Prepared in cooperation with the City of Tulsa, Oklahoma

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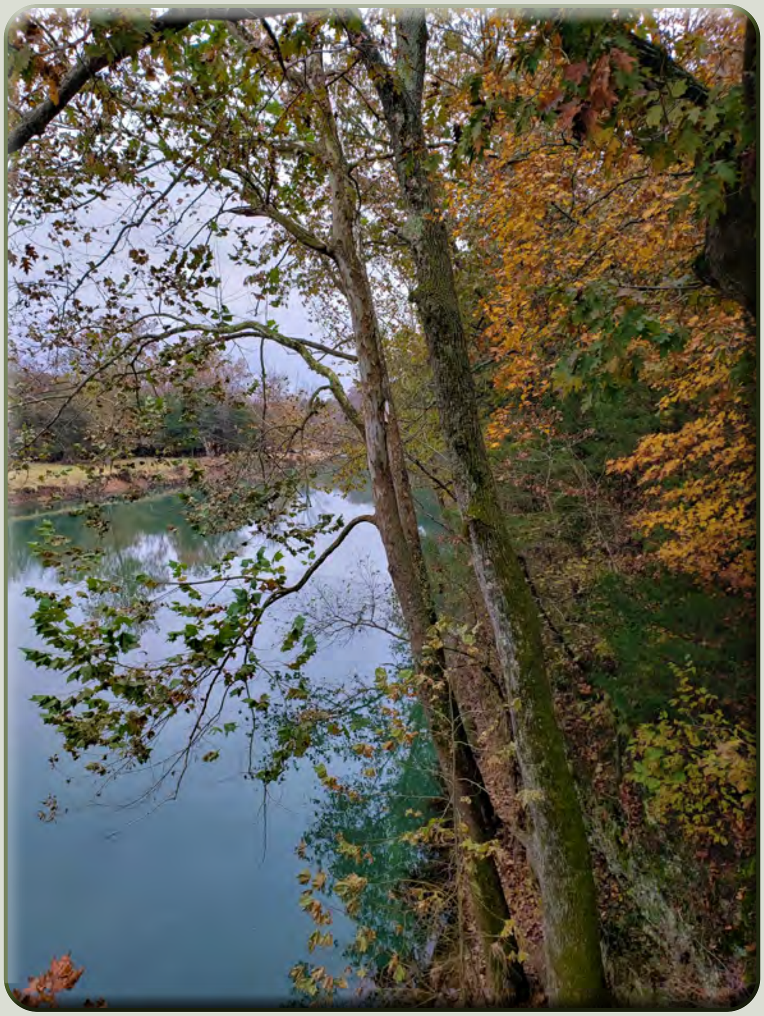

Scientific Investigations Report 2021–5105

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

Cover: Photograph showing Spavinaw Creek in Delaware County, Oklahoma, with the view oriented upstream from the west bank at U.S. Geological Survey streamgage 071912213 Spavinaw Creek near Colcord, Okla. Photograph by Emily Moyer, U.S. Geological Survey, October 2019.

Load Estimation and Trend Analysis for Nitrogen, Phosphorus, and Suspended Sediment in the Eucha-Spavinaw Drainage Area, Northeastern Oklahoma and Northwestern Arkansas, 2011–18

By Nicole Paizis, Carol Becker, and Kayla Lockmiller

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Contents

Figures

Tables

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)
	Area	
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot per second (ft/s)	0.3048	meter per second (m/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
	Application rate	
pound per year (lb/yr)	0.4536	kilogram per year (kg/yr)
pound per day (lb/d)	0.4536	kilogram per day (kg/d)
pound per year per square mile ($lb/yr/mi^2$)	0.1751	kilogram per year per square kilometer ($kg/yr/km^2$)

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

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).

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

Supplemental Information

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

AIC	Akaike information criterion
COT	City of Tulsa
DM_L	daily mean load
EPA	U.S. Environmental Protection Agency
$INST_C$	instantaneous continuous load
LRL	laboratory reporting level
p-value	probability value
R^2	coefficient of determination
RMSE	root mean square error
RPD	relative percent difference
SS	suspended sediment
TN	total nitrogen, as nitrogen
TP	total phosphorus, as phosphorus
USGS	U.S. Geological Survey
WWTP	wastewater-treatment plant

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By Nicole Paizis, Carol Becker, and Kayla Lockmiller

Abstract

Lake Eucha is a source of water for public supply and recreation for the residents of Tulsa and other municipalities in northeastern Oklahoma. Beaty Creek and Spavinaw Creek flow into Lake Eucha and drain about 388 square miles of agricultural and forested land in northeastern Oklahoma and northwestern Arkansas. Beginning in the 1990s, eutrophication of Lake Eucha characterized by excessive algal blooms resulted in taste and odor problems associated with lake water when it is used for public supply. The predominant sources of phosphorus in the Eucha-Spavinaw drainage area were identified by previous investigators as runoff from fertilized agricultural areas (nonpoint sources) and treated effluent from a wastewater-treatment plant (point source). To further evaluate the transport of nitrogen, phosphorus, and suspended sediment in the Eucha-Spavinaw drainage area, the U.S. Geological Survey (USGS), in collaboration with the City of Tulsa, estimated the loads and computed temporal trends of these constituents from water-quality and streamflow data collected at five USGS streamgages in the Beaty Creek and Spavinaw Creek subbasins.

Estimates and comparisons of total nitrogen, total phosphorus, and suspended-sediment loads from the Beaty Creek and Spavinaw Creek subbasins to Lake Eucha during 2011–18 were made by using different types of regression equations. The first type of regression equation is referred to as “daily mean load regression equations” and was developed from water-quality data obtained from periodic water-quality samples and daily mean streamflow data collected at five USGS streamgages. The second type of regression equation is referred to as “instantaneous continuous load regression equations.” In addition to water-quality data obtained from periodic water-quality samples, continuous real-time (every 15 minutes) measurements of physicochemical properties (specific conductance, water temperature, and turbidity), and continuous streamflow data were used to estimate instantaneous continuous loads of total nitrogen, total phosphorus, and suspended sediment at two of the same five streamgages where daily mean loads were estimated. The use of these two types of regression equations was documented by previous investigators who estimated loads of total nitrogen, total phosphorus, and suspended sediment in the study area by using data collected during 2002–10.

The regression equations used to estimate constituent loads that were based on water-quality data obtained from periodic water-quality samples and continuous water-quality and streamflow data (instantaneous continuous load regression equations) better described the temporal variance in constituent loads compared to the regression equations based only on periodic water-quality data and daily mean streamflows (daily mean load regression equations). Estimates computed using instantaneous continuous load regression equations showed that mean annual loads of 1,844,000 pounds of total nitrogen, 150,300 pounds of total phosphorus, and 78,735,000 pounds of suspended sediment were transported into Lake Eucha from the Beaty Creek and Spavinaw Creek subbasins. Most of the estimated mean annual loads from the Beaty Creek and Spavinaw Creek subbasins entered Lake Eucha during runoff conditions, including about 80 percent of total nitrogen, 95 percent of total phosphorus, and 98 percent of suspended sediment.

Daily, annual, and mean annual load estimates varied substantially, depending on streamflow conditions and the independent variables used to develop the regression equations. Daily and annual loads estimated from instantaneous continuous load regression equations that included specific conductance, water temperature, turbidity, and streamflow described the variability in the field data better than did loads estimated from daily mean load regression equations that included streamflow, seasonality, and time. Loads estimated from the instantaneous continuous load regression equations generally were greater than those estimated from the daily mean load regression equations.

Temporal trends in total nitrogen concentrations showed statistically significant (probability value less than or equal to 0.05) downward trends during both base-flow and runoff conditions at all five USGS streamgages except for the streamgage 07191179 Spavinaw Creek near Cherokee City,

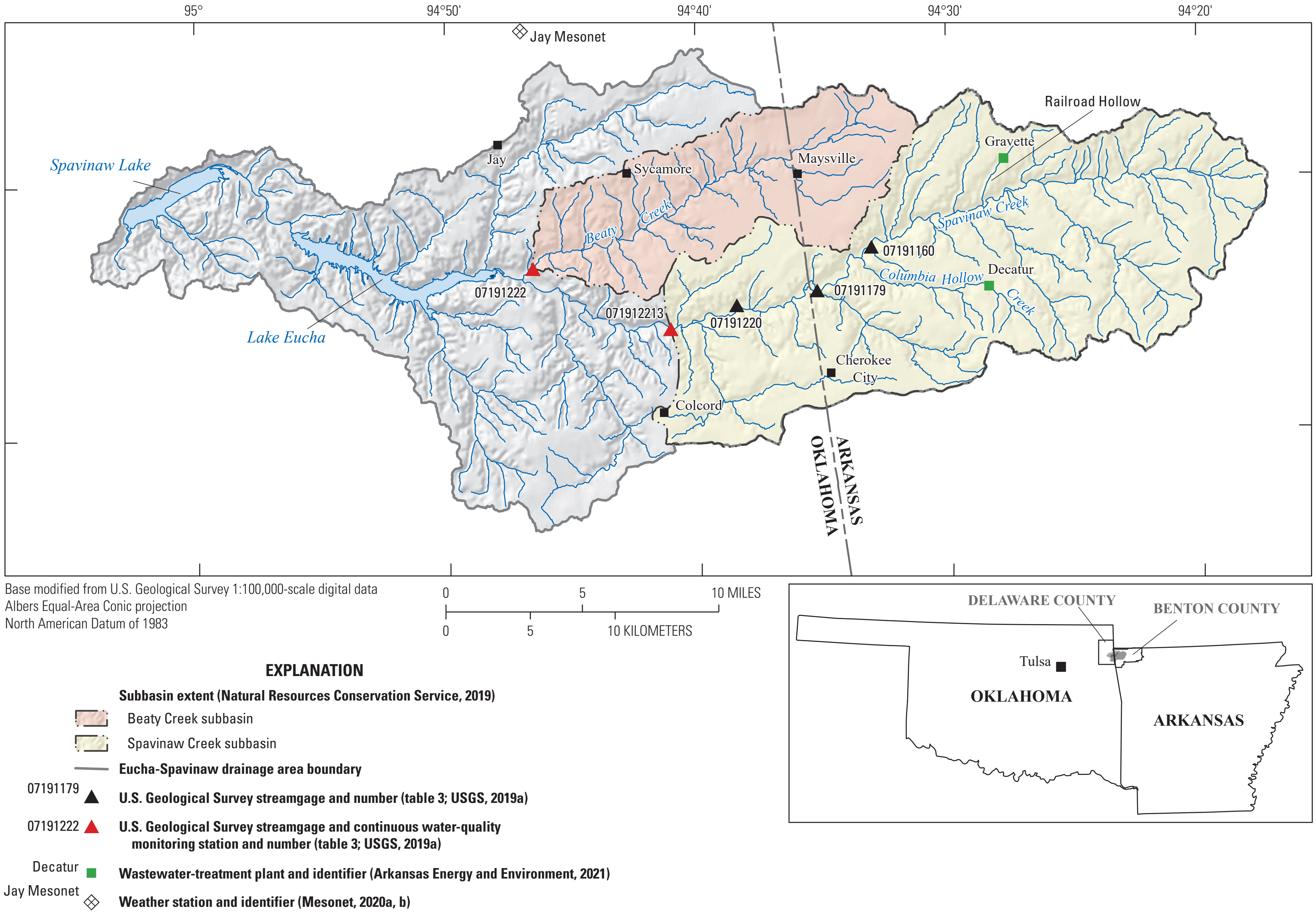
Ark. Temporal trends in total phosphorus concentrations were not consistent between streamgages over the study period, showing upward and downward trends throughout the Eucha-Spavinaw drainage area. Total phosphorus concentrations during base-flow and runoff conditions showed statistically significant upward trends at USGS streamgages 07191160 Spavinaw Creek near Maysville, Ark., and 07191222 Beaty Creek near Jay, Okla. Total phosphorus concentrations showed a statistically significant downward trend during base-flow conditions at USGS streamgage 071912213 Spavinaw Creek near Colcord, Okla., and in both base-flow and runoff conditions at USGS streamgage 07191179 Spavinaw Creek near Cherokee City, Ark. Temporal trends in suspended-sediment concentrations were not consistent between streamgages over the study period and were similar to temporal trends in total phosphorus concentrations.

Introduction

Lake Eucha is a source of water for public supply and recreation for the residents of Tulsa and other municipalities in northeastern Oklahoma (fig. 1). Lake Eucha was impounded in 1952 upstream from Spavinaw Lake, the original and primary water supply reservoir for Tulsa and surrounding municipalities that was impounded in 1924 (City of Tulsa [COT], 2021). Lake Eucha and Spavinaw Lake collect and store water from Spavinaw Creek and Beaty Creek (the largest tributary to Spavinaw Creek), and other, smaller tributaries to supply the Tulsa metropolitan area and other local water users (COT, 2021). The separate drainage areas for Beaty Creek and Spavinaw Creek are referred to in this report as the "Beaty Creek subbasin" and "Spavinaw Creek subbasin," respectively. The combined drainage areas that provide inflow to Lake Eucha and Spavinaw Lake are referred to in this report as the "Eucha-Spavinaw drainage area" (fig. 1). The Eucha-Spavinaw drainage area includes about 388 square miles (mi^2) of agricultural and forested land in northeastern Oklahoma and northwestern Arkansas (figs. 1 and 2). Beginning in the 1990s, eutrophication of Lake Eucha characterized by excessive algal blooms resulted in taste and odor problems associated with the lake water when it was used for public supply (Oklahoma Conservation Commission, 2009). The term "load" in this report refers to the mass or weight of a constituent transported past a point in a stream in a specified unit of time (Rasmussen and others, 2005; U.S. Geological Survey [USGS], 2013). Studies of constituent loads in Lake Eucha began with an unpublished 1997 study showing that the lake was enriched in phosphorus and that Beaty and Spavinaw Creeks supplied about 85 percent of the phosphorus entering the lake (K. Wagner and S. Woodruff, Oklahoma Conservation Commission, written commun., 1997). In most lakes (including Lake Eucha) the amount of phosphorous determines or limits the amount of aquatic plant growth (Maberly and others, 2020). Previous studies published during 2001–2 showed that Lake Eucha was enriched in nitrogen and phosphorus and that concentrations of phosphorus entering the lake needed to be reduced to better support the ongoing use of Lake Eucha as a public water supply (Storm and others, 2001, 2002; Oklahoma Water Resources Board, 2002).

The predominant sources of phosphorus in the Eucha-Spavinaw drainage area were identified by Storm and others (2002) as runoff from agriculture lands fertilized with poultry waste products (poultry litter), commercial fertilizer, and treated effluent from a wastewater-treatment plant (WWTP). Dispersed sources of phosphorous and other contaminants to a water body are referred to as "nonpoint sources," whereas focused sources of contaminants such as effluent from WWTPs are referred to as "point sources." Because nonpoint sources are more difficult to control and regulate than point sources, nonpoint sources are the most common sources of contaminants found in lakes and streams (Fuher and others, 1999). The major nonpoint sources of phosphorus were identified as pastureland for grazing animals and row crops, which accounted for about 17 and 48 percent, respectively, of the phosphorus load contribution to Lake Eucha from the Eucha-Spavinaw drainage area (Storm and others, 2002). The major point-source contributor in the Eucha-Spavinaw drainage area was identified as the City of Decatur, Ark., WWTP, hereinafter referred to as the "Decatur WWTP," which discharges treated effluent into Spavinaw Creek through Columbia Hollow Creek (fig. 1) (Haggard and others, 2001; Storm and others, 2002). Storm and others (2002) reported that discharge from the Decatur WWTP accounted for about 23 percent of the phosphorus load contribution from the drainage area during January 1998–December 2001. Further, a WWTP in Gravette, Ark., discharges into Spavinaw Creek through streams in Railroad Hollow. However, nutrient (total nitrogen and total phosphorus) inflows in the drainage area from the Gravette WWTP were considered small and intermittent during the study (Storm and others, 2002).

Agricultural areas fertilized with poultry litter and commercial fertilizer have been the focus of areawide programs throughout the Eucha-Spavinaw drainage area to reduce the contribution of nutrients and suspended sediment from the drainage area since the late 1990s (Storm and others, 2002; Oklahoma Conservation Commission, 2009). The application of poultry litter to agricultural areas has been a common practice in the drainage area since the 1960s. Best management practices were implemented in the Beaty Creek subbasin beginning in 1998 and the Spavinaw Creek subbasin in 2003 to improve water quality by reducing the number of nonpoint sources of nutrients and suspended sediment (Oklahoma Conservation Commission, 2009). Best management practices have included better management of poultry litter storage and use as fertilizer, establishment of riparian buffers, and stabilization of streambanks. Best management practices were introduced by the Oklahoma Conservation Commission in collaboration with industry, landowners, and local, State, and Federal partners and were still in use at the time of this study (2018).



Base modified from U.S. Geological Survey 1:100,000-scale digital data
Albers Equal-Area Conic projection
North American Datum of 1983

Figure 1. The Beaty Creek and Spavinaw Creek subbasins with locations of U.S. Geological Survey streamgages, wastewater-treatment plants, and weather station in the study area, Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.

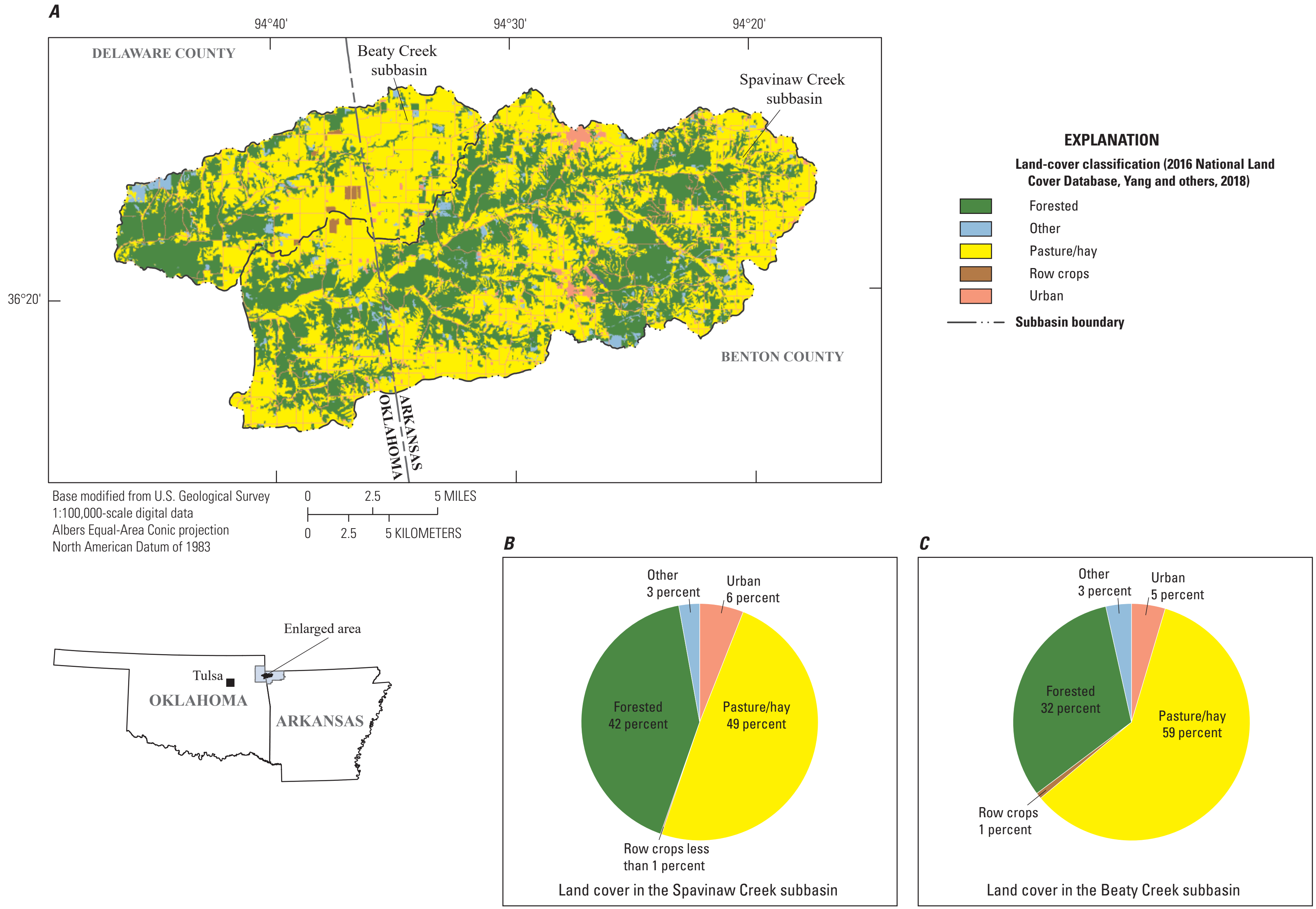


Figure 2. *A*, Areal distribution of land-cover classifications in the Eucha-Spavinaw drainage area and percentages of each land-cover classification in *B*, the Spavinaw Creek subbasin and *C*, the Beaty Creek subbasin, northeastern Oklahoma and northwestern Arkansas.

To characterize and monitor changes in nutrient and suspended-sediment concentrations, the City of Tulsa (COT) began collecting monthly water-quality samples in the 1990s from lakes and stream locations in the Eucha-Spavinaw drainage area. Samples were collected mostly during base-flow (nonrunoff) conditions. In 2002, the USGS began collecting water-quality samples during runoff conditions at five USGS streamgages to supplement the data collected by the COT (USGS, 2019a). The five USGS streamgages (fig. 1) are 07191160 Spavinaw Creek near Maysville, Ark. (hereinafter referred to as the "Maysville streamgage"); 07191179 Spavinaw Creek near Cherokee City, Ark. (hereinafter referred to as the "Cherokee streamgage"); 07191220 Spavinaw Creek near Sycamore, Okla. (hereinafter referred to as the "Sycamore streamgage"); 071912213 Spavinaw Creek near Colcord, Okla. (hereinafter referred to as the "Colcord streamgage"); and 07191222 Beaty Creek near Jay, Okla. (hereinafter referred to as the "Beaty Creek streamgage"). In 2004, continuous real-time water-quality monitors were installed at the Colcord streamgage and Beaty Creek streamgage to measure selected physicochemical properties (specific conductance, water temperature, and turbidity) every 15 minutes. Two types of regression equations were developed. The first type of regression equation only uses daily mean streamflow and water-quality data from periodic sampling events to develop daily mean loads at all five USGS streamgages in the study area. In the second type of regression equation, physicochemical data collected at the Colcord and Beaty Creek streamgages were used with streamflow and water-quality sampling data to estimate total nitrogen, total phosphorus, and suspended-sediment concentrations in the streams on an instantaneous continual basis.

Table 1 lists the estimated mean annual loads of total nitrogen, as nitrogen (hereinafter referred to as "TN"), total phosphorus, as phosphorus (hereinafter referred to as "TP"), and suspended sediment (hereinafter referred to as "SS") entering Lake Eucha from Beaty and Spavinaw Creeks computed as part of previous USGS studies for different multiyear study periods (Tortorelli 2006, 2008; Esralew and Tortorelli, 2010; Esralew and others, 2011). Esralew and others (2011) also developed daily mean load (DM_L) regression equations from water-quality sample data collected at the five USGS streamgages in the study area (Maysville streamgage, Cherokee streamgage, Sycamore streamgage, Colcord streamgage, and Beaty Creek streamgage) and instantaneous-continuous load ($INST_C$) regression equations from water-quality sample data and real-time physicochemical properties collected at the Colcord and Beaty Creek streamgages (USGS, 2019a).

Previous assessments of TN, TP, and SS loads for the Eucha-Spavinaw drainage area have been published using data collected from 2010 or earlier (Tortorelli, 2006, 2008; Esralew and Tortorelli, 2010; Esralew and others, 2011). TN, TP, and SS loads are subject to change because of ongoing land-use changes, different land-management practices, and differences in the hydrologic conditions. Therefore, the USGS completed a study in cooperation with the COT to estimate nutrient (TN and TP) loads and SS loads to Lake Eucha originating from the Beaty Creek and Spavinaw Creek subbasins using more recent data (from 2011 through 2018) compared to the data used in previous assessments (table 1).

