations Report 2024–5130

Cover. See figure 1 on page 3.

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By David E. Ladd and Paul A. Ensminger

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Scientific Investigations Report 2024–5130

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

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
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)
Hydraulic gradient		
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)

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).

Supplemental Information

Water year A 1-year period from October 1 to September 30, defined by the year in which it ends; for example, the 2013 water year is the period October 1, 2012–September 30, 2013.

Abbreviations

AEP	annual exceedance probability
<i>CLIMFAC2YR</i>	2-year recurrence-interval climate factor
<i>CSL10_85</i>	main-channel slope
<i>DRNAREA</i>	drainage area
EMA	expected moments algorithm
GIS	geographic information system
GLS	generalized least squares
HA	hydrologic area
<i>LC11IMP</i>	percent imperviousness
LP3	log-Pearson type III
MGBT	Multiple Grubbs-Beck test
OLS	ordinary least squares
PILF	potentially influential low flood
RRE	regional regression equation
USGS	U.S. Geological Survey
WREG	weighted-multiple-linear regression computer program

Estimating the Magnitude and Frequency of Floods at Ungaged Locations on Streams in Tennessee Through the 2013 Water Year

By David E. Ladd and Paul A. Ensminger

Abstract

To improve estimates of the frequency of annual peak flows for ungaged locations on non-urban, unregulated streams in Tennessee, generalized least-squares multiple linear-regression techniques were used to relate annual peak flows from streamgages operated by the U.S. Geological Survey to physical, climatic, and land-use characteristics of their drainage basins. Geospatial data acquired since the previous study in 2003, annual peak-streamflow data through the 2013 water year, and Bulletin 17C methods for frequency analysis of annual peak-streamflow data were used in the study. Generalized least-squares regression equations were developed for four hydrologic areas with distinct hydrologic, geologic, and topographic characteristics. Drainage area was used as an explanatory variable in equations developed for each hydrologic area. In addition to drainage area, a 2-year recurrence-interval climate factor was used for hydrologic area 1, a 10–85 channel slope was used for hydrologic area 2, and percent imperviousness was used for hydrologic area 4. The regression equations can be used to estimate annual exceedance probability streamflows for ungaged locations on non-urban, unregulated streams in Tennessee. The term “unregulated” indicates that streamflow is not appreciably influenced by regulation from reservoirs or other impoundments. Average standard errors of prediction for the regression equations ranged from 44.4 to 51.4 percent for hydrologic area 1; 30.4 to 42.9 percent for hydrologic area 2; 35.7 to 42.6 percent for hydrologic area 3; and 32.5 to 47.4 percent for hydrologic area 4.

Introduction

Transportation engineers require reliable estimates of the magnitude and frequency of peak streamflows to design bridges, culverts, and other structures near streams and rivers. Methods used to estimate the magnitude and frequency of peak streamflows at ungaged locations are commonly updated at the request of stakeholders to include recent streamflow data, incorporate statistical improvements in frequency

analysis, and implement technological improvements that increase the accuracy of basin and climatic characteristics that affect hydrologic response in streams. The U.S. Geological Survey (USGS) last published methods for estimating the magnitude and frequency of annual peak streamflow at ungaged locations on streams in Tennessee (Law and Tasker, 2003) using streamgages operated by the USGS having at least 10 years of observed annual peak streamflows through the 2000 water year. For this study, more than 10 additional years of streamflow record were available for many of the streamgages used to develop the predictive equations. During this period, previously known maximum flood peaks were exceeded at many USGS streamgages throughout middle and west Tennessee.

Since the USGS last published methods for estimating magnitude and frequency of annual peak streamflow at ungaged locations on streams in Tennessee, updated guidelines for frequency analysis of annual peak streamflow by Federal agencies, referred to as “Bulletin 17C,” have been published (England and others, 2019). Bulletin 17C guidance incorporated in this analysis includes an updated regional skew coefficient for the study area; use of the expected moments algorithm (EMA) for fitting the log-Pearson type III (LP3) distribution to the annual peaks; and the application of the Multiple Grubbs-Beck test (MGBT) for identifying potentially influential low floods (PILFs) in the distribution of annual peak streamflows.

In 2020, the USGS, in cooperation with the Tennessee Department of Transportation, updated the methods for predicting the magnitude and frequency of floods at ungaged locations for streams in Tennessee. Regression equations were developed to predict streamflows corresponding to the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent annual exceedance probabilities (AEPs). The new regression equations will be incorporated into the StreamStats web application (<https://streamstats.usgs.gov/ss/>) (U.S. Geological Survey, 2019) to automate the process of predicting streamflows for selected AEPs for ungaged locations on streams in Tennessee. Geospatial data associated with the study, including drainage basins and basin characteristics, and the tabular data referenced in this report are available in Heal and others (2025).

Purpose and Scope

The purposes of this report are to provide (1) updated estimates of streamflows corresponding to 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs for 454 streamgages operated by the USGS in the study area (figs. 1–5); and (2) updated regional regression equations (RREs) for estimating streamflows corresponding to AEPs at ungaged locations on streams within each of four hydrologic areas (HAs) (figs. 1–5).

Basin characteristics derived from geographic information systems (GIS) and annual peak-streamflow records for 454 streamgages located in generally rural areas of Tennessee and in the adjacent States of Georgia, North Carolina, Virginia, Alabama, Kentucky, and Mississippi (fig. 1) were used to develop the RREs. Streamgages used to develop the RREs were required to have at least 10 years of observed annual peaks through water year 2013 (a water year is defined as the period October 1 through September 30, named for the year in which it ends), and those peak streamflows needed to not have been appreciably affected by urbanization. Of the 454 streamgages used for this study, 443 streamgages were used in the previous study and drained basins with 1 percent to about 30 percent total impervious area (Law and Tasker, 2003). Whereas most of the streamgages used in the current study have drainage basins with a relatively low percentage of urbanization, seven basins for streamgages in middle and east Tennessee (where the percentage of impervious area was not found to be useful in estimating annual peak streamflows) were determined to have greater than 20 percent impervious area. In west Tennessee, where percent imperviousness was found to be useful in estimating annual peak streamflows, only one streamgage used in the current study had a basin with greater than 10 percent impervious area. Of the 454 streamgages used in the current study, 430 streamgages had basins with less than 10 percent impervious area.

Description of the Study Area

The description of this study area was originally presented in Law and Tasker (2003), and it is summarized herein. The diverse physiography and topography of Tennessee ranges from the lowlands of the Mississippi River Valley and Coastal Plain physiographic provinces to the hills of the Western Valley physiographic province and the Central Basin and Highland Rim physiographic sections, across the elevated and incised Cumberland Plateau physiographic section, to the mountains of the Valley and Ridge and Blue Ridge physiographic provinces (Fenneman and Johnson, 1946; Miller, 1974). Other than areas of anthropogenic disturbance such as quarries, land-surface elevations generally range from about 250 feet (ft) above the North American Vertical Datum of 1988 (NAVD 88) along the Mississippi River in west Tennessee to over 6,600 ft above NAVD 88 in the mountains of east Tennessee.

Geology in Tennessee is variable. West Tennessee is characterized by horizontal beds of unconsolidated sand, silt, clay, and gravel. Middle Tennessee is dominated by horizontal beds of karstic limestone. East Tennessee is characterized by folded beds of limestone and dolomite, and the mountains of east Tennessee are underlain by folded beds of complex metamorphic and igneous rock.

The average annual precipitation in Tennessee varies from about 36 to 82 inches (in.), generally increasing from west to east (PRISM Climate Group, Oregon State University, 2014). Generally low average precipitation of 45 in. or less occurs in west Tennessee near the Mississippi River in the Coastal Plain physiographic province and in northern middle Tennessee in the Highland Rim and Nashville Basin sections of the Interior Low Plateaus physiographic province. Other areas of relatively low precipitation are in the northeastern part of the State in the Valley and Ridge physiographic province and the Blue Ridge physiographic province, where precipitation is variable. The highest average precipitation occurs in the eastern part of the State along the eastern boundary of the Appalachian Plateaus physiographic province and in the southeast part of the State along the Great Smoky Mountains in the Blue Ridge physiographic province (Fenneman and Johnson, 1946; Miller 1974). Annual peak streamflows typically occur during the winter and early spring (December through March) when frequent frontal storms yield widespread rains of high intensity on often already saturated ground. Localized peak-streamflow response of small watersheds occurs during the summer when thunderstorms produce intense downpours over relatively small geographic areas. In the fall, the remnants of hurricanes sometimes result in large rain events that can produce annual peak streamflows.

