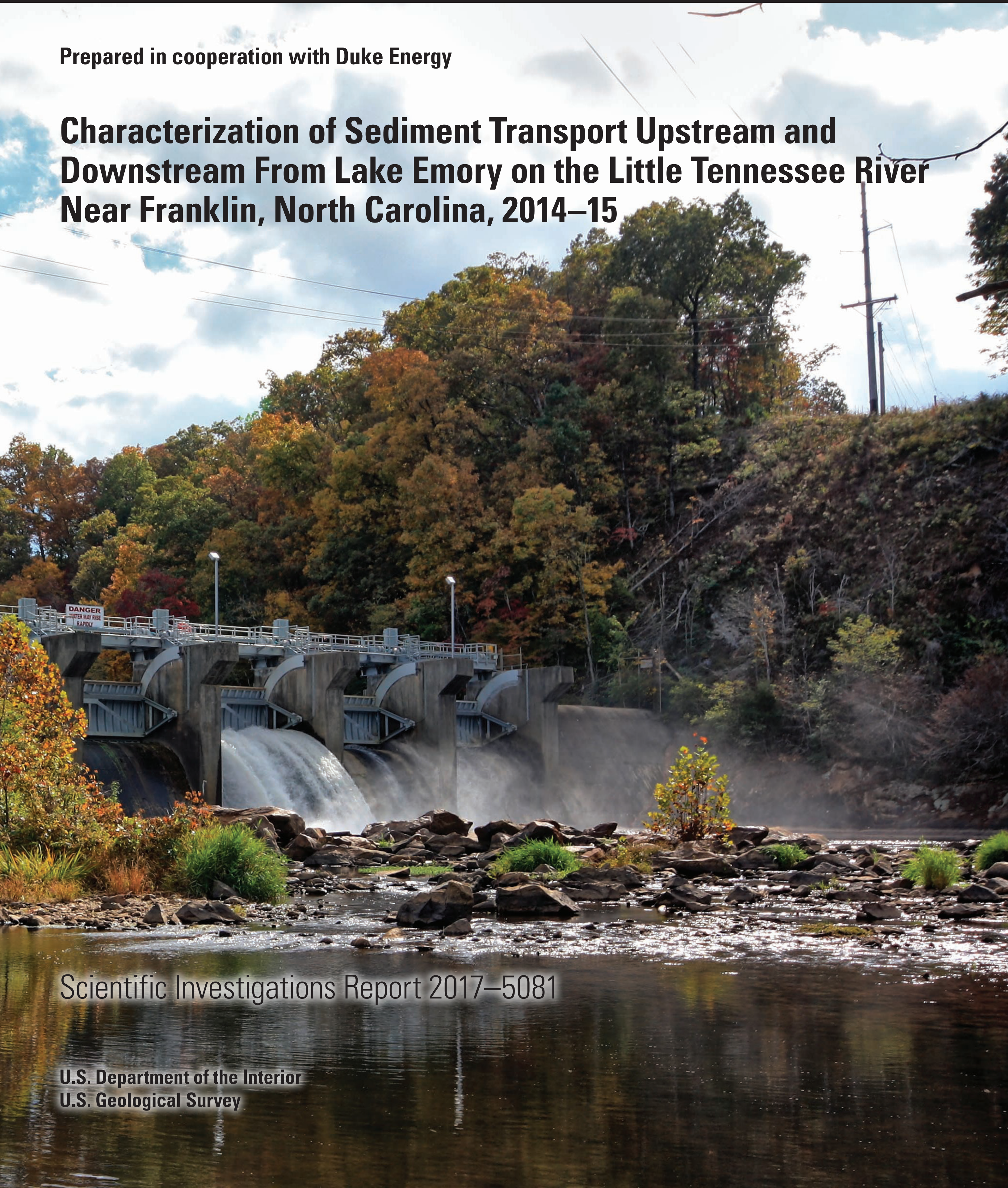
Prepared in cooperation with Duke Energy

Characterization of Sediment Transport Upstream and Downstream From Lake Emory on the Little Tennessee River Near Franklin, North Carolina, 2014–15



Scientific Investigations Report 2017–5081

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

Cover. Porter Bend Dam at Lake Emory, Macon County, North Carolina, October 18, 2016. Photograph by Brad A. Huffman, U.S. Geological Survey.

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RYAN K. ZINKE, Secretary

U.S. Geological Survey
William H. Werkheiser, Acting Director

U.S. Geological Survey, Reston, Virginia: 2017

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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)
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	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile ($[ft^3/s]/mi^2$)	0.01093	cubic meter per second per square kilometer ($[m^3/s]/km^2$)
	Mass	
ton, short (2,000 lb)	0.9072	metric ton (t)
ton, long (2,240 lb)	1.016	metric ton (t)

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.

Datum

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).

Abbreviations

ADVM	acoustic Doppler velocity meter
EDI	equal discharge increment
FISP	Federal Interagency Sedimentation Project
FNU	formazin nephelometric unit
GCLAS	Graphical Constituent Loading Analysis System
IQR	interquartile range
MLR	multiple linear regression
NOAA	National Oceanic and Atmospheric Administration
NWIS	National Water Information System
PPCC	probability-plot correlation coefficient
R^2	coefficient of determination
RMSE	root mean square error
SAID	Surrogate Analysis and Index Developer
SEWI	single equal width increment
SLR	single linear regression
SSC	suspended-sediment concentration
SSL	suspended-sediment load
TVA	Tennessee Valley Authority
USGS	U.S. Geological Survey
VIF	variance inflation factor

Characterization of Sediment Transport Upstream and Downstream From Lake Emory on the Little Tennessee River Near Franklin, North Carolina, 2014–15

By Brad A. Huffman, William F. Hazell, and Carolyn J. Oblinger

Abstract

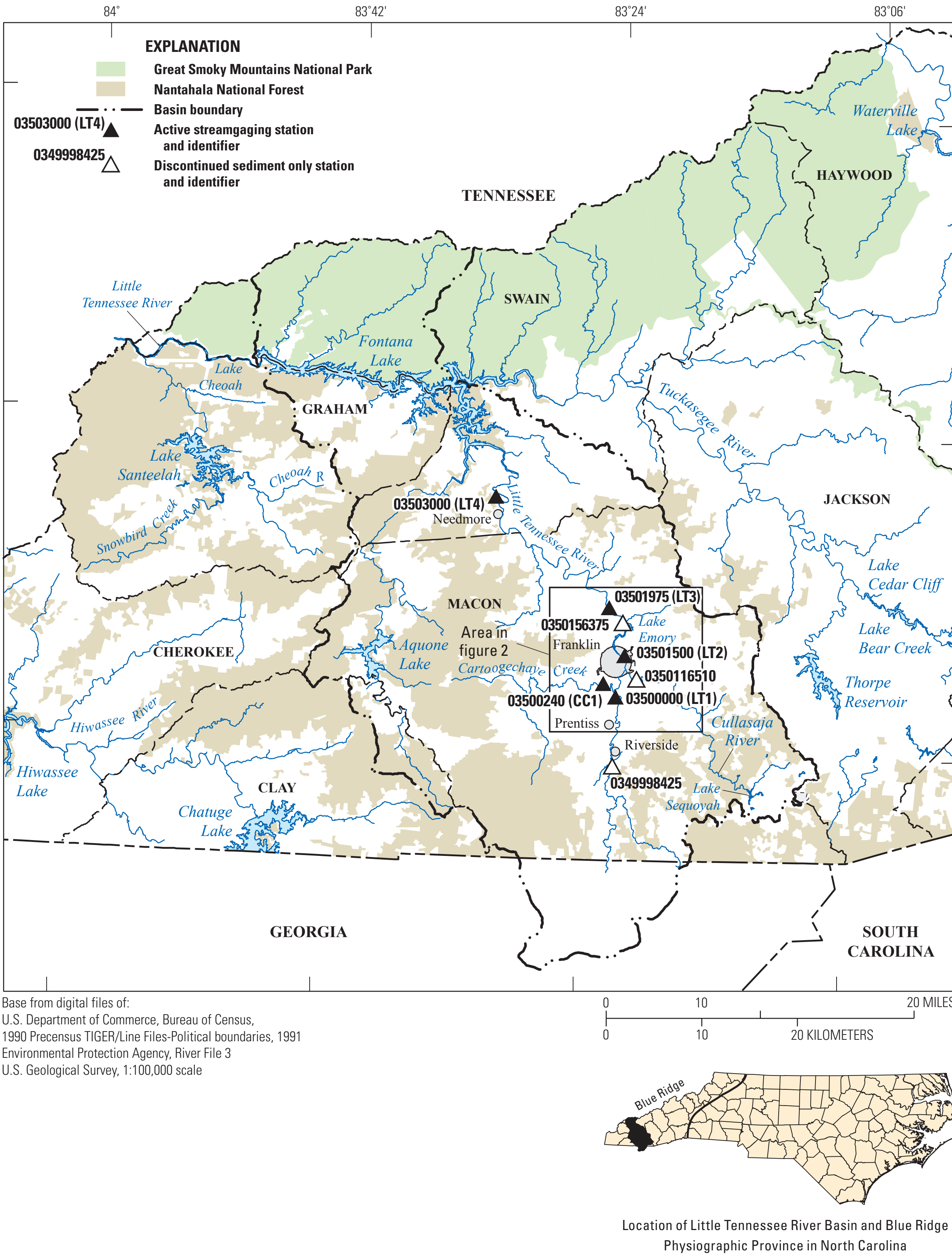
Federal, State, and local agencies and organizations have expressed concerns regarding the detrimental effects of excessive sediment transport on aquatic resources and endangered species populations in the upper Little Tennessee River and some of its tributaries. In addition, the storage volume of Lake Emory, which is necessary for flood control and power generation, has been depleted by sediment deposition. To help address these concerns, a 2-year study was conducted in the upper Little Tennessee River Basin to characterize the ambient suspended-sediment concentrations and suspended-sediment loads upstream and downstream from Lake Emory in Franklin, North Carolina. The study was conducted by the U.S. Geological Survey in cooperation with Duke Energy. Suspended-sediment samples were collected periodically, and time series of stage and turbidity data were measured from December 2013 to January 2016 upstream and downstream from Lake Emory. The stage data were used to compute time-series streamflow. Suspended-sediment samples, along with time-series streamflow and turbidity data, were used to develop regression models that were used to estimate time-series suspended-sediment concentrations for the 2014 and 2015 calendar years. These concentrations, along with streamflow data, were used to compute suspended-sediment loads. Selected suspended-sediment samples were collected for analysis of particle-size distribution, with emphasis on high-flow events. Bed-load samples were also collected upstream from Lake Emory.

The estimated annual suspended-sediment loads (yields) for the upstream site for the 2014 and 2015 calendar years were 27,000 short tons (92 short tons per square mile) and 63,300 short tons (215 short tons per square mile), respectively. The annual suspended-sediment loads (yields) for the downstream site for 2014 and 2015 were 24,200 short tons (75 short tons per square mile) and 94,300 short tons (292 short tons per square mile), respectively. Overall, the suspended-sediment load at the downstream site was about 28,300 short tons greater than the upstream site over the study period.

As expected, high-flow events (the top 5 percent of daily mean flows) accounted for the majority of the sediment load; 80 percent at the upstream site and 90 percent at the downstream site. A similar relation between turbidity (the top 5 percent of daily mean turbidity) and high loads was also noted. In general, when instantaneous streamflows at the upstream site exceeded 5,000 cubic feet per second, increased daily loads were computed at the downstream site. During low to moderate flows, estimated suspended-sediment loads were lower at the downstream site when compared to the upstream site, which suggests that sediment deposition may be occurring in the intervening reach during those conditions. During the high-flow events, the estimated suspended-sediment loads were higher at the downstream site; however, it is impossible to say with certainty whether the increase in loading was due to scouring of lake sediment, contributions from the additional source area, model error, or a combination of one or more of these factors. The computed loads for a one-week period (December 24–31, 2015), during which the two largest high-flow events of the study period occurred, were approximately 52 percent of the 2015 annual sediment load (36 percent of 2-year load) at the upstream site and approximately 72 percent of the 2015 annual sediment load (57 percent of 2-year load) at the downstream site. Six bedload samples were collected during three events; two high-flow events and one base-flow event. The contribution of bedload to the total sediment load was determined to be insignificant for sampled flows. In general, streamflows for long-term streamgages in the study area were below normal for the majority of the study period; however, flows during the last 3 months of the study period were above normal, including the extreme events during the last week of the study period.

Introduction

The upper Little Tennessee River Basin in western North Carolina is part of the Little Tennessee River Basin upstream from Fontana Lake (fig. 1). The upper Tennessee River Basin is mountainous and rural—89 percent of the



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1991
Environmental Protection Agency, River File 3
U.S. Geological Survey, 1:100,000 scale

Figure 1. Location of the upper Little Tennessee River Basin in North Carolina.

basin is forested and less than 5 percent of the land is classified as urban. Parts of the basin lie within the Great Smoky Mountains National Park and Nantahala National Forest. Because the Little Tennessee River is a mountain river, its tributaries typically have relatively steep gradients with pool and riffle habitats capable of supporting trout populations (North Carolina Division of Water Quality, 2000). The Little Tennessee River also supports a large variety of other aquatic species, including three rare species on the Federal endangered species list—the Appalachian elktoe mussel (*Alasmidonta raveneliana*), the little-wing pearly mussel (*Pegias fabula*), and the spotfin chub (*Cyprinella monacha*; North Carolina Wildlife Resources Commission, 2017).

Sedimentation is both a historic and recent major water-quality issue in the rural setting of the Little Tennessee River Basin (North Carolina Division of Water Quality, 2002). Sedimentation is the primary factor affecting ecological communities in the basin (Harding and others, 1998), resulting in aquatic-habitat degradation and loss of instream microhabitats. The sources of sediment contributing to the sedimentation problem are attributed primarily to land-clearing activities, rural roads, loss of riparian vegetation to agriculture and silviculture, and urban runoff (North Carolina Department of Environment, Health, and Natural Resources, 1992, p. 141). In addition, landscape features, such as high stream-channel gradients, are important factors influencing sedimentation rates (Scott and others, 2002). Harding and others (1998) reported that the conditions of current aquatic communities are related more to past land use than to current land use.

Historically, poor erosion controls have affected the upper Little Tennessee River, resulting in heavy sedimentation in Lake Emory (fig. 1; North Carolina Department of Environment, Health, and Natural Resources, 1992, p. 155). Riparian agricultural practices, such as stock watering and growing specialty vegetable crops, and, more recently, increasing urbanization in the upper part of the watershed in the towns of Highlands and Franklin may have increased the river's suspended-sediment load (SSL) and bedload (Oblinger, 2003). By trapping sediments, Lake Emory has contributed to the protection of the federally listed species of freshwater mussels previously mentioned (North Carolina Wildlife Resources Commission, 2017).

Federal, State, and local agencies and organizations are working to restore degraded aquatic resources in the upper Little Tennessee River and some of its tributaries, as well as to protect threatened and endangered species populations and restore wetlands. Key to developing restoration strategies is an understanding of the amount of sediment that is transported in the upper Little Tennessee River, the sediment sources and particle-size characteristics, and the amount of sediment that is transported past Porter Bend Dam at Lake Emory (fig. 2). In addition, the storage volume of Lake Emory, which is necessary for flood control and power generation, has been depleted by sediment deposition. Duke Energy and resource managers have considered conducting dredging operations in Lake Emory to replenish the storage volume; however there are concerns regarding potential downstream water-quality impacts and the cost benefits of dredging, which are related to the current sediment loading rates and how long it will take for the lake to fill back in.