Purpose and Scope

This report documents the development of DM_L and $INST_C$ regression equations from water-quality data collected during 2011–18 to estimate mean annual TN, TP, and SS loads to Lake Eucha. The water-quality data used to develop DM_L and $INST_C$ regression equations are characterized (USGS, 2019a). Loads and trends of TN, TP, and SS in the Eucha-Spavinaw drainage area during 2011–18 are estimated, and comparisons among loads and to loads from previous studies are provided. Estimated loads of TN, TP, and SS are for the Beaty Creek and Spavinaw Creek subbasins, which drain about 62 percent of the contributing area to Lake Eucha and about 57 percent of the contributing area to Spavinaw Lake, respectively.

Description of the Study Area

The Eucha-Spavinaw drainage area encompasses an area of about 388 mi^2 in northeastern Oklahoma (about 70 percent of the drainage area) and northwestern Arkansas (about 30 percent of the drainage area) (fig. 1). The study area is the Eucha-Spavinaw drainage area and encompasses the Spavinaw Creek subbasin, an area of 163 mi^2 upstream from the Colcord streamgage, and the Beaty Creek subbasin, an area of 59 mi^2 upstream from the Beaty Creek streamgage. Beaty and Spavinaw Creeks are the main streams in the drainage area flowing into Lake Eucha and Spavinaw Lake.

The study area is in the southwestern corner of the Ozark Highlands ecoregion (Omernik, 1987). The Mississippian-age Boone Formation, characterized by gray crinoidal limestone and interbedded chert, crops out in parts of the study area (McKnight and Fischer, 1970). In the study area, the Boone Formation contains the Springfield Plateau aquifer (Adamski and others, 1995; Renken, 1998). The Ozark Highlands ecoregion is a highly dissected limestone plateau with some steep, rocky hills and gently rolling plains (Fenneman, 1938). Soils in the Eucha-Spavinaw drainage area are silt and gravelly loams (Storm and others, 2001) and generally have a medium to high potential for erosion and runoff into streams (Adamski and others, 1995). Karstic features such as solution cavities, caves, and springs are common in this ecoregion and are caused by the dissolution of limestone bedrock (Kuniansky, 2008; Weary and Doctor, 2017). Karstic features facilitate the rapid mixing of groundwater and streams and the potential for groundwater contamination from surface-water runoff (Musgrove and Crow, 2012).

Table 1. Summary from previous U.S. Geological Survey investigations of estimated mean annual loads of total nitrogen, total phosphorus, and suspended sediment entering Lake Eucha from Beaty and Spavinaw Creeks in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas (U.S. Geological Survey, 2019a).

[lb, pound; —, not applicable]

U.S. Geological Survey investigation	Study period	Mean annual total nitrogen load (lb)	Mean annual total phosphorus load (lb)	Mean annual suspended-sediment load (lb)
Tortorelli (2006, 2008)	2002–6	[1]1,350,000–[2]1,420,000	[1]77,700–[2]81,700	—
Esralew and Tortorelli (2010)	2002–9	1,681,000	108,390	—
Esralew and others (2011)	2002–10	[3]1,888,000–[4]1,898,000	[3]117,400–[4]139,900	[3]145,300,000–[4]63,100,000

[1] Data collected during 2002–4.

[2] Data collected during 2004–6.

[3] Mean annual load computed from estimated concentrations from a daily mean load ($\mathrm{DM_L}$) regression equation using water-quality samples and daily mean streamflow data collected at five U.S. Geological Survey streamgages, 2002–10.

[4] Mean annual load computed from estimated concentrations from an instantaneous-continuous load ($\mathrm{INST_C}$) regression equation using physicochemical properties (specific conductance, water temperature, and turbidity), streamflow, and seasonality as the independent variables collected during 2004–10 at the U.S. Geological Survey streamgages 071912213 Spavinaw Creek near Colcord, Okla., and 07191222 Beaty Creek near Jay, Okla.

Land cover from the 2016 National Land Cover Database shows that the Eucha-Spavinaw drainage area is dominated by the categories of pasture/hay and forested (Multi-Resolution Land Characteristics Consortium, 2016; Yang and others, 2018) (fig. 2). During 2016, about 49 percent of land in the Spavinaw Creek subbasin was covered by pasture/hay, and about 42 percent was forested. In the Beaty Creek subbasin, about 59 percent of the land was covered by pasture/hay, and about 32 percent was forested. Urban areas account for about 6 percent or less of the areal extents of the two subbasins. About 3 percent of the land cover was characterized as “other,” and about 1 percent or less of the remaining land area was characterized as row crops in each subbasin.

Populations of Delaware County, Okla., and Benton County, Ark., during 2018 were estimated to be 42,733 and 272,608, respectively (U.S. Census Bureau, 2019). This is an increase in population of about 3 percent in Delaware County and about 19 percent in Benton County from 2010 to 2018. Most of the residents of Delaware County and Benton County do not live in the Eucha-Spavinaw drainage area, and only a small percentage of land cover is characterized as urban (fig. 2).

The main industry in the Eucha-Spavinaw drainage area is the raising of cattle and poultry (chickens). Cattle graze over large areas of pasture and hay, whereas chickens are confined to commercial poultry houses. The National Agricultural Statistics Service (2007, 2017) Census of Agriculture states that during 2002–17 the number of cattle in Delaware County ranged from about 73,000 to about 83,200 and the number of cattle in Benton County ranged from about 94,600 to about 115,500 (table 2). From statistics maintained on the number of broilers and other chickens sold during 2002–17, the number of chickens in Delaware County ranged from about 37,100,000 to about 48,200,000; in Benton County the number of chickens ranged from about 110,200,000 to about 128,000,000 during this period. The Beaty Creek and Spavinaw Creek subbasins cover only about 13 percent of the total Delaware County and Benton County area (fig. 1); therefore, the number of cattle and chickens in the study area is likely appreciably smaller than the county totals reported in table 2.

Streamflow Characteristics

Streamflows measured at the five streamgages in the Beaty Creek and Spavinaw Creek subbasins vary as a function of the sizes of their individual drainage areas, groundwater discharge, land cover, seasonal precipitation, and temperature. Of the four streamgages on Spavinaw Creek, the Colcord streamgage has the largest drainage area (163 mi^2) and had the largest mean daily streamflow, 160 cubic feet per second (ft^3/s), during 2011–18 (table 3) (USGS, 2019a). The Beaty Creek streamgage has the smallest drainage area (59 mi^2) of the five streamgages and a mean daily streamflow of 60.0 ft^3/s during the same period.

Wet years were 2015 (67.2 inches [in.]) and 2017 (54.1 in.), when annual precipitation exceeded the long-term (1994–2020) mean annual precipitation of 46.3 in. at the Jay Mesonet weather station, which is in Delaware County near the Eucha-Spavinaw drainage area (figs. 1 and 3*A*) (Mesonet, 2020a, b). Dry years, when annual precipitation was less than the long-term mean, were 2012 (35.7 in.), 2014 (38.7 in.), 2016 (34.7 in.), and 2018 (42.0 in.). Annual precipitation during 2011 (48.7 in.) and 2013 (49.4 in.) was close to the long-term mean of 46.3 in. Streamflow was highest at the five USGS streamgages (USGS, 2019a) during the wet years of 2015 and 2017 and lowest during the dry years of 2012 and 2014 (table 3; fig. 3*A*).

During the study period, streamflow in the Eucha-Spavinaw drainage area varied seasonally in response to changes in precipitation and evapotranspiration in a manner typical of streams in this part of the United States (Garbrecht and others, 2004). Mean seasonal precipitation amounts were highest during spring (March, April, and May) and lowest during winter (December, January, and February) (fig. 3*B*). Mean seasonal streamflow was highest in spring in response to high precipitation amounts and low evapotranspiration rates but decreased through summer (June, July, and August) and fall months (September, October, and November) (fig. 4) as precipitation decreased (fig. 3*B*) and evapotranspiration increased. Even though precipitation rates were lowest in winter (fig. 3*B*), mean seasonal streamflows were higher in winter than in summer and fall in response to the cessation of vegetative growth and consequently low rates of evapotranspiration (fig. 4).

Table 2. Estimates of fertilizer application, number of cattle and calves, and number of broilers and other chickens sold in counties in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2002–17 (National Agricultural Statistics Service, 2007, 2017) (U.S. Geological Survey, 2019a).

[USGS, U.S. Geological Survey]

County (area)	Percentage of the county in the subbasin upstream from USGS streamgage 071912213 Spavinaw Creek near Colcord, Okla.	Percentage of the county in the subbasin upstream from USGS streamgage 07191222 Beaty Creek near Jay, Okla.	Year	Farmland (acres)	Area treated with commercial fertilizer, lime, and soil conditioners (acres)	Area treated with manure (acres)	Total area treated (acres)	Number of cattle (including calves)	Number of broilers and other chickens sold
Delaware, Okla. (792 square miles)	23.5	67.4	2002	282,000	53,200	21,300	74,500	74,700	37,100,000
			2007	309,000	57,600	17,900	75,500	83,200	48,000,000
			2012	283,300	45,000	17,200	62,200	73,000	48,200,000
			2017	291,600	50,800	24,800	75,600	82,200	44,300,000
Benton, Ark. (884 square miles)	76.5	32.6	2002	313,000	84,700	62,800	147,500	114,000	128,000,000
			2007	254,600	57,800	33,800	91,600	94,600	117,000,000
			2012	304,800	63,300	30,600	93,900	115,500	121,900,000
			2017	243,800	53,500	27,400	80,900	96,000	110,200,000

Table 3. Streamflow characteristics at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).

[mi^2, square mile; ft^3/s, cubic foot per second]

U.S. Geological Survey streamgage number and name (fig. 1)	Short name	Drainage area (mi^2)	Mean daily streamflow during 2011–18 (ft^3/s)	Minimum mean daily streamflow (ft^3/s) (date of measurement)	Maximum mean daily streamflow (ft^3/s) (date of measurement)	Peak streamflow (ft^3/s) (date of measurement)
07191160 Spavinaw Creek near Maysville, Ark.	Maysville streamgage	89	80	7.3 (08/07/2012)	10,400 (12/27/2015)	14,800 (12/27/2015)
07191179 Spavinaw Creek near Cherokee City, Ark.	Cherokee streamgage	103	95	8.0 (03/18/2014)	11,000 (12/27/2015)	15,100 (12/27/2015)
07191220 Spavinaw Creek near Sycamore, Okla.	Sycamore streamgage	132	120	4.2 (03/21/2014)	14,000 (04/29/2017)	19,900 (04/29/2017)
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	163	160	12.4 (03/27/2014)	18,100 (04/29/2017)	26,700 (04/29/2017)
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	59.1	60	0 (08/23/2012)	8,200 (04/29/2017)	26,700 (04/29/2017)

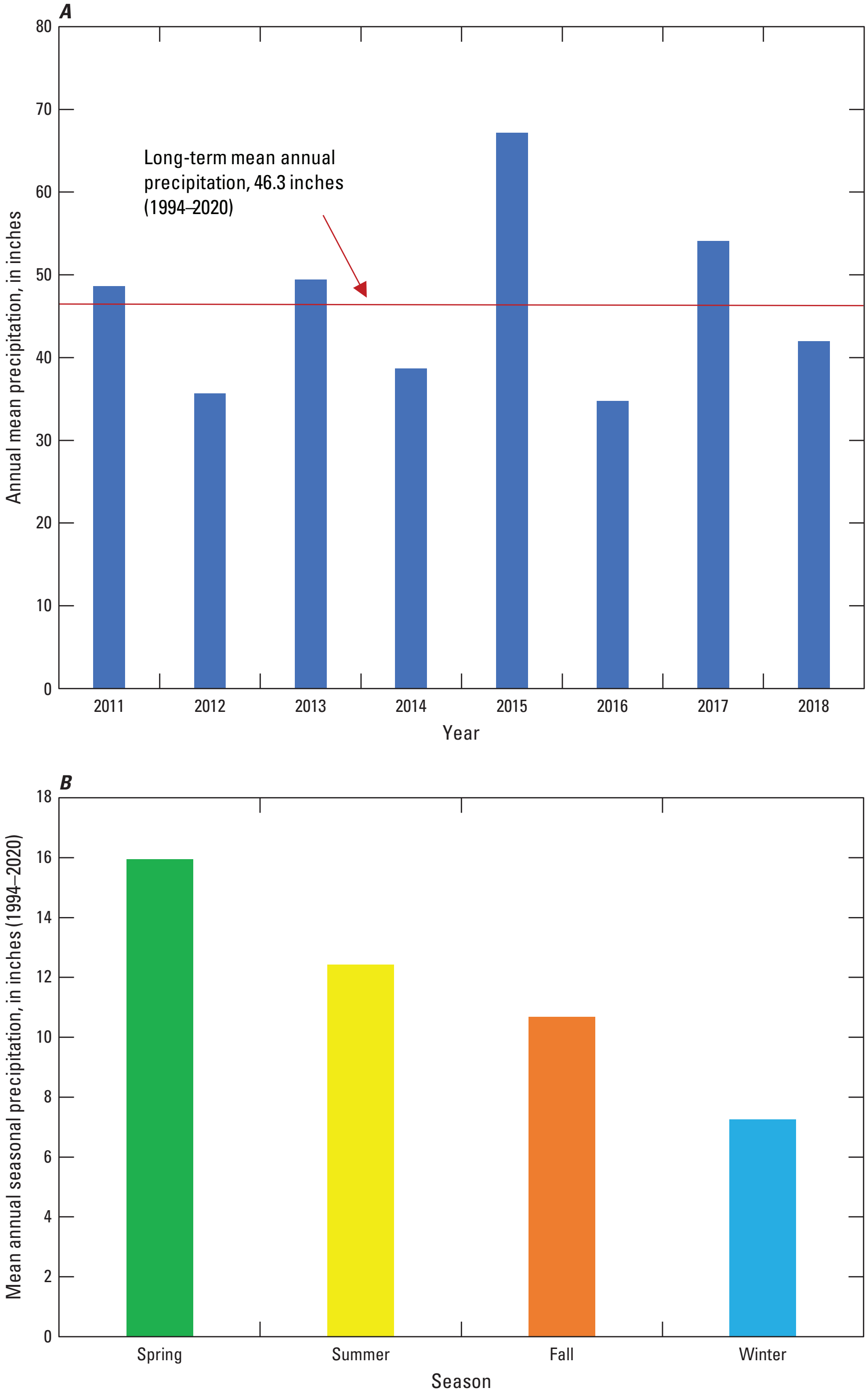
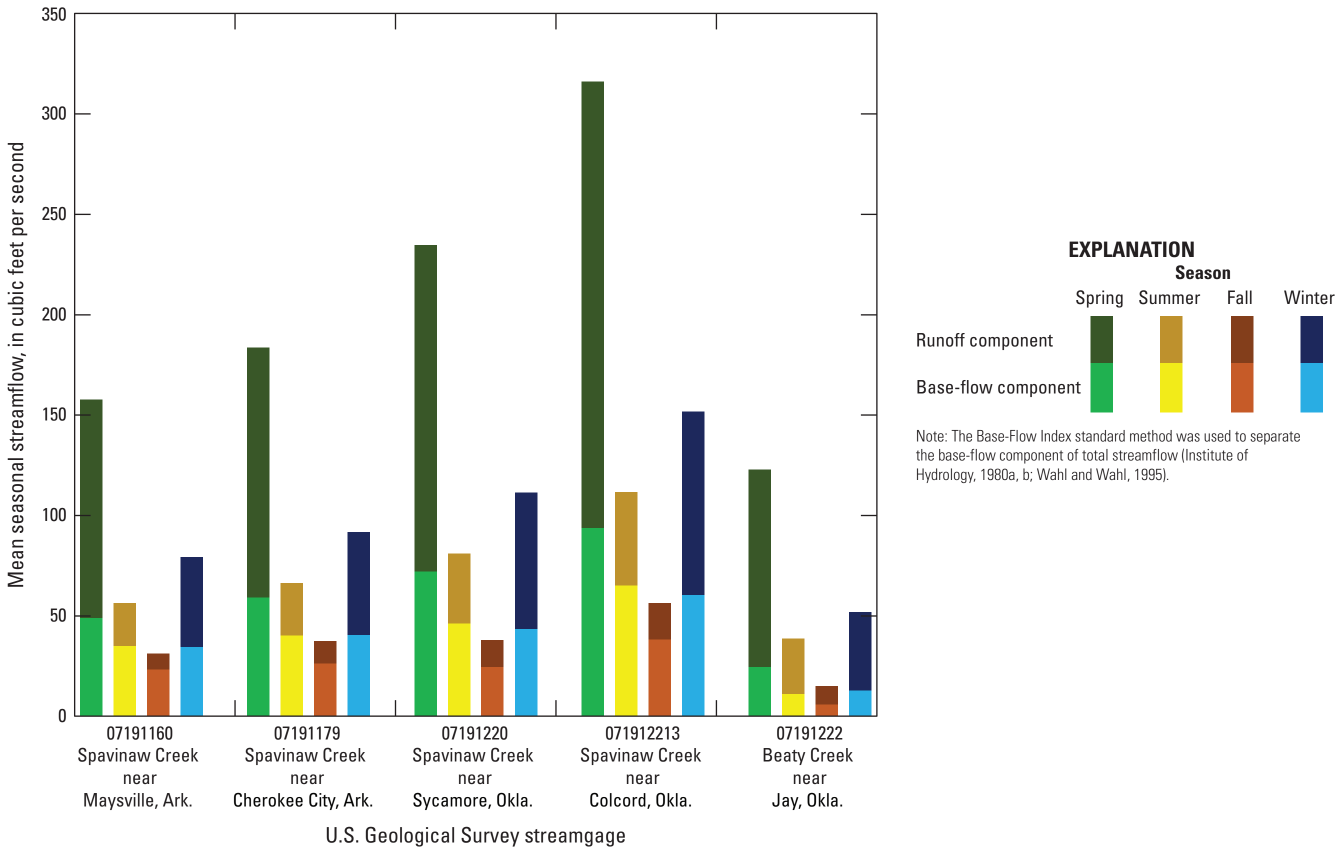


Figure 3. *A*, Annual precipitation measured during each year from 2011 to 2018 and *B*, mean seasonal precipitation during 1994–2020 measured at the Jay Mesonet weather station in Delaware County near the Eucha-Spavinaw drainage area, northeastern Oklahoma (Mesonet, 2020a, b).



Note: The Base-Flow Index standard method was used to separate the base-flow component of total streamflow (Institute of Hydrology, 1980a, b; Wahl and Wahl, 1995).

Figure 4. Mean seasonal streamflow with streamflow separated into base-flow and runoff components at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18. Spring is defined as March, April, and May; summer as June, July, and August; fall as September, October, and November; and winter as December, January, and February.

Methods

USGS water-quality and streamflow data collection and quality-assurance methods are described in this section. Also described are techniques used to analyze streamflow data and water-quality data including the streamflow separation technique, the development of regression equations, and the analysis of temporal trends in concentrations.

Water-Quality and Streamflow Data Collection

Established field procedures were followed to ensure the consistent collection of high-quality data, including USGS protocols for the preparation, collection, and processing of environmental and quality-control samples as described in the USGS “National Field Manual for the Collection of Water-Quality Data” (USGS, variously dated). Water-quality samples were collected by COT and USGS staff from one to three times per month from January 2011 to December 2018; water-quality data collected for this study are available from the USGS National Water Information System (NWIS) (USGS, 2019a) by using the streamgage numbers listed in table 3. The goal was to collect water-quality samples representative of nutrient and SS concentrations over a wide range of streamflow conditions throughout the four seasons each year. The water-quality data were collected to facilitate the development of regression equations for estimating annual loads and yields (amount of nutrient and SS loading per unit area of basin) from the drainage area. Annual mean loads and annual mean yields were determined for each year during the study period. Long-term mean annual loads for the overall 2011–18 study period were also determined. USGS staff targeted peak flows for the collection of runoff water-quality samples, which were collected using equal-width increment techniques described in Edwards and Glysson (1999). Although peak flows were targeted for the collection of runoff water-quality samples, the relatively short duration of peak flows and challenges posed by sampling logistics meant that many samples were collected before or after the peak. Nutrient and SS samples collected by the COT generally were collected during low streamflow conditions at monthly intervals and were collected at a single point near the center of the stream.

Nitrogen and phosphorus compounds were analyzed in 1,320 water-quality samples collected at the five USGS streamgages in the Eucha-Spavinaw drainage area; 223 of these discrete water-quality samples also were analyzed for SS (table 4; fig. 1) (USGS, 2019b). Water-quality samples were analyzed for nitrogen and phosphorus compounds and SS. Nitrogen compounds analyzed were ammonia (as nitrogen), total Kjeldahl nitrogen (ammonia plus organic nitrogen), and nitrate plus nitrite (as nitrogen). TN concentrations were computed for this report by summing the concentrations of total Kjeldahl nitrogen and nitrite plus nitrate. Phosphorus compounds analyzed were orthophosphate (as phosphorus) and TP. Water-quality samples for orthophosphate were filtered and represent the dissolved component in water. Water-quality samples for the other nutrients were not filtered and represent the dissolved and particulate components in water. The COT Water Quality Laboratory in Tulsa, Okla., analyzed all water-quality samples for nitrogen and phosphorus compounds by using methods shown in table 5. The highest minimum laboratory reporting levels (LRLs) and references for the laboratory methods used to analyze for nutrients and SS are also shown in table 5.

Concentrations of SS represent the amount of silt and clay sediment particles that are less than or equal to (≤) 0.0625 millimeters in diameter in 1 liter of water (Wentworth, 1922; Guy, 1969). SS water-quality samples were collected using similar methods as those used to collect nitrogen and phosphorus water-quality samples (Edwards and Glysson, 1999; USGS, variously dated). The SS samples were analyzed according to methods described by Guy (1969) at the sediment laboratory at the USGS Central Midwest Water Science Center in Rolla, Missouri.

Gage height and streamflow at the USGS streamgages were measured according to methods described in Turnipseed and Sauer (2010) and Sauer and Turnipseed (2010). Gage height and streamflow were measured at a fixed interval of 15 minutes at each of the five streamgages in the study area; 15-minute streamflow values are computed from gage height.

Continuous real-time water-quality monitors at the Colcord streamgage and Beaty Creek streamgage measured the selected physicochemical properties (specific conductance, water temperature, and turbidity) at a fixed interval of every 15 minutes. USGS protocols for operating real-time water-quality monitors are described in Wagner and others (2006). Water-quality data and real-time streamflow and physicochemical property data collected at USGS streamgages, including the USGS streamgages where data were collected for this report, are available from NWIS (USGS, 2019a, b).

Table 4. Number of water-quality samples and quality-control samples analyzed for total nitrogen, total phosphorus, and suspended sediment collected at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Short name	Number of samples				
		Water-quality samples			Quality-control samples	
		Total nitrogen[1]	Total phosphorus[2]	Suspended sediment[3]	Field blank[4]	Field replicate[5]
07191160 Spavinaw Creek near Maysville, Ark.	Maysville streamgage	139	138	40	0	8
07191179 Spavinaw Creek near Cherokee City, Ark.	Cherokee streamgage	140	140	41	1	7
07191220 Spavinaw Creek near Sycamore, Okla.	Sycamore streamgage	113	112	46	0	9
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	141	140	48	1	5
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	129	128	48	67	86

[1] Total nitrogen concentrations were computed by summing the concentrations of the nitrogen compounds total Kjeldahl nitrogen and nitrite plus nitrate nitrogen, as nitrogen measured in unfiltered water.

[2] Total phosphorus, as phosphorus was measured in unfiltered water.

[3] Not analyzed in quality-control samples.

[4] Field-blank samples consisted of purified water that was processed through clean sampling equipment to determine if sampling equipment or field procedures were contaminating water-quality samples. Field-blank samples were analyzed for nitrogen and phosphorus compounds only.

[5] Field-replicate samples were two sequential samples collected, prepared, and analyzed identically. Field-replicate samples were analyzed for nitrogen and phosphorus compounds only.

Table 5. Methods and reporting levels used for laboratory analysis of nutrients and suspended sediment in water-quality samples and for measurements of physicochemical properties at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.

