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Prepared in cooperation with the City of Durham Public Works Department, Stormwater and GIS Services Division

Groundwater/Surface-Water Interactions Along Ellerbe Creek in Durham, North Carolina, 2016–18

Scientific Investigations Report 2019–5097

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

Cover. Ellerbe Creek in Durham, North Carolina, looking upstream from site EC-4. Photograph by Kristen McSwain, U.S. Geological Survey.

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U.S. Geological Survey
James F. Reilly II, Director

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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)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per day (ft/d)	0.3048	meter per day (m/d)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

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 either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

Abbreviations

ADCP	acoustic Doppler current profiler
ADV	acoustic Doppler velocimeter
BFI	base-flow index
CRONOS	Climate Retrieval and Observations Network of the Southeast
DGPS	differentially corrected Global Positioning System
DTS	distributed temperature sensing
FLIR	forward-looking infrared
FO-DTS	fiber-optic distributed temperature sensing
GUI	graphical user interface
lidar	light detection and ranging
NDWRF	North Durham Water Reclamation Facility
NLCD	National Land Cover Database
QA/QC	quality assurance and quality control
USGS	U.S. Geological Survey

Groundwater/Surface-Water Interactions Along Ellerbe Creek in Durham, North Carolina, 2016–18

By Dominick J. Antolino

Abstract

An assessment of groundwater/surface-water interactions along Ellerbe Creek, a major tributary to upper Falls Lake in Durham County, North Carolina, was conducted from July 2016 to March 2018 to determine if groundwater is a likely source of elevated nitrate input to the stream. Groundwater/surface-water interactions were characterized by synoptic streamflow measurements, groundwater-level monitoring, hydrograph-separation methods, and a continuous streambed temperature survey to aid in the collection and interpretation of water-quality data. A streamflow gain-loss survey identified gaining and losing reaches within the stream and found that surface-water inflow, including that from a treated wastewater outfall, provided much of the streamflow gain within the study reach. Through the use of two hydrograph-separation methods, base flow for the Ellerbe Creek study reach was estimated to be between 14.0 and 17.7 cubic feet per second during the study period, contributing up to 57 percent of mean streamflow, with the remaining contributions coming from surface runoff to the stream. The effluent discharge accounted for most of the estimated base-flow contribution to the stream below the North Durham Water Reclamation Facility outfall. Hydraulic gradients within the groundwater were determined to flow upward and toward the stream during base-flow conditions and reverse during storm events. Nitrate concentrations ranged from below the method detection level to 2.69 milligrams per liter, with the highest concentrations just downstream from the wastewater outfall. Bank seeps and groundwater samples had lower nitrate concentrations than surface-water samples, ranging from below the method detection level to 1.04 milligrams per liter, with the highest concentration at the piezometer within the stream. Results indicate that groundwater is not a large component of streamflow within Ellerbe Creek nor a major source of nitrate within the study reach.

Introduction

The North Carolina Department of Environmental Quality has included Falls Lake, a reservoir serving as the drinking water source for the city of Raleigh, North Carolina, and surrounding communities, on the 303(d) list of impaired waters because of violations of the State's chlorophyll *a* water-quality standard that have been correlated to excessive nutrient inputs (North Carolina Department of Environment and Natural Resources, 2010). The nutrient management strategies adopted for the reservoir by the North Carolina Environmental Management Commission incorporate comprehensive controls to reduce nitrogen and phosphorus loads from primary sources in the watershed, including urban stormwater, wastewater, and agriculture (North Carolina Department of Environment and Natural Resources, 2010). Estimates of total nitrogen and phosphorus loads to Falls Lake from watershed model analysis show agriculture and point sources as the most important contributors to nitrogen and phosphorus levels within the reservoir (North Carolina Department of Environmental Quality, Division of Water Resources, 2016).

Ellerbe Creek, one of the major tributaries that discharges to upper Falls Lake, has a history of elevated nutrient concentrations that have been largely attributed to wastewater outfall from the North Durham Water Reclamation Facility (NDWRF; National Pollutant Discharge Elimination System permit number NC0023841), which is about 5 miles (mi) upstream from Falls Lake. Ongoing upgrades to and optimization of NDWRF water treatment processing are being implemented to reduce nutrient input to the reservoir. As part of the North Carolina Department of Environmental Quality Falls Lake Nutrient Strategy, Stage I mass limits for the three major wastewater dischargers in the upper watershed, including the NDWRF, were equivalent to an average of 3.09 milligrams per liter (mg/L) of total nitrogen for 110 percent of 2016 flows. The Ellerbe Creek drainage area is under the jurisdiction of the City of Durham, North Carolina. The city's Public Works Department, Stormwater and GIS Services Division, is tasked with assessing nutrient contributions to implement best management practices aimed at reducing nutrient loading in the Falls Lake drainage basin. Recent watershed modeling within the basin indicated that groundwater may be a possibly unquantified source of nutrient contributions to area streams (North Carolina Department of Environmental Quality, Division of Water Resources, 2016).