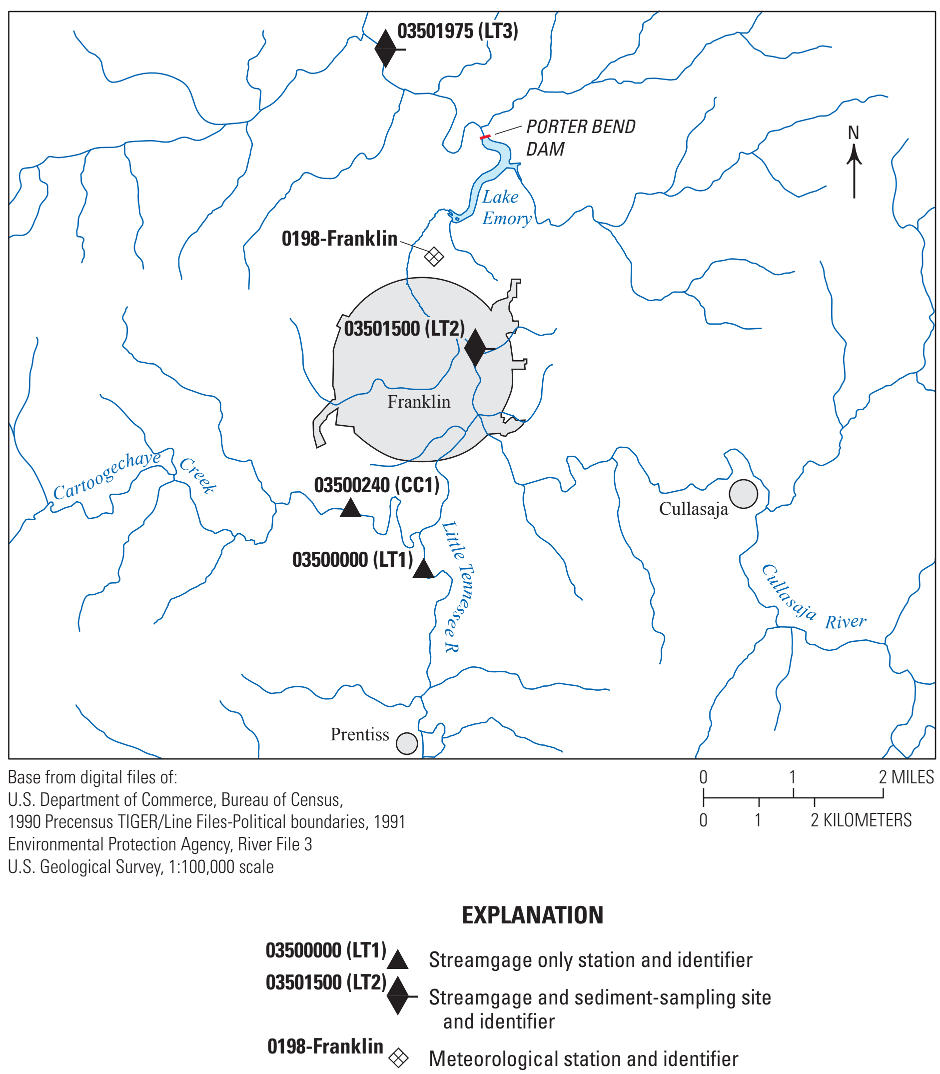


Figure 2. Location of streamgages and sediment-sampling sites in the upper Little Tennessee River Basin, North Carolina.

To help address these concerns, a 2-year study was conducted in the upper Little Tennessee River Basin to characterize the ambient suspended-sediment concentrations (SSCs) and SSLs upstream and downstream from Lake Emory. The study was conducted by the U.S. Geological Survey in cooperation with Duke Energy.

Purpose and Scope

This report describes the results of a study conducted to estimate SSLs and yields for the period January 2014 to December 2015 in the Little Tennessee River upstream and downstream from Lake Emory, a manmade lake located in Macon County in the far western corner of North Carolina. Continuous streamflow, continuous water-quality, and periodic suspended-sediment data were collected at study sites LT2 and LT3 from December 2013 to January 2016 (continuous streamflow at site LT3 is ongoing). Bedload transport and suspended-sediment and bedload-sediment particle sizes were measured for a small number of samples to help characterize the sediments in transport and the potential contribution of bedload to the total load entering Lake Emory.

Study Area

The Little Tennessee River Basin is in the Blue Ridge Physiographic Province. The river rises in Georgia near the North Carolina border and flows north through North Carolina into Tennessee (fig. 1) where it joins the Tennessee River. The upper Little Tennessee River Basin is the area of the Little Tennessee River Basin that is upstream from Fontana Lake and encompasses 839 square miles (mi^2). The study area is in the vicinity of Franklin, N.C., in Macon County, and includes the portions of the upper Tennessee River Basin both upstream and downstream from Porter Bend Dam at Lake Emory (fig. 2). The study area is drained by the Little Tennessee River, the Cullasaja River, and Cartoogechaye Creek. The Cullasaja River and Cartoogechaye Creek join the Little Tennessee River near Franklin, N.C. (fig. 2). Data were collected from two sites as part of the study, U.S. Geological Survey (USGS) streamgaging station 03501500 Little Tennessee River at Franklin, NC (site LT2) and 03501975 Little Tennessee River above NC Highway 28 at Iotla, NC (site LT3). Site LT2 was located near the upstream end of Lake Emory (approximately 0.75 river mile downstream from the confluence with the Cullasaja River), and site LT3 was located downstream from Lake Emory (approximately 2.5 river miles below Porter Bend Dam). The drainage areas of these sites are 295 mi^2 and 323 mi^2, respectively. It is worth noting that study site LT3 encompasses 28 mi^2 of drainage area (approximately 9 percent more) more than site LT2, 14 mi^2 of which are below the Lake Emory dam. The land use in the study area is 79 percent forested and 10 percent developed. The remainder of the study area consists of agriculture and rural uses (U.S. Geological Survey, 2016a). The average annual precipitation of the study area is estimated to be about 54 inches (Arguez and others, 2010) and is fairly evenly distributed throughout the year.

Lake Emory is a 188-acre reservoir built in the 1920s as a source of hydropower. Nantahala Power and Light Company, now Duke Energy, has owned and operated the lake since 1933. On the basis of lake samples collected in July 1988, the lake has been described as eutrophic and shallow and having a short retention time (North Carolina Department of Environment, Health, and Natural Resources, 1992).

Analysis of Observed and Historical Data

In addition to data collected for this study, historical streamflow and suspended-sediment data from long-term stations 03500000 Little Tennessee River near Prentiss, NC (site LT1), 03503000 Little Tennessee River at Needmore, NC (site LT4), and 03500240 Cartoogechaye Creek near Franklin, NC (site CC1) and precipitation data from a nearby meteorological site were compiled. These data are discussed in the following sections of this report.

Precipitation and Streamflow

The Tennessee Valley Authority (TVA) maintains a meteorological data station (0198-Franklin,) about 1 mile northwest of study site LT2 (fig. 2). On the basis of the National Oceanic and Atmospheric Administration (NOAA) U.S. Daily Climate Normals (1981 to 2010; 30-year average), the average annual precipitation for Franklin, N.C., is 54.15 inches (Arguez and others, 2010; fig. 3). Two distinct periods of precipitation totals are evident during the study period; the first 21 months exhibited lower than normal precipitation totals, and the last 3 months exhibited well above normal precipitation totals (fig. 4). Although the total precipitation for the first 21 months of the study period was below normal, it was preceded by well above average precipitation totals in 2013 (fig. 3). This antecedent condition resulted in near normal streamflows at the beginning of the study period. On the basis of the Palmer Modified Drought Index (National Oceanic and Atmospheric Administration, 2016), conditions were, for the most part, normal throughout the study period, with moist to very moist conditions at the beginning and end of the study. Only one month, August 2015, indicated moderate drought conditions.

To put the observed streamflow during the study period into historical perspective, the annual mean streamflows at long-term sites LT1, CC1, and LT4 were evaluated. In general, the observed streamflows during the 2-year study represented below normal conditions during the first 21 months and above normal conditions during the last 3 months. The mean annual streamflows during the study period (2014–15) at these long-term sites were approximately 89 percent of the long-term mean annual streamflow (table 1; fig. 5). The mean annual

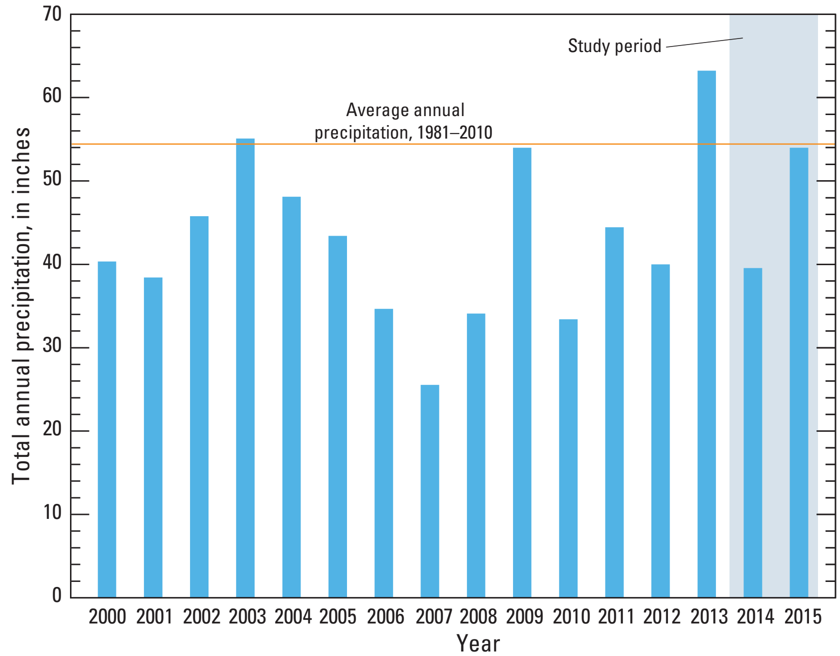


Figure 3. Annual precipitation at nearby Tennessee Valley Authority meteorological data station (0198-Franklin), 2000–15.

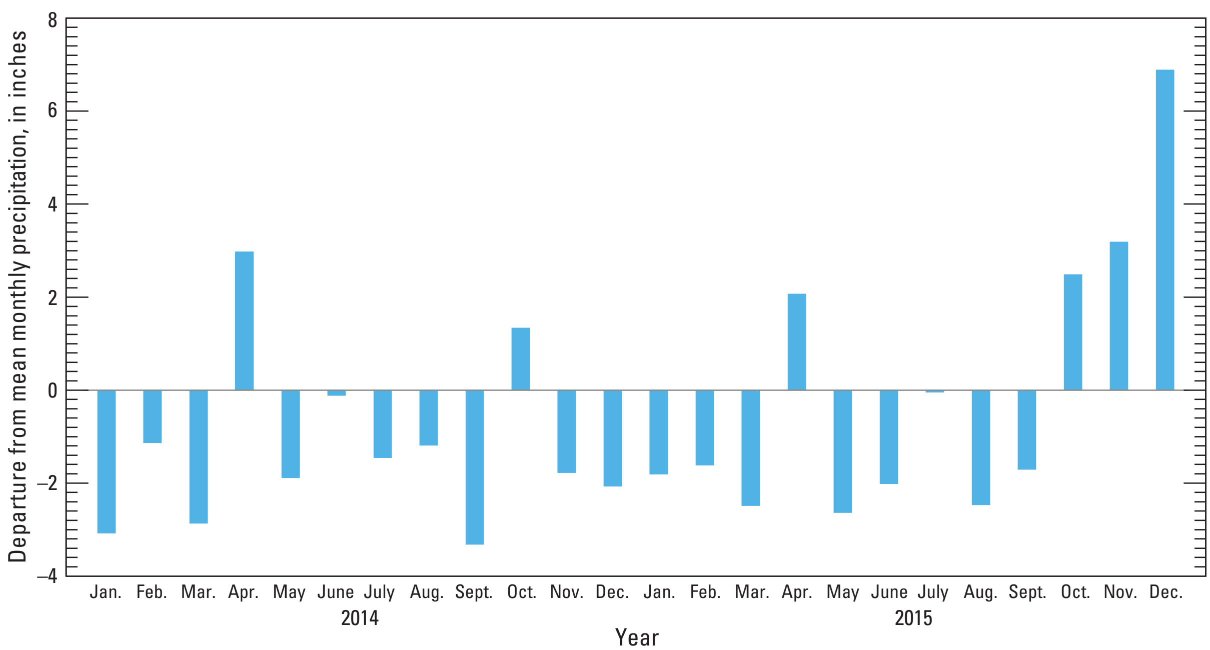


Figure 4. Departure from mean monthly precipitation at Tennessee Valley Authority meteorological data station (0198-Franklin) for the study period, 2014–15.

Table 1. Study period comparisons for selected U.S. Geological Survey streamgaging stations in the upper Little Tennessee River Basin, North Carolina.

[USGS, U.S. Geological Survey; mi², square mile; ft³/s, cubic foot per second; t, short ton; t/mi², short ton per square mile; SS, suspended sediment; —, no data]

Site identifier[a]	USGS station number[b]	Station name	Drainage area, in mi²	Period of record	Period of record annual mean streamflow (through Dec. 2015), in ft³/s	1970s study			2000–2001 study			2014–15 study		
						Mean annual streamflow, in ft³/s	Annual SS load, in t	Annual SS yield, in t/mi²	Mean annual streamflow, in ft³/s	Annual SS load, in t	Annual SS yield, in t/mi²	Mean annual streamflow, in ft³/s (percentage of long-term mean)	Mean annual SS load, in t	Mean annual SS yield, in t/mi²
—	0349998425	Little Tennessee River at Riverside	120	—	—	—	—	—	162[c]	6,300	53	—	—	—
LT1	03500000	Little Tennessee River near Prentiss	140	1945–present	379	454	—	—	192	—	—	336 (89)	—	—
CC1	03500240	Cartoogechaye Creek near Franklin	57.1	1961–present	139	155	11,000	190	74	1,100	19	126 (91)	—	—
—	0350116510	Cullasaja River near Franklin	91.1	—	—	—	—	—	120[c]	1,300	14	—	—	—
LT2	03501500	Little Tennessee River at Franklin	295	Apr. 1909–Mar. 1910, Apr. 1921–Sept. 1925, Dec. 2013–Jan. 2016	775	—	—	—	—	—	—	681	45,150	153
—	0350156375	Lake Emory at Dam near Franklin	310	—	—	—	—	—	388[c]	4,400	14	—	—	—
LT3	03501975	Little Tennessee River above NC Highway 28 at Iotla	323	Mar. 2012–present	859	—	—	—	—	—	—	733	59,268	183
LT4	03503000	Little Tennessee River at Needmore	436	1945–present	1,030	1,190	110,000	250	542	—	—	904 (88)	—	—

[a]Site identifier was assigned for study purpose.

[b]Station number is assigned by the U.S. Geological Survey on the basis of geographic location. The downstream order number system is used for surface-water sites.

[c]Estimated.