Previous Investigations

Jenkins (1960), Patterson (1964), Speer and Gamble (1964), Randolph and Gamble (1976), Weaver and Gamble (1993), and Law and Tasker (2003) previously reported methods for estimating the magnitude and frequency of annual peak streamflows for rural streams in Tennessee. Randolph and Gamble (1976) delineated and statistically validated four HAs (fig. 1) similar to those used in subsequent studies. Weaver and Gamble (1993) used methods from Bulletin 17B (Interagency Advisory Committee on Water Data, 1982) and conducted the first study to use generalized least-squares (GLS) techniques for developing regional regression equations (Stedinger and Tasker, 1985). Law and Tasker (2003) presented regional regression equations and a region of influence method for predicting the magnitude and frequency of annual peak streamflows, in which a subset of streamgages is used to develop unique regression equations for estimating peak streamflows for AEPs at ungaged locations.

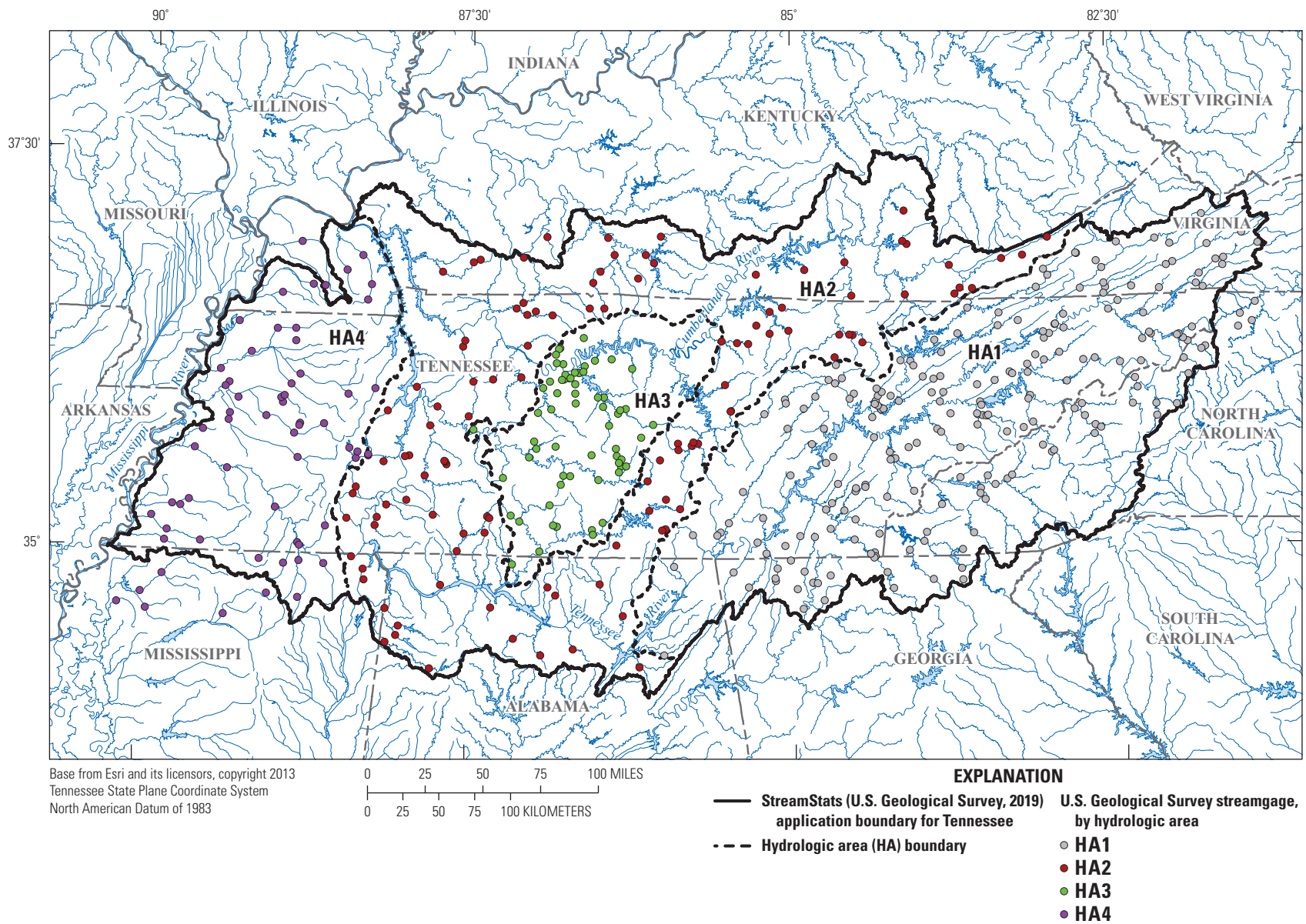


Figure 1. Streamgages, hydrologic areas, and the Tennessee StreamStats application boundary, Tennessee and parts of Alabama, Georgia, Kentucky, Mississippi, North Carolina, and Virginia.

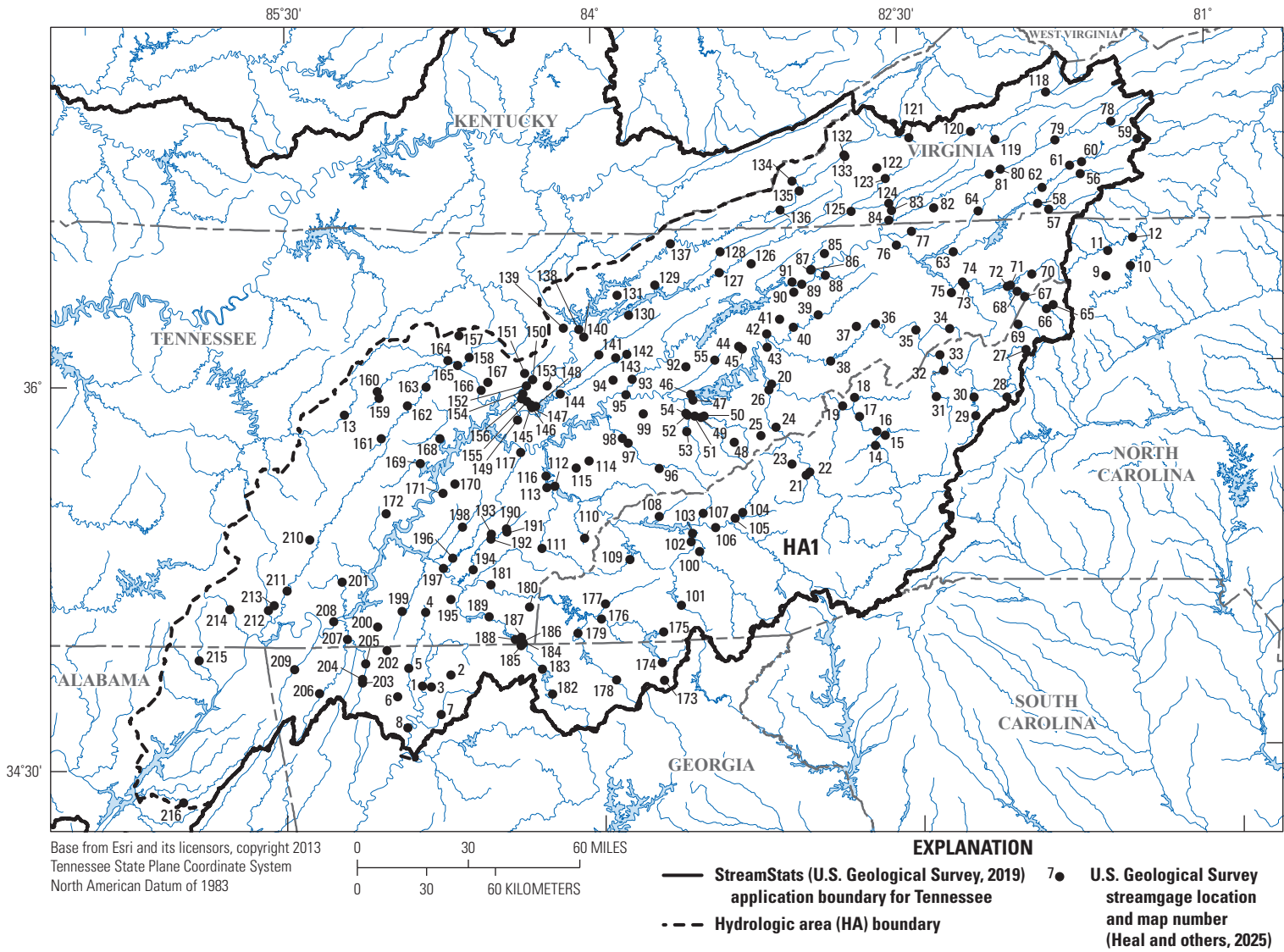


Figure 2. Streamgages in hydrologic area 1, east Tennessee and parts of Alabama, Georgia, North Carolina, and Virginia.