[mg/L, milligram per liter; N, nitrogen; EPA, U.S. Environmental Protection Agency; P, phosphorus; NEMI, National Environmental Methods Index; µS/cm at 25 °C, microsiemens per centimeter at 25 degrees Celsius; °C, degree Celsius; —, not applicable; <, less than]

Nutrients and physicochemical properties	Method	Highest minimum laboratory reporting level
City of Tulsa laboratory		
Ammonia nitrogen (mg/L as N)	Automated colorimetry, 350.1 (EPA, 1993a)	0.1 mg/L
Nitrate nitrogen (mg/L as N)	Automated colorimetry, 353.2 (EPA, 1993b)	0.1 mg/L
Nitrite plus nitrate nitrogen (mg/L as N)	Automated colorimetry, 353.2 (EPA, 1993b)	0.2 mg/L
Total Kjeldahl, nitrogen (ammonia plus organic nitrogen) (mg/L as N)	Colorimeter, 351.2 (EPA, 1993c)	0.5 mg/L
Dissolved orthophosphate (mg/L as P)	Spectroscopy, SM 4500P-E (NEMI, 2020)	0.01 mg/L
Total phosphorus (mg/L as P) (sample collection from 12/01/2001 to 08/31/2007)	Spectroscopy, 365.2 (EPA, 1971)	0.015 mg/L
Total phosphorus (mg/L as P) (sample collection from 09/01/2007 to 12/31/2018)	Spectroscopy, SM 4500-P E (NEMI, 2020)	0.01 mg/L
U.S. Geological Survey		
Specific conductance (µS/cm at 25 °C)	Wagner and others (2006)	3 significant digits
Water temperature (°C)	Wagner and others (2006)	0.5
Turbidity	Wagner and others (2006)	—
Suspended sediment	Guy (1969)	<0.5 mg/L

Quality Assurance

USGS protocols pertaining to quality assurance that are described in the “National Field Manual for the Collection of Water-Quality Data” (USGS, variously dated) were followed. The collection of quality-control samples was a key part of the quality-assurance plan for the study (Mueller and others, 2015). Field quality-control samples were collected by the COT and USGS staff to provide overall estimates of bias (field-blank samples) and variability (field-replicate samples) in the environmental data resulting from sample collection, processing, handling, and analysis (USGS, variously dated).

Field-blank samples consisted of purified water that was processed through clean sampling equipment (analyzed for nitrogen and phosphorus compounds only) to determine if sampling equipment or field procedures were contaminating water-quality samples. Field-blank samples are prepared and processed at a given sampling site prior to the collection of environmental samples (Mueller and others, 1997). By collecting field-blank samples in this manner, the frequency and magnitude of any contamination found in the field-blank samples is indicative of contamination in the associated environmental samples (Mueller and others, 2015). A total of 69 field-blank samples were collected (table 4). Field-blank samples were collected about every 6 weeks with the largest number collected during 2014 and 2016 (13 field-blank samples) and the smallest number collected during 2018 (2 field-blank samples). A field-blank sample was collected at the beginning of a sampling event. Most field-blank samples were collected at the Beaty Creek streamgage (67 field-blank samples), but one field-blank sample was collected at both the Colcord streamgage and Cherokee streamgage. Although most field-blank samples were collected at the Beaty Creek streamgage, results are expected to represent potential contamination at all sites because similar protocols were followed with respect to sampling equipment, sample collection, processing, and analysis at each streamgage. There was no measurable contamination detected in any of the 69 field-blank samples.

Field-replicate samples were two sequential samples collected, prepared, and analyzed (for nitrogen and phosphorus compounds only) following the same methods and protocols and are expected to be identical. Any differences between field-replicate sample results indicate sample variability (Mueller and others, 1997). A total of 115 field-replicate samples were collected (table 4). Field-replicate samples were collected at the Beaty Creek streamgage (86 field-replicate samples), Cherokee streamgage (7 field-replicate samples), Colcord streamgage (5 field-replicate samples), Maysville streamgage (8 field-replicate samples), and Sycamore streamgage (9 field-replicate samples). Relative percent differences (RPDs) were computed with the following equation:

$$RPD = \frac{|C_1 - C_2|}{(C_1 + C_2)/2} \times 100 \qquad (1)$$

where

C_1 is the concentration measured in the environmental sample, and

C_2 is the concentration measured in the field-replicate sample.

The RPD value was not computed if the concentration measured in either the environmental sample or the field-replicate sample was smaller than the LRL. TN concentrations consisted mostly of nitrate and nitrite. Most concentrations of ammonia (about 96 percent) and total Kjeldahl (about 91 percent) nitrogen were smaller than the LRL. All RPDs for ammonia field-replicate samples (four samples) were less than 6 percent. Although RPDs for total Kjeldahl were larger than 20 percent in 5 of 10 field-replicate concentrations, the concentrations were small (less than 1.5 mg/L). All measured concentrations of nitrate plus nitrite and nitrate were greater than the applicable LRLs, and the mean RPD was less than 1 percent. Only one field-replicate RPD for nitrate plus nitrite was greater than 20 percent.

Quality-control data for the COT Water Quality Laboratory were assessed to evaluate the performance of analytical methods over time that might affect interpretation of the water-quality data analyzed for this study. Quality-control data included method blanks, minimum reporting level standards, blank-water spikes, and sample-matrix spikes. Results showed that there was no evidence of changes in the performance of analytical methods over time that would affect the interpretation of the data.

Streamflow Separation and Annual Trends

The base-flow and runoff components of total streamflow at each streamgage were analyzed to identify potential sources of nitrogen and phosphorus concentrations within the Beaty Creek and Spavinaw Creek subbasins. An example of the base-flow and runoff components at a given streamgage in the Beaty Creek and Spavinaw Creek subbasins is provided for the Beaty Creek streamgage (fig. 5). Water-quality samples were collected on either a “base-flow day” or a “runoff day” (fig. 5). Base-flow days were designated as those days in which base flow composed 70 percent or more of the daily streamflow. Runoff days were designated as those days in which runoff composed more than 30 percent of daily streamflow (table 6).

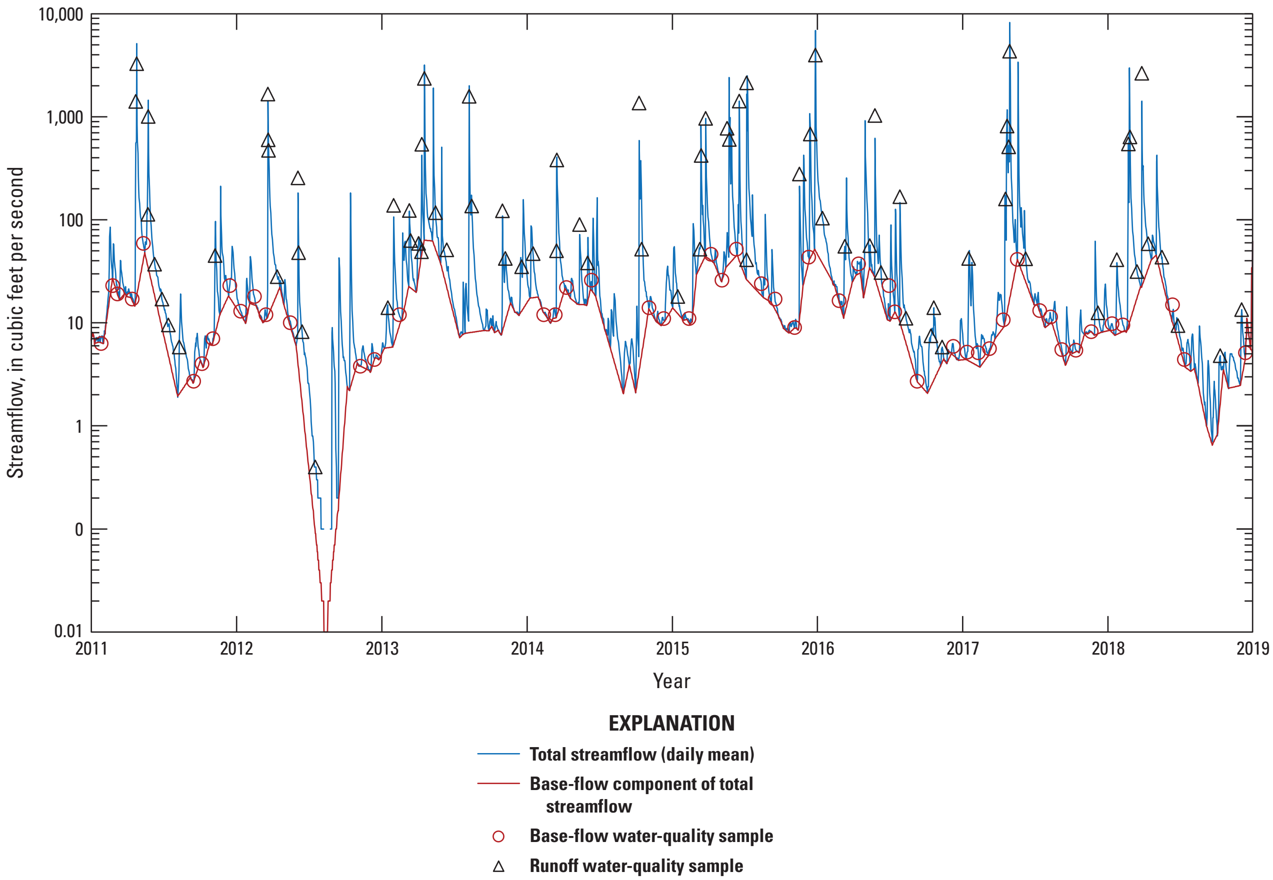
Base flow is streamflow composed primarily of groundwater seepage along the stream channel, whereas runoff is streamflow primarily derived from precipitation transported to streams during storm events (Langbein and Iseri, 1960). Concentrations of nutrients and SS in streams during base flow can be heavily influenced by point sources, whereas nutrients and SS in runoff are more representative of nonpoint sources. Base-flow and runoff components of total streamflow (daily mean) were identified with the base-flow separation analytical tool implemented through the USGS Groundwater Toolbox application (Barlow and others, 2016). The Base-Flow Index standard method was used to calculate the mean annual and mean seasonal percentages of the base-flow and runoff components of total streamflow at the five USGS streamgages in the study area (Institute of Hydrology, 1980a, b; Wahl and Wahl, 1995).

The mean annual percentage of total streamflow attributed to base flow at the USGS streamgages on Spavinaw Creek ranged from about 48 to 53 percent (table 6). Base flow made up a much smaller percentage of the total streamflow at the Beaty Creek streamgage (about 28 percent) than at the streamgages on Spavinaw Creek. The base-flow and runoff component percentages determined for this report are within about 5 percent of the mean annual base-flow and runoff components reported for the same streamgages by Esralew and Tortorelli (2010, table 3) and indicate that groundwater composes a smaller percentage of total streamflow in Beaty Creek compared to Spavinaw Creek.

The mean seasonal (spring, summer, fall, and winter) base-flow and runoff component percentages of total streamflow at the five streamgages were also computed (table 6). At streamgages on Spavinaw Creek, on average, base flow made up the largest percentage of the total streamflow during summer and fall, and runoff made up the largest percentage of the total streamflow during spring and winter. At the Beaty Creek streamgage, on average, runoff was the largest component of total streamflow during every season and composed more than 70 percent of total streamflow in all seasons except fall, when runoff was about 61 percent of total streamflow.

Statistical Analysis of Nutrient Concentrations

Nonparametric statistical tests were used to test for statistically significant differences and trends in nutrient concentrations in water-quality samples. The Wilcoxon (1945) rank-sum test was used to test for differences between TN and TP concentrations in base-flow and runoff water-quality samples and between seasonal base-flow and runoff water-quality samples collected at each streamgage. The Wilcoxon rank-sum test was used to determine if there is a statistically significant



Notes: The Base-Flow Index standard method was used to calculate the base-flow and runoff components of total streamflow (Institute of Hydrology, 1980a, b; Wahl and Wahl, 1995; Barlow and others, 2016).

Water-quality samples were collected on either a “base-flow day” or a “runoff day.” Base-flow days are those in which base flow constituted greater than or equal to 70 percent of the total streamflow. Runoff days are those in which runoff constituted 30 percent or more of the total streamflow.

Figure 5. Total streamflow (U.S. Geological Survey, 2019a) and base-flow component of total streamflow and date of base-flow and runoff water-quality sample collection during 2011–18 at the U.S. Geological Survey streamgage 07191222 Beaty Creek near Jay, Okla., in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas.

difference between the two groups of data for a given level of significance and was selected because it does not require normally distributed data (Helsel and others, 2020). The null hypothesis is that there is no difference in the median concentrations between the sample groups compared. By selecting a 5-percent significance level, a probability value (p-value) less than 0.05 indicates a statistically significant difference between the two groups. If the null hypothesis was rejected, then median concentrations were described as being statistically different. The Mann-Kendall (Mann, 1945) and Seasonal Mann-Kendall (Hirsch and others, 1982) trend tests were used to analyze for annual and seasonal trends in flow-weighted TN, TP, and SS mean concentrations at each streamgage. Flow-weighted mean concentrations were computed by dividing the total mass load over the time period analyzed by the total streamflow volume during that period. The Seasonal Mann-Kendall trend test was used to analyze monthly streamflow periods for monotonic trends. The trend analyses used the nonparametric Kendall’s *tau* correlation coefficient to detect upward or downward trends in streamflow over time. The sign of the Kendall’s *tau* correlation coefficient was used to test for temporal trends in streamflow. A positive Kendall’s *tau* indicates an upward monotonic trend, whereas a negative Kendall’s *tau* indicates a downward monotonic trend; the trend analysis results indicate the direction and not the magnitude of change in streamflow (Barbie and others, 2012; Helsel and others, 2020). For the null hypothesis, streamflow and time are independent variables and the sampling distribution of Kendall’s *tau* has an expected value of zero. Streamflow trends were considered statistically significant if the p-value associated with the Kendall’s *tau* correlation coefficient was ≤ 0.05.

Table 6. Mean annual and mean seasonal base-flow and runoff components of total streamflow at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.

U.S. Geological Survey streamgage number and name	Short name	Component of total streamflow[2,3]	Number of days in study period	Seasonal streamflow component (in percent)[1]				
				Annual	Spring	Summer	Fall	Winter
07191160 Spavinaw Creek near Maysville, Ark.	Maysville streamgage	Base flow	2,262	53	31	62	74	43
		Runoff	660	47	69	38	26	57
07191179 Spavinaw Creek near Cherokee City, Ark.	Cherokee streamgage	Base flow	2,229	52	32	61	71	44
		Runoff	693	48	68	39	29	56
07191220 Spavinaw Creek near Sycamore, Okla.	Sycamore streamgage	Base flow	2,037	48	31	57	65	39
		Runoff	880	52	69	43	35	61
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	Base flow	2,201	49	30	58	68	40
		Runoff	721	51	70	42	32	60
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	Base flow	1,562	28	20	29	39	25
		Runoff	1,360	72	80	71	61	75

[1] Spring is defined as March, April, and May; summer as June, July, and August; fall as September, October, and November; and winter as December, January, and February.

[2] Base-flow days are those in which base flow constituted greater than or equal to 70 percent of the total streamflow. Runoff days are those in which runoff constituted 30 percent or more of the total streamflow. Base-flow and runoff days were identified using the base-flow separation analytical tool implemented through the U.S. Geological Survey Groundwater Toolbox application (Barlow and others, 2016).

[3] The Base-Flow Index standard method was used to calculate the mean annual and mean seasonal percentages of the base-flow and runoff components of total streamflow at the five streamgages over the study period (Institute of Hydrology, 1980a, b; Wahl and Wahl, 1995).

Development of DM_L and $INST_C$ Regression Equations

Esralew and others (2011) used DM_L and $INST_C$ regression equations to estimate concentrations and loads of TN, TP, and SS in the Eucha-Spavinaw drainage area by using data collected during 2002–10. The two types of regression equations in this report were created from data collected during 2011–18 as part of this study (USGS, 2019a) by using the same regression methods described in Esralew and other (2011). Similarly, TN, TP, and SS loads were estimated by using rloadest, a script designed for the R programming language (R version 3.6.3) (R Core Team, 2019) that replicates the regression equation methods in Esralew and others (2011).

DM_L regression equations were developed for the five USGS streamgages in the study area by regressing daily mean TN, TP, and SS loads (the product of daily mean concentration and daily mean streamflow) on daily means of streamflow and functions of time (table 7). $INST_C$ regression equations were developed for the Colcord and Beaty Creek streamgages to estimate the concentrations of TN, TP, and SS from streamflow and instantaneous measurements of physicochemical properties (specific conductance, water temperature, and turbidity) obtained every 15 minutes with water-quality monitors (table 8). Regression equations were developed by using the rloadest script (Runkel and others, 2004; Runkel and DeCicco, 2017; USGS, 2020).

Linear regression equations were used to evaluate relations between TN, TP, and SS loads (dependent variables) and streamflow and time (independent variables) (Helsel and others, 2020). Regression equations facilitate the estimation of daily water-quality constituent (TN, TP, or SS) loads from continuous streamflow data. Daily mean streamflow and water-quality concentration data were used in the regression analyses.

Table 7. Regression equations for estimating daily mean load of total nitrogen, total phosphorus, and suspended sediment developed from streamflow, seasonality, time, and water-quality samples at five U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.

[R^2, coefficient of determination; USGS, U.S. Geological Survey; ln, natural logarithm; $DM_{L\ TN}$, total nitrogen daily mean load, in pounds per day; Q, daily mean streamflow, in cubic feet per second; T, decimal time, time variable in decimal years; sin, sine; cos, cosine; SS, seasonality variable; $DM_{L\ TP}$, total phosphorus daily mean load, in pounds per day; $DM_{L\ SS}$, suspended sediment daily mean load, in pounds per day; lb/d, pound per day; RMSE, root mean square error]

Number of observations	Constituent	Daily mean load regression equation	Estimated residual variance (lb/d)	RMSE (lb/d)	R^2 (percentage)
USGS streamgage 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage) (fig. 1, table 3)					
136	Total nitrogen	$\ln(DM_{L\ TN}) = 8.37 + 1.07{\times}\ln Q - 0.028{\times}T + 0.050{\times}\sin SS + 0.101{\times}\cos SS$	0.021	0.144	99.2
138	Total phosphorus	$\ln(DM_{L\ TP}) = 4.25 + 1.53{\times}\ln Q + 0.107{\times}(\ln Q)^2 - 0.100{\times}\sin SS - 0.138{\times}\cos SS$	0.197	0.444	96.5
138	Suspended sediment	$\ln(DM_{L\ SS}) = 10.33 + 1.76{\times}\ln Q$	2.230	1.100	74.5
USGS streamgage 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage) (fig. 1, table 3)					
139	Total nitrogen	$\ln(DM_{L\ TN}) = 8.49 + 1.03{\times}\ln Q$	0.036	0.189	98.4
139	Total phosphorus	$\ln(DM_{L\ TP}) = 4.59 + 0.95{\times}\ln Q + 0.041{\times}(\ln Q)^2 - 0.106{\times}T + 0.216{\times}\sin SS - 0.017{\times}\cos SS$	0.423	0.650	84.0
139	Suspended sediment	$\ln(DM_{L\ SS}) = 10.31 + 1.66{\times}\ln Q + 0.078{\times}(\ln Q)^2 - 0.020{\times}T - 0.079{\times}(T)^2 + 0.241{\times}\sin SS - 0.031{\times}\cos SS$	1.620	1.200	80.6
USGS streamgage 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage) (fig. 1, table 3)					
108	Total nitrogen	$\ln(DM_{L\ TN}) = 8.89 + 1.08{\times}\ln Q - 0.031{\times}T + 0.051{\times}\sin SS + 0.103{\times}\cos SS$	0.046	0.215	98.5
108	Total phosphorus	$\ln(DM_{L\ TP}) = 4.96 + 1.40{\times}\ln Q + 0.115{\times}(\ln Q)^2 - 0.032{\times}T$	0.204	0.450	95.7
108	Suspended sediment	$\ln(DM_{L\ SS}) = 10.87 + 1.41{\times}\ln Q + 0.111{\times}(\ln Q)^2 - 0.147{\times}\sin SS + 0.547{\times}\cos SS$	1.400	1.180	73.4
USGS streamgage 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage) (fig. 1, table 3)					
143	Total nitrogen	$\ln(DM_{L\ TN}) = 8.90 + 1.09{\times}\ln Q - 0.02{\times}T + 0.062{\times}\sin SS + 0.130{\times}\cos SS$	0.030	0.173	99.0
143	Total phosphorus	$\ln(DM_{L\ TP}) = 5.29 + 1.45{\times}\ln Q + 0.087{\times}(\ln Q)^2$	0.284	0.533	94.9
143	Suspended sediment	$\ln(DM_{L\ SS}) = 11.24 + 1.62{\times}\ln Q + 0.115{\times}T$	1.580	1.260	80.1

Table 7. Regression equations for estimating daily mean load of total nitrogen, total phosphorus, and suspended sediment developed from streamflow, seasonality, time, and water-quality samples at five U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.—Continued

[R^2, coefficient of determination; USGS, U.S. Geological Survey; ln, natural logarithm; $DM_{L\ TN}$, total nitrogen daily mean load, in pounds per day; Q, daily mean streamflow, in cubic feet per second; T, decimal time, time variable in decimal years; sin, sine; cos, cosine; SS, seasonality variable; $DM_{L\ TP}$, total phosphorus daily mean load, in pounds per day; $DM_{L\ SS}$, suspended sediment daily mean load, in pounds per day; lb/d, pound per day; RMSE, root mean square error]

Number of observations	Constituent	Daily mean load regression equation	Estimated residual variance (lb/d)	RMSE (lb/d)	R^2 (percentage)
USGS streamgage 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage) (fig. 1, table 3)					
127	Total nitrogen	$\ln(DM_{L\ TN}) = 7.36 + 1.080\times\ln Q - 0.014\times T + 0.0966\times\sin SS + 0.095\times\cos SS$	0.056	0.237	98.7
127	Total phosphorus	$\ln(DM_{L\ TP}) = 3.58 + 1.383\times\ln Q + 0.089\times(\ln Q)^2 + 0.018\times T + 0.012\times(T)^2 - 0.045\times\sin SS - 0.114\times\cos SS$	0.129	0.359	98.2
127	Suspended sediment	$\ln(DM_{L\ SS}) = 10.29 + 1.425\times\ln Q - 0.322\times T$	2.770	1.600	74.5

Table 8. Regression equations for estimating instantaneous continuous load of total nitrogen, total phosphorus, and suspended sediment developed from water-quality samples and instantaneous measurements of specific conductance, water temperature, turbidity, and streamflow at two U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.

[R^2, coefficient of determination; USGS, U.S. Geological Survey; ln, natural logarithm; $INST_C$, instantaneous continuous load; *TN*, total nitrogen concentration, in milligrams per liter; *Q*, streamflow, in cubic feet per second; *DEGC*, temperature in degrees Celsius; *SC*, specific conductance, in microsiemens per centimeter at 25 degrees Celsius; *FNU*, turbidity, in formazin nephelometric units; *TP*, total phosphorus concentration, in milligrams per liter; *SS*, seasonality variable; RMSE, root mean square error; lb/d, pound per day]

Number of observations	Constituent	Instantaneous continuous load regression equation	Estimated residual variance (lb/d)	RMSE (lb/d)	R^2 (percentage)	Bias-correction factor
		USGS streamgage 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage) (fig. 1, table 3)				
143	Total nitrogen	$\ln(INST_{C\ TN}) = 3.52 + 1.081\times\ln Q - 0.38\times\ln DEGC + 0.011\times\ln SC + 0.019\times\ln FNU$	0.034	0.184	98.9	1.01
138	Total phosphorus	$\ln(INST_{C\ TP}) = 3.60 + 1.42\times\ln Q + 0.087\times(\ln Q)^2 + 0.586\times\ln DEGC$	0.168	0.410	96.3	1.15
138	Suspended sediment	$\ln(INST_{C\ SS}) = 13.09 + 1.52\times\ln Q - 0.091\times(\ln Q)^2 + 1.06\times\ln DEGC - 1.17\times\ln SC + 0.389\times\ln FNU$	0.740	0.860	87.9	1.31
		USGS streamgage 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage) (fig. 1, table 3)				
130	Total nitrogen	$\ln(INST_{C\ TN}) = 2.86 + 1.078\times\ln Q - 0.181\times\ln DEGC + 0.012\times\ln SC + 0.017\times\ln FNU$	0.050	0.243	98.6	1.02
128	Total phosphorus	$\ln(INST_{C\ TP}) = 4.25 + 1.31\times\ln Q + 0.09\times(\ln Q)^2 + 0.24\times\ln DEGC - 0.289\times\ln SC$	0.090	0.310	98.0	1.10
127	Suspended sediment	$\ln(INST_{C\ SS}) = 6.30 + 1.08\times\ln Q - 0.01\times(\ln Q)^2 + 0.860\times\ln DEGC + 0.591\times\ln FNU$	1.090	1.040	90.1	1.40

Constituent load (L) is computed as the product of streamflow (Q), the constituent concentration (C), and time (T) multiplied by a conversion factor to convert the product of cubic feet per second and milligrams per liter to pounds per day, or mass per unit of time. Maximum likelihood regression equations (Dempster and others, 1977; Wolynetz, 1979; Cohn and others, 1992) built into rloadest were used to estimate regression variables and daily mean loads. The script rloadest contains nine predefined regression equations featuring different combinations of variables. The regression equation used for this report (eq. 1 in Runkel and others, 2004) includes time and seasonality variables to simulate the relation between the natural logarithms of constituent load, streamflow, and streamflow squared by using a derivation of the following equation:

$$\begin{aligned}\ln(L) \;=\; & b_0 + b_1 \times \ln Q + b_2 \\ & \times \ln Q^2 + b_3 \times T + b_4 \times T^2 + b_5 \\ & \times \sin SS + b_6 \times \cos SS\end{aligned} \qquad (2)$$

where

ln is natural logarithm;
L is constituent load, in pounds per day;
b_0 is a regression constant, dimensionless;
b_1, b_2, b_3, b_4, b_5, b_6 are regression coefficients, dimensionless;
$\ln Q$ is the centered natural logarithm of daily mean streamflow, in units of the natural logarithm of cubic feet per second;
T is the centered time, in decimal calendar years;
sin is sine;
SS is seasonality variable $2\pi T$ where π is the quantity “pi” of approximately 3.14159; and
cos is cosine.