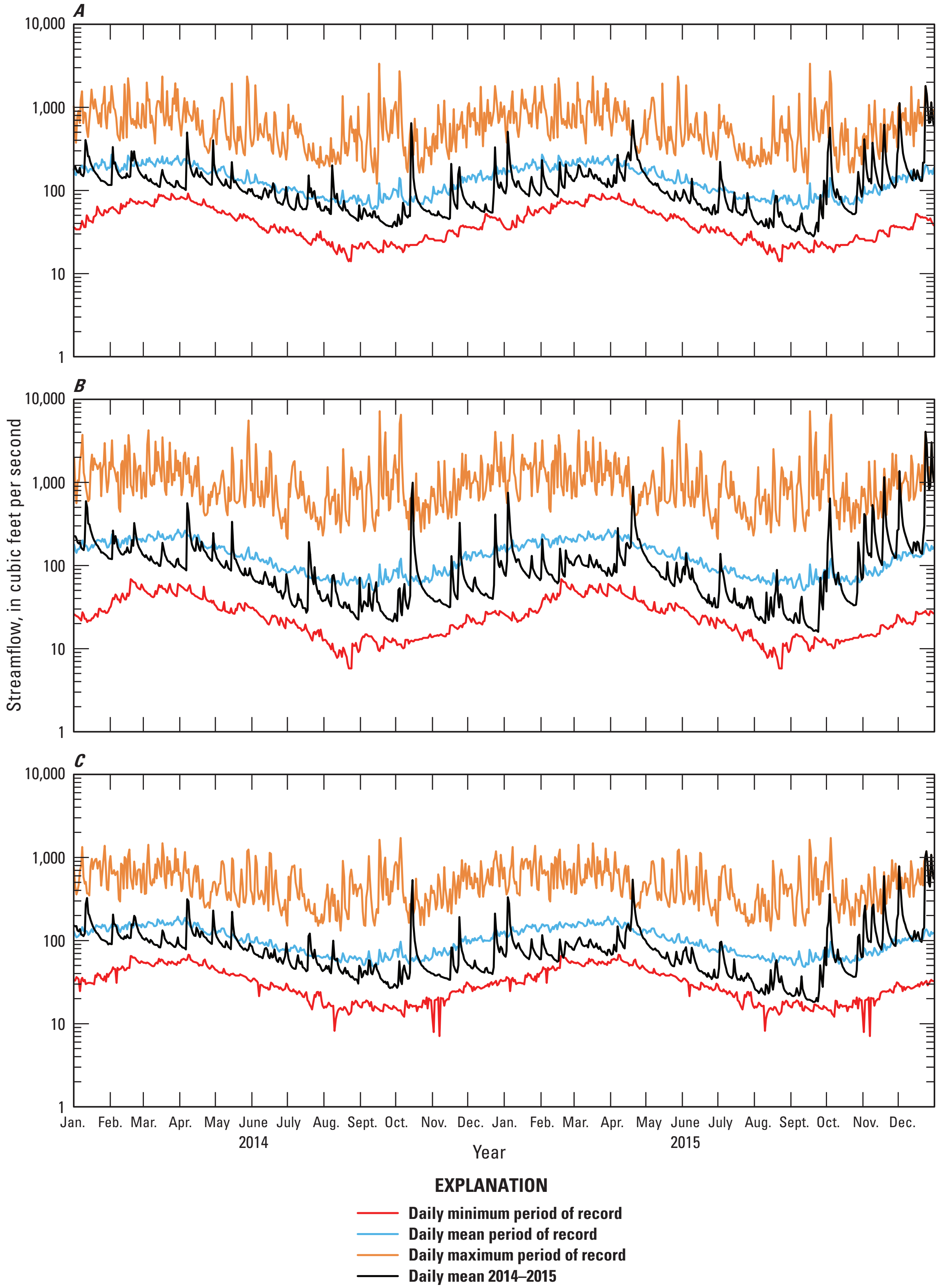


Figure 5. Daily mean streamflow for January 2014–December 2015 and long-term daily streamflow statistics at *A*, Cartoogechaye Creek near Franklin, North Carolina (CC1), *B*, Little Tennessee River near Prentiss (LT1), and *C*, Little Tennessee River at Needmore (LT4). Site locations are in figure 1.

streamflows during the study period were approximately 1.7 times greater than streamflow during the 2000–2001 sediment study. As discussed previously, the 2-year study period can be divided into two distinct periods of precipitation totals. This resulted in average streamflows of approximately 74 percent of the long-term average during the first 21 months of the study period and approximately 197 percent of the long-term average during the final 3 months of the study period. It is worth noting that the peak streamflows associated with extreme events during the last week of the study period were the sixth and seventh highest computed streamflows (since 1945) at sites LT1 and LT4, respectively.

Historical Sediment Comparisons

A comprehensive study was conducted in the 1970s to document suspended-sediment characteristics in streams across North Carolina (Simmons, 1993). As a result of that study, historical suspended-sediment data are available for Cartoogechaye Creek near Franklin (station 03500240; CC1) and Little Tennessee River at Needmore (station 03503000; LT4; table 1). Average annual suspended-sediment loads from the 1970s study were calculated to be 11,000 short tons (t) for Cartoogechaye Creek near Franklin and 110,000 t for Little Tennessee River at Needmore. Average annual suspended-sediment yields at these sites were 190 and 250 short tons per square mile (t/mi^2), respectively.

More recently, a study was conducted between November 2000 and November 2001 to characterize sediment transport into Lake Emory from the main stem of the Little Tennessee River and two major tributaries—Cartoogechaye Creek and the Cullasaja River (Oblinger, 2003). Average annual suspended-sediment loads from this study were calculated to be 6,300 t for Little Tennessee River at Riverside, 1,100 t for Cartoogechaye Creek near Franklin, 1,300 t for Cullasaja River near Franklin, and 4,400 t for Lake Emory at the dam near Franklin (table 1). Average annual suspended-sediment yields at these sites were 53 t/mi^2, 19 t/mi^2, 14 t/mi^2 and 14 t/mi^2, respectively. It should be noted that the study conducted in 2000–2001 occurred during a period of moderate to severe drought (National Oceanic and Atmospheric Administration, 2016). By comparison, during the 1970s study the average yield at site CC1 and site LT4 was 190 t/mi^2 and 250 t/mi^2, respectively (Simmons, 1993).

For these previous studies, traditional USGS methods were used to compute SSL, using SSC and streamflow time series, along with graphical computational techniques and sediment transport curves as described in Porterfield (1972) and Glysson (1987). These methods involve the interpolation of SSCs and streamflows between measured values, using hydrologic judgment, and is, therefore, subjective and not easily reproducible. Although this is a valid approach, it is widely known that suspended-sediment transport can be extremely variable during storm events, making it difficult to correlate a SSC to a given streamflow. In recent years, improvements in turbidimeters have made it possible to use continuous turbidity measurements as a surrogate for SSC under a wide range of conditions. Turbidity values typically are well correlated with SSC because they represent a measure of water clarity that is directly influenced by suspended sediment; therefore, turbidity generally is a better predictor of SSC than streamflow (Jastram and others, 2009). Continuously measured turbidity allows for the computation of estimated SSC time series, which in turn can be used to estimate SSL when paired with streamflow time series. Therefore, in many cases, a turbidity-SSC model can provide an accurate and reproducible SSC and SSL time series. For this study, the addition of streamflow as a second explanatory variable (along with turbidity) was determined to result in a more accurate time series of SSC and, therefore, SSL. It is difficult to compare the results from this study to the previous studies because of the differences in methods used to compute sediment loads (that is, sediment-transport curves versus surrogate models) as well as hydrologic factors such as streamflow conditions and land use.

Data-Collection Methods

Continuous streamflow, continuous water-quality, and periodic suspended-sediment data were collected at study sites LT2 and LT3 from December 2013 to January 2016 (continuous streamflow at site LT3 is ongoing). Continuous streamflow and turbidity data were collected at 15-minute intervals. Discrete fixed-point and depth-integrated cross-sectional suspended-sediment samples were collected throughout the study period. At both study sites, the depth-integrated cross-sectional suspended-sediment samples were collected at a bridge downstream from the streamgages. To evaluate the bedload contribution to the sediment load going into Lake Emory, periodic bedload-sediment samples were collected at site LT2.

Streamflow, continuous water-quality, suspended-sediment, and bedload measurements were made and quality-assurance procedures were followed in accordance with established USGS protocols (Rantz and others, 1982; Edwards and Glysson, 1999; Simpson, 2001; Mueller and Wagner, 2009; Turnipseed and Sauer, 2010; Levesque and Oberg, 2012). In addition, long-term streamflow stations, LT1 (1944–present), CC1 (1961–present), and LT4 (1944–present) were in operation during the study period and were used as comparison stations for streamflow and sediment loads (where available from previous studies). All results are stored in the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2016b).

Streamflow Data

Two USGS streamgaging stations were used to obtain continuous streamflow data for the study period. Site LT2, which was reestablished for the study, was located approximately 300 feet (ft) upstream from the previous streamgage location. Historical daily mean streamflow data for site LT2 are available in NWIS for periods April 1909 to March 1910, and April 1921 to September 1925. Study site LT2 is located near the upstream end of Lake Emory and is affected by variable backwater conditions; therefore, an index-velocity technique, using an acoustic Doppler velocity meter (ADVM), was used to compute continuous discharge (Levesque and Oberg, 2012). Continuous streamflow data are available from December 2013 to January 2016 (U.S. Geological Survey, 2016b).

Site LT3 was installed in March 2012 as part of a 10-year Federal Energy Regulatory Commission license for minimum flow requirements. Site LT3 is located approximately 500 ft upstream from historical USGS streamgage 03502000 Little Tennessee River at Iotla, NC. Historical daily mean streamflow data are available in NWIS for station 03502000 for the period July 1929 to September 1945. Continuous streamflow data are available for site LT3 from March 2012 to current (2017) (U.S. Geological Survey, 2016b).

Study sites LT1, CC1, and LT4 are long-term streamflow stations in the upper Little Tennessee River Basin (fig. 1). Although these gages were not part of the current study, data from these sites are useful for comparing streamflow at the two study sites as well as providing a historical context for interpreting results of the current study.

Continuous Turbidity Data

Continuous turbidity data were collected at 15-minute intervals at both the upstream and downstream study sites, using YSI OMS 600 water-quality monitoring sondes with 6136 turbidity sensors, following USGS procedures (Wagner and others, 2006). The 6136 turbidity sensor uses a single, near-infrared light source, and turbidity data are reported in formazin nephelometric units (FNU). The optical turbidity sensor is equipped with a wiper that is intended to remove debris and reduce fouling of the optical sensor. The continuous water-quality record spans the study period and is available in NWIS for the period December 21, 2013, through January 31, 2016. Water temperature and specific conductance data also were collected at each station and were used for quality control. Although temperature may influence sediment transport, these data were not incorporated into the sediment analysis.

The water-quality monitors were installed so that the instruments would be in flowing water and protected from damage by floating debris, and could to be serviced at all stages. Locations were selected to be representative of average conditions in the stream cross section being monitored. Site visits were typically made every 2 weeks (or more frequently as needed) to service the sondes and remove any debris or fouling. At both study sites, the water-quality monitors were located approximately 5 ft from the right bank and housed in perforated 4-inch polyvinyl chloride pipes in the vicinity of the streamgage. Comparisons of cross-section and fixed-location instream water-quality properties (turbidity, temperature, and specific conductance) at low streamflows indicate the stream was well mixed at the continuous monitoring location. Due to high velocities at elevated streamflow, it was not feasible to perform comparisons during these conditions; however, on the basis of visual observations during high-flow events, this well mixed condition is assumed throughout the range of streamflows.

Suspended-Sediment Sampling

Suspended-sediment samples were collected periodically at study sites LT2 and LT3 throughout the study period during a variety of flow conditions. Suspended-sediment sample results were used to define the relations between SSC and turbidity and (or) streamflow. These samples consisted of cross-sectional, depth-integrated samples as well as fixed-point, automatic-sampler samples (point samples), with the majority collected during targeted high-streamflow, high-turbidity events. Because turbidity is well correlated with SSC, samples were collected on the basis of measured turbidity values. At both sites, adequate samples were collected throughout the range of observed turbidity values (fig. 6). For the most part, adequate samples were collected throughout the range of observed streamflow values at both study sites (fig. 7); however, extreme high-flow events occurred during the last week of the study period, and flows were approximately twice those of events in which samples were collected.

Cross sections were sampled using the equal-discharge-increment (EDI) sampling method (Edwards and Glysson, 1999) using isokinetic water samplers. Streamflow and depths were such that the US-D-74 sampler was used for the majority of sampling events. A US-D-95 sampler was used for a few high-flow events because of depth and velocities. Also, a US-DH-59 sampler was used for select base-flow samples. The US-D-74, US-D-95, and US-DH-59 samplers were designed by the Federal Interagency Sedimentation Project (FISP) for collecting isokinetic suspended-sediment samples under various flow conditions (Davis, 2005). These samplers are used to collect depth-integrated samples from the water surface to within approximately 4 inches above the streambed. Due to site limitations, the EDI samples were collected at a bridge downstream from the gage location (where streamflow, turbidity, and point samples were collected) at both study sites. The bridge was approximately 450 ft downstream from the gage at site LT2 and approximately 1,500 ft downstream from the gage at site LT3. Ten EDI sampling events at site LT2 and 12 at site LT3 were used in the computation of SSC. For this study, a sampling event is described as sample collection at a targeted flow or turbidity range, and, in some cases, multiple sampling events occurred on the same day. Two sets of EDI samples (sets A and B) were collected simultaneously at both study sites for the majority of sampling events; samples were analyzed individually as well as averaged to produce a single

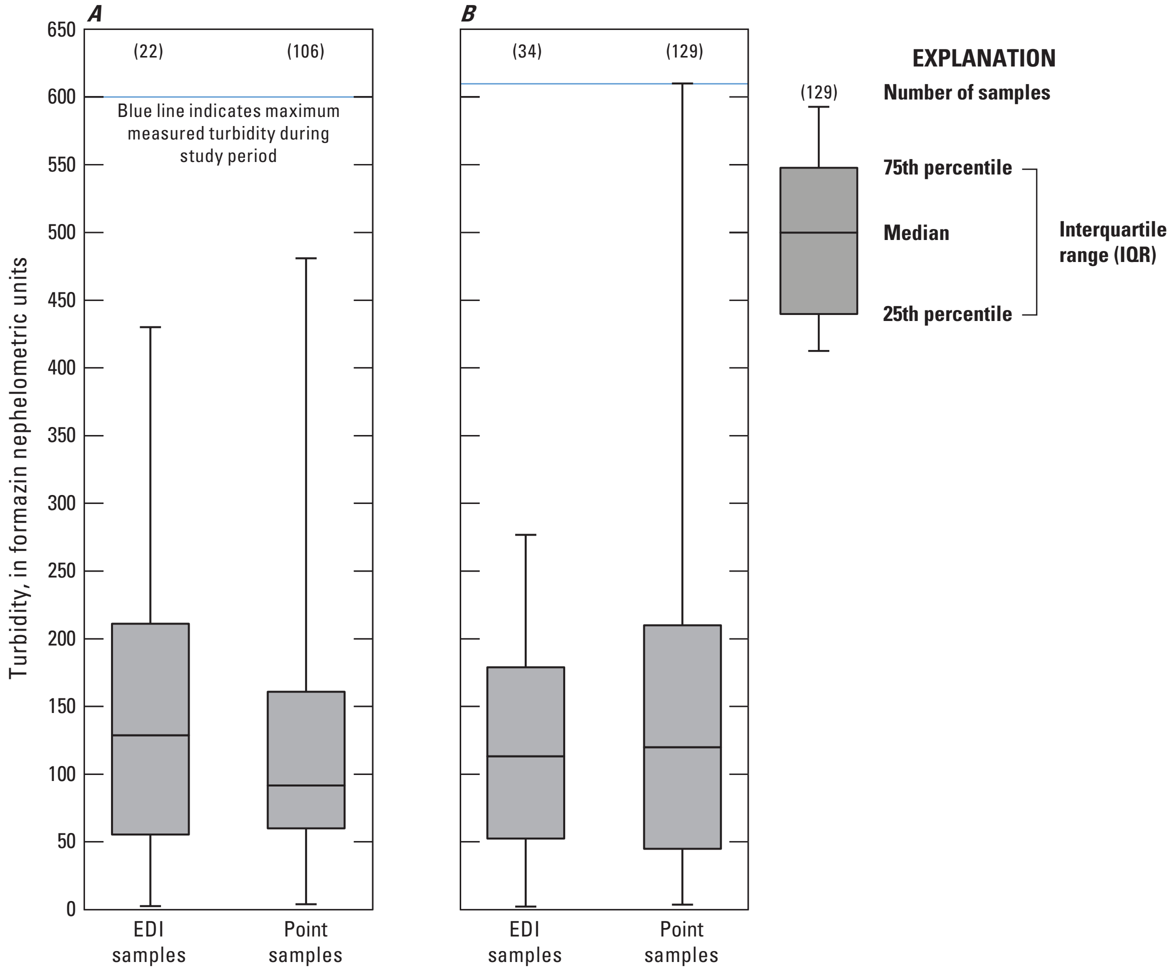


Figure 6. Boxplots showing the range of measured turbidity for equal-discharge-increment (EDI) and point samples at *A*, Little Tennessee River at Franklin (station 03501500; LT2) and *B*, Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

concentration (sample event average). The EDI sample sets typically consisted of five vertical samples (bottles); however, early in the study six vertical (bottle) EDI samples were collected. In addition, for a majority of EDI samples, concentrations were determined for individual bottles along with the composite concentration. The concentration results for the individual bottles were not published, but were used to assess the homogeneity of the cross section and also served as a check to identify potential outliers in results from the individual vertical samples within the sample set. No outliers were identified at either site. On the basis of individually analyzed vertical samples, SSC was found to decrease from left to right (looking downstream) during elevated streamflows at site LT2. At both sites, SSC results from the EDI sampling locations were used to compare to point samples (when collected concurrently) as well as to develop regression models. In addition to SSC, turbidity was measured simultaneously at each sampling vertical to associate turbidity values with individual vertical results as well as to compute an average turbidity to associate with the cross-section average concentrations.