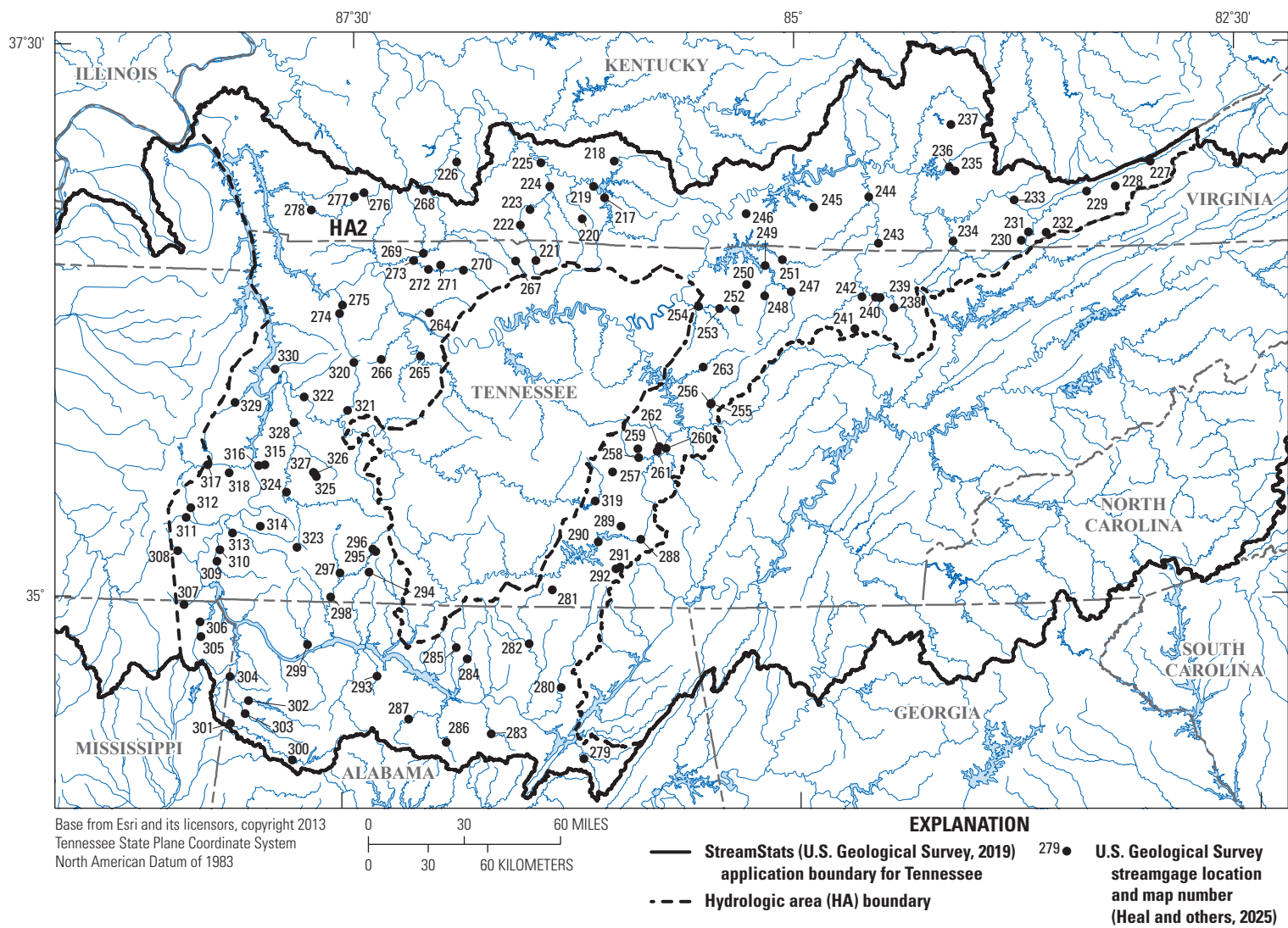


Figure 3. Streamgages in hydrologic area 2, middle Tennessee and parts of Alabama, Kentucky, and Mississippi.

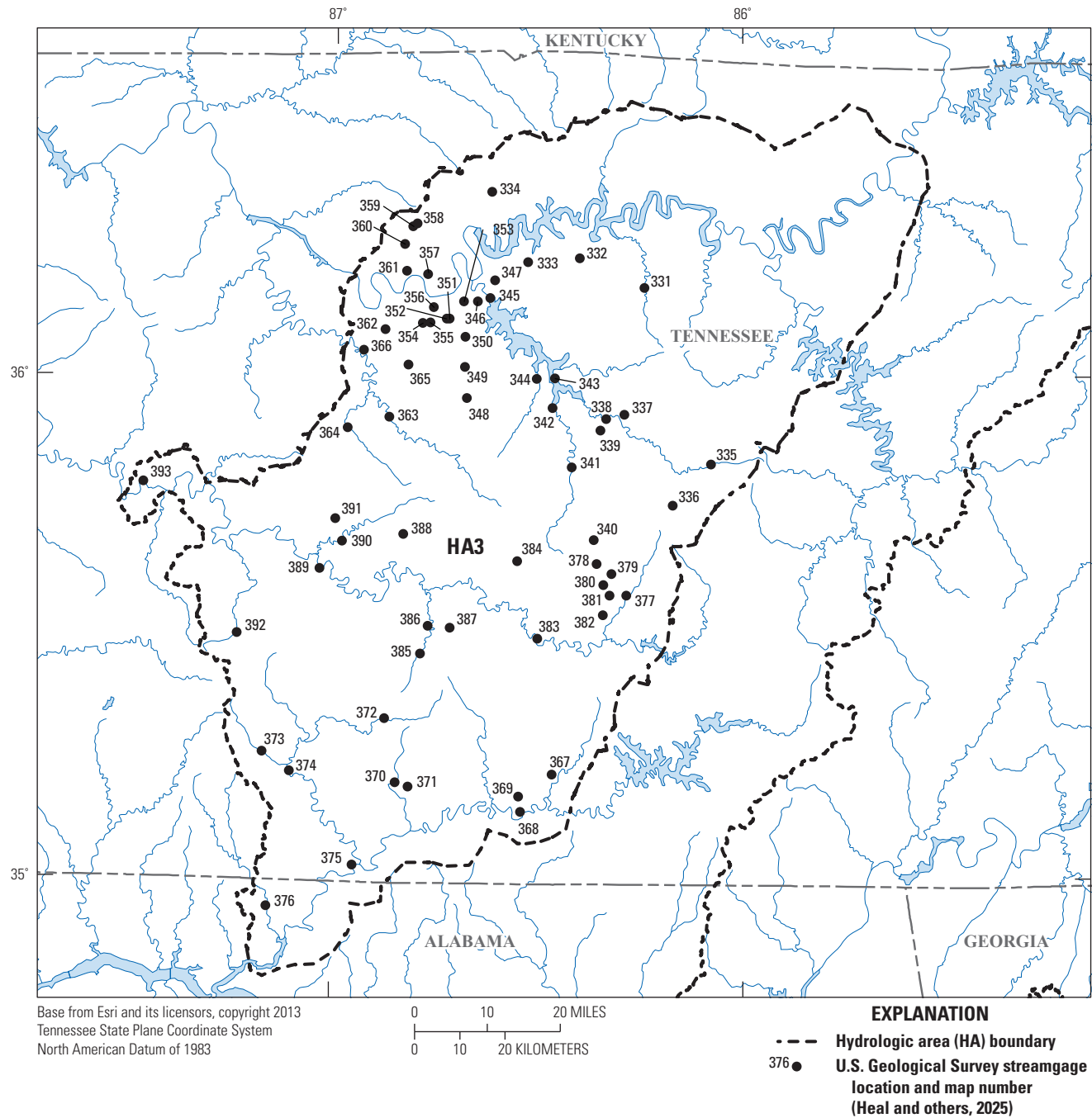


Figure 4. Streamgages in hydrologic area 3, middle Tennessee and part of Alabama.