Users of rloadest select the best regression equation to estimate constituent load from various combinations of streamflow, seasonality, and time coefficients by using one or all of the variables from equation 2. The Akaike information criterion (AIC) from each possible regression equation is computed, and the equation with the lowest AIC is selected as the “best” equation. The “best” regression equation fits the data well (based on the computed AIC) and minimizes the number of independent variables (Akaike, 1974; Runkel and others, 2004). AIC uses an equation’s maximum likelihood estimation as a measure of fit. The “best” regression equation will be the one that is chosen that neither underfits nor overfits (Akaike, 1974).

Collinearity arises when one of the independent variables is related to one or more of the other independent variables in a regression equation (Helsel and others, 2020). Streamflow is the volume of water flowing past a fixed point in the stream per unit time (typically cubic feet per second) (Sauer and Turnipseed, 2010; Turnipseed and Sauer, 2010). Because time is part of a streamflow measurement, collinearity between the linear and quadratic forms of streamflow and time are accounted for in eq. 2. To account for the collinearity between streamflow and time in eq. 2, time and the natural log of streamflow were centered as described in Runkel and others (2004). Within rloadest the centering constant is subtracted from each measured concentration in the calibration dataset, and the resulting centered values are used to develop the linear regression equation. As a result of using this centering method, the linear and quadratic terms are orthogonal and no longer collinear (Gilroy and others, 1990; Cohn and others, 1992; Runkel and others, 2004).

DM_L regression equations differed by constituent and streamgage (table 7). One general regression equation was selected to estimate daily loads (based on eq. 2) for each constituent at all streamgages in a given drainage area. Developing general equations for each constituent facilitated the selection of the “best” equations compared with this general equation and indicated only a very small reduction in the standard errors of estimate in the “best” equations compared to the general equations. Each final regression equation selected to estimate daily TN, TP, and SS loads was based on only those observations where complete data (no missing values) were available for all the independent variables. The use of one equation is beneficial for evaluation of the changes in the slope between load and streamflow with time for the entire sampling period. A statistically significant time variable (positive or negative) respectively indicates a statistically significant upward or downward trend in flow-adjusted constituent loads during the sampling period (Helsel and others, 2020).

The script rloadest was used to estimate daily constituent loads, which in turn were used to compute annual loads. For consistency with previous publications (Esralew and Tortorelli, 2010; Esralew and others, 2011), all annual loads were computed by calendar year (January 1–December 31). The script rloadest provides the estimate of the daily load, in pounds per day, and that number is then multiplied by the number of days, such as 365 for a year, to compute the annual load. The daily load estimate from the rloadest equation is considered a daily mean load, not an instantaneous load for a single point in time. A limitation of this approach is that the relation between instantaneous streamflow and instantaneous load is not the same as the relation between daily mean streamflow and instantaneous load. Daily constituent loads might be overestimated or underestimated, depending on the streamflow conditions. For longer periods (entire seasons or years), estimation uncertainty is less compared to the uncertainty for shorter periods such as during runoff events (Christensen and others, 2008; Tortorelli, 2008). During large runoff events, underestimated constituent loads might result when the instantaneous streamflow is larger than daily mean streamflow and the constituent concentrations are relatively low. Relatively low constituent concentrations can occur when dense vegetation impedes mobilization of nutrients and SS from the land surface to the stream. This type of scenario might result in computed daily mean loads that are smaller than the actual total daily loads. During large runoff events, overestimated constituent loads are also possible if, for example, the instantaneous streamflow is larger than daily mean streamflow and the nutrient and SS concentrations are relatively high. Relatively high nutrient and SS concentrations can occur when sparse vegetation enhances mobilization of nutrients and SS from the land surface to the stream. This type of scenario might result in computed daily mean loads that are larger than the actual total daily loads.

$INST_C$ regression equations were developed to estimate concentrations and loads of TN, TP, and SS in real time by using the same methods as Christensen and others (2008) and Esralew and others (2011) (table 8). Instantaneous concentrations and instantaneous streamflow corresponded to a single moment in time as opposed to a daily mean. Unlike in the DM_L regression equations, time was not considered an independent variable in the $INST_C$ regression equations. Hence, the $INST_C$ regression equations could be used to estimate future concentrations in real-time data from continuous water-quality monitors (Christensen and others, 2008) with the added advantage that by not considering time as an independent variable the $INST_C$ regression equations are consistent with the regression equations in previous reports (Esralew and Tortorelli, 2010; Esralew and others, 2011). The residual errors in the $INST_C$ regression equations were checked for possible trends in the variables used in these regression equations by using the Kendall's tau trend test (Kendall, 1975); no trends in the variables were detected. In instances of missing instantaneous measurements of physicochemical properties, instantaneous concentrations and loads could not be estimated using the $INST_C$ regression. Daily load estimates and prediction intervals from the DM_L regression equations were substituted when (1) less than one-half of $INST_C$ estimates were available for a day and streamflow and physicochemical properties were not substantially variable, or (2) more than one-half of $INST_C$ estimates were available and streamflow and physicochemical properties were substantially variable or there were data gaps. Uncertainties of $INST_C$ estimates were determined from the rloadest script by using a 90-percent prediction interval (Helsel and others, 2020). The 90-percent prediction interval was used for all estimates and might contain substantial uncertainty depending on the amount of substituted data used to fill data gaps.

It is important to consider the uncertainty associated with the $INST_C$ regression equations if the equations are used to estimate future TN, TP, and SS loads. The coefficient of determination (R^2), root mean square error (RMSE), and prediction intervals provide indications of uncertainty (Legates and McCabe, 1999; Harmel and Smith, 2007; Helsel and others, 2020). Duan's smearing estimator is used for bias correction (Duan, 1983). Streamflow uncertainty was not evaluated in this report.

Loads, temporal trends, and yields of TN, TP, and SS were computed from flow-weighted concentrations developed from DM_L regression equations. Loads were computed from daily mean flow-weighted concentrations in milligrams per liter. These values were summed and converted to pounds per day and pounds per year after multiplying by the flow-weighted concentration by the streamflow volume during the time period analyzed. Loads during base-flow and runoff days were computed after separating the daily mean streamflow into base-flow and runoff groups for the entire sampling period by using the base-flow separation methods described in the "Streamflow Separation and Annual Trends" section of this report. Mean annual yields were computed by dividing mean annual loads by the drainage area of each streamgage. Mean annual yields are reported in pounds per year per square mile.

Characterization of Water-Quality Data Used To Develop Regression Equations

TN, TP, and SS concentrations were measured in water-quality samples and used to develop DM_L regression equations for estimating mean annual loads in the drainage area. TN, TP, and SS concentrations are characterized in this section of the report in terms of seasonal concentrations in base flow and runoff and are compared among streamgages and between subbasins (USGS, 2019a).

Higher TN and TP concentrations were related to higher streamflows and higher runoff components of total streamflow (figs. 6 and 7). Mean concentrations of TN and TP were consistently higher in runoff water-quality samples than in base-flow water-quality samples during all seasons (table 9). By using a Wilcoxon rank-sum test, it was determined that median concentrations were also significantly higher during runoff than during base flow as indicated by the p-value that was ≤ 0.05 in spring runoff water-quality samples than in base-flow water-quality samples at all five streamgages. Higher concentrations of TN and TP in runoff water-quality samples can indicate that nonpoint sources such as fertilized fields are contributors of nutrients. Figure 8 shows the distributions of TN and TP concentrations in base-flow and runoff water-quality samples.

Mean and median and TN concentrations were consistently highest during spring and winter in both base-flow and runoff water-quality samples at all five streamgages (table 9; fig. 9) and might have multiple causes. By using a Wilcoxon rank-sum test it was determined that median TN concentrations were significantly higher (p-value ≤ 0.05) in runoff water-quality samples than in base-flow samples during spring and winter at the four streamgages on Spavinaw Creek; this is likely a result of the fertilizer that is applied to crops in spring and can run off into streams and leak into groundwater during precipitation events. During winter, available nitrogen in the soils is not utilized by vegetation and during precipitation events can readily become part of surface-water runoff to streams or seep into groundwater as recharge occurs and subsequently contribute to base flow. In Spavinaw Creek, median TN concentrations for all seasons ranged from 3.30 to 3.80 mg/L in base-flow samples and 3.90 mg/L to 4.45 mg/L in runoff water-quality samples (table 9). In Beaty Creek at the Beaty Creek streamgage, median TN concentrations for individual seasons ranged from 2.18 to 3.10 mg/L in base-flow samples and 2.70 to 3.55 mg/L in runoff water-quality samples (table 9).

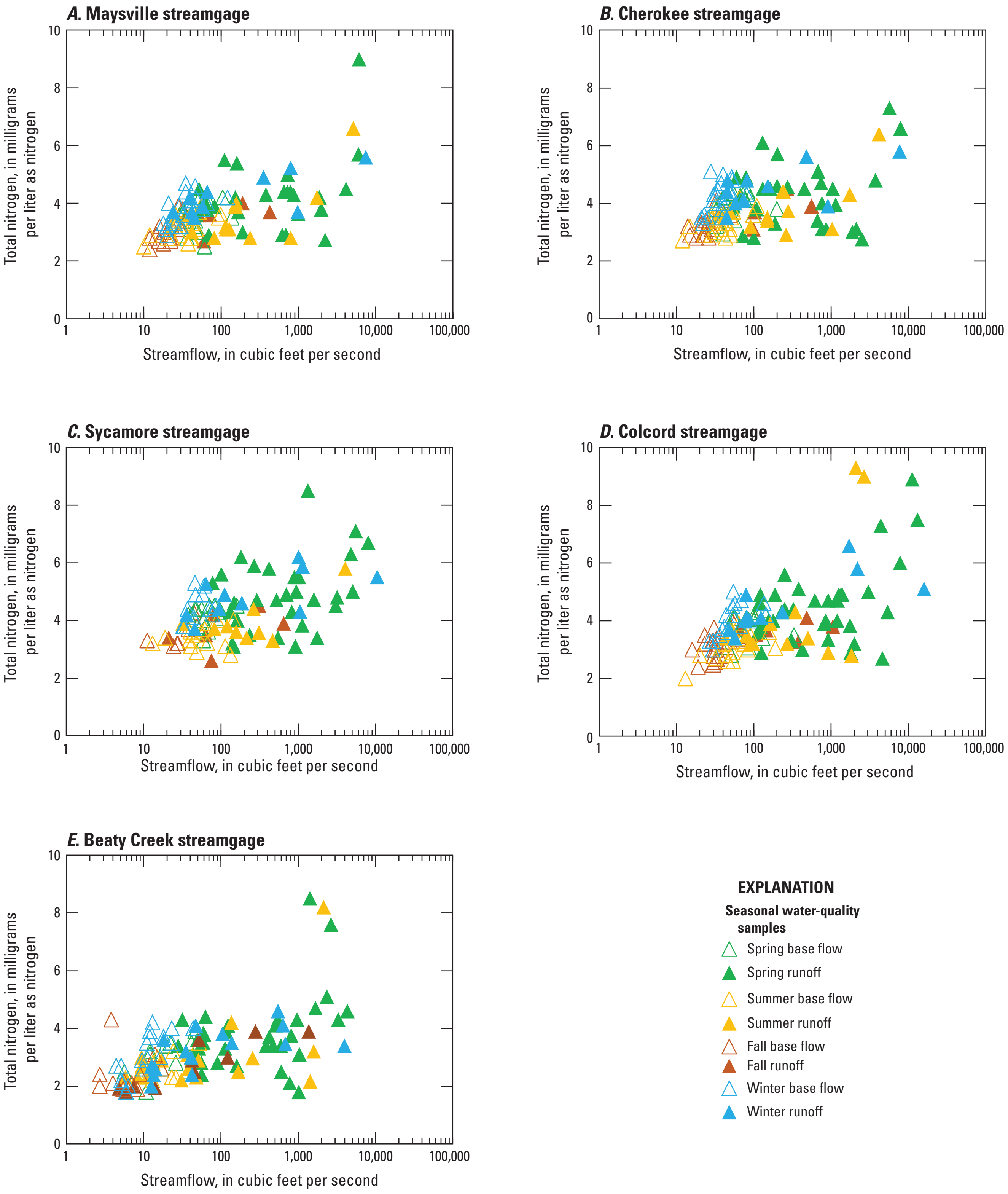


Figure 6. Relation between seasonal total nitrogen concentrations and streamflow in base-flow and runoff water-quality samples collected during 2011–18 at U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) *A*, 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage); *B*, 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage); *C*, 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage); *D*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage); and *E*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage). Spring is defined as March, April, and May; summer as June, July, and August; fall as September, October, and November; and winter as December, January, and February.

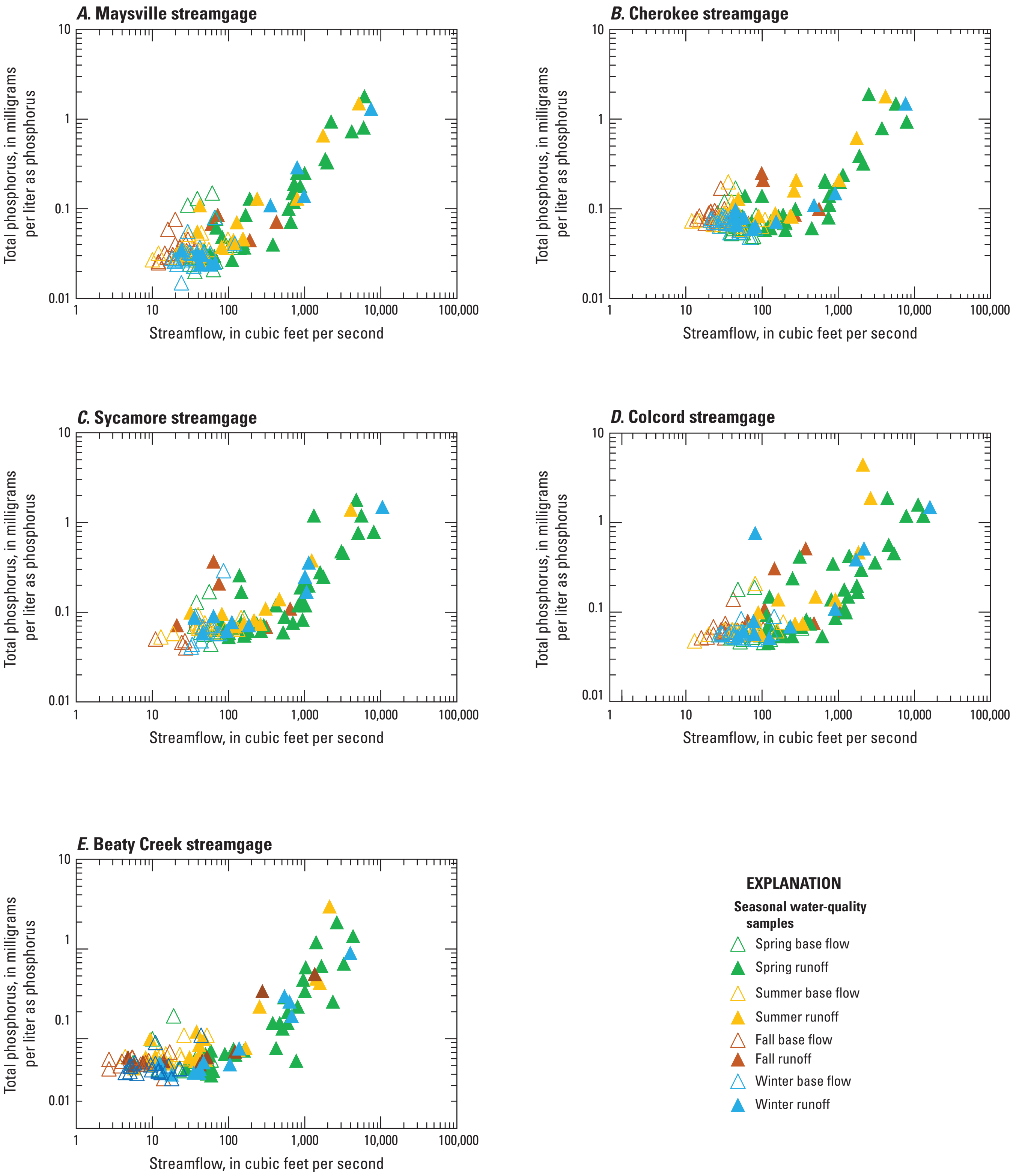


Figure 7. Relation between seasonal total phosphorus concentrations and streamflow in base-flow and runoff water-quality samples collected during 2011–18 at U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) *A*, 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage); *B*, 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage); *C*, 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage); *D*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage); and *E*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage). Spring is defined as March, April, and May; summer as June, July, and August; fall as September, October, and November; and winter as December, January, and February.

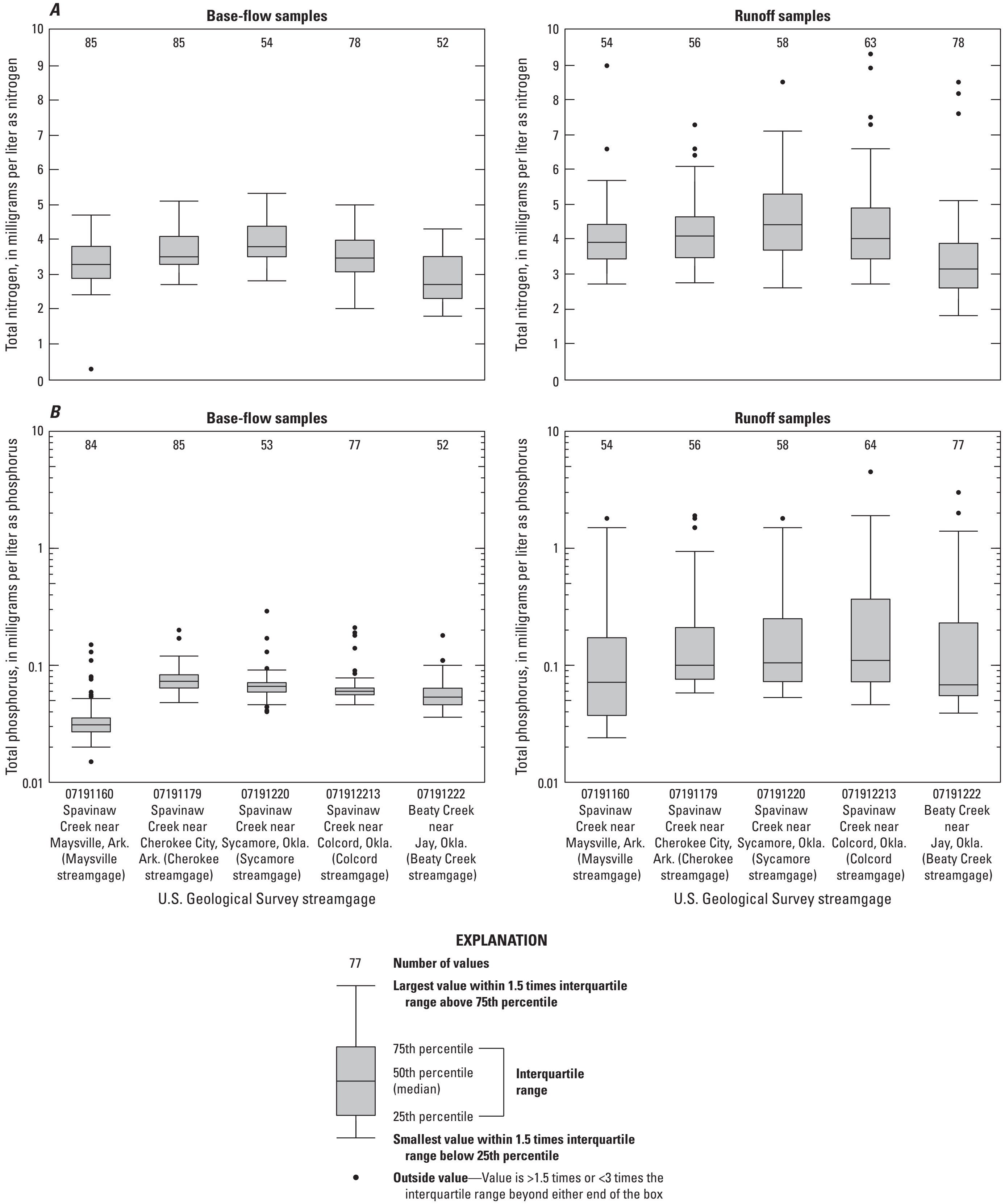


Figure 8. Distributions of *A*, total nitrogen concentrations and *B*, total phosphorus concentrations in base-flow and runoff water-quality samples collected during 2011–18 at five U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas. The total nitrogen concentration of 24.20 milligrams per liter measured in the runoff sample at the Sycamore streamgage (table 9) is off scale and therefore not shown.