Automatic-pumping, fixed-point samplers (automatic samplers) were installed at both study sites. The automatic samplers were installed so that the intake was fixed and adjacent to the continuous turbidity monitors, and could be serviced (cleaned) at all streamflows. The automatic samplers were mounted on the right bank, and upstream from the bridge used for EDI samples, at both sites. Automatic samples (point samples) were collected near or at the same

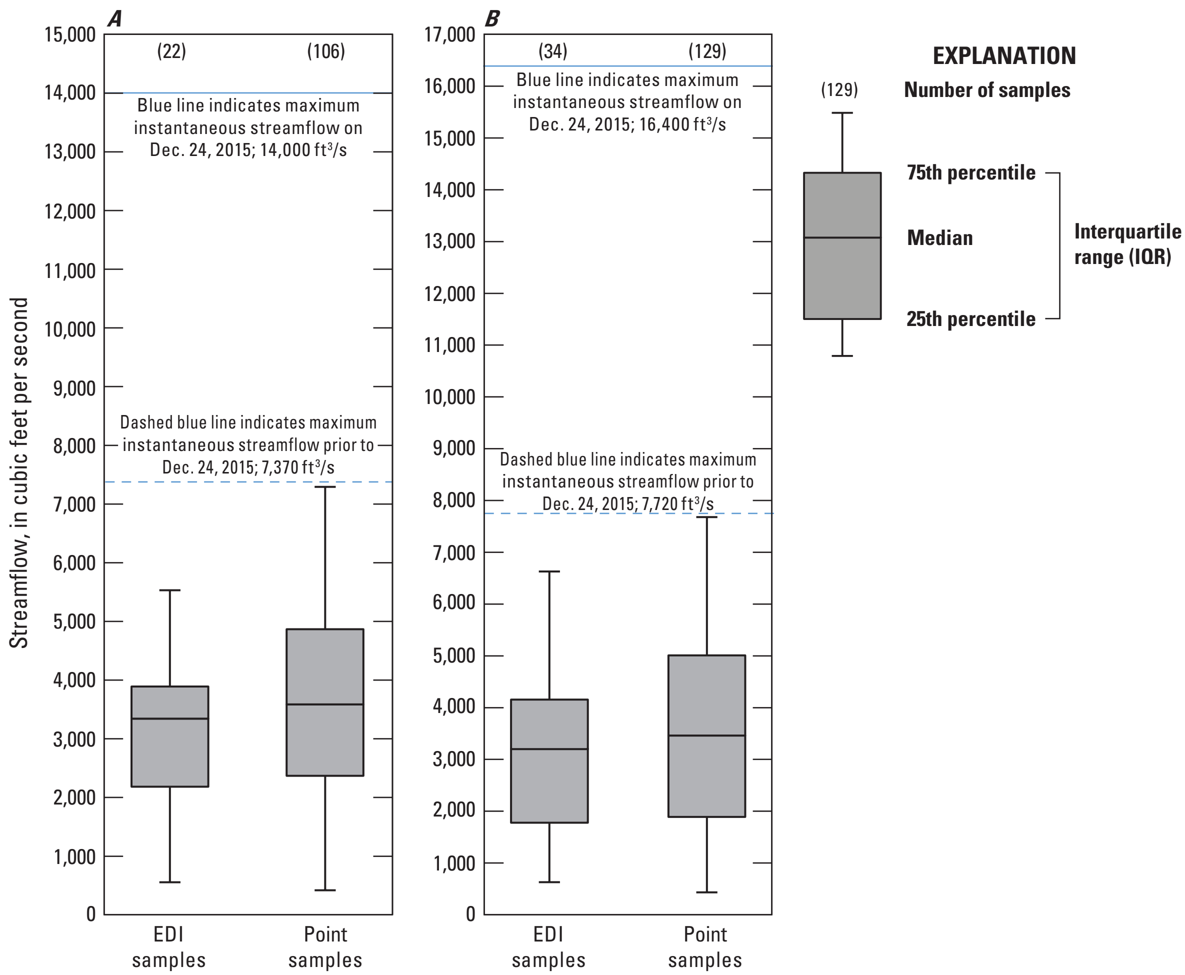


Figure 7. Boxplots showing the range of computed streamflow for equal-discharge-increment (EDI) and point samples at *A*, Little Tennessee River at Franklin (station 03501500; LT2) and *B*, Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

time the continuous turbidity was being measured so that a turbidity value could be associated with the sample. These point samples were used to augment the EDI cross-sectional samples for periods between manual sampling events and to quantify the relation between results from the EDI samples and automatic-sampler samples. The automatic samplers also allowed for sample collection during times when it was not feasible to collect manual EDI samples as well as the ability to collect samples throughout an event (rising and falling limbs on a hydrograph). These more frequent (time-based) samples collected for a selected event allowed for the evaluation of SSC hysteresis between streamflow and turbidity. Automatic samplers draw water from a single (fixed) point, whereas the EDI method captures variability in concentrations throughout the stream cross section associated with both location and varying stream velocities. To evaluate whether or not a correction coefficient was needed, the automatic samplers were manually triggered both before and after most of the EDI samples were collected. A total of 106 point samples were collected at site LT2, and 129 were collected at site LT3 (table 2).

Samples were shipped to the USGS sediment laboratory in Louisville, Kentucky, and analyzed for SSC using methods described by Guy (1969). Selected samples were also analyzed by means of a wet-sieving method (Shreve and Downs, 2005) to determine the percentage of the sediment mass that was finer than sand, that is, with diameters less than 0.0625 millimeter (mm).

Table 2. Summary of suspended-sediment samples collected at study sites Little Tennessee River at Franklin (station 03501500; LT2) and Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

[mg/L, milligram per liter; SSC, suspended-sediment concentration; FNU, formazin nephelometric unit; ft³/s, cubic foot per second]

Site identifier[a]	Number of samples	Mean concentration, in mg/L	Median concentration, in mg/L	Range of sampled SSC, in mg/L	Model estimated range, in mg/L	Range of sampled turbidity, in FNU	Range of observed turbidity, in FNU	Range of sampled flow, in ft³/s	Range of observed flow, in ft³/s
Equal-discharge-increment (EDI) samples									
LT2	22	519	380	4–1,180	1–2,117	2–430	0.6–600	547–5,520	72–14,000
LT3	34	271	201	3–741	1–1,882	3–277	0.7–610	631–6,630	105–16,400
Point samples									
LT2	106	286	206	6–1,200	1–2,117	3–480	0.6–600	409–7,280	72–14,000
LT3	129	371	267	5–1,620	1–1,882	4–610	0.7–610	434–7,680	105–16,400

[a]Site identifier was assigned for study purpose.

Bedload Samples

Bedload is the sediment that moves by sliding, rolling, or bouncing along on or very near the streambed. Bedload is difficult to measure accurately, because samplers placed on the streambed may disturb the flow and rate of bedload movement, and the bedload can be highly variable both spatially and temporally. Bedload samples were collected at the upstream study site (LT2) in order to help characterize the contribution of bedload into Lake Emory relative to the suspended load. Six bedload samples were collected to provide estimates of the bedload transport: four at high-flow conditions (two separate events) and two at base-flow conditions (one event) (table 3).

A US BL-84 sampler was used to sample bedload sediment. This cable-suspended bedload sampler is designed to collect particles ranging from about 0.25 mm (the sample bag mesh opening size) to 38 mm at stream velocities up to 9 feet per second. The sampler has a 3- by 3-inch entrance nozzle and an area expansion ratio (ratio of nozzle exit area to entrance area) of 1.4 (Edwards and Glysson, 1999). A polyester mesh sample bag with mesh openings of 0.25 mm was attached to the rear of the sampler. Samples were collected at each stream site by using a modified single equal-width-increment (SEWI) method (Edwards and Glysson, 1999). Each stream cross section was sampled by collecting subsamples at 10 to 11 evenly spaced locations along the cross section (table 3). Bedload subsamples were combined into one composite sample for each transect. At least two transects were collected during sampling events and typically were analyzed individually. The sampler was positioned on the streambed at each location for 60 seconds during individual transects. The average streamflow during the sampling period, stream width, number of subsections, length of time the sampler was on the streambed at each subsection, and total sampling time were recorded (table 3). This information, along with the analyzed weight of the composited material, was used to compute bedload for each sampling event. Bedload

Table 3. Summary of bedload sampling results for the Little Tennessee River at Franklin, North Carolina (station 03501500; LT2).

[ft³/s, cubic foot per second; t/d, short ton per day]

Sample date	Mean sample time	Streamflow, in ft³/s	Stream width, in feet	Number of subsections	Sampling time at each subsection, in seconds	Total sampling time, in seconds	Weight of composited sample, in grams	Instantaneous bedload, in t/d
04/20/2015	1312	3,460	138	11	60	660	251	20
04/20/2015	1405	3,200	138	11	60	660	170	14
12/02/2015	1012	6,220	150	10	60	600	2,160	206
12/02/2015	1523	5,630	150	10	60	600	2,290	218
02/01/2016[a]	1438	1,030[a]	148	10	60	600	28.3	2.7
02/01/2016[a]	1512	1,070[a]	148	10	60	600	3.4	0.3

[a]Base-flow conditions.

samples were analyzed at the USGS sediment laboratory in Louisville, Kentucky, for total weight and particle-size distribution (for one set), ranging from diameters less than 0.0625 mm to less than 16 mm and using sieving methods described by Guy (1969). As bedload sediment is collected in the bag (along with organic debris), the effective flowthrough area of the mesh openings can be decreased, resulting in the collection of particles of sizes less than the mesh size of the sample bag (0.25 mm). This was especially noteworthy for a bedload sample collected on December 2, 2015 (heavy organics throughout). Quality-assurance procedures used by the laboratory are documented in the "Quality-Assurance Plan for the Analysis of Fluvial Sediment by the U.S. Geological Survey Kentucky Water Science Center Sediment Laboratory" (Shreve and Downs, 2005). Because a limited number of bedload samples were collected, only the relative contribution of bedload samples to total sediment load could be assessed.

Data Analysis

Suspended-sediment, continuous streamflow, and continuous turbidity data were used to evaluate hysteresis, develop cross-section coefficients, develop regression models for computation of unit-value SSCs, and compute daily SSLs.

Suspended Sediment

The delivery and transport of suspended sediment in streams are affected by several factors, including soil characteristics, topography, land use, rainfall intensity, and streamflow. Samples for suspended-sediment analyses were collected periodically at sites LT2 and LT3 from March 2014 through November 2015, with the majority collected during targeted high-streamflow, high-turbidity events. The resulting SSC samples at both study sites represented SSCs across almost the entire range of turbidity observed at both sites (figs. 6, 7; table 2). Suspended-sediment samples also represented SSCs across almost the entire range of streamflow occurring during the study period up to the last week of the study.

Concentrations

During the study period, a total of 22 EDI suspended-sediment samples were collected at site LT2, and 34 EDI suspended-sediment samples were collected at site LT3 (fig. 8; table 2). A total of 106 point samples were collected at site LT2, and 129 point samples were collected at site LT3. As noted above, these samples do not cover the entire range of observed streamflows or turbidity, predominately due to the extreme high-flow events that occurred during the last week

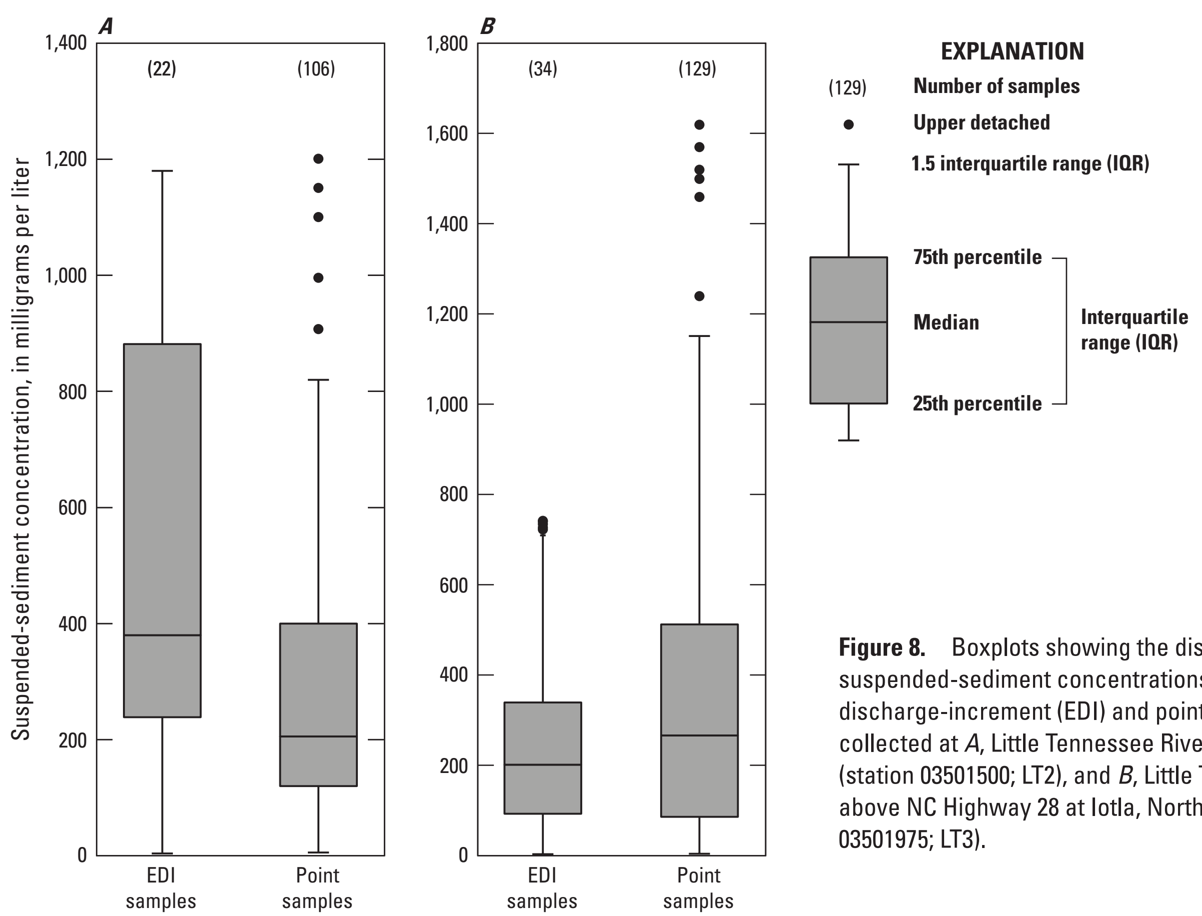


Figure 8. Boxplots showing the distribution of suspended-sediment concentrations for equal-discharge-increment (EDI) and point samples collected at *A*, Little Tennessee River at Franklin (station 03501500; LT2), and *B*, Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

of the study. To put into a historical perspective, the peak streamflows associated with this series of events were the sixth and seventh highest computed streamflows (since 1945) at long-term sites LT1 and LT4, respectively. Maximum sampled streamflows at both sites were only about 50 percent of the maximum computed streamflows during the study period. Maximum sampled turbidity was 80 and 100 percent of the maximum measured turbidity at sites LT2 and LT3, respectively. Maximum suspended-sediment concentrations from samples collected at the study sites were 1,200 milligrams per liter (mg/L) at site LT2, and 1,620 mg/L at site LT3. (table 2; figs. 6, 7, 8).