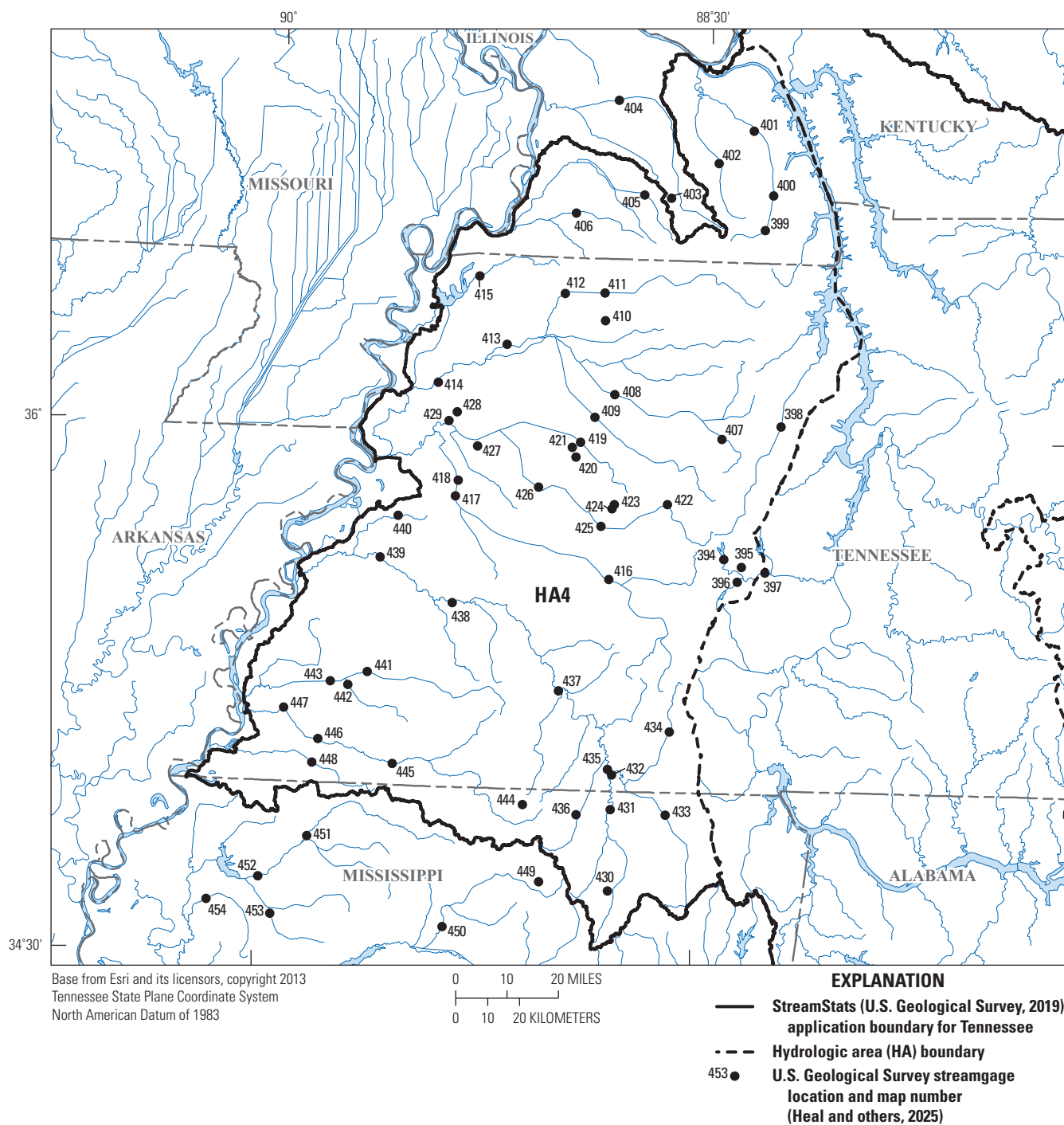


Figure 5. Streamgages in hydrologic area 4, west Tennessee and parts of Kentucky and Mississippi.

Data Compilation

A first step in conducting a flood-frequency analysis is the selection of candidate streamgages within the study area. The chosen streamgages must be reviewed for quality assurance and quality control prior to the computation of peak streamflows for selected AEPs. After the streamgages are selected and reviewed, basin characteristics for each streamgage must be calculated or acquired from other sources. For streamgages within a particular HA, the peak streamflows for AEPs are the dependent variables in the regional regression equations; the basin characteristics are the independent variables.

Streamgage Selection

Streamgages within Tennessee and parts of Mississippi, Alabama, Georgia, North Carolina, Virginia, and Kentucky were considered for use in the study. USGS peak-streamflow data were acquired from the USGS National Water Information System (NWIS; USGS, 2016). Streamgages used in the study had at least 10 years of observed annual peaks through water year 2013 and were free from regulation by large dams and reservoirs. Annual peak-streamflow data from a final dataset of 454 streamgages (302 in Tennessee, 18 in Alabama, 19 in Georgia, 36 in Kentucky, 14 in Mississippi, 37 in North Carolina, and 28 in Virginia) were used in the flood-frequency analysis and to develop the RREs; of these 454 streamgages, 443 were used in the previous study (Law and Tasker, 2003).

Basin Delineation and Characteristics

Of the 454 candidate streamgages used in the study, 441 are within the StreamStats application boundary for Tennessee (fig. 1). GIS-based methods similar to those incorporated in

the StreamStats application (USGS, 2019) for Tennessee were used to delineate drainage basins and determine drainage area (*DRNAREA*), main-channel slope (*CSL10_85*), and 2-year recurrence-interval climate factor (*CLIMFAC2YR*) (table 1) for streamgages within the StreamStats application boundary for Tennessee. Calculated *DRNAREA* values for the streamgages were compared to published values available from NWIS (USGS, 2016) for validation. Geospatial- and StreamStats-based delineations for streamgages 07030240 and 02348600 produced basins that were inaccurate and required manual correction before basin characteristics could be computed. For 13 streamgages located outside of the StreamStats application boundary for Tennessee (fig. 1), delineation of drainage basins and calculation of *DRNAREA* were accomplished by using StreamStats (USGS, 2019), and *CSL10_85* and *CLIMFAC2YR* values were obtained from Law and Tasker (2003). For 450 of the 454 streamgages in the study area, percent imperviousness (*LCIIMP*) (table 1) was calculated by using National Land Cover Database Percent Developed Imperviousness data, 2011 edition (USGS, 2014). For the four streamgages in North Carolina that are outside the StreamStats application boundary for Tennessee (fig. 1), *LCIIMP* was obtained from StreamStats.

Drainage Area

Drainage area (*DRNAREA*) is the surface area of the drainage basin of a streamgage, in square miles. For the 441 streamgages within the Tennessee StreamStats application boundary (fig. 1), drainage basins were delineated by using flow-direction grids derived from the 1/3 arc-second (approximately 10-meter [m]) National Elevation Dataset (USGS, variously dated). For the remaining 13 streamgages which lie outside of the Tennessee StreamStats application boundary (fig. 1), delineations of drainage basins and computations of *DRNAREA* were accomplished by using StreamStats.

Table 1. Physical and climatic basin characteristics used as explanatory variables in the generalized least-squares regression equations.

Basin characteristic	Unit of measure	Definition
Physical characteristics		
<i>DRNAREA</i>	Square miles	Drainage area is the basin area for the location of interest.
<i>CSL10_85</i>	Feet per mile	The 10–85 channel slope is the change in elevation measured between points along the main channel at 10 and 85 percent of the stream length upstream from the streamgage of interest, divided by the stream-wise distance between the points.
<i>LCIIMP</i>	Percent	Imperviousness is the percentage of area beneath which precipitation is unable to infiltrate into the soil within the basin of a location of interest.
Climatic characteristic		
<i>CLIMFAC2YR</i>	Dimensionless	2-year recurrence-interval climate factor, describing spatial variability in the peak-streamflow frequency of small basins

10–85 Channel Slope

The 10–85 channel slope (*CSL10_85*), in feet per mile, is the change in elevation between points along the main channel at 10 and 85 percent of the stream length upstream from the streamgage, divided by the stream-wise distance between the points. Ideally, the stream length used for determining points at 10 and 85 percent upstream from the streamgage is measured from the outlet to the basin divide. The further the headwaters of the main channel are from the watershed divide, the more subjective the manual computation of stream length can become. A GIS method was used to determine the stream length by identifying the longest flow path upstream from the site of interest; the longest flow path does not always conform to the main-channel path from the streamgage to the basin divide.

Percent Imperviousness

Percent imperviousness is the percentage of surface area of a drainage basin through which precipitation is unable to infiltrate into the soil. Impervious surface can increase storm runoff to streams. *LCIIMP* was calculated for the basins of 450 streamgages in this study by using the National Land Cover Database 2011 Percent Developed Imperviousness dataset (USGS, 2014). For the remaining four streamgages located in North Carolina, *LCIIMP* was obtained from StreamStats (USGS, 2019).

Conceptually, *LCIIMP* is relatively high in drainage basins of urban streams, where much of the surface area is paved. Even though most of the basins for streamgages used in this study had relatively low values of *LCIIMP*, seven of the basins had *LCIIMP* values greater than 20 percent. These basins with *LCIIMP* values greater than 20 percent are in HAs 1–3, where *LCIIMP* was not determined to be a statistically useful explanatory variable in prediction of streamflows for AEPs. Within HA4, only streamgage 07032200 had an *LCIIMP* value (13.7 percent) greater than 10 percent.