Table 9. Summary statistics for seasonal concentrations of total nitrogen, total phosphorus, and suspended sediment in base-flow and runoff water-quality samples collected at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; SS, suspended sediment. Concentrations were measured in discrete water-quality samples, not flow-weighted samples]

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Season	Base-flow conditions					Runoff conditions				
		Number of samples	Minimum (mg/L as N)	Maximum (mg/L as N)	Median (mg/L as N)	Mean (mg/L as N)	Number of samples	Minimum (mg/L as N)	Maximum (mg/L as N)	Median (mg/L as N)	Mean (mg/L as N)
					Total nitrogen concentrations						
07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage)	All seasons	85	0.26	4.7	3.3	3.3	54	2.7	9	3.9	3.9
	Spring	18	2.5	4.2	3.65	3.57	27	2.73	9	4.2	4.25
	Summer	24	2.5	3.9	3.2	3.18	12	2.8	6.6	3.15	3.59
	Fall	22	0.26	3.9	3.05	2.94	5	2.7	4	3.6	3.52
	Winter	21	2.9	4.7	3.8	3.76	10	3.5	5.6	4.05	4.28
07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage)	All seasons	84	2.7	5.1	3.5	3.66	56	2.75	7.3	4.1	4.21
	Spring	17	2.94	4.4	3.9	3.89	29	2.75	7.3	4.5	4.3
	Summer	24	2.7	4.2	3.35	3.36	12	2.9	6.4	3.6	3.88
	Fall	22	2.8	4.1	3.3	3.29	5	3.1	4.5	3.9	3.86
	Winter	21	3.3	5.1	4.3	4.19	10	3.5	5.8	4.5	4.55
07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage)	All seasons	54	2.8	5.3	3.8	3.89	58	2.6	24.2	4.45	4.94
	Spring	16	3.3	4.5	4.25	4.15	32	3.1	8.5	4.71	4.87
	Summer	19	2.8	4	3.5	3.45	10	3.3	24.2	3.75	5.97
	Fall	8	3.1	4.3	3.5	3.6	6	2.6	4.5	3.69	3.68
	Winter	11	3.8	5.3	4.4	4.5	10	3.7	6.2	4.75	4.89
071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage)	All seasons	78	2	5	3.45	3.48	63	2.7	9.3	4	4.42
	Spring	17	2.8	4.4	3.9	3.75	35	2.7	8.9	4.4	4.53
	Summer	20	2	3.9	3.2	3.12	12	2.8	9.3	3.4	4.34
	Fall	23	2.4	4.1	3.2	3.19	6	3.27	4.1	3.69	3.68
	Winter	18	3	5	4.05	4.01	10	3.4	6.6	4.2	4.6
07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage)	All seasons	51	1.8	4.3	2.7	2.87	82	1.8	8.5	3.15	3.37
	Spring	13	1.8	3.9	3.1	3.02	34	1.8	8.5	3.55	3.79
	Summer	9	2.2	3.5	2.7	2.72	23	2.16	8.2	2.9	3.04
	Fall	11	1.9	4.3	2.18	2.45	10	1.8	3.9	2.7	2.75
	Winter	18	1.8	4.2	3	3.08	15	2	4.6	3.4	3.26

Table 9. Summary statistics for seasonal concentrations of total nitrogen, total phosphorus, and suspended sediment in base-flow and runoff water-quality samples collected at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).—Continued

[mg/L, milligram per liter; N, nitrogen; P, phosphorus; SS, suspended sediment. Concentrations were measured in discrete water-quality samples, not flow-weighted samples]

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Season	Base-flow conditions					Runoff conditions				
		Number of samples	Minimum (mg/L as P)	Maximum (mg/L as P)	Median (mg/L as P)	Mean (mg/L as P)	Number of samples	Minimum (mg/L as P)	Maximum (mg/L as P)	Median (mg/L as P)	Mean (mg/L as P)
Total phosphorus concentrations											
07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage)	All seasons	84	0.015	0.15	0.031	0.037	54	0.024	1.8	0.072	0.072
	Spring	18	0.02	0.15	0.029	0.048	27	0.027	1.8	0.1	0.256
	Summer	23	0.026	0.05	0.032	0.035	12	0.038	1.5	0.064	0.24
	Fall	22	0.025	0.076	0.032	0.036	5	0.029	0.086	0.068	0.06
	Winter	21	0.015	0.08	0.028	0.032	10	0.024	1.3	0.034	0.201
07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage)	All seasons	85	0.048	0.2	0.073	0.077	56	0.058	1.9	0.1	0.269
	Spring	17	0.048	0.17	0.063	0.071	29	0.058	1.9	0.11	0.289
	Summer	25	0.059	0.2	0.074	0.081	12	0.077	1.8	0.12	0.305
	Fall	22	0.057	0.17	0.08	0.085	5	0.07	0.25	0.1	0.143
	Winter	21	0.048	0.083	0.071	0.069	10	0.06	1.5	0.082	0.228
07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage)	All seasons	53	0.04	0.29	0.066	0.072	58	0.053	1.8	0.105	0.274
	Spring	16	0.044	0.17	0.067	0.075	32	0.053	1.8	0.12	0.304
	Summer	18	0.053	0.094	0.068	0.069	10	0.07	1.4	0.098	0.253
	Fall	8	0.04	0.072	0.057	0.057	6	0.066	0.37	0.091	0.15
	Winter	11	0.041	0.29	0.059	0.082	10	0.059	1.5	0.089	0.273
071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage)	All seasons	77	0.046	0.21	0.06	0.07	64	0.05	4.5	0.11	0.37
	Spring	17	0.046	0.19	0.056	0.071	35	0.046	1.9	0.14	0.322
	Summer	20	0.048	0.21	0.063	0.069	12	0.056	4.5	0.12	0.646
	Fall	23	0.052	0.14	0.062	0.065	6	0.076	0.52	0.105	0.2
	Winter	17	0.05	0.09	0.058	0.06	11	0.052	1.5	0.08	0.333
07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage)	All seasons	52	0.036	0.18	0.054	0.06	77	0.039	3	0.068	0.243
	Spring	13	0.044	0.18	0.054	0.065	34	0.039	2	0.078	0.295
	Summer	10	0.048	0.11	0.067	0.073	19	0.047	3	0.075	0.274
	Fall	11	0.036	0.071	0.056	0.055	10	0.051	0.53	0.06	0.134
	Winter	18	0.036	0.11	0.047	0.052	14	0.04	0.91	0.054	0.154

Table 9. Summary statistics for seasonal concentrations of total nitrogen, total phosphorus, and suspended sediment in base-flow and runoff water-quality samples collected at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).—Continued

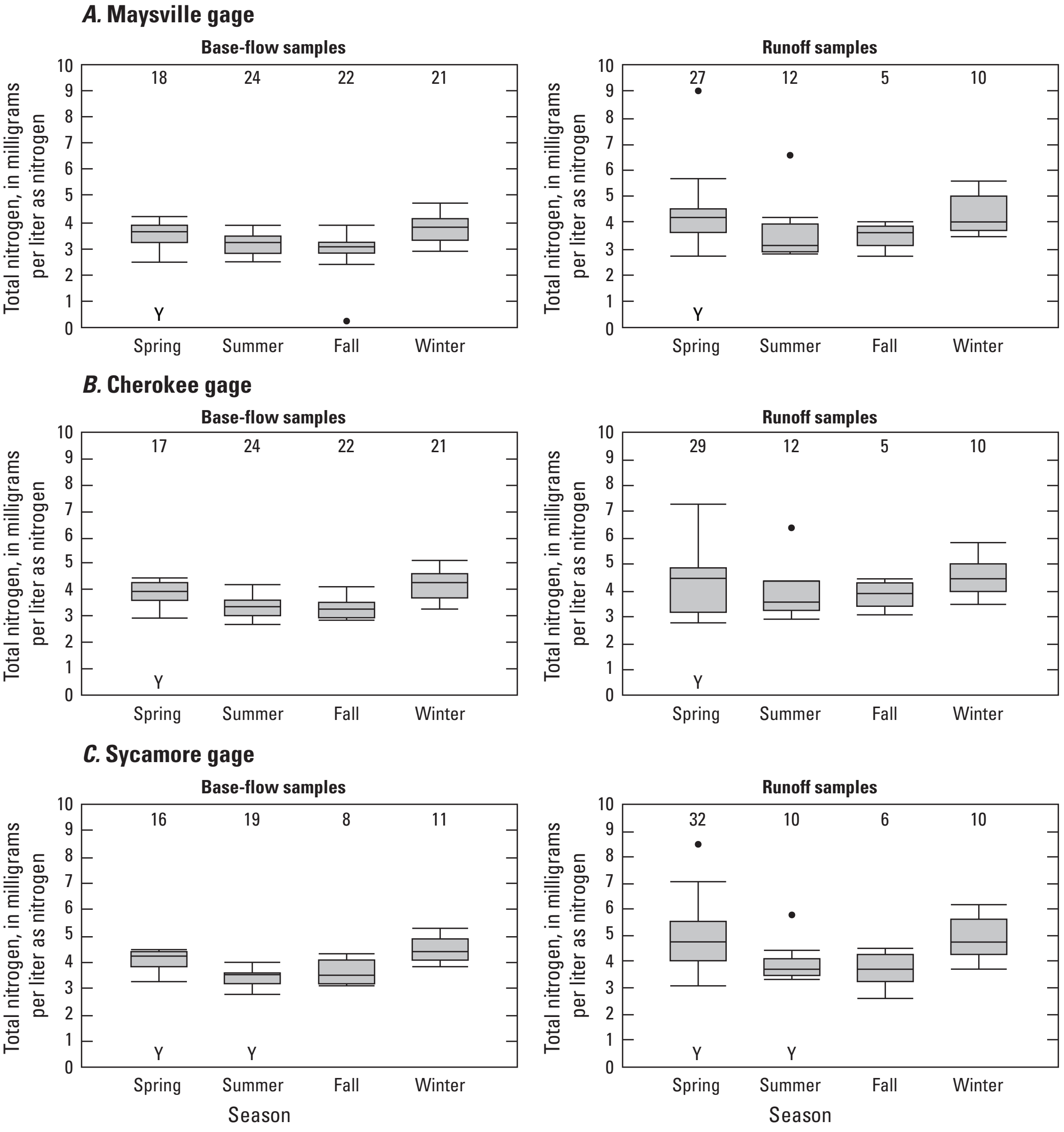
[mg/L, milligram per liter; N, nitrogen; P, phosphorus; SS, suspended sediment. Concentrations were measured in discrete water-quality samples, not flow-weighted samples]

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Season	Base-flow conditions					Runoff conditions				
		Number of samples	Minimum (mg/L of SS)	Maximum (mg/L of SS)	Median (mg/L of SS)	Mean (mg/L of SS)	Number of samples	Minimum (mg/L of SS)	Maximum (mg/L of SS)	Median (mg/L of SS)	Mean (mg/L of SS)
Suspended-sediment concentrations											
07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage)	All seasons	7	0.5	50	9	15.9	33	1	1,910	28	254
07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage)	All seasons	8	0.5	13	4.5	5.94	33	0.5	1,330	18	180
07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage)	All seasons	8	1	11	3.5	4.63	37	2	1,710	40	215
071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage)	All seasons	5	3	9	4	5.4	43	2	1,780	62	255

Table 9. Summary statistics for seasonal concentrations of total nitrogen, total phosphorus, and suspended sediment in base-flow and runoff water-quality samples collected at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).—Continued

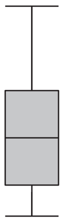
[mg/L, milligram per liter; N, nitrogen; P, phosphorus; SS, suspended sediment. Concentrations were measured in discrete water-quality samples, not flow-weighted samples]

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Season	Base-flow conditions					Runoff conditions				
		Number of samples	Minimum (mg/L of SS)	Maximum (mg/L of SS)	Median (mg/L of SS)	Mean (mg/L of SS)	Number of samples	Minimum (mg/L of SS)	Maximum (mg/L of SS)	Median (mg/L of SS)	Mean (mg/L of SS)
Suspended-sediment concentrations—Continued											
07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage)	All seasons	3	0.5	6	3	3.17	45	0.5	3,380	25	253



EXPLANATION

18 Number of values



Largest value within 1.5 times interquartile range above 75th percentile

75th percentile

50th percentile (median)

25th percentile

Interquartile range

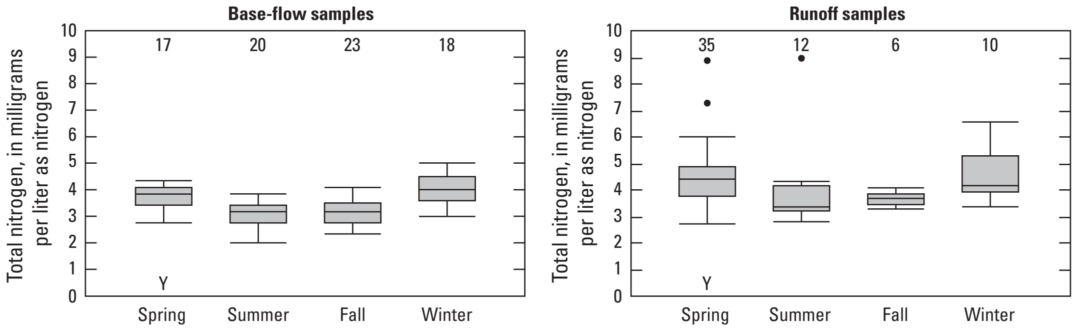
Smallest value within 1.5 times interquartile range below 25th percentile

● **Outside value**—Value is >1.5 times or <3 times the interquartile range beyond either end of the box

Y **Seasonal base-flow and runoff sample distributions from the same streamgage with a Y are significantly different as a result of the Wilcoxon (1945) rank-sum test**

Figure 9. Seasonal distribution of total nitrogen concentrations in base-flow and runoff water-quality samples collected during 2011–18 at U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) *A*, 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage); *B*, 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage); *C*, 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage); *D*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage); and *E*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage). The total nitrogen concentration of 24.20 milligrams per liter measured in the runoff sample at the Sycamore streamgage (table 9) (July 8, 2015) is off scale and therefore not shown. Spring is defined as March, April, and May; summer as June, July, and August; fall as September, October, and November; and winter as December, January, and February.

***D.* Colcord gage**



***E.* Beaty Creek gage**

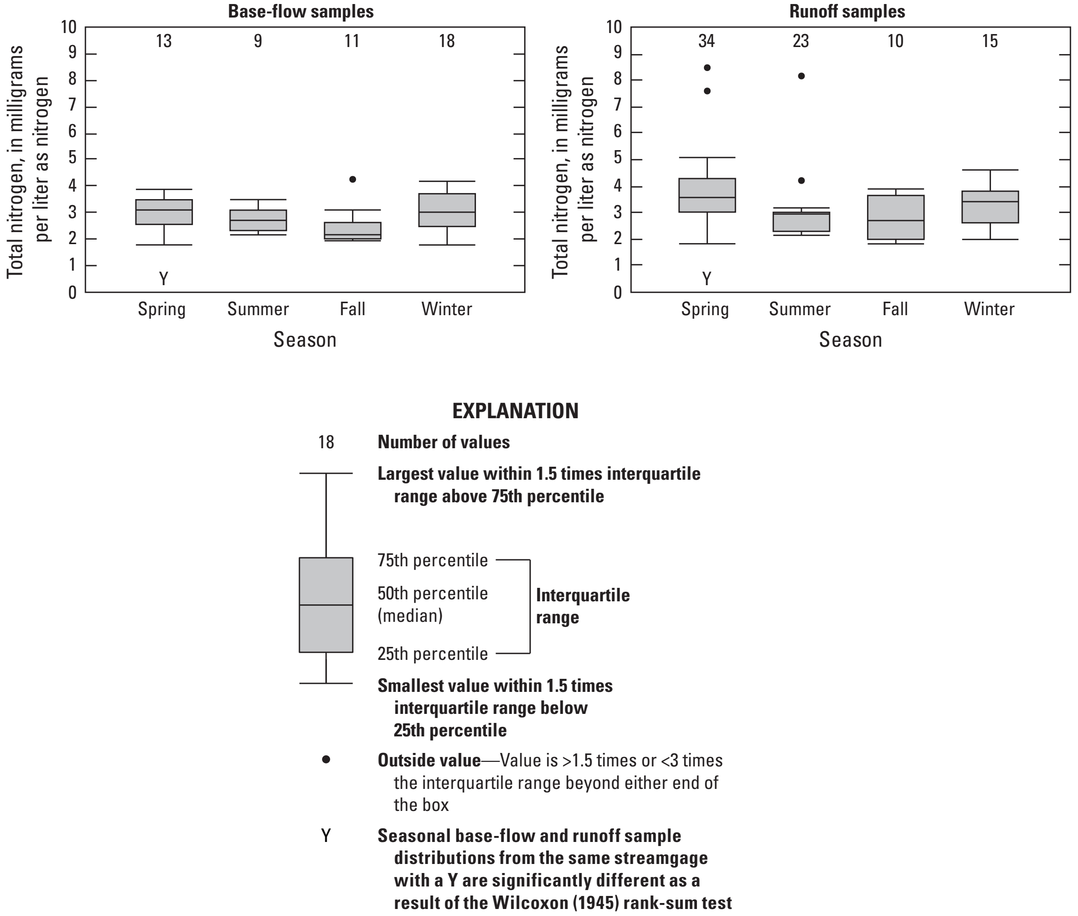


Figure 9. Seasonal distribution of total nitrogen concentrations in base-flow and runoff water-quality samples collected during 2011–18 at U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) *A*, 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage); *B*, 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage); *C*, 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage); *D*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage); and *E*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage). The total nitrogen concentration of 24.20 milligrams per liter measured in the runoff sample at the Sycamore streamgage (table 9) (July 8, 2015) is off scale and therefore not shown. Spring is defined as March, April, and May; summer as June, July, and August; fall as September, October, and November; and winter as December, January, and February.—Continued

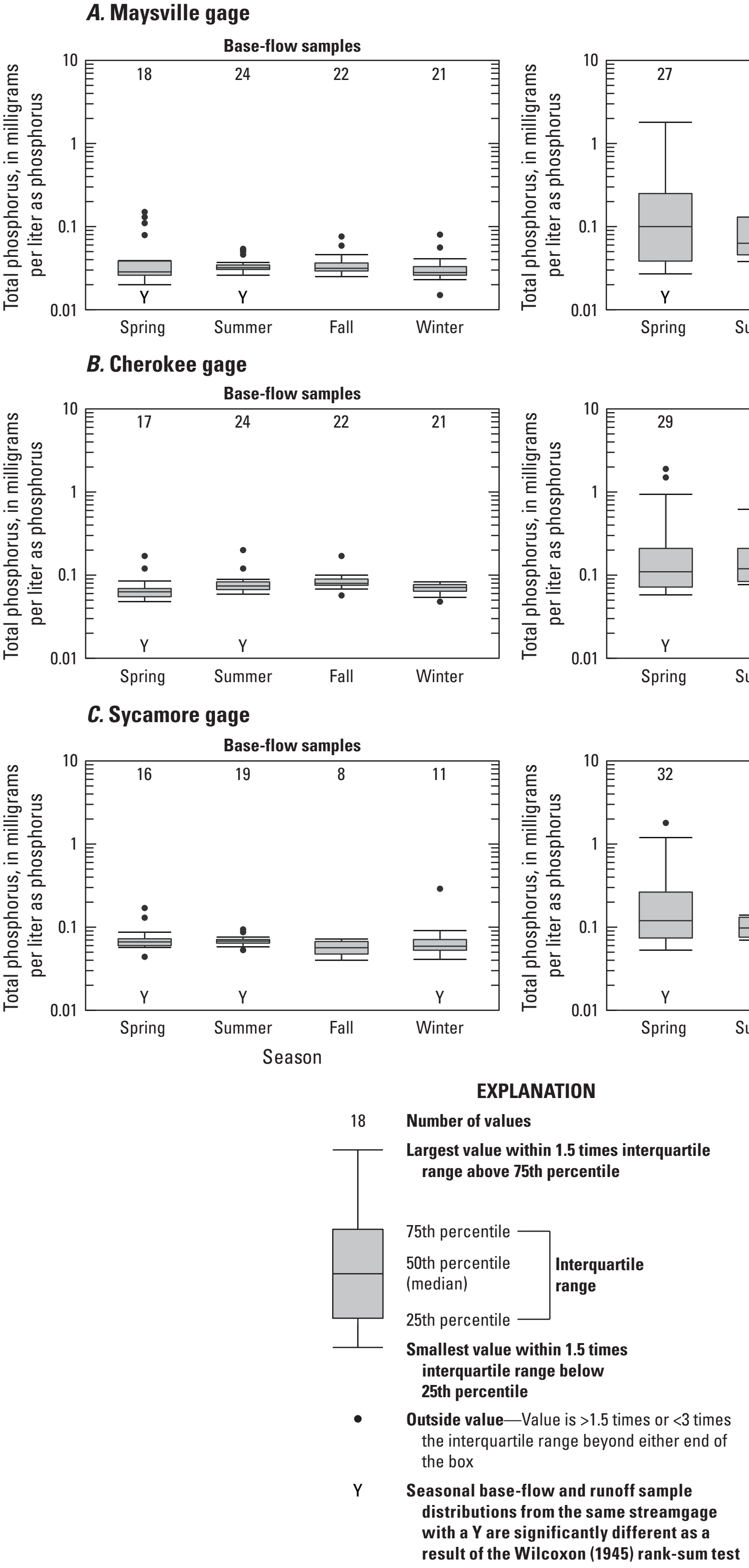
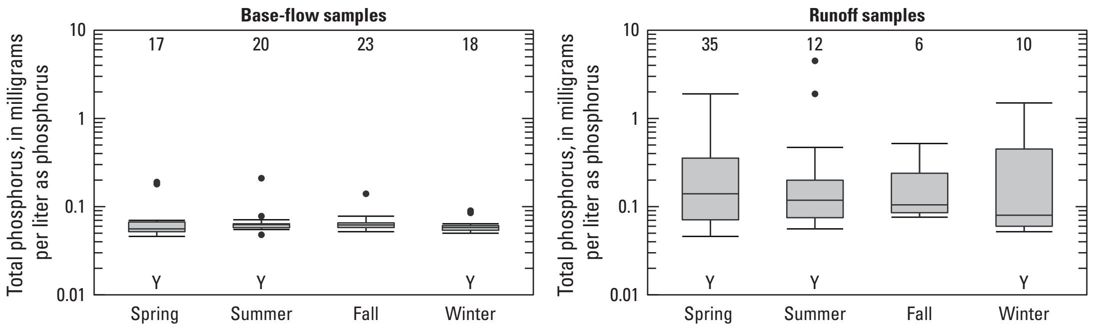
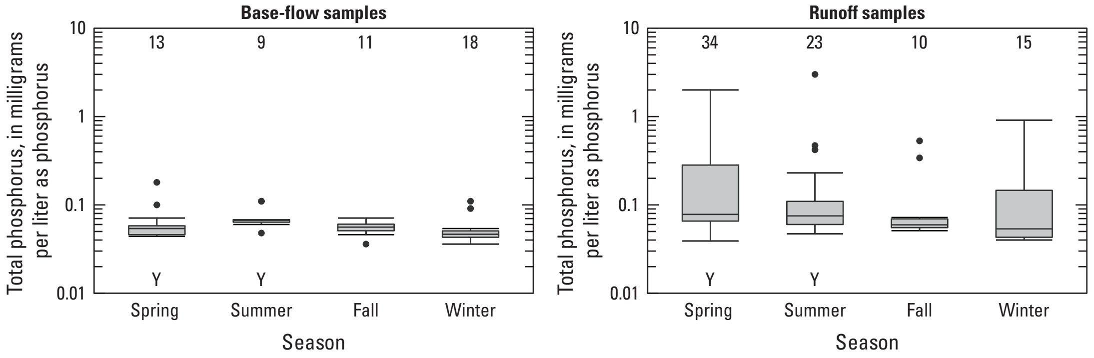


Figure 10. Seasonal distribution of total phosphorus concentrations in base-flow and runoff water-quality samples collected during 2011–18 at U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) *A*, 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage); *B*, 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage); *C*, 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage); *D*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage); and *E*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage). Spring is defined as March, April, and May; summer as June, July, and August; fall as September, October, and November; and winter as December, January, and February.

D. Colcord gage



E. Beaty Creek gage



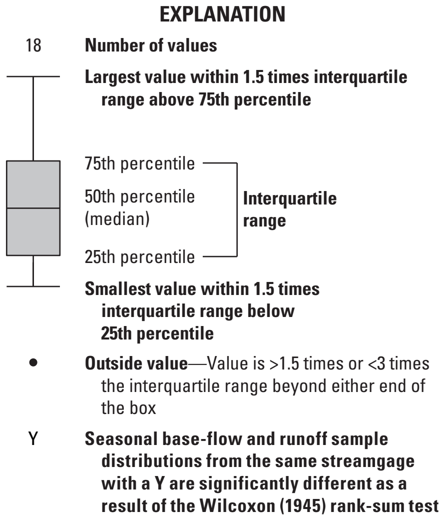


Figure 10. Seasonal distribution of total phosphorus concentrations in base-flow and runoff water-quality samples collected during 2011–18 at U.S. Geological Survey streamgages (U.S. Geological Survey, 2019a) *A*, 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage); *B*, 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage); *C*, 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage); *D*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage); and *E*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage). Spring is defined as March, April, and May; summer as June, July, and August; fall as September, October, and November; and winter as December, January, and February.—Continued

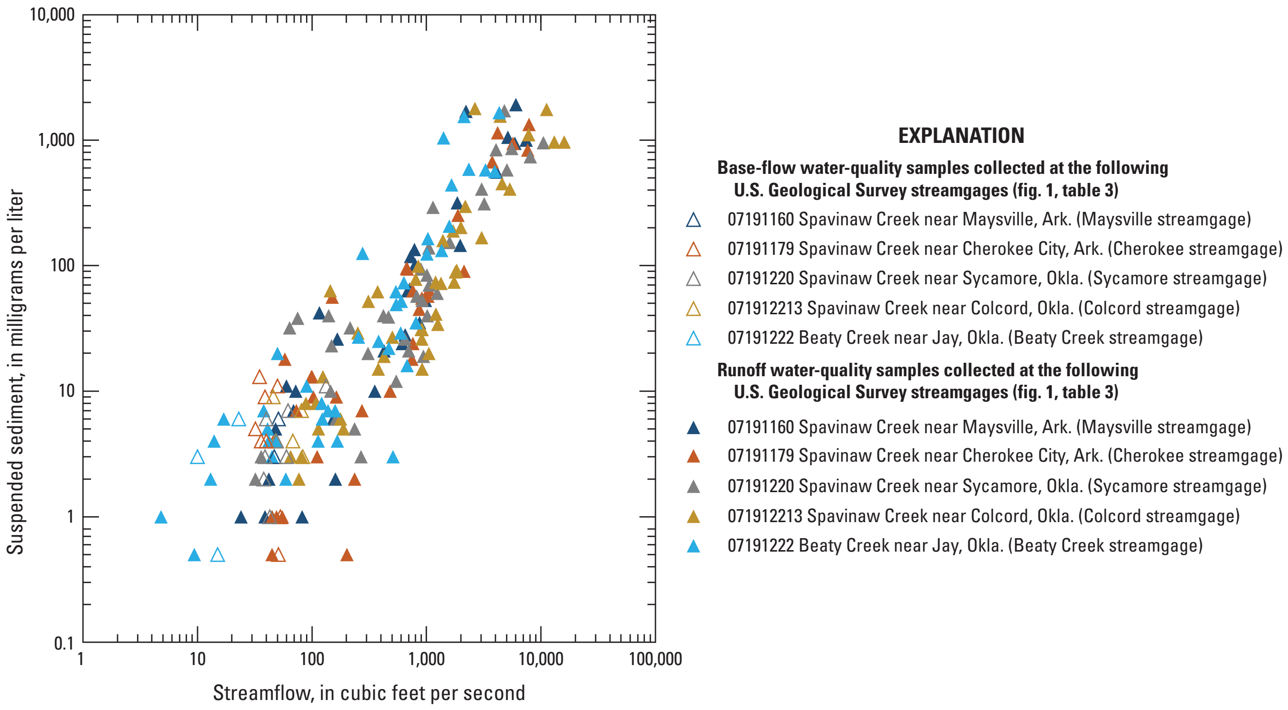


Figure 11. Suspended-sediment concentrations in base-flow and runoff water-quality samples collected during 2011–18 at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas (U.S. Geological Survey, 2019a).