Particle-Size Distribution

Suspended sediment consists of particles small enough to be transported in suspension—primarily sands, silts, and clays. Selected suspended-sediment samples for high-flow events from both study sites were analyzed to determine the percentage of particles finer than 0.0625 mm, which corresponds to the breakpoint between sands (0.0625 to 2.0 mm in diameter) and the finer particulates known as silts and clays. Eighteen suspended-sediment samples were analyzed at site LT2, and 20 suspended-sediment samples were analyzed at site LT3 for the range of flows observed during the study period. The total range and interquartile range (IQR) in percentage of fine-grained particles by weight was 55 to 84 (IQR 65 to 76.5) at site LT2 and 51 to 83 (IQR 61.75 to 74.25) at site LT3 (fig. 9). The median percentage of fine-grained particles was 68 percent at both site LT2 and site LT3. This suggests that the percentage of suspended sediment above and below 0.0625 mm is about the same at the two sites, and silts and clays make up the majority of suspended-sediment particles in flux at these locations. The percentage of fine-grained particles (less than 0.0625 mm) varied as a function of streamflow (fig. 10). In general, the higher the flow, the lower percentage of fine-grained particles were found.

Automatic Sample Hysteresis

Analysis of hysteresis in the relation between SSC and streamflow (SSC-Q) and SSC and turbidity (SSC-T) can help in understanding watershed sediment transport characteristics, as well as evaluate uncertainty in SSC-Q transport curves (Walling, 1977; Wood, 1977; Lawler and others, 2006). Concurrent measurements of streamflow, turbidity, and SSCs (unadjusted to cross-section average) from samples collected with the automatic samplers on the rising and falling limbs of four storm events were compared in order to evaluate the occurrence and magnitudes of hysteresis at study sites LT2 and LT3. The relations of both SSC-Q and SSC-T were evaluated. Analysis of SSC to streamflow indicates a clockwise hysteresis for the majority of the storm events at both study sites, where the SSC peak precedes the streamflow peak (fig. 11).

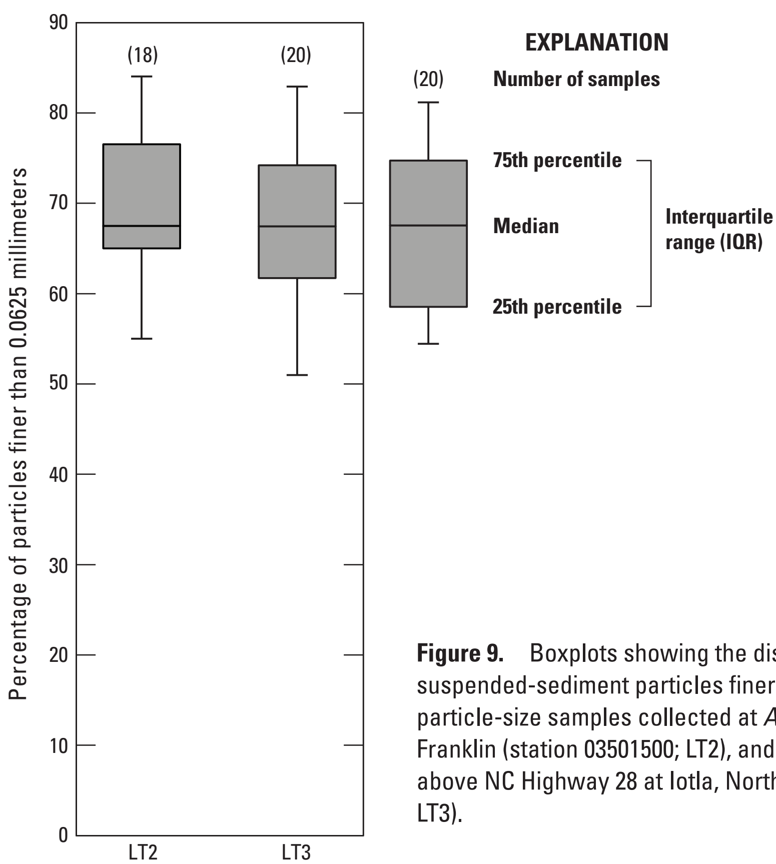


Figure 9. Boxplots showing the distribution of percentages of suspended-sediment particles finer than 0.0625 millimeters for particle-size samples collected at *A*, Little Tennessee River at Franklin (station 03501500; LT2), and *B*, Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

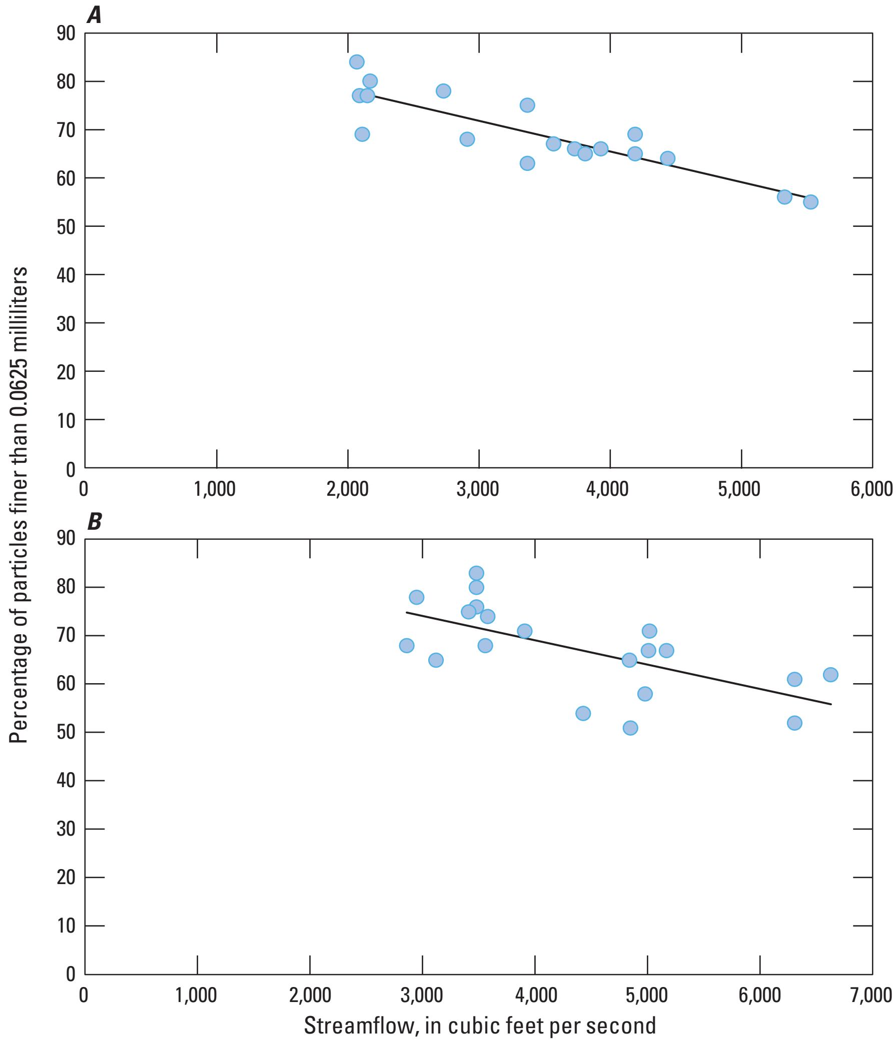


Figure 10. Distribution of percentages of suspended-sediment particles finer than 0.0625 millimeter versus streamflow at *A*, Little Tennessee River at Franklin (station 03501500; LT2), and *B*, Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

According to Landers and Sturm (2013): "The SSC~Q relation typically exhibits leading, clockwise hysteresis which is often ascribed to resuspension of sediment from the stream channel at the initiation of storm runoff and to relatively limited sediment supply on the stormflow recession."

No distinct hysteresis was evident on the basis of SSC to turbidity at site LT2 for the sampled storm events. Turbidity and SSC generally exhibited near-synchronous peaks, as well as similar slopes on the rising and falling limbs. This indicates that the ratio of turbidity to SSC was relatively unchanged throughout the majority of the sampled events. At site LT3, turbidity and SSC generally exhibited near-synchronous peaks, except for the storm event on October 14–15, 2014, in which the turbidity peak preceded the SSC peak. A slight counter clockwise SSC-T hysteresis was noted in a few of the storm events, which could possibly indicate stormflow dominated by tributary runoff (as opposed to reservoir release flow) (Gilvear and Petts, 1985).

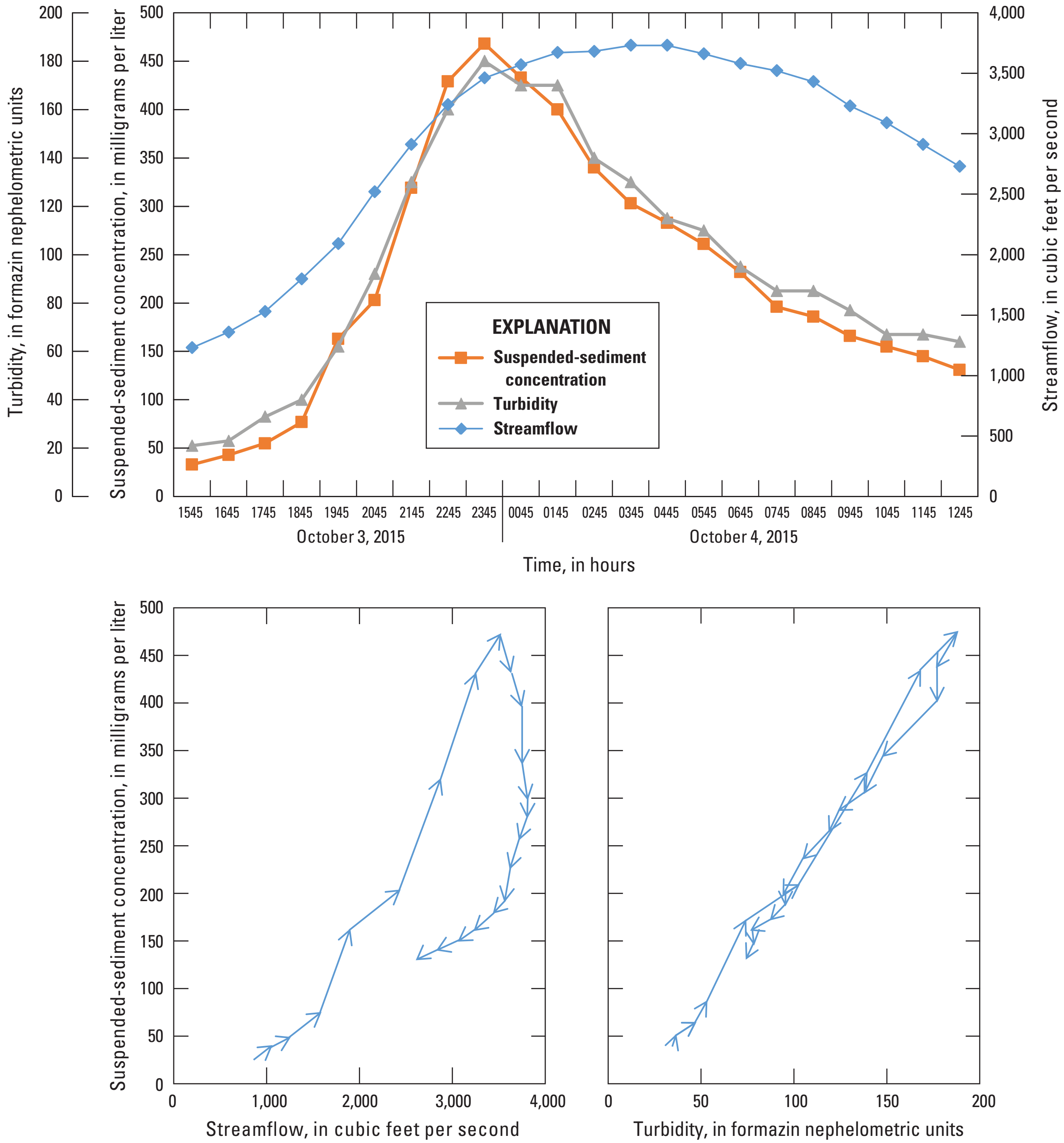


Figure 11. Time series (hourly) of streamflow, turbidity, and suspended-sediment concentration, and bivariate sequence plots of concentration and streamflow and concentration and turbidity, for the high-flow event on October 3–4, 2015, at study site LT2. Sequential time-series values in the bivariate plots are represented as arrow heads.

Cross-Section Corrections

Because of potential variability in SSCs throughout the stream cross section as well as intake efficiency of automatic pumping samplers, point samples typically do not represent the mean sediment concentration (Edwards and Glysson, 1999). Point samples, therefore, must be compared with depth-integrated, cross-sectional samples in order to determine if a correction (or coefficient) needs to be applied. During the 2-year study, the automatic (point) sample concentrations for the upstream site (LT2) were consistently less than concentrations in concurrently collected EDI samples. For the downstream study site (LT3), however, the point sample concentrations were consistently greater than the concurrent

EDI sample concentrations. These observed differences could be attributed to the location of the automatic sampler intake within the cross section as well as the longitudinal stream-channel differences in sampling locations between the intake for the automatic sampler and the cross sections where EDI samples were collected. Turbidities measured near the sampler intake and at EDI sample locations (measured near surface during EDI sampling) were also compared, and the results verified this bias.

Cross-section corrections were computed using linear regression of the average of the "before and after" automatic sample SSCs and the EDI sample SSCs in logarithmic space. The coefficient of determination (R^2) values for sites LT2 and LT3, using the linear regression model calibrations, are 0.97 and 0.99, respectively (fig. 12). Even though the slopes (in log space) are close to 1.0, the corrections are not constant and are, therefore, applied. The model equations were used to adjust the automatic sampler concentrations to better reflect the mean cross-section concentration defined by the manual EDI samples. These adjusted SSCs were input into the regression models (along with EDI SSCs) used for the estimation of time series SSC.