2-Year Climate Factor

Lichty and Karlinger (1990) describe a method for integrating long-term rainfall and pan evaporation data into a climate factor to help describe the spatial variability in the frequency of annual peak streamflow of small basins. Climate factors for 2-, 25-, and 100-year recurrence-interval floods (streamflows for 0.5, 0.04, and 0.01 AEPs, respectively) were developed using data from 71 long-term rainfall stations and regression analysis relating peak-streamflow estimates from 50 rainfall-runoff models to basin characteristics. The climate factors, which describe the effects of climate variability on peak streamflows, were developed and regionalized by kriging within a large part of the United States. Law and Tasker (2003) used only the 2-year recurrence interval climate factor

(*CLIMFAC2YR*) for predicting peak-streamflow-frequency magnitudes within the study area, and *CLIMFAC2YR* is the only climate variable used in this study.

Annual Exceedance Probability Analysis

An AEP is the probability that a streamflow of a given magnitude will be met or exceeded in a given year. For this study, streamflows corresponding to the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs were computed. The previous study of the magnitude and frequency of flooding in Tennessee (Law and Tasker, 2003) reported flood recurrence intervals, such as the 100-year flood. An annual recurrence interval is the reciprocal of an AEP for a given flood magnitude; for example, a flood having an AEP of 1 percent (0.01, or 1/100) is equivalent to the 100-year recurrence interval (table 2).

AEPs corresponding to annual peak streamflows for the 454 streamgages in the study area were computed by using the USGS program PeakFQ, version 7.0.29368 (Flynn and others, 2006; Feaster and others, 2014; Veilleux and others, 2014). The PeakFQ program was used to fit a log-Pearson type III distribution to base-10 logarithms of annual peak streamflows per Bulletin 17C guidelines (England and others, 2019), which include the use of EMA (Cohn and others, 1997) and MGBT (Cohn and others, 2013) for identifying PILFs during the fitting process. The LP3 distribution is a three-moment distribution that requires estimating the population mean, standard deviation, and skew coefficient.

Expected Moments Algorithm

The EMA method (Cohn and others, 1997) for estimating streamflows corresponding to AEPs incorporates streamflow intervals and perception thresholds that describe peak-streamflow knowledge for every year in the period of record for a streamgage, including the systematic peak

Table 2. Recurrence intervals that correspond with annual exceedance probabilities.

Annual exceedance probability	Recurrence interval (in years)
0.5	2
0.2	5
0.1	10
0.04	25
0.02	50
0.01	100
0.005	200
0.002	500

streamflows, historical peak streamflows, and gaps in the peak-streamflow record (Southard and Veilleux, 2014). Using streamflow intervals and perception thresholds, the EMA can accommodate censored peak-streamflow data (streamflows that are known only to be greater than or less than some value) and interval peak-streamflow data (streamflows that are known only to be greater than some value and less than another value).

Multiple Grubbs-Beck Test for Detecting Potentially Influential Low Floods

The distribution of annual peak streamflows for a streamgage can contain one or more low outliers, which are small observations that deleteriously affect the upper-tail results (decreasing AEP) (Interagency Advisory Committee on Water Data, 1982; Cohn and others, 2013). For example, during drier years, some small annual peak streamflows may not represent floods or whole basin response to precipitation inputs. These small annual peak streamflows, or PILFs, are small observations that could potentially exert a large influence on the fitted flood-frequency curve (Cohn and others, 2013; England and others, 2019). PILFs can result from physical processes different from those associated with large floods and should not affect the part of the flood-frequency curve representing large floods (Cohn and others, 2013). The MGBT used with EMA provides a standard approach for detecting multiple PILFs. The use of the MGBT can improve the fit of the flood-frequency curve for large floods (Cohn and others, 2013; Southard and Veilleux, 2014).

Regional Skew

The skew coefficient is a measure of asymmetry of the distribution of a set of annual peak streamflows about the median. If the mean of a distribution of annual peak streamflows is equal to the median, the distribution has zero skew. One or more extremely high annual peak streamflows in a distribution can result in a positive skew, when the mean of the distribution exceeds the median. One or more extremely low annual peak streamflows in a distribution can result in a negative skew, when the mean of the distribution is less than the median. The skew coefficient estimated from a series of annual peak streamflows at a given streamgage (the station skew) may not provide an accurate estimate of the population skew. England and others (2019) suggested that the station skew be weighted with a regional skew determined by analysis of skew of annual peak-streamflow data from selected long-term streamgages in the study area. For this study, a regional skew was determined for input to the weighted skew computation.

Station skew coefficients and their associated mean square errors for 214 streamgages in the study area with at least 30 years of record were used to compute a weighted mean skew. The inverses of the mean square errors of the

station skews were used as the weights. The weighted mean regional skew for the study area was estimated to be a constant value of 0.10 with a mean square error of 0.132.

Development of Regional Regression Equations

Streamflows corresponding to the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs were related to basin characteristics by using multiple linear regression techniques. Ordinary least-squares (OLS) regression techniques were used to validate previously defined HAs (Randolph and Gamble, 1976; Law and Tasker, 2003) and to determine the most useful significant values for basin characteristics for use in predicting streamflows corresponding to AEPs within each HA. Once the most useful basin characteristics were determined, final regression equations were developed by using GLS regression techniques (Tasker and Stedinger, 1989).

Validation of Hydrologic Areas

Parts of eight physiographic divisions defined by Fenneman and Johnson (1946) and Miller (1974) were combined to create four HAs (HAs 1–4), which had been previously defined by Randolph and Gamble (1976). The boundaries of these HAs were modified slightly for use in the most recent low-flow and flow duration study for Tennessee (Law and others, 2009), and those modifications were adopted for the current peak-streamflow study. Each HA has distinct hydrologic, geologic, and topographic characteristics (Law and Tasker, 2003). HA1 covers most of east Tennessee ([fig. 1](#)), including most of the Cumberland Plateau physiographic section and the entirety of the parts of the Valley and Ridge and Blue Ridge physiographic provinces that are in Tennessee. HA2 includes almost all the Highland Rim and parts of the Cumberland Plateau physiographic sections and the Western Valley physiographic province. HA3 is predominantly in the Central Basin physiographic section. HA4 includes the Coastal Plain physiographic province and the western part of the Western Valley physiographic province (Fenneman and Johnson, 1946; Miller, 1974). Of the 454 streamgages used in this study, HA1 contains 216, HA2 contains 114, HA3 contains 63, and HA4 contains 61 streamgages ([table 3](#)).

To determine the validity of the previously defined HAs for use in this study, a Wilcoxon signed-rank test (Tasker, 1982) was performed on the residuals of a single-variable OLS regression equation developed using all 454 streamgages in the study, with the base-10 logarithm of *DRNAREA* as the explanatory variable and the base-10 logarithm of the streamflow corresponding to the 0.01 AEP as the dependent variable. At a significance level of 0.05 ($p \leq 0.05$), the residuals from HAs 1–3 were determined to be a statistically different population than the residuals from all the streamgages. The residuals from HA4 were not found to be significantly

Table 3. Numbers of streamgages by State and hydrologic area used to estimate the magnitude and frequency of floods at ungaged location on streams in Tennessee through the 2013 water year.

State	Number of streamgages by hydrologic area (fig. 1)				Total streamgages by State
	1	2	3	4	
Alabama	2	15	1	0	18
Georgia	19	0	0	0	19
Kentucky	0	28	0	8	36
Mississippi	0	3	0	11	14
North Carolina	37	0	0	0	37
Tennessee	130	68	62	42	302
Virginia	28	0	0	0	28
Total streamgages by hydrologic area	216	114	63	61	454

different from the residuals of all the streamgages, but the residuals from HA4 were determined to be a statistically different population than the residuals from each of the other regions (HAs 1–3) when tested separately at a significance level of 0.05.

Evaluation of Basin Characteristics

Exploratory regression techniques can be used to iterate through all unique combinations of explanatory variables (basin characteristics) to determine the optimal combination that explains the independent variables (streamflows corresponding to the AEPs). Exploratory OLS regression was used to determine which basin characteristics were statistically significant in explaining streamflows corresponding to the selected AEPs, and therefore would be used in the development of the final GLS regression equations for each HA. For a subset of AEPs, unique combinations of *DRNAREA*, *CSL10_85*, *CLIMFAC2YR*, and *LC11IMP* were evaluated. All basin characteristics and AEPs were logarithmically transformed using base-10 logarithms, and 1 was added to *LC11IMP* prior to the transformation. Within each HA, the combination of explanatory variables with the highest adjusted R-squared value and for which all variables were significant at the 95-percent confidence level ($p \leq 0.05$) was selected from the suite of possible combinations. The selected basin characteristics were then used to develop the final GLS regression equations for this study.