Mean and median TP concentrations varied slightly by season and tended to be lowest during winter in both base-flow and runoff water-quality samples (table 9; fig. 10). Median TP concentrations were significantly higher (p-value ≤ 0.05) in runoff water-quality samples than in base-flow samples during spring and summer at the four streamgages on Spavinaw Creek as shown by the results of the Wilcoxon rank-sum test. At the Beaty Creek streamgage, median TP concentrations were significantly higher only in runoff samples than in base-flow samples during spring. In Spavinaw Creek, median TP concentrations for all seasons ranged from 0.031 to 0.073 mg/L in base-flow samples and from 0.072 to 0.110 mg/L in runoff water-quality samples (table 9). In Beaty Creek at the Beaty Creek streamgage, median TP concentrations for individual seasons ranged from 0.047 to 0.067 mg/L in base-flow samples and from 0.054 to 0.078 mg/L in runoff water-quality samples (table 9).

TN concentrations in Spavinaw Creek in both base-flow and runoff water-quality samples increased from the Maysville streamgage (and the confluence of Columbia Hollow Creek, where effluent from the Decatur WWTP enters Spavinaw Creek) downstream to the Sycamore streamgage (figs. 1 and 8). TN mean and median concentrations increased for all seasons in base-flow and runoff water-quality samples downstream from the Maysville streamgage to the Colcord streamgage (fig. 9). TN concentrations decreased slightly downstream from the Sycamore streamgage to the Colcord streamgage. Mean and median TN and TP concentrations in base-flow and runoff water-quality samples collected at the Cherokee, Sycamore, and Colcord streamgages in Spavinaw Creek were higher than in samples from Beaty Creek at the Beaty Creek streamgage for all seasons.

Similar to TN and TP, SS concentrations increased with increasing streamflow at each streamgage (fig. 11). Median SS concentrations during base-flow conditions ranged from 3.00 to 9.00 mg/L at the five streamgages and were substantially smaller than the median SS concentrations during runoff conditions, which ranged from 18.0 to 62.0 mg/L (table 9). At all five streamgages, large differences between mean and median SS concentrations in runoff water-quality samples show that the distribution of values is skewed by large SS concentrations at higher streamflow. For example, at the Beaty Creek streamgage, the median SS concentration in runoff water-quality samples of 25.0 mg/L is an order of magnitude smaller than the mean value of 253 mg/L (table 9). Boxplots show the distributions of SS concentrations at each streamgage (fig. 12).

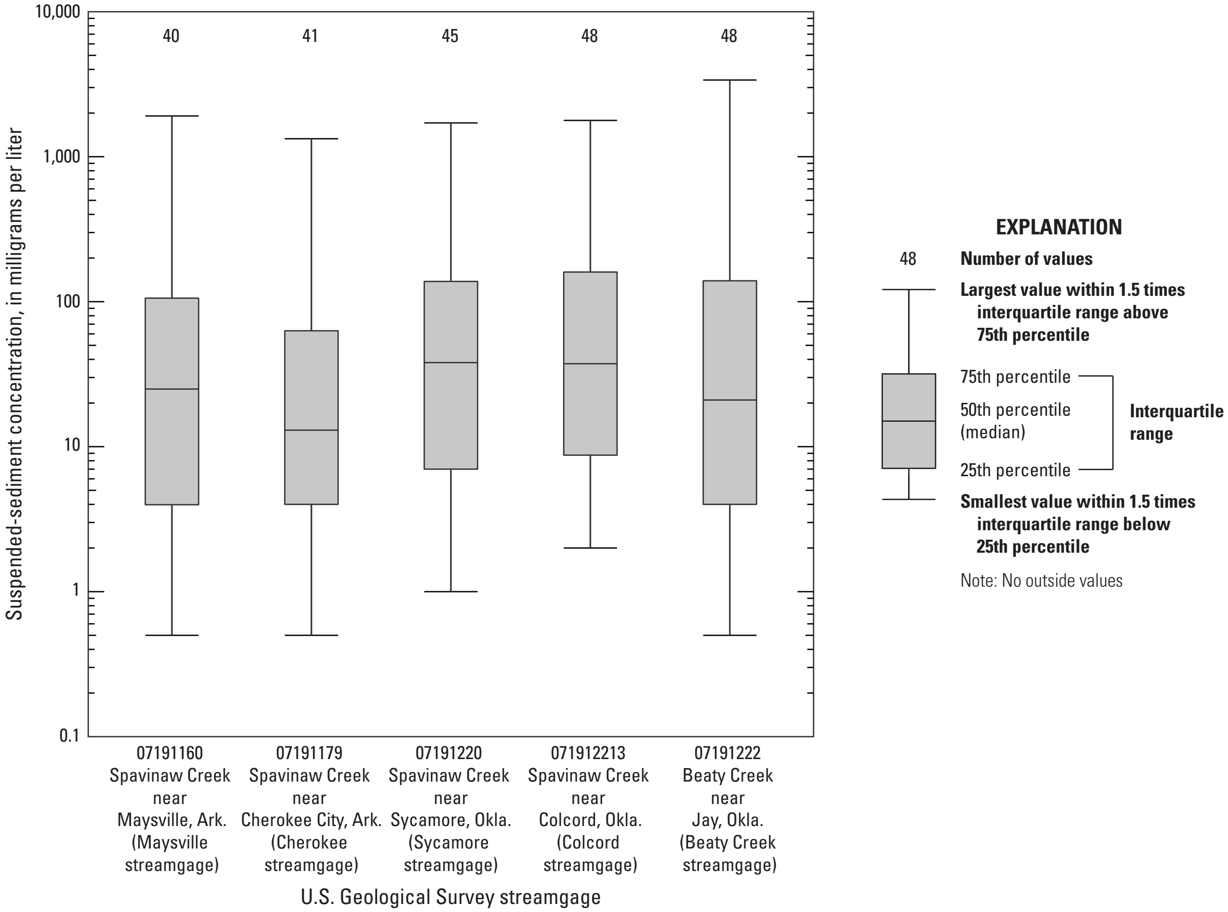


Figure 12. Distribution of suspended-sediment concentrations in water-quality samples collected during 2011–18 at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas (U.S. Geological Survey, 2019a).

Estimated Loads, Yields, and Trend Analysis

Estimated mean annual TN, TP, and SS loads and yields computed by using DM_L regression equations are provided in this section along with estimated mean annual loads to Lake Eucha computed by using DM_L and $INST_C$ regression equations. Temporal trends of flow-weighted TN and TP concentrations during the study period also are discussed in this section.

Estimated Loads and Yields Using DM_L Regression Equations

Estimated mean annual TN loads computed by using DM_L regression equations ranged from 392,000 pounds per year (lb/yr) at the Beaty Creek streamgage to 1,425,000 lb/yr at the Colcord streamgage for the study period (table 10). About 89 percent of the total TN load was transported during runoff days in Beaty Creek, and the total TN load transported during runoff days ranged from about 69 to 76 percent in Spavinaw Creek. Daily mean loads of TN transported by streams ranged from 1,080 pounds per day (lb/d) at the Beaty Creek streamgage to 3,900 lb/d at the Colcord streamgage (table 10).

Estimated mean annual TP loads computed by using DM_L regression equations ranged from 36,700 lb/yr at the Beaty Creek streamgage to 115,900 lb/yr at the Colcord streamgage for the study period (table 10). Almost all TP was transported during runoff days. About 98 percent of TP loads were transported during runoff days in Beaty Creek and about 93 percent in Spavinaw Creek. Estimated daily mean loads of TP transported by streams ranged from 100 lb/d at the Beaty Creek streamgage to 315 lb/d at the Colcord streamgage.

Estimated mean annual SS loads computed by using DM_L regression equations were 52,460,000 lb/yr at the Beaty Creek streamgage and ranged from 32,740,000 lb/yr to 90,510,000 lb/yr at the Spavinaw Creek streamgages for the study period (table 10). Similar to TP, almost all SS was transported during runoff conditions. About 96 percent of SS

Table 10. Estimated mean annual load and yield for total nitrogen, total phosphorus, and suspended sediment computed for the entire study period by using daily mean load (DM_L) regression equations at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).

[Regression variables representing constituent concentrations measured in water-quality samples, streamflow, time, and seasonality were used to develop the daily mean load (DM_L) regression equations. lb/d, pound per day; lb/yr, pound per year; lb/yr/mi^2, pound per year per square mile; N, nitrogen; P, phosphorus; SS, suspended sediment]

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Short name	Daily mean load[1,2] (lb/d as N)	Mean annual loads and yields						
			Base-flow load[3] (lb/yr as N)	Runoff load[4] (lb/yr as N)	Sum of base-flow and runoff loads[1,2] (lb/yr as N)	Base-flow yield[3] (lb/yr/mi^2 as N)	Runoff yield[4] (lb/yr/mi^2 as N)	Sum of base-flow and runoff yields[2] (lb/yr/mi^2 as N)	Load transported during runoff (percentage)
Total nitrogen									
07191160 Spavinaw Creek near Maysville, Ark.	Maysville streamgage	1,830	185,000	482,000	667,000	2,100	5,480	7,580	72
07191179 Spavinaw Creek near Cherokee City, Ark.	Cherokee streamgage	2,060	237,000	517,000	754,000	2,280	4,970	7,250	69
07191220 Spavinaw Creek near Sycamore, Okla.	Sycamore streamgage	3,010	260,000	840,000	1,100,000	1,960	6,320	8,270	76
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	3,900	342,000	1,083,000	1,425,000	2,100	6,650	8,740	76
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	1,080	44,400	348,000	392,000	750	5,900	6,650	89

Table 10. Estimated mean annual load and yield for total nitrogen, total phosphorus, and suspended sediment computed for the entire study period by using daily mean load (DM_L) regression equations at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).—Continued

[Regression variables representing constituent concentrations measured in water-quality samples, streamflow, time, and seasonality were used to develop the daily mean load (DM_L) regression equations. lb/d, pound per day; lb/yr, pound per year; lb/yr/mi^2, pound per year per square mile; N, nitrogen; P, phosphorus; SS, suspended sediment]

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Short name	Daily mean load[1,2] (lb/d as P)	Mean annual loads and yields						
			Base-flow load[3] (lb/yr as P)	Runoff load[4] (lb/yr as P)	Sum of base-flow and runoff loads[1,2] (lb/yr as P)	Base-flow yield[3] (lb/yr/mi^2 as P)	Runoff yield[4] (lb/yr/mi^2 as P)	Sum of base-flow and runoff yields[2] (lb/yr/mi^2 as P)	Load transported during runoff (percentage)
Total phosphorus									
07191160 Spavinaw Creek near Maysville, Ark.	Maysville streamgage	140	2,060	48,500	50,600	23	550	575	96
07191179 Spavinaw Creek near Cherokee City, Ark.	Cherokee streamgage	145	6,500	46,800	53,300	62	450	510	88
07191220 Spavinaw Creek near Sycamore, Okla.	Sycamore streamgage	235	5,120	80,500	85,500	39	605	645	94
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	315	7,050	109,000	115,900	43	670	710	94
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	100	900	35,800	36,700	15	610	620	98

Table 10. Estimated mean annual load and yield for total nitrogen, total phosphorus, and suspended sediment computed for the entire study period by using daily mean load (DM_L) regression equations at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18 (U.S. Geological Survey, 2019a).—Continued

[Regression variables representing constituent concentrations measured in water-quality samples, streamflow, time, and seasonality were used to develop the daily mean load (DM_L) regression equations. lb/d, pound per day; lb/yr, pound per year; lb/yr/mi^2, pound per year per square mile; N, nitrogen; P, phosphorus; SS, suspended sediment]

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Short name	Daily mean load[1,2] (lb/d as SS)	Mean annual loads and yields						
			Base-flow load[3] (lb/yr as SS)	Runoff load[4] (lb/yr as SS)	Sum of base-flow and runoff loads[1,2] (lb/yr as SS)	Base-flow yield[3] (lb/yr/mi^2 as SS)	Runoff yield[4] (lb/yr/mi^2 as SS)	Sum of base-flow and runoff yields[,2] (lb/yr/mi^2 as SS)	Load transported during runoff (percentage)
				Suspended sediment					
07191160 Spavinaw Creek near Maysville, Ark.	Maysville streamgage	127,000	1,439,000	45,100,000	46,500,000	16,400	513,000	528,000	97
07191179 Spavinaw Creek near Cherokee City, Ark.	Cherokee streamgage	89,700	1,179,000	31,580,000	32,740,000	11,300	304,000	315,000	96
07191220 Spavinaw Creek near Sycamore, Okla.	Sycamore streamgage	183,000	3,876,000	63,140,000	66,980,000	29,100	475,000	504,000	94
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	248,000	4,378,000	86,190,000	90,510,000	26,900	529,000	555,000	95
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	144,000	2,146,000	50,350,000	52,460,000	36,400	853,000	889,000	96

[1] As a result of rounding differences, base-flow loads plus runoff loads do not sum precisely to the total loads in this table.

[2] Mean annual loads were computed from daily mean loads during each year in the study period from 2011 to 2018.

[3] Means of the base-flow loads were computed from daily values of base-flow days only.

[4] Means of the runoff loads were computed from daily values of runoff days only.

Table 11. Estimated mean annual total nitrogen, mean annual total phosphorus, and mean annual suspended-sediment loads in base flow and runoff to Lake Eucha in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.

[Estimated mean annual loads were computed by using instantaneous continuous load (INST$_{C}$) regression equations developed from measurements of constituents in water-quality samples and instantaneous measurements of streamflow (computed from stage), specific conductance, water temperature, and turbidity at two U.S. Geological Survey streamgages. lb/yr, pound per year; N, nitrogen; P, phosphorus]

Flow type	Total nitrogen				Total phosphorus				Suspended sediment			
	Lake Eucha		Colcord streamgage[1]	Beaty Creek streamgage[2]	Lake Eucha		Colcord streamgage[1]	Beaty Creek streamgage[2]	Lake Eucha		Colcord streamgage[1]	Beaty Creek streamgage[2]
	Mean annual total nitrogen load[3]		Contribution to mean annual total nitrogen load	Contribution to mean annual total nitrogen load	Mean annual total phosphorus load[3]		Contribution to mean annual total phosphorus load	Contribution to mean annual total phosphorus load	Mean annual suspended-sediment load[3]		Contribution to mean annual suspended-sediment load	Contribution to mean annual suspended-sediment load
	(lb/yr as N)	(percentage)	(percentage)	(percentage)	(lb/yr as P)	(percentage)	(percentage)	(percentage)	(lb/yr)	(percentage)	(percentage)	(percentage)
Base flow[4]	378,000	20	87	13	7,800	5	90	10	1,202,000	2	73	27
Runoff[5]	1,466,000	80	74	26	142,500	95	77	23	77,533,000	98	79	21
Total[6]	1,844,000	100	77	23	150,300	100	78	22	78,735,000	100	79	21

[1] U.S. Geological Survey (USGS) streamgage 071912213 Spavinaw Creek near Colcord, Okla. (fig. 1, table 3).

[2] USGS streamgage 07191222 Beaty Creek near Jay, Okla. (fig. 1, table 3).

[3] Mean annual loads entering Lake Eucha from Beaty and Spavinaw Creeks were determined by computing overall mean annual values from the mean annual loads for each constituent measured at the Colcord streamgage and the Beaty Creek streamgage during 2011–18.

[4] Means of the base-flow loads were computed from base-flow day only by rloadest (Runkel and others, 2004; Runkel and DeCicco, 2017; USGS, 2020) and are statistics of all of the data from 2011 to 2018.

[5] Means of the runoff loads were computed from runoff day only by rloadest (Runkel and others, 2004; Runkel and DeCicco, 2017; USGS, 2020) and are statistics of all of the data from 2011 to 2018.

[6] As a result of rounding differences, the base-flow loads plus runoff load do not sum precisely to the total loads in this table.

loads were transported during runoff days in both the Beaty Creek and Spavinaw Creek subbasins. Estimated daily mean loads of SS transported by streams ranged from 89,700 lb/d at the Cherokee streamgage to 248,000 lb/d at the Colcord streamgage.

In general, mean annual TN, mean annual TP, and mean annual SS yields increased downgradient in Spavinaw Creek as drainage area increased, from 7,580 pounds per year per square mile (lb/yr/mi^2) at the Maysville streamgage to 8,740 lb/yr/mi^2 at the Colcord streamgage (table 10). Mean annual summed TN yields ranged from 6,650 lb/yr/mi^2 at the Beaty Creek streamgage to 8,740 lb/yr/mi^2 at the Colcord streamgage. Base-flow yield of TN at the Beaty Creek streamgage (750 lb/yr/mi^2) was less than half of base-flow yield values at the streamgages on Spavinaw Creek (1,960–2,280 lb/yr/mi^2), whereas the runoff yield at the Beaty Creek streamgage (5,900 lb/yr/mi^2) was similar to runoff yields at the streamgages on Spavinaw Creek (4,970–6,650 lb/yr/mi^2). With base flow making up a smaller percentage of total streamflow in Beaty Creek (table 6; fig. 4), a greater percentage of TN load is transported during runoff than for Spavinaw Creek (table 10).

Mean annual TP yields were 620 lb/yr/mi^2 at the Beaty Creek streamgage and ranged from 510 to 710 lb/yr/mi^2 at the streamgages on Spavinaw Creek (table 10). Because the majority of TP is transported during runoff conditions (about 98 percent at the Beaty Creek streamgage and 88–96 percent at the streamgages on Spavinaw Creek), TP yields transported during base-flow conditions were small at 15 lb/yr/mi^2 at the Beaty Creek streamgage and ranged from 23 to 62 lb/yr/mi^2 at the four streamgages on Spavinaw Creek.

Mean annual SS yields were 889,000 lb/yr/mi^2 at the Beaty Creek streamgage and ranged from 315,000 to 555,000 lb/yr/mi^2 at the four streamgages on Spavinaw Creek (table 10). The mean annual SS yield at the Beaty Creek streamgage was 1.6 to 2.8 times larger than yields estimated for the streamgages on Spavinaw Creek. The SS runoff yield at the Beaty Creek streamgage was 853,000 lb/yr/mi^2 and ranged from 304,000 to 529,000 lb/yr/mi^2 at the streamgages on Spavinaw Creek.

Estimated Loads Using INST$_C$ Regression Equations

Mean annual loads of TN, TP, and SS entering Lake Eucha from Beaty and Spavinaw Creeks were determined by computing annual mean loads from constituents measured in water-quality samples and instantaneous continuous measurements of streamflow and physicochemical measurements (specific conductance, water temperature, and turbidity) made every 15 minutes at two U.S. Geological Survey streamgages during 2011–18 (table 11). The mean annual load is a mean value computed for the entire study period, whereas the annual mean load is the mean load for a given year. Constituent loading from the Beaty Creek and Spavinaw Creek subbasins is not representative of the constituent loading from the entire Eucha-Spavinaw drainage area. The Beaty Creek and Spavinaw Creek subbasins account for about 62 percent of the contributing area to Lake Eucha and 57 percent of the contributing area to Spavinaw Lake (fig. 1).

The mean annual TN load to Lake Eucha estimated from INST$_C$ regression equations for Beaty Creek and Spavinaw Creek was 1,844,000 lb/yr, which represents about 80 percent of the TN load transported during runoff conditions (table 11). Of the two streams, the subbasin for Spavinaw Creek, which composes about 73 percent of the combined Eucha-Spavinaw drainage area (fig. 1), added the majority (about 77 percent) of the TN load. In runoff conditions, the mean annual loads for TP transported to Lake Eucha increased relative to the mean annual TN loads.

As estimated from INST$_C$ regression equations, Beaty Creek and Spavinaw Creek contributed an estimated mean annual TP load of about 150,300 lb/yr into Lake Eucha (table 11). Compared to the estimated percentage of the TN load transported to the lake during runoff conditions (80 percent), the estimated percentage of the TP load transported to the lake during runoff conditions was much larger (95 percent). Similar to the mean annual TN load, most (about 78 percent) of the mean annual TP load was from the Spavinaw Creek subbasin. TP is frequently the limiting nutrient in most lakes (Correll, 1999), so TP is likely a limiting nutrient in Lake Eucha. The transport of larger amounts of TP as compared to TN during runoff might increase the risk of algal blooms in the lake (Schindler, 1971). Dissolved nitrogen is a major component of TN, but a large part of the TP load is bound to sediment; thus, TP is likely less bioavailable than TN. Evaluating the bioavailable components might provide more insight into eutrophication processes in the lake but was beyond the scope of this study.

As estimated from INST$_C$ regression equations, Beaty Creek and Spavinaw Creek contributed an estimated mean annual SS load of about 78,735,000 lb/yr; about 98 percent of this load was transported during runoff conditions (table 11). The Spavinaw Creek subbasin accounted for about 79 percent of the estimated mean annual SS load.

The best-fit INST$_C$ regression equations used for load computations are listed in table 8. The forms of the equations differed depending on the constituent and streamgage. All of the dependent and independent variables were natural-log transformed. Most of the equations included the natural log of streamflow, the natural log of water temperature, and natural log of turbidity as explanatory variables.

The estimation of TN loads at the Colcord and Beaty Creek streamgages were based on streamflow, water temperature, specific conductance, and turbidity (table 8). Turbidity and streamflow were positively associated with TN, indicating that TN is transported during runoff. The negative association of TN with water temperature reflects higher TN concentrations observed in winter and spring compared to summer and fall, which might be from the greater seasonal application and runoff of animal waste and fertilizer (Esralew and Tortorelli, 2010). The two regression equations for estimating TN fit the field data well for the Colcord and Beaty Creek streamgages, as indicated by the corresponding R^2 values of 98.9 and 98.6 percent, respectively.

The estimation of TP at the Beaty Creek streamgage was based on streamflow, water temperature, and specific conductance (table 8). At the Colcord streamgage, streamflow and water temperature were the independent variables. At the Beaty Creek streamgage water temperature and streamflow were positively associated with TP, most likely because of the sorption of TP to sediment. The positive association with streamflow is consistent with increases in sediment-sorbed phosphorus during runoff conditions. The regression equations for estimating TP loads fit the field data well for the Colcord and Beaty Creek streamgage regression equations, as indicated by R^2 values of 96.3 and 98.0 percent, respectively.

At both the Beaty Creek and Colcord streamgages, including a quadratic streamflow term ($Q+Q^2$) in the regression equation provided a better fit to the TP data compared to including a linear turbidity variable, indicating that at higher streamflows TP concentrations might increase at a faster rate than at lower streamflows. During periods of higher streamflows, runoff is more likely to transport animal waste to the streams compared to periods of lower streamflows. Streamflow and water temperature were positively associated in the Beaty Creek TP $INST_C$ equation. The positive turbidity and streamflow association indicates of TP loads increase during runoff conditions.