Linear Regression Model Development

The Surrogate Analysis and Index Developer (SAID) standalone tool, developed by the USGS, assists in the development of ordinary least-squares regression models that can be used to estimate constituent concentrations as a function of surrogate measures (Domanski and others, 2015). SAID provides both visual and quantitative diagnostics that facilitate evaluation of the linear regression models, as well as computing a predicted time series. SAID also computes and applies bias-correction factors that are required when regression equations are developed with mathematically transformed dependent variables. For this study, SAID was used to develop linear regression models as well as to calculate a regression-estimated time series of SSC. Three linear regression models were evaluated for both study sites (table 4) to determine which model was most suitable. Both simple linear regression (SLR) and multiple linear regression (MLR) models were assessed. Turbidity and streamflow were evaluated individually as independent variables in the SLR models and together as variables in the MLR models. Turbidity and (or) streamflow data were paired with SSC data by matching EDI concentrations and cross-section-coefficient-corrected point-sample concentrations to the closest-in-time streamflow and turbidity value(s) computed or measured at the gage location. At site LT2, a total of 128 SSCs were used: 22 EDI samples and 106 automatic samples. At site LT3, a total of 163 SSCs were used: 34 EDI samples and 129 point samples. Regression models originally were developed using log (base 10) transformed dependent (SSC) and independent (turbidity and (or) streamflow) variables. Normal probability plots of the regression residuals (figs. 13, 14) indicated deviations from normality, and computed probability-plot correlation coefficients (PPCCs) indicated that the null hypothesis of normally distributed residuals was rejected at an alpha level of 0.05. At site LT2, the PPCC value was 0.974 and the critical value (alpha = 0.05) was 0.989, whereas at site LT3, the PPCC value was 0.961 and the critical value was 0.991. Non-normality of residuals can result in hypothesis tests that have low power and confidence intervals that are too wide (Helsel and Hirsch, 1995). In an attempt to produce models with normally distributed residuals, models were developed on the basis of Box-Cox transformations (Box and Cox, 1964) of

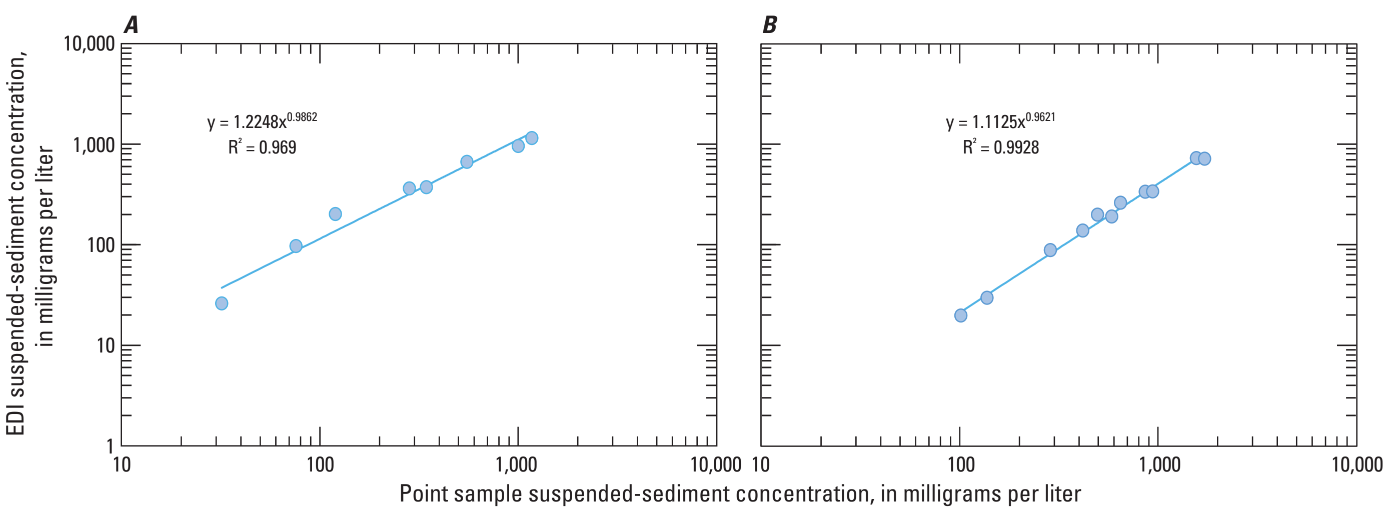


Figure 12. Regression equations used to adjust suspended-sediment concentrations of point samples collected at Little Tennessee River at Franklin (station 03501500; LT2) and Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3). [Blue line represents a linear regression trendline.]

Table 4. Expressions for determining use of simple linear regression or multiple linear regression models for study sites Little Tennessee River at Franklin (station 03501500; LT2) and Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

[n, number of samples; R^2_a, adjusted coefficient of determination; RMSE, root mean squared error in log units; SLR, simple linear regression; MLR, multiple linear regression; Log, log base 10; SSC, suspended-sediment concentration, in milligrams per liter; Q, streamflow, in cubic feet per second; T, turbidity, in formazin nephelometric units]

Model	Variable		Regression model equation	Diagnostic regression statistic			
	Dependent	Independent		*n*	R^2_a	*RMSE*	*Bias correction factor*
			LT2				
SLR	Log SSC	Log Q	$\log_{10}SSC = -2.89 + 1.5\log_{10}Q$	128	0.696	0.296	1.27
SLR	Log SSC	Log T	$\log_{10}SSC = 0.147 + 1.13\log_{10}T$	128	0.97	0.093	1.02
MLR	Log SSC	Log T, Log Q	$\log_{10}SSC = -0.481 + 0.252\log_{10}Q + 1.01\log_{10}T$	128	0.977	0.081	1.02
			LT3				
SLR	Log SSC	Log Q	$\log_{10}SSC = -4.09 + 1.83\log_{10}Q$	163	0.855	0.217	1.15
SLR	Log SSC	Log T	$\log_{10}SSC = 0.0119 + 1.14\log_{10}T$	163	0.949	0.128	1.04
MLR	Log SSC	Log T, Log Q	$\log_{10}SSC = -1.64 + 0.668\log_{10}Q + 0.798\log_{10}T$	163	0.98	0.081	1.02

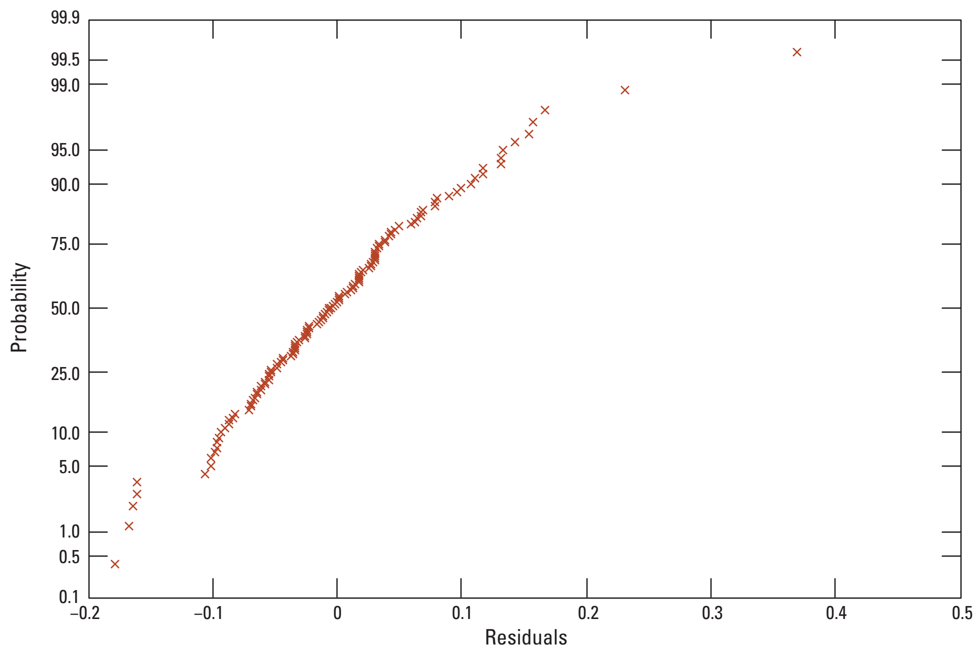


Figure 13. Normal probability plot of residuals for study site Little Tennessee River at Franklin, North Carolina (station 03501500; LT2).

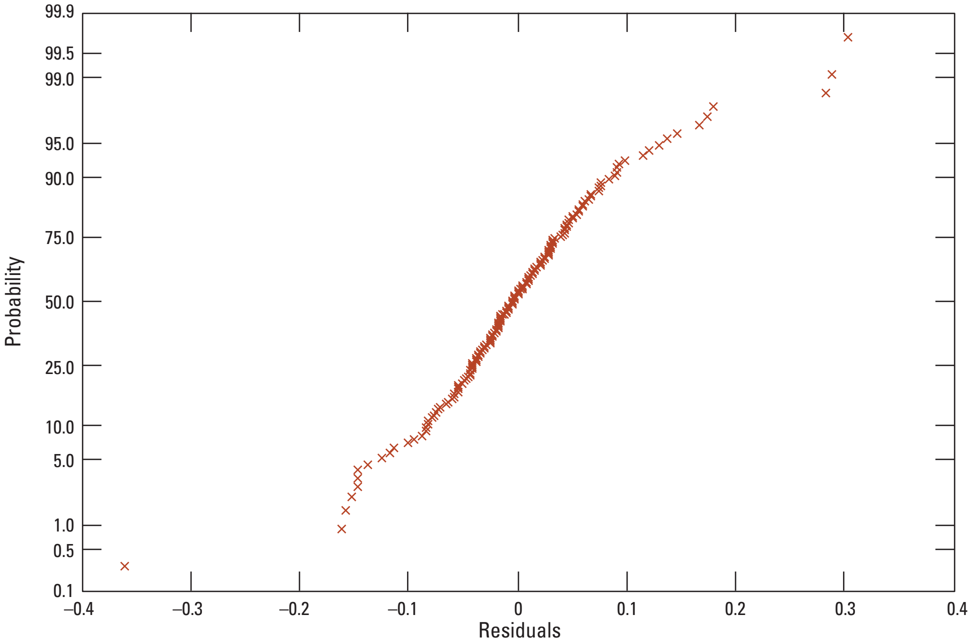


Figure 14. Normal probability plot of residuals for study site Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

regression variables with a ladder of powers ranging from 2 to –2. None of the Box-Cox-transformed model forms that were tested yielded more normally distributed residuals than the log models.

Adjusted R^2 values, residual plots, and root mean squared errors (RMSEs) were evaluated to determine which regression model provided the best estimates of SSC (table 4). As expected, the SLR model evaluations indicated that turbidity was more strongly correlated with SSC than was streamflow (fig. 15; table 4). Multicollinearity between the two explanatory variables (turbidity and streamflow) was also evaluated to determine if using both variables in the MLR should be avoided. A variance inflation factor (VIF) was used in the assessment. The square root of the VIF indicates how much larger the standard error for the coefficient is, compared with what it would be if that variable were uncorrelated with the other predictor variable(s) in the model. According to Helsel and Hirsch (2002), "Serious problems are indicated when the VIF is greater than 10." For both study sites, the VIF was well below 10 (LT2=2.7 and LT3=3.8), suggesting that both turbidity and streamflow could be used together as explanatory variables. Plots of residuals versus streamflow when using turbidity as the sole explanatory variable (figs. 16*A*, 17*A*) showed that the residuals increased in value with increasing streamflow, suggesting that there was unexplained variability in the turbidity-based SLR model that was explained by streamflow. Both explanatory variables (streamflow and turbidity) were statistically significant in the MLR models at a 5 percent level and, as shown in table 4, the MLR models resulted in small improvements over the SLR models in adjusted R^2 values at both sites, with the greatest improvement at site LT3. Plots of measured SSCs versus regression-estimated SSCs and raw residual plots were also evaluated (figs. 18, 19). Although adding streamflow as an explanatory variable improved the regression models, concentrations at high flows tended to be underpredicted at both study sites.

On the basis of all findings, the decision was made to use the MLR model to compute time series of SSC. The SSC time series (15 minute), in milligrams per liter, were computed with SAID for both study sites for the 2014–15 calendar years. The model-predicted unit-value SSCs were entered into the NWIS database (U.S. Geological Survey, 2016b). It should be noted that there may be uncertainty about the accuracy of these prediction intervals because of the non-normal distribution of residuals. It also should be noted that computed streamflows for the extreme high-flow events that occurred during the last week of the study period were approximately twice as large as any sampled streamflows. Consequently, regression estimates for portions of the high-flow events are extrapolations, which, coupled with the tendency for the regression equations to underpredict concentrations at high flows, adds uncertainty to estimates of loading during this important high-flow period.

Load Computation

The Graphical Constituent Loading Analysis System (GCLAS; Koltun and others, 2006) was used to compute daily SSL, in short tons, for the 2014–15 annual years at both study sites. GCLAS computes loads as a function of an equal-interval streamflow time series and an equal- or unequal-interval time series of constituent concentrations (Koltun and others, 2006). For this study, 15-minute regression-estimated SSCs (as computed in SAID) along with streamflow data were used in the load computations. Periods with missing turbidity or streamflow values and, therefore, missing unit-value suspended-sediment concentrations were estimated by means

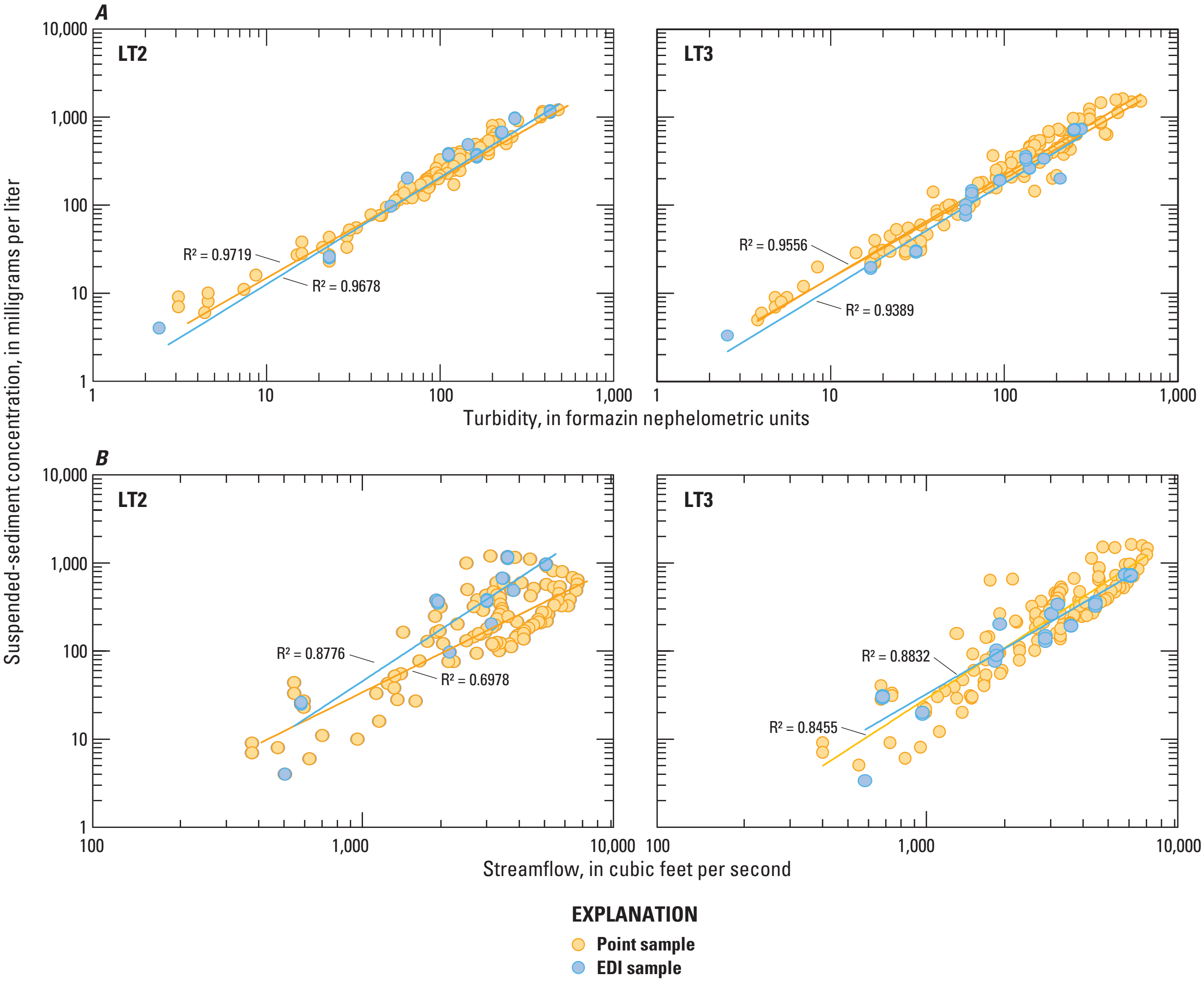


Figure 15. Relation between *A*, suspended-sediment concentration and turbidity, and *B*, suspended-sediment concentration and streamflow, at Little Tennessee River at Franklin (station 03501500; LT2) and Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3). [Fitted lines are linear regression trendlines, color coded for sample type. EDI, equal discharge increment]