Generalized Least-Squares Regression

GLS regression techniques, which can account for differences in streamflow record length, variability of the streamflow record, and cross correlation of concurrent streamflow at different streamgages, were used to generate the final regression equations and measures of accuracy. Particularly when these issues affect streamflow data used in the analysis, GLS regression techniques produce more

accurate predictions and better estimates of accuracy than OLS techniques (Stedinger and Tasker, 1985). Using GLS regression, streamflows corresponding to selected AEPs were estimated using Bulletin 17C (England and others, 2019) methods. The GLS RREs were determined by using the weighted-multiple-linear regression (WREG) computer program (Eng and others, 2009; U.S. Geological Survey, 2013).

GLS RREs predicting streamflows corresponding to the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs were developed for HAs 1–4 (fig. 1; table 4). Explanatory variables used in the final equations were *DRNAREA* and *CLIMFAC2YR* for HA1; *DRNAREA* and *CSL10_85* for HA2; *DRNAREA* for HA3; and *DRNAREA* and *LC11IMP* for HA4 (table 4). Because *LC11IMP* is expressed as a percentage of basin area and is zero at many locations, 1 was added to the values of *LC11IMP* before the logarithmic transformation.

Other than the explanatory variable *CSL10_85* used in equations predicting streamflows corresponding to the 0.005 and 0.002 (0.5- and 0.2-percent) AEPs for HA2, all basin characteristics used in the final GLS regression equations (table 4) were statistically significant ($p \leq 0.05$). For HA2, *DRNAREA* and *CSL10_85* were statistically significant in predicting streamflows corresponding to the 0.5, 0.2, 0.1, 0.04, 0.02, and 0.01 (50-, 20-, 10-, 4-, 2-, and 1-percent) AEPs. For the 0.005 and 0.002 AEPs, *CSL10_85* was not statistically significant when *DRNAREA* and *CSL10_85* were used as the only explanatory variables. To avoid the potential for predictions of streamflows corresponding to greater AEPs to exceed the predictions for the 0.005 and 0.002 AEPs, *DRNAREA* and *CSL10_85* were used as explanatory variables in all equations for HA2. Average standard errors of prediction for the regression equations ranged from 44.4 to 51.4 percent for HA1, 30.4 to 42.9 percent for HA2, 35.7 to 42.6 percent for HA3, and 32.5 to 47.4 percent for HA4 (table 4). The relation between residuals and predicted streamflow corresponding to the 0.01 (or 1-percent) AEP using the GLS equations is shown in figure 6.

Table 4. Final generalized least-squares regression equations for estimating streamflows corresponding to selected annual exceedance probabilities on rural streams in Tennessee and associated performance metrics.

[AEP, annual exceedance probability; RI, recurrence interval; GLS, generalized least squares; ft³/s, cubic foot per second; Pseudo-R², pseudo coefficient of determination; AVP, average variance of prediction; log₁₀(ft³/s), base-10 logarithm of cubic feet per second; %, percent; Q , annual exceedance probability streamflow; $DRNAREA$, drainage area, in square miles; $CLIMFAC2YR$, 2-year recurrence-interval climate factor; $CSL10_85$, 10 and 85 percent channel slope, in feet per mile; $LCIIMP$, impervious area, in percent]

AEP	RI, in years	GLS equations, in ft ³ /s	Pseudo-R ²	AVP, in squared log ₁₀ (ft ³ /s)	Average standard error of prediction, in percent
Hydrologic area 1 (fig. 2)—216 streamgages					
0.5	2	$Q_{50\%} = 4.86 DRNAREA^{0.735} CLIMFAC2YR^{4.068}$	92.3	0.04	46.7
0.2	5	$Q_{20\%} = 9.55 DRNAREA^{0.726} CLIMFAC2YR^{3.844}$	92.7	0.03	44.4
0.1	10	$Q_{10\%} = 14.1 DRNAREA^{0.721} CLIMFAC2YR^{3.687}$	92.5	0.03	45.0
0.04	25	$Q_{4\%} = 21.8 DRNAREA^{0.716} CLIMFAC2YR^{3.486}$	92.1	0.04	45.7
0.02	50	$Q_{2\%} = 29.0 DRNAREA^{0.712} CLIMFAC2YR^{3.350}$	91.6	0.04	47.3
0.01	100	$Q_{1\%} = 37.8 DRNAREA^{0.708} CLIMFAC2YR^{3.219}$	91.0	0.04	48.9
0.005	200	$Q_{0.5\%} = 48.5 DRNAREA^{0.705} CLIMFAC2YR^{3.090}$	90.7	0.04	49.7
0.002	500	$Q_{0.2\%} = 65.8 DRNAREA^{0.701} CLIMFAC2YR^{2.928}$	90.0	0.04	51.4
Hydrologic area 2 (fig. 3)—114 streamgages					
0.5	2	$Q_{50\%} = 84.9 DRNAREA^{0.796} CSL10_85^{0.196}$	95.4	0.02	33.2
0.2	5	$Q_{20\%} = 155 DRNAREA^{0.776} CSL10_85^{0.182}$	95.9	0.02	30.4
0.1	10	$Q_{10\%} = 214 DRNAREA^{0.766} CSL10_85^{0.172}$	95.6	0.02	31.1
0.04	25	$Q_{4\%} = 306 DRNAREA^{0.753} CSL10_85^{0.158}$	94.4	0.02	35.1
0.02	50	$Q_{2\%} = 388 DRNAREA^{0.745} CSL10_85^{0.148}$	93.9	0.02	36.7
0.01	100	$Q_{1\%} = 483 DRNAREA^{0.736} CSL10_85^{0.139}$	93.0	0.03	39.0
0.005	200	$Q_{0.5\%} = 589 DRNAREA^{0.729} CSL10_85^{0.130}$	92.5	0.03	40.5
0.002	500	$Q_{0.2\%} = 753 DRNAREA^{0.719} CSL10_85^{0.118}$	91.6	0.03	42.9
Hydrologic area 3 (fig. 4)—63 streamgages					
0.5	2	$Q_{50\%} = 348 DRNAREA^{0.659}$	93.7	0.03	37.7
0.2	5	$Q_{20\%} = 540 DRNAREA^{0.651}$	94.2	0.02	35.7
0.1	10	$Q_{10\%} = 676 DRNAREA^{0.648}$	93.9	0.02	36.5
0.04	25	$Q_{4\%} = 853 DRNAREA^{0.645}$	93.6	0.02	37.3
0.02	50	$Q_{2\%} = 989 DRNAREA^{0.643}$	93.1	0.03	39.0
0.01	100	$Q_{1\%} = 1,127 DRNAREA^{0.642}$	92.8	0.03	39.9
0.005	200	$Q_{0.5\%} = 1,268 DRNAREA^{0.641}$	92.5	0.03	40.9
0.002	500	$Q_{0.2\%} = 1,459 DRNAREA^{0.640}$	91.9	0.03	42.6
Hydrologic area 4 (fig. 5)—61 streamgages					
0.5	2	$Q_{50\%} = 348 DRNAREA^{0.527} (LCIIMP+1)^{0.271}$	91.2	0.02	34.2
0.2	5	$Q_{20\%} = 498 DRNAREA^{0.542} (LCIIMP+1)^{0.285}$	92.4	0.02	32.5
0.1	10	$Q_{10\%} = 600 DRNAREA^{0.550} (LCIIMP+1)^{0.290}$	92.1	0.02	33.7
0.04	25	$Q_{4\%} = 724 DRNAREA^{0.560} (LCIIMP+1)^{0.294}$	91.0	0.02	36.8
0.02	50	$Q_{2\%} = 817 DRNAREA^{0.566} (LCIIMP+1)^{0.297}$	89.9	0.03	39.6
0.01	100	$Q_{1\%} = 908 DRNAREA^{0.572} (LCIIMP+1)^{0.299}$	89.1	0.03	41.9
0.005	200	$Q_{0.5\%} = 1,002 DRNAREA^{0.578} (LCIIMP+1)^{0.300}$	88.2	0.03	44.3
0.002	500	$Q_{0.2\%} = 1,127 DRNAREA^{0.584} (LCIIMP+1)^{0.300}$	87.0	0.04	47.4