At the Beaty Creek streamgage, the independent variables for the $INST_C$ equations for SS were streamflow, water temperature, and turbidity. At the Colcord streamgage, the independent variables for the $INST_C$ equations for SS were streamflow, water temperature, specific conductance, and turbidity. All independent variables were positively correlated with SS for the Colcord streamgage, except for specific conductance, which was negatively correlated with SS (table 8). The negative correlation between specific conductance and SS at the Colcord streamgage and the lack of any correlation between specific conductance and SS at the Beaty Creek streamgage might reflect differences in rock-water interactions. Compared to the Beaty Creek subbasin, the Spavinaw Creek subbasin where the Colcord streamgage is located has more exposed bedrock. Groundwater chemistry is influenced by the mineral composition of the formations through which the water flows during rock-water interaction (Elango, 2007). Groundwater chemistry changes as a result of the dissolution and precipitation of minerals in the aquifer source rock and ion-exchange processes (Kresse and others, 2012). The effects of rock-water interactions on stream chemistry depend on flow conditions and will be more pronounced during base flow when groundwater is the predominant source of streamflow (Winter and others, 1998).

For the SS $INST_C$ equations, a quadratic streamflow term ($Q-Q^2$) with negative square term might indicate a nonlinear increase of SS with streamflow. This might indicate that at higher streamflows dilution might cause the rate of increase in concentrations to decline relative to the start of a storm event. At the Beaty Creek streamgage, streamflow, water temperature, and turbidity were all positively correlated to SS loads as well. As indicated by a quadratic streamflow term, with a negative square term ($Q-Q^2$) there might be a nonlinear increase of SS with streamflow, which is similar to the pattern observed at the Colcord streamgage. Turbidity was positively correlated with sorbed phosphorus, indicating the high sediment concentrations in runoff events at both streamgages. As streamflow increases, turbidity and SS concentrations increase, which likely result from a combination of overland transport of sediment into streams caused by land erosion, scouring of streambanks, and resuspension of sediment from channel beds (Kondolf and Piegay, 2016).

Comparison of Regression-Based Load Estimates

Estimates of mean annual loads and yields during 2011–18 of TN, TP, and SS were compared for the Colcord and Beaty Creek streamgages (table 12). The mean annual loads and yield determined from DM_L and $INST_C$ regression equations were used in the comparisons.

DM_L regression equations incorporate periodic water-quality sampling data and daily mean streamflow; in addition to periodic water-quality sampling data, $INST_C$ regression equations also incorporate physicochemical properties and streamflow measured every 15 minutes and thus can better describe the variance in loads compared to DM_L regression equations. DM_L regression equations used daily mean streamflows, which can be positively skewed by the presence of large streamflow events and negatively skewed by the absence of large streamflow events. DM_L regression equations could potentially overestimate the loads of TN, TP, and SS during periods of high streamflow and underestimate the loads of these constituents during periods of low streamflow compared to the $INST_C$ regression equations. $INST_C$ and DM_L regression load estimates during large streamflow events can exceed the upper range of water-quality and streamflow conditions represented by the samples used to develop the regression equations, indicating that the load computations could be improved by the collection of additional data representing large streamflow events.

Differences in streamflow make it difficult to directly compare the loads estimated in this study to the loads estimated in previous studies (table 1). However, relative increases or decreases in constituent loads in this study were compared to the loads in Esralew and others (2011).

Estimates of mean annual and annual mean TN loads obtained from the two types of regression equations did not differ substantially at the Colcord or Beaty Creek streamgages; at each of these streamgages, the mean annual and annual mean TN loads determined by the two types of regression equations differed by less than about 1 percent (table 12, fig. 13). Estimated 90-percent prediction intervals for annual

Table 12. Comparison of estimated mean annual total nitrogen, mean annual total phosphorus, and mean annual suspended-sediment loads and yields computed by using daily mean load (DM_L) and instantaneous continuous load ($INST_C$) regression equations for streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.

[lb/d, pound per day; N, nitrogen; lb/yr, pound per year; lb/yr/mi², pound per year per square mile; DM_L, daily mean load regression equation using water-quality data, streamflow, seasonality, and time; $INST_C$, instantaneous continuous load regression equation using water-quality data and instantaneous measurements of specific conductance, water temperature, turbidity, and stage (streamflow computed from stage); P, phosphorus; SS, suspended sediment]

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Short name	Regression type	Daily mean load[2] (lb/d as N)	Mean annual loads and yields[1]						
				Mean annual load (lb/yr as N)	Total yield (lb/yr/mi² as N)	Mean annual base-flow load[3] (lb/yr as N)	Total base-flow yield (lb/yr/mi² as N)	Mean annual runoff load[4] (lb/yr as N)	Total runoff yield (lb/yr/mi² as N)	Load transported during runoff (percentage)
				Total nitrogen						
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	DM_L	3,900	1,425,000	8,740	342,000	2,100	1,083,000	6,650	76
		$INST_C$	3,880	1,414,000	8,680	330,000	2,000	1,085,000	6,660	77
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	DM_L	1,080	392,000	6,650	44,400	750	348,000	5,900	89
		$INST_C$	1,180	429,000	7,270	48,200	820	381,000	6,460	89

U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Short name	Regression type	Daily mean load[2] (lb/d as P)	Mean annual loads and yields[1]						
				Mean annual load (lb/yr as P)	Total yield (lb/yr/mi² as P)	Mean annual base-flow load[3] (lb/yr as P)	Total base-flow yield (lb/yr/mi² as P)	Mean annual runoff load[4] (lb/yr as P)	Total runoff yield (lb/yr/mi² as P)	Load transported during runoff (percentage)
				Total phosphorus						
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	DM_L	320	116,000	710	7,050	43	109,000	670	94
		$INST_C$	319	116,800	720	7,000	43	109,800	670	94
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	DM_L	100	36,700	620	900	15	35,800	610	98
		$INST_C$	92	33,500	570	820	14	32,700	550	97

Table 12. Comparison of estimated mean annual total nitrogen, mean annual total phosphorus, and mean annual suspended-sediment loads and yields computed by using daily mean load (DM_L) and instantaneous continuous load ($INST_C$) regression equations for streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.—Continued

[lb/d, pound per day; N, nitrogen; lb/yr, pound per year; lb/yr/mi^2, pound per year per square mile; DM_L, daily mean load regression equation using water-quality data, streamflow, seasonality, and time; $INST_C$, instantaneous continuous load regression equation using water-quality data and instantaneous measurements of specific conductance, water temperature, turbidity, and stage (streamflow computed from stage); P, phosphorus; SS, suspended sediment]

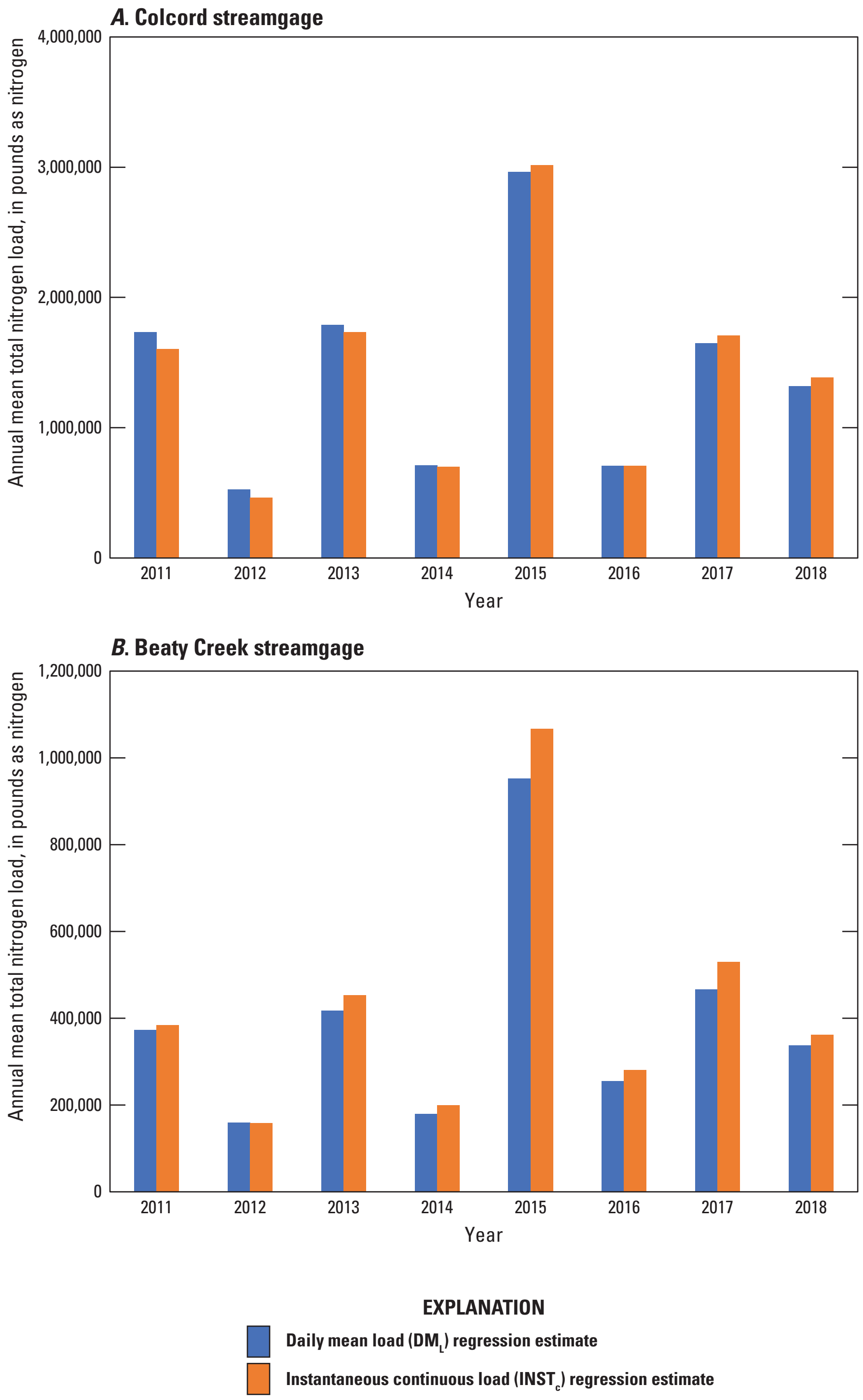
U.S. Geological Survey streamgage number and name (fig. 1, table 3)	Short name	Regression type	Daily mean load[2] (lb/d as SS)	Mean annual loads and yields[1]						
				Mean annual load (lb/yr as SS)	Total yield (lb/yr/mi^2 as SS)	Mean annual base-flow load[3] (lb/yr as SS)	Total base-flow yield (lb/yr/mi^2 as SS)	Mean annual runoff load[4] (lb/yr as SS)	Total runoff yield (lb/yr/mi^2 as SS)	Load trans ported during runoff (percentage)
Suspended sediment										
071912213 Spavinaw Creek near Colcord, Okla.	Colcord streamgage	DM_L	248,000	90,510,000	555,000	4,380,000	26,900	86,194,000	529,000	95
		$INST_C$	170,200	62,142,700	381,100	878,200	5,400	6,128,900	376,000	99
07191222 Beaty Creek near Jay, Okla.	Beaty Creek streamgage	DM_L	144,000	52,459,000	889,000	2,146,000	36,400	50,349,000	853,000	96
		$INST_C$	45,400	16,556,100	280,600	325,300	5,500	16,242,200	275,300	98

[1] Mean annual load was computed as the mean of the annual mean loads during each year in the study period from 2011 to 2018.

[2] Mean annual loads were computed from daily mean loads during each year in the study period from 2011 to 2018.

[3] Means of the base-flow loads are computed from base-flow days only.

[4] Means of the runoff loads are computed from runoff days only.



Note: The annual mean load is the sum of all daily means divided by the number of days in that year.

Figure 13. Estimated annual mean total nitrogen loads computed during each year during the 2011–18 study period by using two types of regression equations at two U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, *A*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage), and *B*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage).

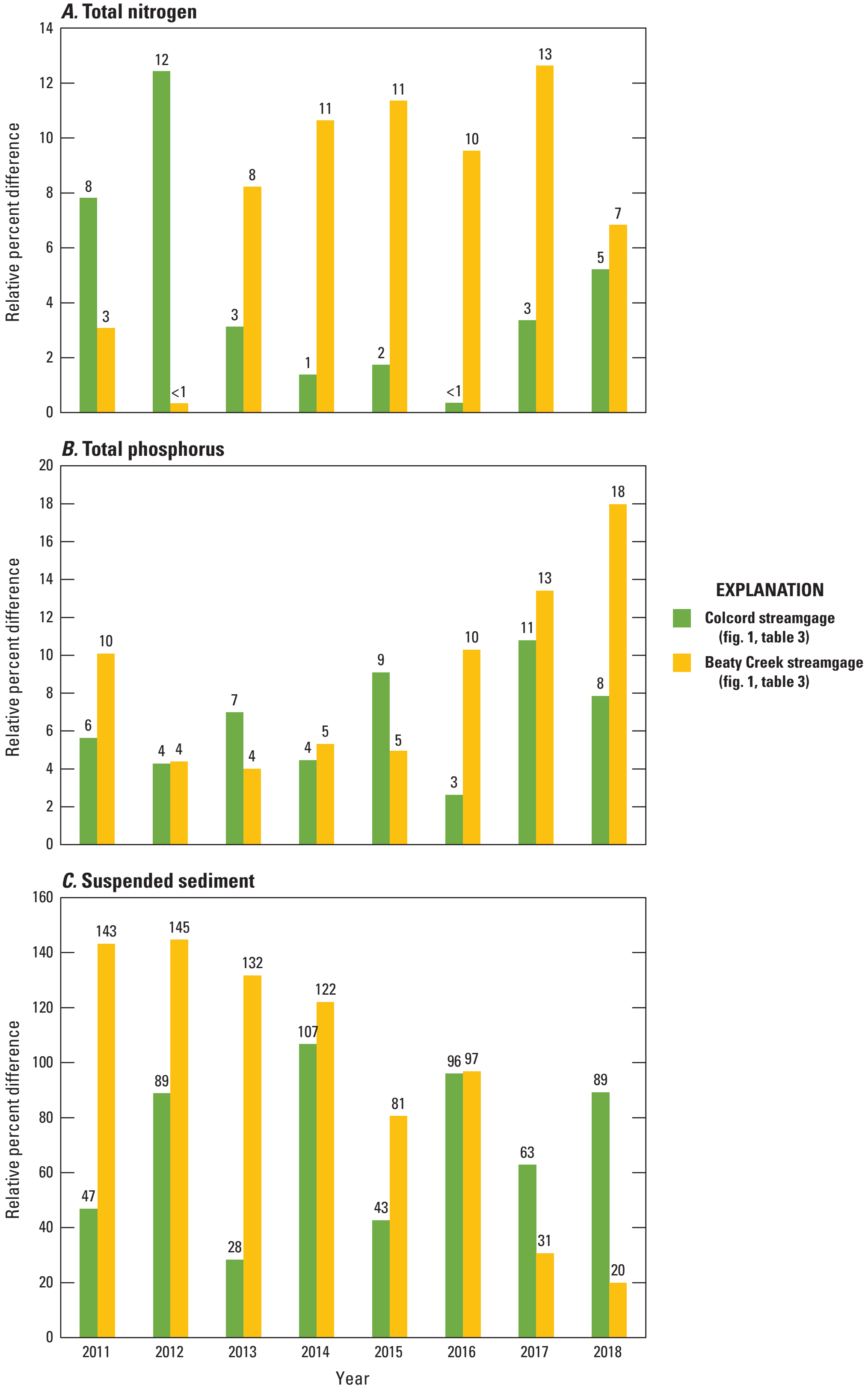


Figure 14. Relative percent differences in annual mean total loads during each year of the study period (2011–18) at two U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage), and 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage), for *A*, total nitrogen, *B*, total phosphorus, and *C*, suspended sediment.

mean TN loads were similar for both types of regression equations. The RPDs between annual mean TN loads estimated from the DM_L and $INST_C$ regression equations ranged from less than 1 to 12 percent for the Colcord streamgage and from less than 1 to 13 percent for the Beaty Creek streamgage (fig. 14*A*).

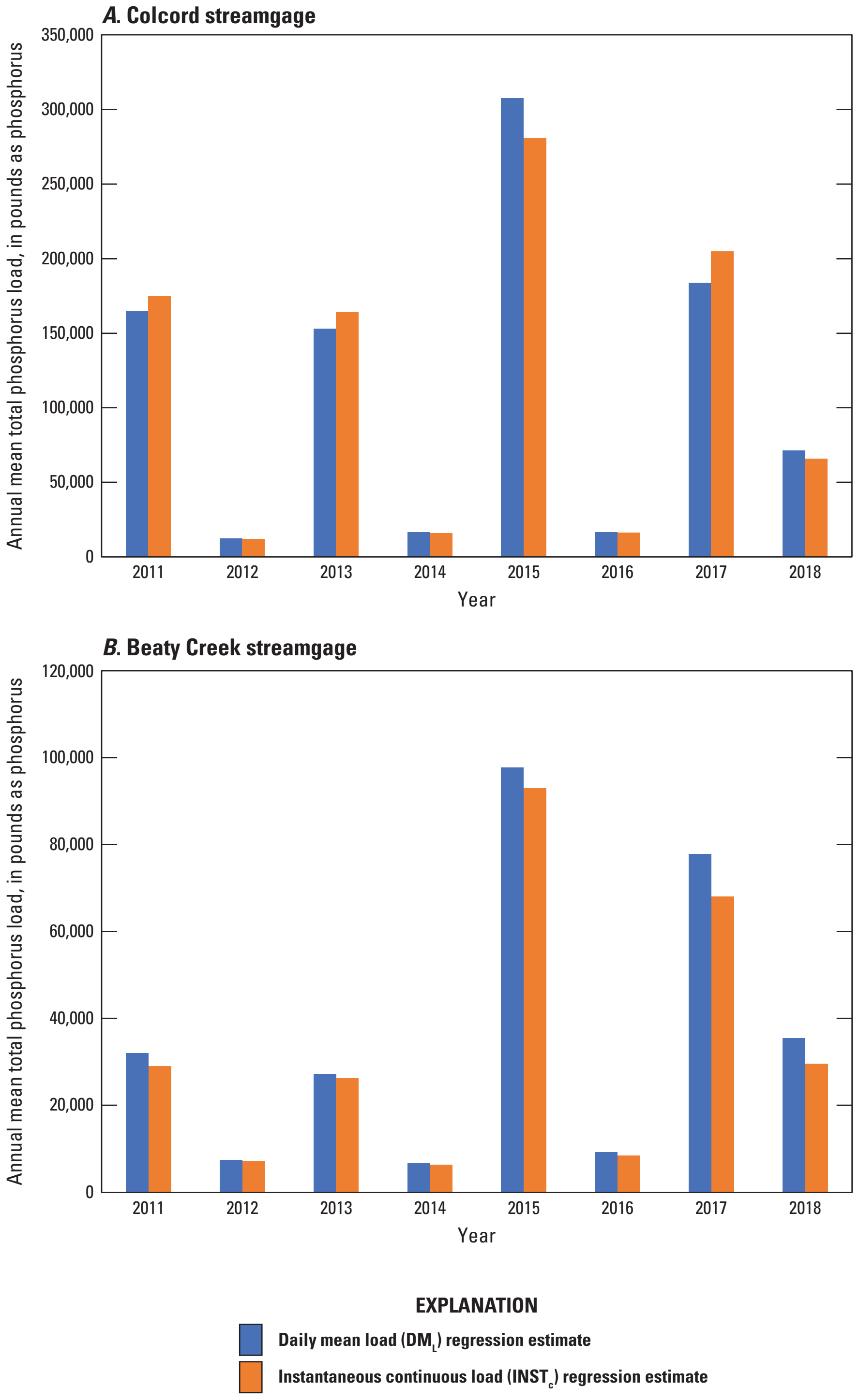
Estimates of mean daily TN load generally were higher from the DM_L regression equations than from the $INST_C$ regression equations, but differences varied depending on streamflow conditions. For the Colcord streamgage, daily TN loads for base-flow days estimated from the $INST_C$ regression equation were lower than the estimates from the DM_L regression, but daily TN loads on runoff days estimated from the $INST_C$ regression equation were slightly higher than the estimates from the DM_L regression equation (table 12). Daily TN loads for the Beaty Creek streamgage estimated from the $INST_C$ regression equation were higher than those estimated from the DM_L regression equation under all streamflow conditions. Above-average streamflow was measured in 2015 and 2017 as indicated by the streamflow record for the Beaty Creek streamgage (fig. 5). The above average streamflow in 2015 and 2017 contributed to large annual mean loads in 2015 and 2017 (fig. 15). Differences in annual mean TN loads between the $INST_C$ and DM_L regression equations for the Beaty Creek streamgage were variable by year, with a similar pattern of higher loads in years with above-average streamflow (fig. 13). When comparing the $INST_C$ loads in this study to the $INST_C$ loads previously reported by Esralew and others (2011), the TN loads decreased by about 2.3 percent at the Colcord streamgage and by about 3.8 percent at the Beaty Creek streamgage.

Mean annual and annual mean TP load estimates from the two types of regression equations differed at both the Colcord streamgage and Beaty Creek streamgage (table 12; fig. 15). RPDs for mean annual TP load estimates between the $INST_C$ and DM_L regression equations were variable by year for both streamgages. The RPDs for TP loads ranged from about 3 to 11 percent for the Colcord streamgage and from about 4 to 18 percent for the Beaty Creek streamgage (fig. 14*B*). For the Colcord streamgage, DM_L total and runoff loads usually were higher than $INST_C$ loads from 2011 to 2018. The above-average streamflow in 2015 and 2017 resulted in relatively large annual mean loads being measured in 2015 and 2017 compared to all other years during 2011–18 (fig. 15). Differences in annual mean TP loads between the $INST_C$ and DM_L estimates for the Beaty Creek streamgage were variable by year, and followed a similar pattern compared to the differences in annual mean TP loads between the $INST_C$ and DM_L estimates for the Colcord streamgage (fig. 13). Differences in estimates of mean daily TP load from both regression equations varied slightly for both streamgages, depending on streamflow conditions (table 12). For the Colcord streamgage, the mean daily TP loads estimated from the $INST_C$ regression equation was slightly lower than that estimated from the DM_L regression. For the Beaty Creek streamgage, the mean daily TP loads during the entire study period (2011–18) estimated from the $INST_C$ regression equation were lower than estimates from the DM_L regression equations. Comparing the $INST_C$ load estimations in this study (table 12) to previously published $INST_C$ load estimations (table 8 in Esralew and others, 2011) indicates about a 19.5 percent increase in TP loads at the Colcord streamgage and about a 20.7 percent decrease in TP loads at the Beaty Creek streamgage.

Mean annual SS loads estimated from the $INST_C$ regression equations were substantially lower than those estimated from the DM_L regression equations at both the Colcord streamgage and Beaty Creek streamgage (table 12). Similar differences were observed for the annual mean SS loads estimated from the $INST_C$ and DM_L regression equations (fig. 16). Differences in annual loads between the $INST_C$ and DM_L regression equations for the Colcord streamgage also varied by year and followed similar higher patterns in years with above- or below-average streamflow (figs. 5 and 13). Large differences in loading estimates between the two types of regression equations result from differences in streamflow-estimated sediment load (DM_L regression) compared to turbidity-estimated sediment load ($INST_C$ regression). Differences in fit between turbidity-based $INST_C$ regression equations and streamflow-based DM_L regression equations indicate that the turbidity-based regression equation (the $INST_C$ regression) produced a better fit of load estimate than the DM_L regression equation did, as indicated by the R^2 value.