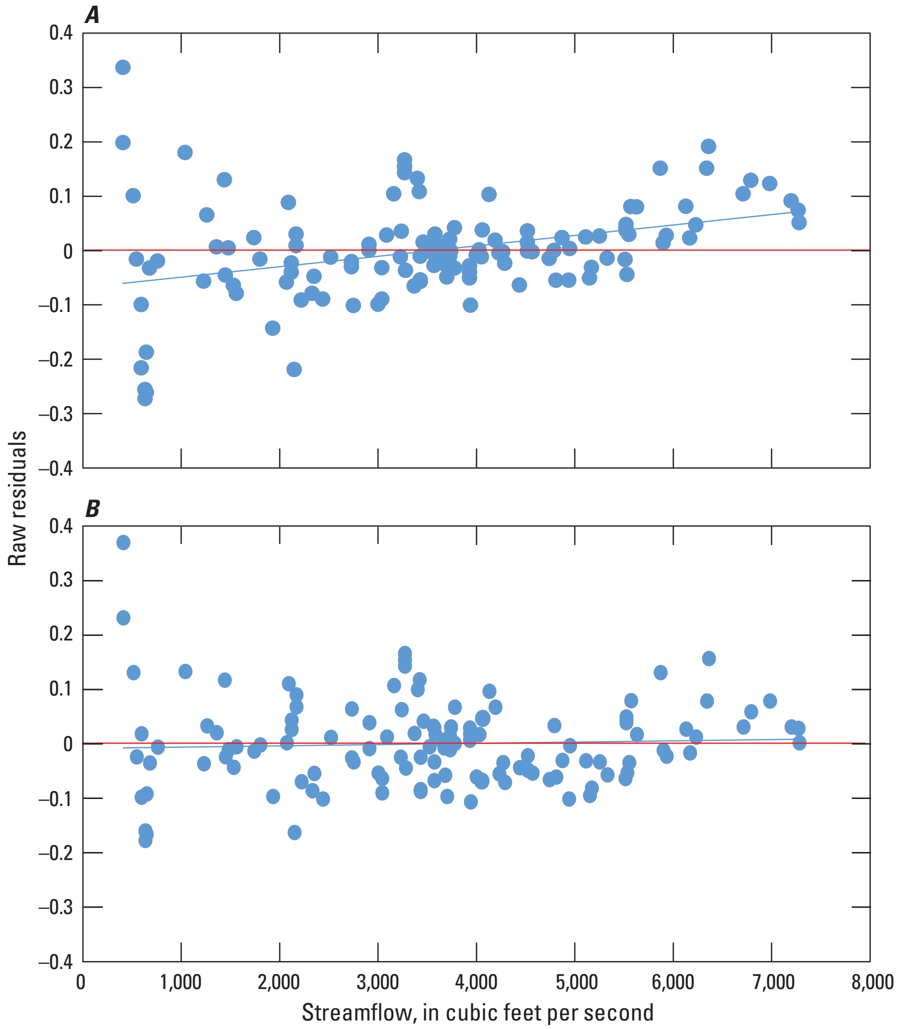


Figure 16. Relation between streamflow and residuals from *A*, simple linear regression model, and *B*, multiple linear regression model, at Little Tennessee River at Franklin, North Carolina (station 03501500; LT2). [Blue line represents a linear regression trendline.]

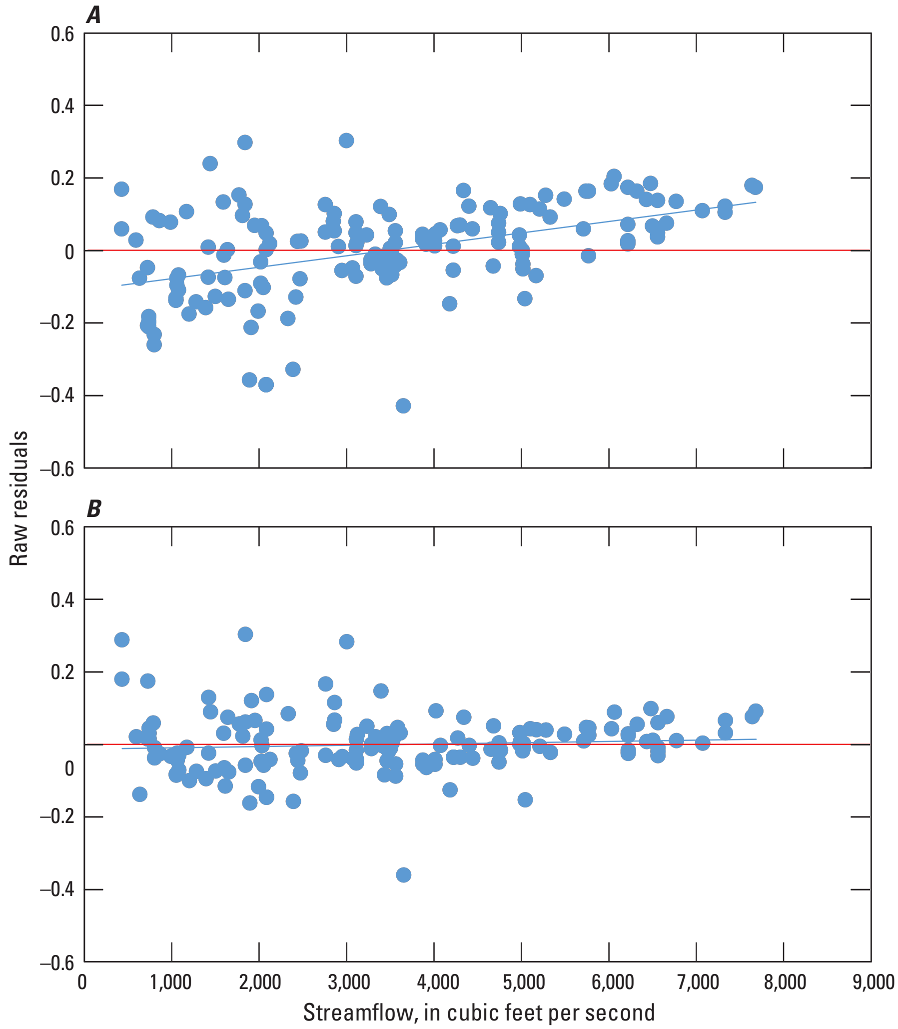


Figure 17. Relation between streamflow and residuals from *A*, simple linear regression model, and *B*, multiple linear regression model, at Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3). [Blue line represents a linear regression trendline.]

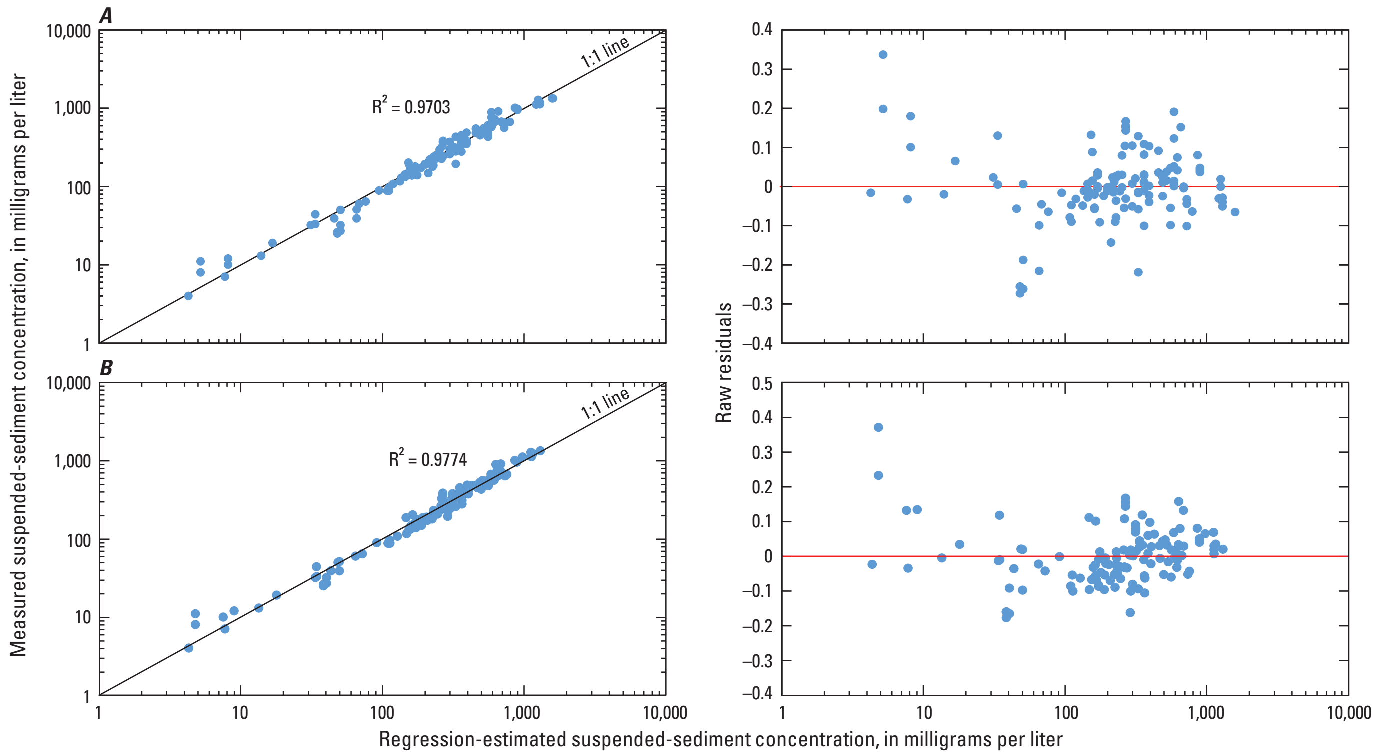


Figure 18. Relation between measured and regression-estimated suspended-sediment concentrations, and residuals and regression-estimated suspended-sediment concentrations from *A*, simple linear regression model, and *B*, multiple linear regression model, at Little Tennessee River at Franklin, North Carolina (station 03501500; LT2).

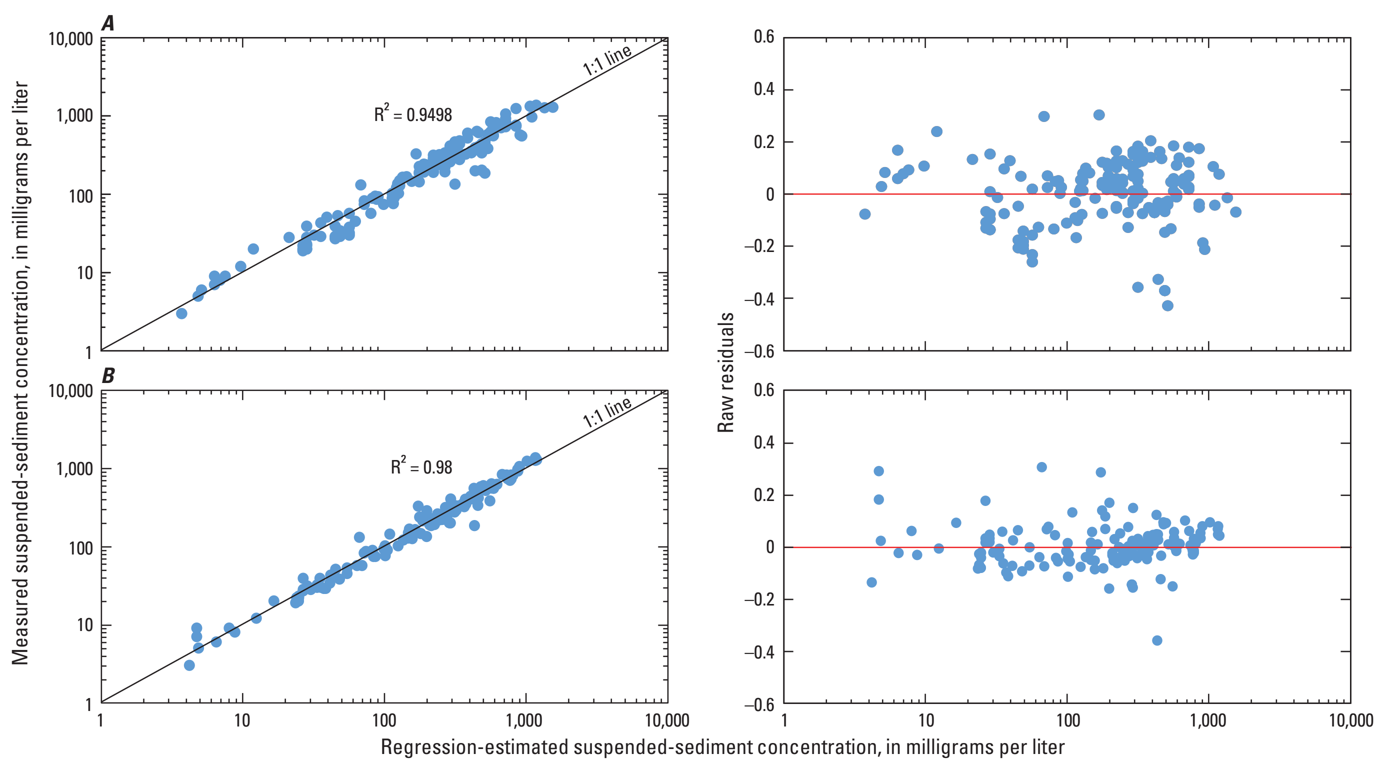


Figure 19. Relation between measured and regression-estimated suspended-sediment concentrations, and residuals and regression-estimated suspended-sediment concentrations from *A*, simple linear regression model, and *B*, multiple linear regression model, at Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

of transport curves (using streamflow and (or) concentration data from the same site or another site) in order to compute a complete record of SSLs. Turbidity time series for both sites were incomplete due to sensor fouling or maintenance issues. Missing streamflow records were less common and typically resulted from instrumentation issues. The majority of the missing data were during periods between storm events when the least amount of suspended sediment was being transported. Annual SSL was computed by summing the daily SSL values at each site. The daily SSLs are stored in the NWIS database (U.S. Geological Survey, 2016b). Daily SSLs using the low and high 90-percent prediction interval SSCs were also computed to help quantify the uncertainty in the regression model. As stated previously, there is an added level of uncertainty with these prediction intervals because of the non-normal distribution of residuals from the regression models.

The total SSL at site LT2 during the study period was estimated at 90,300 t with a range of uncertainty of –27 to +37 percent based on the 90-percent confidence interval load estimates (65,800 to 124,000 t), with an average annual yield of 153 short tons per square mile per year (t/mi^2/yr; table 5). The annual SSLs for site LT2 for the 2014 and 2015 calendar years were 27,000 t and 63,300 t, respectively. The annual suspended-sediment yields were 92 t/mi^2/yr and 215 t/mi^2/yr, respectively. The total SSL at site LT3 during the study period was estimated at 119,000 t with a range of uncertainty of –26 to +37 percent based on the 90-percent confidence interval load estimates (87,300 to 162,000 t), with an average annual yield of 183 t/mi^2/yr (table 5). The annual SSLs at site LT3 for 2014 and 2015 were 24,200 t and 94,300 t, respectively. The annual yields were 75 t/mi^2/yr and 292 t/mi^2/yr, respectively. Some of the differences in SSL computed at site LT3 (aside from uncertainties) relative to site LT2 may be attributed to the fact that site LT3 has an additional 28 mi^2 of drainage area (approximately 9 percent more) of which 14 mi^2 are below the Lake Emory dam.

As expected, the majority of the SSL occurred during high-flow events. Daily SSLs in which the daily value streamflows exceeded the 95th percentile (>1,500 cubic feet per second [ft^3/s] at site LT2; > 1,550 ft^3/s at site LT3) accounted for 80 percent of the total study-period load at site LT2 and 90 percent at site LT3 (table 6). During those high-flow events in which instantaneous streamflows at site LT2 exceeded 5,000 ft^3/s, more load generally was computed for the downstream site (LT3; fig. 20). This suggests that sediment from Lake Emory may be scoured during events in which streamflow exceeds 5,000 ft^3/s or that the additional drainage area for site LT3 contributed more sediment than would be trapped in the lake (or was added by the intervening area between the dam and site LT3). Only one event in which streamflows at site LT2 exceeded 5,000 ft^3/s (December 2–4, 2015) had a smaller downstream SSL, and this may have been due to a decreased availability of stored, easily erodible sediment resulting from a similar magnitude event just 12 days prior. During the last week of the study period (December 24–31, 2015), back-to-back extreme high-flow events occurred, in which unit-value streamflows exceeded the 99.9th percentile of streamflows for the period of record. Approximately 34,900 t of additional suspended sediment were estimated to have passed through site LT3 during these events compared to site LT2. As previously noted, streamflows during these events were approximately twice as large as streamflows associated with sediment samples collected and for which concentrations paired with concurrent streamflows were used for model calibration. Therefore the regression estimates of sediment concentration during this extreme high-flow period represent substantial extrapolations of the regression model and add uncertainty that may exceed that implied by the RMSE and model standard percentage error statistics reported for the regression equations. This series of high-flow events accounted for approximately 52 percent of the 2015 annual sediment load at site LT2 (32,700 t) and approximately 72 percent of the 2015 annual sediment load at site LT3 (67,600 t; table 6). Prior to these events, the suspended-sediment load at site LT2 (upstream site) was approximately 6,630 t greater than at site LT3 (downstream site), suggesting net deposition was occurring in the intervening reach, which includes Lake Emory.