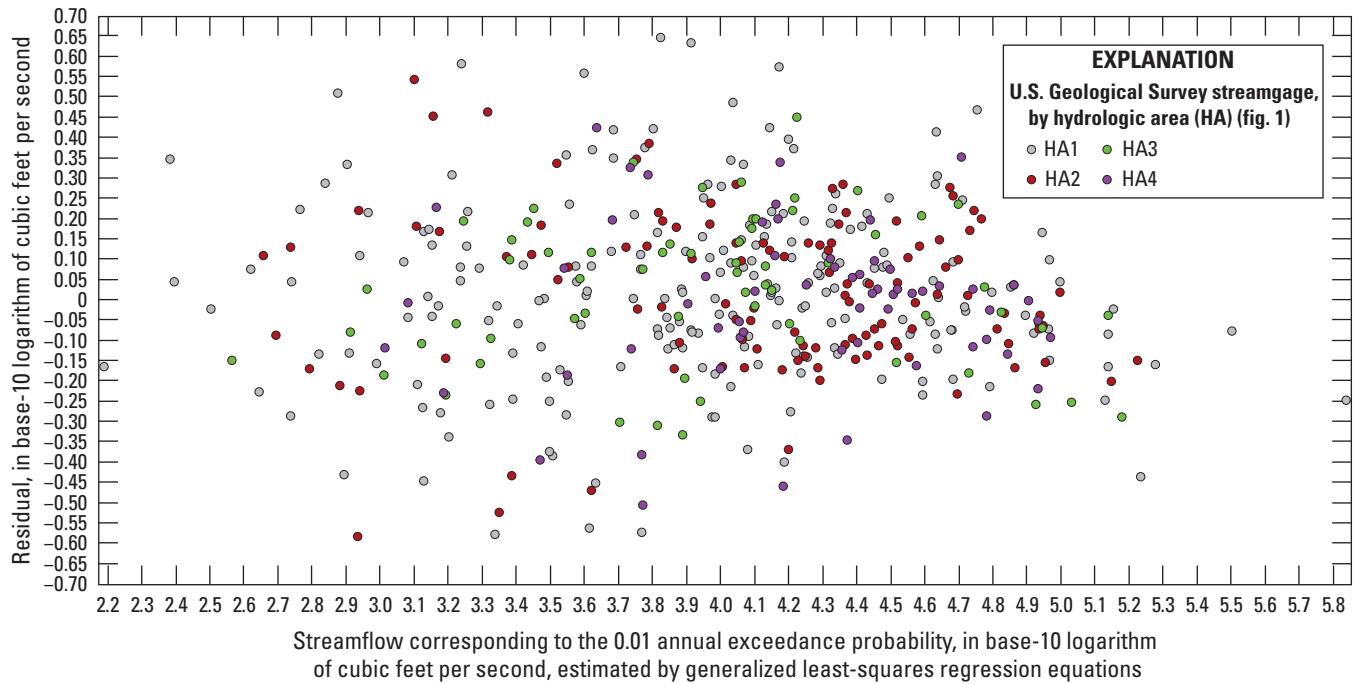


Figure 6. Relation between residuals and predicted streamflows corresponding to the 0.01 annual exceedance probability using the generalized least-squares equations.

Applications of Methods

RREs are statistical models that must be interpreted and applied within the limits of the data used to develop them and with the understanding that the results are best-fit estimates with an associated variance. The RREs are not valid at locations where dams, flood-control structures, channelization, diversion, or backwater have an appreciable effect on annual peak streamflow. Applications of the equations for estimating streamflows corresponding to selected AEPs differ for gaged locations on streams, ungaged locations on gaged streams, and locations on ungaged streams. EMA estimates for gaged locations and GLS estimates for ungaged locations can be used to determine weighted estimates for gaged locations and ungaged locations near streamgages. EMA, GLS, and weighted estimates for streamgages used in the study are available in tables A and B of Heal and others (2025).

Streamgage Locations

Accuracy of at-site estimates of streamflows corresponding to AEPs computed for a streamgage can be increased by weighting the at-site estimates with estimates computed by using the GLS equations. If the at-site and GLS estimates of a given AEP are weighted inversely proportional to their associated variances, the variance of the weighted estimate will be less than the variances of either the at-site or the GLS estimate. The weighted estimate is computed by using the following equation (England and others, 2019):

$$\log_{10} Q_{p(g)w} = \frac{VP_{p(g)r} * \log_{10} Q_{p(g)s} + VP_{p(g)s} * \log_{10} Q_{p(g)r}}{VP_{p(g)r} + VP_{p(g)s}}, \quad (1)$$

where

- $Q_{p(g)w}$ is the weighted estimate of streamflow corresponding to the selected p -percent AEP at streamgage (g), in cubic feet per second;
- $VP_{p(g)r}$ is the variance of prediction of streamflow corresponding to the p -percent AEP at streamgage (g) from the GLS regression model, in log base-10 units;
- $Q_{p(g)s}$ is the estimate of streamflow corresponding to the p -percent AEP at streamgage (g) from the EMA analysis, in cubic feet per second;
- $VP_{p(g)s}$ is the variance of prediction of streamflow corresponding to the p -percent AEP at streamgage (g) from the EMA analysis, in log base-10 units; and
- $Q_{p(g)r}$ is the estimate of streamflow corresponding to the p -percent AEP at streamgage (g) from the GLS regression model, in cubic feet per second.

The variance of prediction of the weighted estimate for streamgage (g) (in log base-10 units) can be computed as:

$$VP_{p(g)w} = \frac{VP_{p(g)s} * VP_{p(g)r}}{VP_{p(g)s} + VP_{p(g)r}}, \quad (2)$$

where

- $VP_{p(g)w}$ is the variance of prediction of the weighted estimate of streamflow corresponding to the p -percent AEP at streamgage (g), in log base-10 units.

A 95-percent confidence interval for the weighted estimate (in cubic feet per second) can be computed as:

$$95\%_{CI\ upper,i} = 10(\log_{10} Q_{p(g)w} + 1.96\sqrt{VP_{p(g)w}}), \quad (3)$$

$$95\%_{CI\ lower,i} = 10(\log_{10} Q_{p(g)w} - 1.96\sqrt{VP_{p(g)w}}), \quad (4)$$

where

- $95\%_{CI\ upper,i}$ is the upper 95-percent confidence interval for the weighted estimate of the streamflow corresponding to the selected AEP at streamgage (g), and
- $95\%_{CI\ lower,i}$ is the lower 95-percent confidence interval for the weighted estimate of the streamflow corresponding to the selected AEP at streamgage (g).

Ungaged Locations on Gaged Streams

For ungaged locations, streamflows corresponding to selected AEPs are estimated by using the appropriate GLS equation (table 4). Streamflows at ungaged locations on gaged streams can be improved by applying a drainage area ratio. The following procedure is recommended if the drainage area at the ungaged location is within 50 percent of the drainage area at the gaged location (drainage area ratio is more than 0.5 or less than 1.5) (Ries and Dillow, 2006):

$$Q_{p(u)} = \left(\frac{DRNAREA_{(u)}}{DRNAREA_{(g)}} \right)^b Q_{p(g)w}, \quad (5)$$

where

$Q_{p(u)}$ is the estimate of streamflow corresponding to the p -percent AEP at the ungaged location after transferring the weighted estimate from the gaged location, u , in cubic feet per second;

$DRNAREA_{(u)}$ is the drainage area at the ungaged location, in square miles;

$DRNAREA_{(g)}$ is the drainage area at the streamgage location, in square miles;

b is the exponent of drainage area from the appropriate GLS equation (table 5); and

$Q_{p(g)w}$ is the weighted estimate of streamflow corresponding to the p -percent AEP at the streamgage location, in cubic feet per second.

The weighted flood estimate at the ungaged location can be computed by using the following equation:

$$Q_{p(u)w} = \left(\frac{2|AA|}{DRNAREA_{(g)}} \right) Q_{p(u)r} + \left(1 - \frac{2|AA|}{DRNAREA_{(g)}} \right) Q_{p(u)}, \quad (6)$$

where

$Q_{p(u)w}$ is the weighted estimate of streamflow at the ungaged location for the p -percent AEP, in cubic feet per second;

$|AA|$ is the absolute difference in drainage areas between the ungaged location ($DRNAREA_{(u)}$) and the streamgage ($DRNAREA_{(g)}$) location, in square miles;

$DRNAREA_{(g)}$ is the drainage area at the streamgage location, in square miles;

$Q_{p(u)r}$ is the GLS estimate of streamflow at the ungaged location corresponding to the p -percent AEP, in cubic feet per second; and

$Q_{p(u)}$ is the estimate of streamflow corresponding to the p -percent AEP at the ungaged location after transferring the weighted estimate from the gaged location, u , in cubic feet per second.

If the drainage area of an ungaged location differs by more than 50 percent from that of the streamgage location, the GLS estimate becomes considerably more uncertain. If an ungaged location is between two streamgages on the same stream, the streamgage with the closest drainage area ratio and longest period of record is suggested for use (Sauer, 1964).

Accuracy and Limitations of GLS Equations

Accuracy and limitations of the GLS equations are affected by several factors. The equations are applicable at locations on streams in Tennessee where annual peak streamflows are not substantially affected by regulation, diversion, channelization, urbanization, or backwater. The equations are most applicable when estimating streamflow for basins having characteristics (explanatory variables) within the ranges of those used to develop the GLS equations (table 6); using explanatory variables outside of these ranges may result in prediction errors greater than expected (table 4).