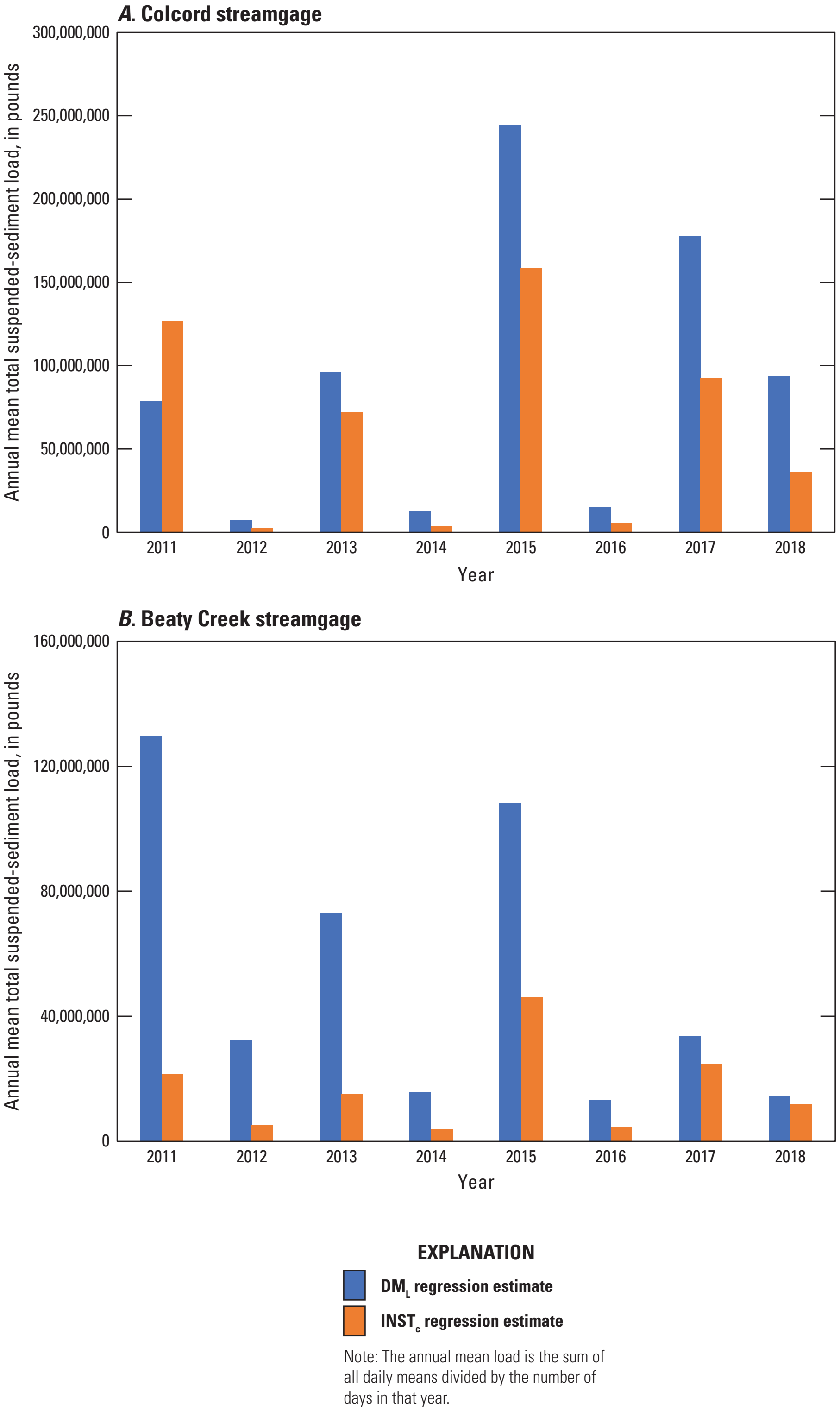
The loads computed by using the DM_L regression equations were overestimated compared to the loads computed by using the $INST_C$ regression equations. One possible explanation for at least part of the possible overestimation of sediment load from the DM_L regression equations is that, during large runoff events, higher streamflow is sustained for a longer period of time than higher turbidity is, causing larger estimates of sediment load from streamflow than from turbidity. This relation was previously described in Rasmussen and others (2005), which compared streamflow-based sediment regression equations to turbidity-based sediment regression equations. However, in addition to the differences during large runoff events, the estimated daily sediment loads were substantially larger for the DM_L regression equations than for the $INST_C$ regression equations for all streamflow conditions at both streamgages. Runoff components of TN and TP were about 1–2 percent less for 2002–10 than for those in 2011–18. An increase of about 41.5 percent in SS loads at the Colcord streamgage and a decrease of about 13.7 percent in SS loads at the Beaty Creek streamgage were found by comparing the $INST_C$ loads from this study to those in Esralew and others (2011).

Annual mean SS loads (the sum of all daily means divided by the number of days in that year) were computed for each year from 2011 through 2018 and mean annual SS loads for the entire study period (2011–18) were computed. For all annual mean loads, the SS loads estimated at the Beaty Creek streamgage by using the $INST_C$ regression equation were lower than the SS loads estimated by using the DM_L regression equation. With the exception of 2011, the SS loads



Note: The annual mean load is the sum of all daily means divided by the number of days in that year.

Figure 15. Estimated annual mean total phosphorus loads computed during each year of the study period (2011–18) by using two types of regression equations at two U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, *A*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage), and *B*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage).



Note: The annual mean load is the sum of all daily means divided by the number of days in that year.

Figure 16. Estimated annual mean suspended-sediment loads computed during each year of the study period (2011–18) by using two types of regression equations at two U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, *A*, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage), and *B*, 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage).

estimated by using the $INST_C$ regression equation at the Colcord streamgage were also lower than the SS loads estimated by using the DM_L regression equation (fig. 16).

The mean annual SS loads estimations during 2011–18 at the Beaty Creek and Colcord streamgages from the $INST_C$ regression equations were also computed and were lower than the mean annual SS loads estimations from DM_L regression equations at both streamgages for all load comparisons (table 12). The large DM_L values obtained during runoff events are not reflected in the $INST_C$ values. Thus, larger mean annual SS load estimations are obtained by using the DM_L regression equations compared to load estimates obtained by using the $INST_C$ regression equations.

The prediction intervals for the estimates of SS loads obtained by the two types of regression equations (DM_L and $INST_C$) and RPD values provide additional insights regarding the SS load estimates at the Colcord streamgage and Beaty Creek streamgage. For the Beaty Creek streamgage, 90-percent prediction intervals were similar for mean annual total SS loads estimated for both types of regression equations for all years (fig. 12). The RPD between annual mean SS loads was about 37 percent for the Colcord streamgage and about 104 percent for the Beaty Creek streamgage. RPDs for annual mean loads of SS ranged from about 28 to 107 percent for the Colcord streamgage and from about 20 to 145 percent for the Beaty Creek streamgage (fig. 14*C*).

Table 13. Temporal trends of flow-weighted total nitrogen, total phosphorus, and suspended-sediment concentrations computed from daily mean load (DM$_L$) regression equations at five U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 2011–18.

[*p*-value, probability value; *tau*, Mann-Kendall correlation coefficient (Mann, 1945); USGS, U.S. Geological Survey; MK, Mann-Kendall trend test (Mann, 1945); SMK, seasonal Mann-Kendall trend test (Hirsch and others, 1982); trends were statistically significant if the *p*-value was less than or equal to 0.05; <, less than; red shading indicates downward trend; blue shading indicates upward trend; orange shading indicates no trend]

Constituent	Trend test	Base flow			Runoff		
		p-value	*tau*	Trend	*p*-value	*tau*	Trend
USGS streamgage 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage) (fig. 1, table 3)							
Total nitrogen	MK	<0.05	−0.407	downward	<0.05	−0.370	downward
	SMK	<0.05	−0.692	downward	<0.05	−0.440	downward
Total phosphorus	MK	<0.05	0.043	upward	<0.05	0.094	upward
	SMK	<0.05	0.046	upward	0.46	0.025	no trend
Suspended sediment	MK	0.20	0.018	no trend	<0.05	0.077	upward
	SMK	<0.05	0.063	upward	0.52	0.022	no trend
USGS streamgage 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage) (fig. 1, table 3)							
Total nitrogen	MK	0.47	0.010	no trend	<0.05	0.115	upward
	SMK	<0.05	0.070	upward	0.04	0.060	no trend
Total phosphorus	MK	<0.05	−0.731	downward	<0.05	−0.353	downward
	SMK	<0.05	−0.657	downward	<0.05	−0.508	downward
Suspended sediment	MK	<0.05	−0.061	downward	<0.05	0.132	upward
	SMK	<0.05	−0.039	downward	<0.05	0.114	upward
USGS streamgage 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage) (fig. 1, table 3)							
Total nitrogen	MK	<0.05	−0.408	downward	<0.05	−0.280	downward
	SMK	<0.05	−0.596	downward	<0.05	−0.401	downward
Total phosphorus	MK	0.29	0.016	no trend	0.29	−0.024	no trend
	SMK	0.12	0.022	no trend	0.14	−0.038	no trend
Suspended sediment	MK	0.50	0.009	no trend	<0.05	0.067	upward
	SMK	0.86	−0.003	no trend	0.07	0.052	no trend
USGS streamgage 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage) (fig. 1, table 3)							
Total nitrogen	MK	<0.05	−0.258	downward	<0.05	−0.165	downward
	SMK	<0.05	−0.457	downward	<0.05	−0.261	downward
Total phosphorus	MK	<0.05	−0.073	downward	<0.05	0.110	upward
	SMK	<0.05	−0.037	downward	0.34	0.028	no trend
Suspended sediment	MK	<0.05	0.407	upward	<0.05	0.350	upward
	SMK	<0.05	0.480	upward	<0.05	0.288	upward
USGS streamgage 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage) (fig. 1, table 3)							
Total nitrogen	MK	<0.05	−0.287	downward	<0.05	−0.084	downward
	SMK	<0.05	−0.358	downward	<0.05	−0.210	downward
Total phosphorus	MK	<0.05	0.316	upward	<0.05	0.077	upward
	SMK	<0.05	0.317	upward	<0.05	0.167	upward
Suspended sediment	MK	<0.05	−0.724	downward	<0.05	−0.528	downward
	SMK	<0.05	−0.727	downward	<0.05	−0.564	downward

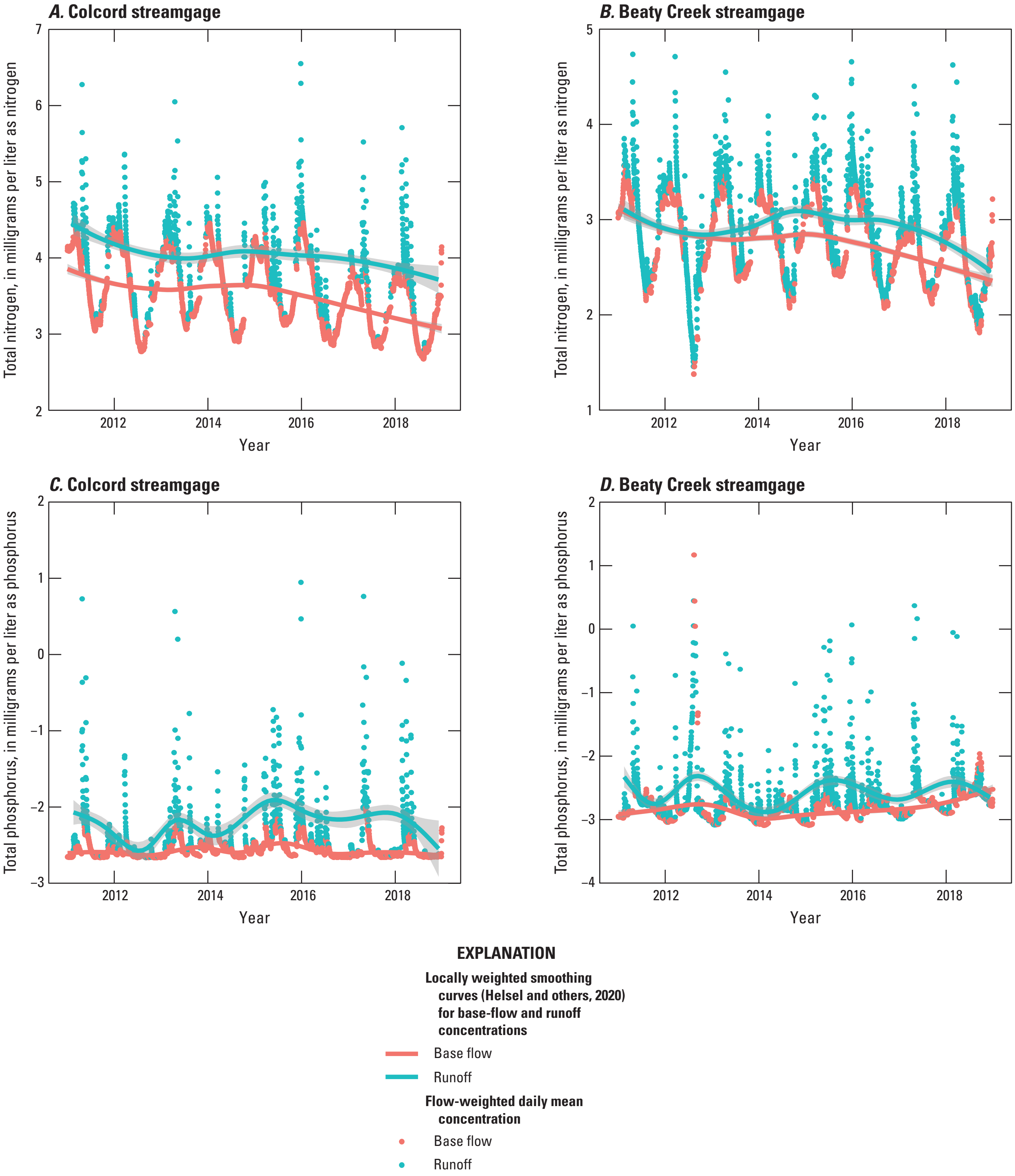


Figure 17. Flow-weighted daily mean concentrations with locally weighted smoothing curves representing base-flow and runoff conditions during 2011–18 at two U.S. Geological Survey streamgages in the Eucha-Spavinaw drainage area, northeastern Oklahoma and northwestern Arkansas, 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage), and 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage). *A*, Total nitrogen at the Colcord streamgage; *B*, total nitrogen at the Beaty Creek streamgage; *C*, total phosphorus at the Colcord streamgage; and *D*, total phosphorus at the Beaty Creek streamgage (U.S. Geological Survey, 2019a). Locally weighted smoothing curves (Helsel and others, 2020) depict changes over time in the flow-weighted daily mean concentrations of TN and TP representing base-flow and runoff conditions.

Temporal Trends

Flow-weighted TN, TP, and SS concentrations during base-flow and runoff conditions computed from DM_L regression equations were analyzed for temporal trends during the study period. Temporal trends in TN concentrations showed statistically significant (p-value ≤ 0.05) downward trends during both base-flow and runoff conditions at all streamgages except for the Cherokee streamgage on Spavinaw Creek (table 13). A statistically significant upward trend in TN concentrations was indicated in base-flow and runoff conditions at the Cherokee streamgage, though the seasonal Mann-Kendall test indicates that the upward trend in base-flow TN concentrations is related to seasonal effects.

Temporal trends in TP were not consistent among the five streamgages over the study period, showing both upward and downward trends throughout the Eucha-Spavinaw drainage area (table 13). TP concentrations during base-flow and runoff conditions mostly showed statistically significant (p-value ≤ 0.05) upward trends at the Maysville and Beaty Creek streamgages. TP concentrations also mostly showed a statistically significant upward trend at the Colcord streamgage, but only during runoff conditions. TP concentrations showed a statistically significant downward trend during base-flow conditions at the Colcord streamgage and during both base-flow and runoff conditions at the Cherokee streamgage. No trends in TP concentrations were detected during either base-flow or runoff conditions at the Sycamore streamgage. Locally weighted smoothing curves (Helsel and others, 2020) depicting changes over time in the flow-weighted daily mean concentrations of TN and TP representing base-flow and runoff conditions during 2011–18 are depicted in figure 17.

Similar to the lack of consistency in temporal trends in TP concentrations, temporal trends in SS concentrations were not consistent among streamgages over the study period. SS base-flow concentrations showed statistically significant (p-value ≤ 0.05) downward trends only at the Cherokee and Beaty Creek streamgages (table 13). Statistically significant upward trends in SS concentrations during base-flow conditions were detected at the Maysville and Colcord streamgages, though the seasonal Mann-Kendall test indicates that the upward trend at the Maysville streamgage is related to seasonal effects. SS concentrations during runoff conditions showed statistically significant upward trends at all four streamgages on Spavinaw Creek. SS concentrations during runoff conditions showed a statistically significant downward trend at the Beaty Creek streamgage.

Summary

Lake Eucha is a source of water for public supply and recreation for the City of Tulsa and other municipalities in northeastern Oklahoma. Beaty and Spavinaw Creeks flow into Lake Eucha draining about 388 square miles of agricultural and forested land in northeastern Oklahoma and northwestern Arkansas. Beginning in the 1990s, eutrophication of Lake Eucha characterized by excessive algal blooms resulted in taste and odor problems associated with the lake water when it was used for public supply. Previous studies published during 2001–2 showed that Lake Eucha was enriched in nitrogen and phosphorus and that concentrations of phosphorus entering the lake needed to be reduced to better support the ongoing use of Lake Eucha as public supply. Previous assessments of nutrient and suspended-sediment loads for the Eucha-Spavinaw drainage area have been published using data collected from 2010 or earlier. Because of ongoing land-use changes and changes in the land-management practices in the study area, the U.S. Geological Survey (USGS), in cooperation with the City of Tulsa, completed a study to characterize total nitrogen (TN), total phosphorus (TP), and suspended-sediment (SS) loads to Lake Eucha originating from the Beaty Creek and Spavinaw Creek subbasins using more recently collected data from 2011 to 2018. In 2002, the USGS began collecting water-quality samples during runoff conditions at five USGS streamgages to supplement the data collected by the City of Tulsa. In 2004, continuous real-time water-quality monitors were installed at the streamgages 071912213 Spavinaw Creek near Colcord, Okla. (Colcord streamgage), and 07191222 Beaty Creek near Jay, Okla. (Beaty Creek streamgage), to measure physicochemical properties, including specific conductance, water temperature, and turbidity. The intent was to use the physicochemical data with streamflow and water-quality sampling data to develop regression equations that could be used to continually estimate nutrient concentrations in the streams.

Daily mean load (DM_L) regression equations were developed using data collected from 2011 to 2018 to estimate TN, TP, and SS loads and yields at the five streamgages in the Eucha-Spavinaw drainage area. Instantaneous TN, TP, and SS concentrations were estimated from regression equations (instantaneous continuous load [$INST_C$] regression equations). $INST_C$ regression equations were developed by using continuous measurements of physicochemical properties and streamflow in conjunction with periodic water-quality samples from 2011 to 2018 for the Colcord and Beaty Creek streamgages. Daily, annual, and mean annual loads estimated from these two types of regression equations were compared for the two streamgages for 2011–18. DM_L regression equations for TN and TP had better fit to field data than DM_L regression equations for SS did for all streamgages as indicated by coefficient of determination values. Daily and annual loads estimated from instantaneous continuous load regression equations that included specific conductance, water temperature, turbidity, and streamflow described the variability in the field data better than loads estimated from daily mean load regression equations that included streamflow, seasonality, and time. Loads estimated from the instantaneous continuous load regression equations generally were greater than those estimated from the daily mean load regression equations.

The runoff component of the mean annual TN load to Lake Eucha ranged from about 77 percent for the Colcord streamgage to about 23 percent for the Beaty Creek streamgage. The runoff component of the mean annual TP load ranged from about 78 percent for the Colcord streamgage to about 22 percent for the Beaty Creek streamgage. The runoff component of the mean annual total SS load ranged from about 79 percent for the Colcord streamgage to about 21 percent for the Beaty Creek streamgage. Runoff components of the TN and TP loads were about 1–2 percent less during 2002–10 compared to the runoff components of TN and TP loads during 2011–18.

Based on estimates obtained using $INST_C$ regression equations, mean annual loads of 1,844,000 pounds of TN, 150,300 pounds of TP, and 78,735,000 pounds of SS were transported into Lake Eucha from the Beaty Creek and Spavinaw Creek subbasins. Most of the estimated mean annual loads from the Beaty Creek and Spavinaw Creek subbasins entered Lake Eucha during runoff conditions, including about 80 percent of TN, 95 percent of TP, and 98 percent of SS. When comparing the $INST_C$ loads estimated for this study to the $INST_C$ loads reported in a previous study, the total TN loads decreased by about 2.3 percent at the Colcord streamgage and by about 3.8 percent at the Beaty Creek streamgage. The TP loads increased by about 19.5 percent at the Colcord streamgage and decreased by about 20.7 percent at the Beaty Creek streamgage when compared to loads reported in the previous study. An increase of about 41.5 percent in SS loads at the Colcord streamgage and a decrease of about 13.7 percent in SS loads at the Beaty Creek streamgage were found by comparing the $INST_C$ loads from this study to those published in a previous 2011 study.

Daily, annual, and mean annual load estimates varied substantially, depending on streamflow conditions and the independent variables used to develop regression equations and on streamflow conditions. Differences in fit between turbidity-based $INST_C$ regression equations and alternate streamflow-based $INST_C$ regression equations indicate that the turbidity-based regression equation (the $INST_C$ regression equation) produced a better fit of load estimate than the DM_L regression equation did, as indicated by the coefficient of determination value.

Loads estimated from the $INST_C$ regression equations generally were greater than those estimated from the DM_L regression equations. Large differences in daily, annual, and mean annual loads between regression equations might be caused by differences in streamflow-estimated sediment load (DM_L regression) compared to turbidity-estimated sediment load ($INST_C$ regression). The DM_L equations used mean daily streamflow, which included above-average flow events and could potentially overestimate the load predicted as compared to the $INST_C$. Many instantaneous and daily load estimates for extremely high streamflow events were beyond the range of water-quality and streamflow conditions represented by the samples used to develop the regression equations, indicating that the load computations could be improved with data from more high-flow samples.

Temporal trends in TN concentrations showed statistically significant (*p*-value less than or equal to 0.05) downward trends during both base-flow and runoff conditions at all streamgages except for 07191179 Spavinaw Creek near Cherokee City, Ark. (Cherokee streamgage), on Spavinaw Creek. Temporal trends in TP concentrations were not consistent among the five streamgages in study area over the study period, showing both upward and downward trends throughout the Eucha-Spavinaw drainage area. TP concentrations during base-flow and runoff conditions showed statistically significant (*p*-value less than or equal to 0.05) upward trends at the streamgages 07191160 Spavinaw Creek near Maysville, Ark. (Maysville streamgage), and Beaty Creek. Total phosphorus concentrations showed a statistically significant downward trend in runoff water-quality samples at the streamgage 071912213 Spavinaw Creek near Colcord, Okla., and in both base-flow and runoff conditions at the streamgage 07191179 Spavinaw Creek near Cherokee City, Ark. Temporal trends in SS concentrations were not consistent among streamgages over the study period and were similar to temporal trends in TP concentrations.

Higher concentrations of TN and TP in runoff water-quality samples can be an indicator that nonpoint sources such as fertilized fields are likely contributors of nutrients. Mean and median TN concentrations were consistently largest during spring and winter in both base-flow and runoff water-quality samples at all five streamgages and might have multiple causes. Fertilizer is applied to crops in spring and can run off into streams and leak into groundwater during high precipitation events. During winter, available nitrogen in the soils is not utilized by vegetation and also can run off into streams and leak into groundwater when runoff occurs during high precipitation events. Mean and median TP concentrations varied slightly by season and tended to be smallest during winter in both base-flow and runoff water-quality samples. TP concentrations in Spavinaw Creek in both base-flow and runoff water-quality samples increased from the Maysville streamgage (and the confluence of Columbia Hollow Creek, where effluent from the Decatur wastewater-treatment plant enters Spavinaw Creek) downstream to the streamgage 07191220 Spavinaw Creek near Sycamore, Okla. (Sycamore streamgage). TP mean and median concentrations increased for all seasons in base-flow and runoff water-quality samples downstream from the Maysville streamgage to the Colcord streamgage. TN concentrations slightly decreased downstream from the Sycamore streamgage to the Colcord streamgage. Both TN and TP concentrations in base-flow and runoff water-quality samples collected at the Cherokee, Sycamore, and Colcord streamgages in Spavinaw Creek were larger than concentrations in samples collected at the Beaty Creek streamgage in Beaty Creek for all seasons (mean and median concentrations). Statistically significant upward trends in TP concentrations and statistically significant downward trends in SS concentrations at the Beaty Creek streamgage were observed for runoff water-quality samples, indicating that the amount of phosphorus adsorbed to sediment transported during runoff might have increased with time even though SS concentrations decreased.

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