Table 5. Estimated suspended-sediment loads and yields at Little Tennessee River at Franklin (station 03501500; LT2) and Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3), for the study period.

[USGS, U.S. Geological Survey; SSL, suspended-sediment load; t, short ton; t/mi^2, ton per square mile]

Site identifier[a]	USGS station number	Station name	2014 annual year: Annual SSL, in t	2014 annual year: Annual yield, in t/mi^2	2015 annual year: Annual SSL, in t	2015 annual year: Annual yield, in t/mi^2	Entire study period: Total SSL, in t	Entire study period: Average annual yield, in t/mi^2
LT2	03501500	Little Tennessee River at Franklin	27,000	92	63,300	215	90,300	153
LT3	03501975	Little Tennessee River at Iotla	24,200	75	94,300	292	119,000	183

[a]Site identifier was assigned for study purpose.

Table 6. Estimated suspended-sediment loads during high-flow events at Little Tennessee River at Franklin (station 03501500; LT2) and Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3), for the study period.

[t, short ton]

Event date(s)	LT2			LT3		
	Load, in t	Percentage of annual total	Percentage of study period total	Load, in t	Percentage of annual total	Percentage of study period total
January 11–12, 2014	1,970	7.3	2.2	1,790	7.4	1.5
February 21, 2014	1,000	3.7	1.1	410	1.7	0.3
April 7–8, 2014	2,880	10.7	3.2	2,940	12.1	2.5
April 29, 2014	1,800	6.7	2.0	1,200	4.9	1.0
May 15, 2014	1,400	5.2	1.6	860	3.5	0.7
October 14–15, 2014	7,900[a]	29.3	8.8	10,100[a]	41.7	8.5
November 24, 2014	390	1.4	0.4	300	1.2	0.3
December 24, 2014	760	2.8	0.8	460	1.9	0.4
January 4–5, 2015	2,350	3.7	2.6	2,430	2.6	2.1
April 19–21, 2015	4,820[a]	7.6	5.3	5,140[a]	5.5	4.3
October 3–4, 2015	2,350	3.7	2.6	2,250	2.4	1.9
November 2–3, 2015	1,070	1.7	1.2	1,210	1.3	1.0
November 9–10, 2015	1,210	1.9	1.3	1,400	1.5	1.2
November 18–20, 2015	4,790[a]	7.6	5.3	6,020[a]	6.4	5.1
December 2–4, 2015	4,370[a]	6.9	4.8	2,420[a]	2.6	2.0
December 24–31, 2015	32,700[a]	51.7	36.2	67,600[a]	71.7	57.0
Total	**71,760**		**80**	**106,530**		**90**

[a]Extreme high-flow event, in which instantaneous streamflows at LT2 exceeded 5,000 cubic feet per second.

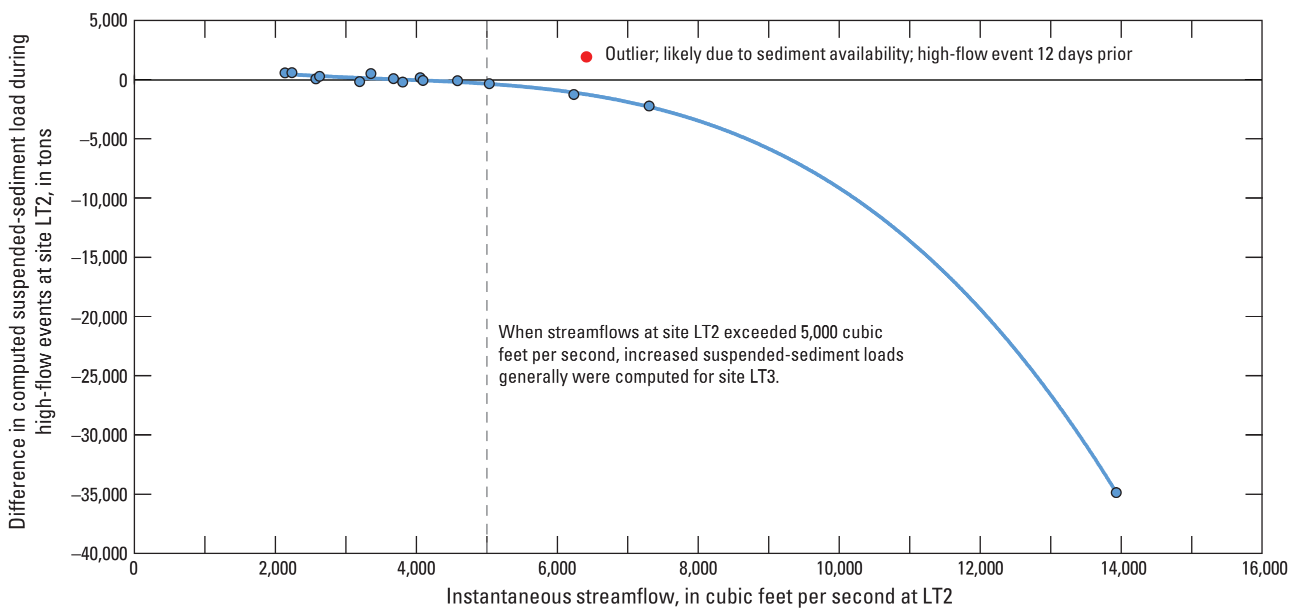


Figure 20. Difference in suspended-sediment loads during high-flow events between Little Tennessee River at Franklin (station 03501500; LT2) and Little Tennessee River above NC Highway 28 at Iotla, North Carolina (station 03501975; LT3).

Table 7. Bedload particle-size percentage finer than distributions in samples collected during two high-flow events at Little Tennessee River at Franklin, North Carolina (station 03501500; LT2), April 20, 2015, and December 2, 2015.

[ft^3/s, cubic foot per second]

Date	Discharge, in ft^3/s	Percentage of bedload particles finer than size indicated, in millimeters								
		0.062	0.125	0.250	0.500	1.00	2.00	4.00	8.00	16.0
04/20/15	3,440	0	1	6	42	84	94	97	98	100
04/20/15	3,110	0	1	5	38	78	94	97	99	100
12/02/15	6,220	0	1	12	60	78	88	93	95	97
12/02/15	5,630	1	2	12	52	88	97	98	99	99

Bedload

Samples for bedload analyses were collected on three separate dates at site LT2. Samples collected on April 20, 2015, and December 2, 2015, represent high-flow events, and samples collected on February 1, 2016, represent low-flow conditions. Because of the limited bedload samples collected, only the relative contribution of bedload samples to total sediment load could be assessed.

Particle-Size Distribution

Bedload samples for two of the high-flow events at site LT2 were analyzed to determine the distribution of particle sizes expressed at the percentage of mass finer than nine size breakpoints (table 7). Samples from the event on December 2, 2015, had an appreciably greater percentage of particles finer than 0.5 mm than did the April samples, possibly due to enhanced trapping of fine material by organic debris that had accumulated in the bag.

Computation of Bedloads

The average streamflow during the sampling period, stream width, number of subsections, length of time the sampler was on the streambed at each subsection, and total sampling time were recorded (table 3). This information, and the analyzed weight of the composited material, were used to compute instantaneous bedload for each sampling event (table 8). The equation (Edwards and Glysson, 1999, p. 80) for the computation of bedload, in short tons per day (t/d), is

$$Q_B = K * {}^{Wt}/t_T * M_{T,}$$

where

- Q is the instantaneous bedload discharge, as measured by bedload sampler, in short tons per day;
- W is the total width of the sampled cross section, in feet;
- T is the total time the sampler was on the streambed, in seconds, computed by multiplying the individual sample time by the number of subsamples;
- M is the total mass of sample collected from all verticals in the cross section, in grams; and
- K is a conversion factor used to convert grams per second per foot into short tons per day per foot. The conversion factor for the BL-84 samplers with a 3-inch opening is 0.381 (Edwards and Glysson, 1999).

At elevated flows, the instantaneous bedload ranged from 14 to 218 t/d. Instantaneous bedload during low-flow conditions on February 1, 2016, ranged from 0.3 to 2.7 t/d (table 8). This bedload sample was collected after the study period ended. In order to estimate the contribution of bedload to the total load for the sampled range of streamflows, instantaneous suspended-sediment discharges were computed for the three sample dates. The equation for instantaneous suspended-sediment discharge, in t/d, is

$$Q_s = Q_w * C_s * k,$$

where

- Q is the instantaneous suspended-sediment discharge, in short tons per day;
- Q_w is computed streamflow, in cubic feet per second;
- C_s is the regression-estimated suspended-sediment concentration, in milligrams per liter; and
- K is a coefficient based on the unit of measurement of streamflow that assumes a specific weight of 2.65, for sediment, and equals 0.0027 in inch-pound units.

The streamflow and regression-estimated SSC used in the formula are those nearest in time to the bedload sample time. The estimated percentages of instantaneous total discharge occurring as bedload varied widely (1 to 14 percent). The reason for the variability is uncertain; however, when

Table 8. Total daily suspended-sediment discharges at Little Tennessee River at Franklin, North Carolina (station 03501500; LT2), for three bedload sampling events.

[ft^3/s, cubic foot per second; t/d, short ton per day]

Date	Mean sample time	Streamflow, in ft^3/s	Instantaneous suspended-sediment discharge,[a] in t/d	Instantaneous bedload discharge,[a] in t/d	Instantaneous total sediment discharge,[a] in t/d
04/20/2015	1312	3,460	1,460	20	1,480
04/20/2015	1405	3,200	1,320	14	1,330
12/02/2015	1012	6,220	4,940	206	5,150
12/02/2015	1523	5,630	3,570	218	3,790
02/01/2016	1438	1,030[b]	16.0	2.7	18.7
02/01/2016	1512	1,070[b]	16.8	0.3	17.1

[a]Instantaneous suspended-sediment discharges were estimated using the MLR regression equations and the turbidity and streamflow at the time of the bedload sample. Instantaneous sediment discharges may exceed daily discharges because it is assumed that the instantaneous concentration and streamflow remain constant for a 24-hour period whereas a daily discharge takes into account the changing concentrations and streamflows.

[b]Low-flow conditions.

suspended-sediment loads are small, bedload sampling errors and (or) the natural temporal variability in bedload transport can result in bedload estimates that are highly variable with respect to the total load.

Summary and Conclusions

The U.S. Geological Survey conducted a 2-year study (2014–15), in cooperation with Duke Energy, to characterize the ambient suspended-sediment concentrations and sediment loads upstream and downstream from Lake Emory in Franklin, North Carolina. This report includes data collected between December 2013 and January 2016.

Continuous streamflow, continuous turbidity, and periodic suspended-sediment samples were collected at two study sites on the Little Tennessee River, upstream and downstream from the Lake Emory dam. Both equal discharge increment (EDI) and point samples were collected to define relations between suspended-sediment concentration and turbidity and streamflow. Six bedload samples were collected at the upstream site (LT2) to help assess the contribution of bedload to the total sediment load into Lake Emory.

In order to put the streamflow observed during the study period into historical perspective, the annual mean streamflows at long-term sites LT1, CC1, and LT4 were evaluated. In general, the observed streamflows during the 2-year study represented near normal conditions. The mean annual streamflow during the study period (2014–15) at these long-term sites was approximately 89 percent of the long-term mean annual streamflow. Although the total precipitation for the majority of the study period was below normal, the months prior to the study period were appreciably above normal (extremely moist), which resulted in near normal streamflows at the beginning of the study period. Precipitation and streamflow during the final 3 months of the study period were well above normal. The study period can be separated into two distinct periods based on precipitation and streamflow—the first 21 months had below normal precipitation and near normal to below normal streamflow, and the last 3 months exhibited above normal precipitation and streamflow. These data represent average streamflows of approximately 74 percent of the long-term average during the first 21 months of the study period and approximately 197 percent of the long-term average during the final 3 months of the study period

During the study period, 22 EDI suspended-sediment sampling sets and 106 automatic-sampler point samples were collected at site LT2, and 34 EDI suspended-sediment sampling sets and 129 automatic-sampler point samples were collected at site LT3. Maximum suspended-sediment concentrations from samples collected at the study sites were 1,200 milligrams per liter (mg/L) at site LT2, and 1,620 mg/L at site LT3. The total range and interquartile range (IQR) in percentage of fine-grained particles by weight was 55 to 84 (IQR 65 to 76.5) at site LT2 and 51 to 83 (IQR 61.75 to 74.25) at site LT3. The percentage of fine-grained particles (less than 0.0625 millimeter) varied as a function of streamflow. In general, the higher the flow, the lower the percentage of fine-grained particles was found. The median percentage of fine-grained particles was 68 percent at both sites LT2 and LT3, which suggests that the percentage of suspended-sediment above and below 0.0625 millimeter are about the same at the two sites, and silts and clays make up the majority of suspended-sediment particles in flux at these locations.

The total suspended-sediment loads for the 2-year study were 90,300 short tons (t) at site LT2 and 119,000 t at site LT3. High-flow events that occurred during the study period accounted for a large percentage of the total suspended-sediment load, which in general suggests that the bulk of the total suspended-sediment load is transported during high flows. A large proportion of the suspended-sediment load at both study sites occurred during back-to-back high-runoff events in the last week of the study period. Those events accounted for 36 percent of the total suspended-sediment load at site LT2 and 57 percent of the total suspended-sediment load at site LT3. Prior to those events, the load computed for the upstream site (LT2) was approximately 6,630 t greater than the load computed for the downstream site (LT3). The maximum observed streamflows during this series of events were approximately twice those of sampled streamflows at both study sites. Therefore, there is considerable uncertainty in computed suspended-sediment concentrations and suspended-sediment loads during portions of the events because application of the regression models resulted in extrapolation appreciably beyond the range of the calibration data. The bedload samples collected at site LT2 during high-flow events indicated that the percentage of total load transported as bedload during runoff conditions may not be significant. Although these sampled streamflows appear to represent typical high-flow events, there is uncertainty as to the bedload contribution during extreme high-flow events such as those seen during the last week of the study period. During low to moderate flows, estimated suspended-sediment loads were lower at site LT3 compared to those at site LT2, which suggests that sediment deposition may be occurring in the intervening reach during those conditions. During the high-flow events, the estimated suspended-sediment loads were higher at site LT3 compared to those at site LT2; however, it is impossible to say with certainty whether the increase in loading was due to scouring of lake sediment, contributions from the additional source area, model error, or a combination of one or more of these factors.

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Glossary

annual mean streamflow The arithmetic mean of the daily mean streamflows for the year noted. For example, the annual mean streamflow for 2015 is the arithmetic mean of all daily mean streamflow for that year.

bedload sediment That part of the total load (transport) in almost continuous contact with the streambed, carried forward by rolling, sliding, or bouncing.

daily mean streamflow The mean streamflow for any one day. For example, the daily mean streamflow for October 12, 2008.

mean annual streamflow The arithmetic mean of the annual mean streamflows for the designated period. For example, the mean annual streamflow for 1945–2015 is the arithmetic mean of all annual mean streamflows for that period.

mean monthly precipitation The arithmetic mean of monthly precipitation totals for the designated period. For example, the mean monthly precipitation for January is the arithmetic mean of all the January monthly totals for that period.

suspended sediment Sediments that remain in suspension in streams for a considerable period of time without contact with the streambed. Such material remains in suspension because the upward components of turbulence and currents exceed sediment settling velocities.

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