The GLS equations are intended for use with basin characteristics computed using the methods described in this report. The StreamStats application (USGS, 2019) for Tennessee contains the same GIS layers and measurement methods used to calculate basin characteristics and estimates streamflows corresponding to various AEPs by using the GLS equations developed for this study.

Table 5. Drainage area generalized least-squares regression equations for estimating exponent b for equation 5 (Ries and Dillow, 2006).

[AEP, annual exceedance probability; RI, recurrence interval; GLS, generalized least squares; ft³/s, cubic foot per second; Pseudo-R², pseudo coefficient of determination; AVP, average variance of prediction; log₁₀(ft³/s), base-10 logarithm of cubic feet per second; %, percent; Q , annual exceedance probability streamflow; $DRNAREA$, drainage area, in square miles]

AEP	RI, in years	GLS equations, in ft ³ /s	Exponent b	Pseudo-R ²	AVP, in squared log ₁₀ (ft ³ /s)	Average standard error of prediction, in percent
Hydrologic area 1 (fig. 2)—216 streamgages						
0.5	2	$Q_{50\%} = 127 DRNAREA^{0.732}$	0.732	91.6	0.04	48.9
0.2	5	$Q_{20\%} = 207 DRNAREA^{0.725}$	0.725	92.3	0.04	45.8
0.1	10	$Q_{10\%} = 269 DRNAREA^{0.721}$	0.721	92.0	0.04	46.4
0.04	25	$Q_{4\%} = 355 DRNAREA^{0.716}$	0.716	91.7	0.04	47.0
0.02	50	$Q_{2\%} = 424 DRNAREA^{0.712}$	0.712	91.3	0.04	47.8
0.01	100	$Q_{1\%} = 497 DRNAREA^{0.709}$	0.709	90.8	0.04	49.3
0.005	200	$Q_{0.5\%} = 574 DRNAREA^{0.706}$	0.706	90.4	0.04	50.1
0.002	500	$Q_{0.2\%} = 684 DRNAREA^{0.703}$	0.703	89.8	0.04	51.8
Hydrologic area 2 (fig. 3)—114 streamgages						
0.5	2	$Q_{50\%} = 201 DRNAREA^{0.716}$	0.716	94.7	0.04	35.7
0.2	5	$Q_{20\%} = 344 DRNAREA^{0.702}$	0.702	95.4	0.04	32.1
0.1	10	$Q_{10\%} = 456 DRNAREA^{0.695}$	0.695	94.9	0.04	33.4
0.04	25	$Q_{4\%} = 628 DRNAREA^{0.689}$	0.689	94.1	0.04	35.7
0.02	50	$Q_{2\%} = 748 DRNAREA^{0.684}$	0.684	93.4	0.04	37.9
0.01	100	$Q_{1\%} = 889 DRNAREA^{0.680}$	0.680	92.8	0.04	39.4
0.005	200	$Q_{0.5\%} = 1,045 DRNAREA^{0.676}$	0.676	92.3	0.04	40.9
0.002	500	$Q_{0.2\%} = 1,271 DRNAREA^{0.671}$	0.671	91.4	0.04	43.2
Hydrologic area 3 (fig. 4)—63 streamgages						
0.5	2	$Q_{50\%} = 348 DRNAREA^{0.659}$	0.659	93.7	0.03	37.7
0.2	5	$Q_{20\%} = 528 DRNAREA^{0.651}$	0.651	94.2	0.02	35.7
0.1	10	$Q_{10\%} = 676 DRNAREA^{0.648}$	0.648	93.9	0.02	36.5
0.04	25	$Q_{4\%} = 853 DRNAREA^{0.645}$	0.645	93.6	0.02	37.3
0.02	50	$Q_{2\%} = 989 DRNAREA^{0.64}$	0.643	93.1	0.03	39.0
0.01	100	$Q_{1\%} = 1,127 DRNAREA^{0.642}$	0.642	92.8	0.03	39.9
0.005	200	$Q_{0.5\%} = 1,268 DRNAREA^{0.641}$	0.641	92.5	0.03	40.9
0.002	500	$Q_{0.2\%} = 1,459 DRNAREA^{0.640}$	0.640	91.9	0.03	42.6
Hydrologic area 4 (fig. 5)—61 streamgages						
0.5	2	$Q_{50\%} = 439 DRNAREA^{0.525}$	0.525	90.0	0.02	36.3
0.2	5	$Q_{20\%} = 640 DRNAREA^{0.539}$	0.539	91.2	0.02	34.8
0.1	10	$Q_{10\%} = 775 DRNAREA^{0.547}$	0.547	90.6	0.02	36.5
0.04	25	$Q_{4\%} = 944 DRNAREA^{0.556}$	0.556	89.8	0.03	39.0
0.02	50	$Q_{2\%} = 1,072 DRNAREA^{0.562}$	0.562	88.9	0.03	41.2
0.01	100	$Q_{1\%} = 1,194 DRNAREA^{0.568}$	0.568	87.8	0.03	44.0
0.005	200	$Q_{0.5\%} = 1,321 DRNAREA^{0.573}$	0.573	86.9	0.04	46.3
0.002	500	$Q_{0.2\%} = 1,489 DRNAREA^{0.579}$	0.579	85.9	0.04	48.9

Table 6. Ranges of physical and climatic basin characteristics for use in generalized least-squares regression equations, by hydrologic area.

[*DRNAREA*, drainage area; mi², square miles; *CSL10_85*, 10 and 85 percent channel slope; ft/mi, feet per mile; *LC11IMP*, imperviousness; *CLIMFAC2YR*, 2-year recurrence-interval climate factor; N/A, not applicable]

Hydrologic area (fig. 1)	Number of streamgages used	Range of basin characteristic			
		<i>DRNAREA</i> , in mi ²	<i>CSL10_85</i> , in ft/mi	<i>LC11IMP</i> , in percent	<i>CLIMFAC2YR</i> , dimensionless
1	216	0.20–21,400	N/A	N/A	2.05–2.42
2	114	0.42–2,560	1.74–356	N/A	N/A
3	63	0.17–2,050	N/A	N/A	N/A
4	61	0.95–2,310	N/A	0.26–13.7	N/A

Summary

Methods for estimating the magnitude and frequency of flooding at ungaged locations on rural streams in Tennessee were last updated in 2003. Since then, many years of additional annual peak-streamflow data have been collected, more geospatial data for calculation of explanatory variables have become available, and improved statistical methods have been developed for flood-frequency analysis. Thus, the U.S. Geological Survey (USGS), in cooperation with the Tennessee Department of Transportation, developed multiple linear regression equations to estimate streamflows corresponding to selected annual exceedance probabilities (AEPs) at ungaged locations on streams in Tennessee. Version 7.0.29368 of USGS PeakFQ software was used to conduct frequency analyses of annual peak streamflows for 454 streamgages operated by the USGS in Tennessee and surrounding States. Streamflows corresponding to the 50-, 20-, 10-, 4-, 2-, 1-, 0.5-, and 0.2-percent AEPs (the 2-, 5-, 10-, 25-, 50-, 100-, 200-, and 500-year floods, respectively) were estimated by using the expected moments algorithm in PeakFQ.

Four hydrologic areas used in previous flood-frequency studies in Tennessee were validated for statistical independence. For each hydrologic area, generalized least squares (GLS) regression equations were developed, incorporating combinations of drainage area (*DRNAREA*), 10–85 channel slope (*CSL10_85*), 2-year recurrence-interval climate factor (*CLIMFAC2YR*), and percent imperviousness (*LC11IMP*) as explanatory variables. Statistically significant ($p \leq 0.05$) explanatory variables used in the equations were *DRNAREA* and *CLIMFAC2YR* for HA1; *DRNAREA* and *CSL10_85* for HA2; *DRNAREA* for HA3; and *DRNAREA* and *LC11IMP* for HA4.

The final GLS regression models were generated using the USGS weighted-multiple-linear regression (WREG) program, resulting in standard errors of prediction ranging from 30.4 to 51.4 percent. The GLS regression equations are applicable at locations on streams in Tennessee where annual peak streamflows are not substantially affected by regulation, diversion, channelization, backwater, or urbanization. The

applicability and accuracy of the GLS regression models depend on the basin characteristics measured for an ungaged location on a stream being within range of those used to develop the equations. Methods are presented for using the GLS regression equations to estimate streamflows corresponding to selected AEPs at ungaged locations on both gaged and ungaged streams and to calculate weighted at-site estimates of streamflows corresponding to AEPs at streamgage locations. The final GLS regression equations and methods for estimating streamflows corresponding to selected AEPs have been incorporated in the USGS StreamStats application for Tennessee.

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