Purpose and Scope

This report presents the results of a study to describe the interaction of groundwater and surface water in a reach of Ellerbe Creek downstream from the NDWRF. Streamflow measurements and groundwater-level monitoring were used to assess hydraulic gradients and estimate groundwater discharge to Ellerbe Creek. These monitoring data were coupled with temperature surveys and water-quality samples to assess whether groundwater may be a possible nonpoint source of nutrients to Ellerbe Creek and the Falls Lake watershed. This approach can improve understanding regarding the usefulness of the methods and techniques used in this study to characterize groundwater/surface-water interactions within Piedmont streams in Triassic sedimentary basins.

Study Area Description

The study area is in Durham County, North Carolina, within the Piedmont physiographic province. Ellerbe Creek is within the upper Neuse River Basin, upstream from Falls Lake (fig. 1), and is monitored for stage and streamflow by the U.S. Geological Survey (USGS) at streamgage 0208675010 (EC-1) and streamgage 02086849 (EC-11). The drainage area of Ellerbe Creek at EC-11, located at the downstream end of the study area, is 21.9 square miles (mi^2) and includes areas along Interstate 85 and north of downtown Durham. The land cover within the drainage area is predominantly urban (77 percent) with some forested coverage (15 percent) (fig. 2), according to the 2011 National Land Cover Database (NLCD) (Homer and others, 2015). The drainage area is underlain primarily by the sandstones and interbedded siltstones and mudstones of the Durham and Sanford subbasins of the Deep River Mesozoic basin (formerly known as the Triassic basin) (Brown and Parker, 1985; Hanna and Bradley, 2016) (fig. 3). Soils in the Ellerbe Creek drainage area are composed of unconsolidated, poorly sorted, and stratified sand, silt, and clay alluvium. The dominant hydrologic soil types for the study area are group C soils that have low infiltration rates, with more moderately drained group B soils farther upgradient from the stream. The U.S. Army Corps of Engineers straightened and channelized Ellerbe Creek in the early 1960s to control large volumes of surface runoff caused by the clayey, poorly draining soils and increased impervious surface area in the city of Durham (North Carolina Department of Environment and Natural Resources, 2003). Most of the Ellerbe Creek streambed is composed of alluvial sand and silt-sized particles that mobilize readily under the rapidly changing high flows caused by surface runoff during storm events.

The groundwater system in the study area is composed of weathered regolith material at the land surface and underlying sedimentary bedrock that yields small quantities of water because of compaction and cementation within the rock (Chapman and others, 2013). Permeability of the aquifer may be slightly enhanced along lithologic contacts and bedding planes, as well as the openings and weathered areas around resistant diabase dikes within the study area that can provide preferential flow paths (fig. 3). The shallow regolith, which consists of soil residuum (clay), alluvium (older stream deposits), and saprolite (weathered bedrock material), is the shallowest portion of the groundwater system and serves as the primary storage reservoir for recharge to the deeper portions of the aquifer (Chapman and others, 2005).

The NDWRF, which is within the study reach, has a permitted capacity of 20 million gallons per day (Mgal/d) and discharges about 10 Mgal/d (15.5 cubic feet per second [ft^3/s]) of treated wastewater into Ellerbe Creek. A closed, unlined solid waste landfill that stopped receiving waste in 1997 is north of the NDWRF, approximately 1,000 feet (ft) east of Ellerbe Creek (fig. 4). A small, unnamed stream meanders along the southern and western edges of the landfill and discharges to Ellerbe Creek through a culvert located 1,800 ft downstream from the NDWRF outfall.

Previous Investigations

According to previous regional studies of shallow groundwater (Hallberg and Keeney,1993; Dubrovsky and others, 2010), the most widespread contaminant in groundwater from nonpoint anthropogenic sources is nitrogen. Messier and others (2014) developed a nonlinear land-use regression geostatistical model to predict point-level groundwater nitrate concentrations in North Carolina by using data from shallow groundwater monitoring wells and deeper private wells; median nitrate input values ranged from 0.10 to 1.30 mg/L. Nitrate concentrations within the shallow monitoring wells varied widely, with wastewater treatment residuals and swine confined animal feeding operations as the dominant nitrate sources. McSwain and others (2014) assessed nitrate sources by using stable isotope compositions of nitrogen and oxygen at sites in three tributary creeks to Falls Lake, including USGS site 0208675010 on Ellerbe Creek, which is about 2.5 mi upstream from the NDWRF. Organic nitrogen accounted for more than 50 percent of the total measured nitrogen within the creeks, and nitrate plus nitrite concentrations were below 0.40 mg/L in all samples. Of the many potential sources of nitrate (for example, soil, atmospheric deposition, fertilizer, and manure and septic waste), the dominant source of nitrate to the three creeks was found to be the nitrification of soil nitrogen. Some storm samples also had atmospheric inputs of nitrate as a result of impervious-surface runoff directly entering streams. No evidence of septic or wastewater discharge was observed.

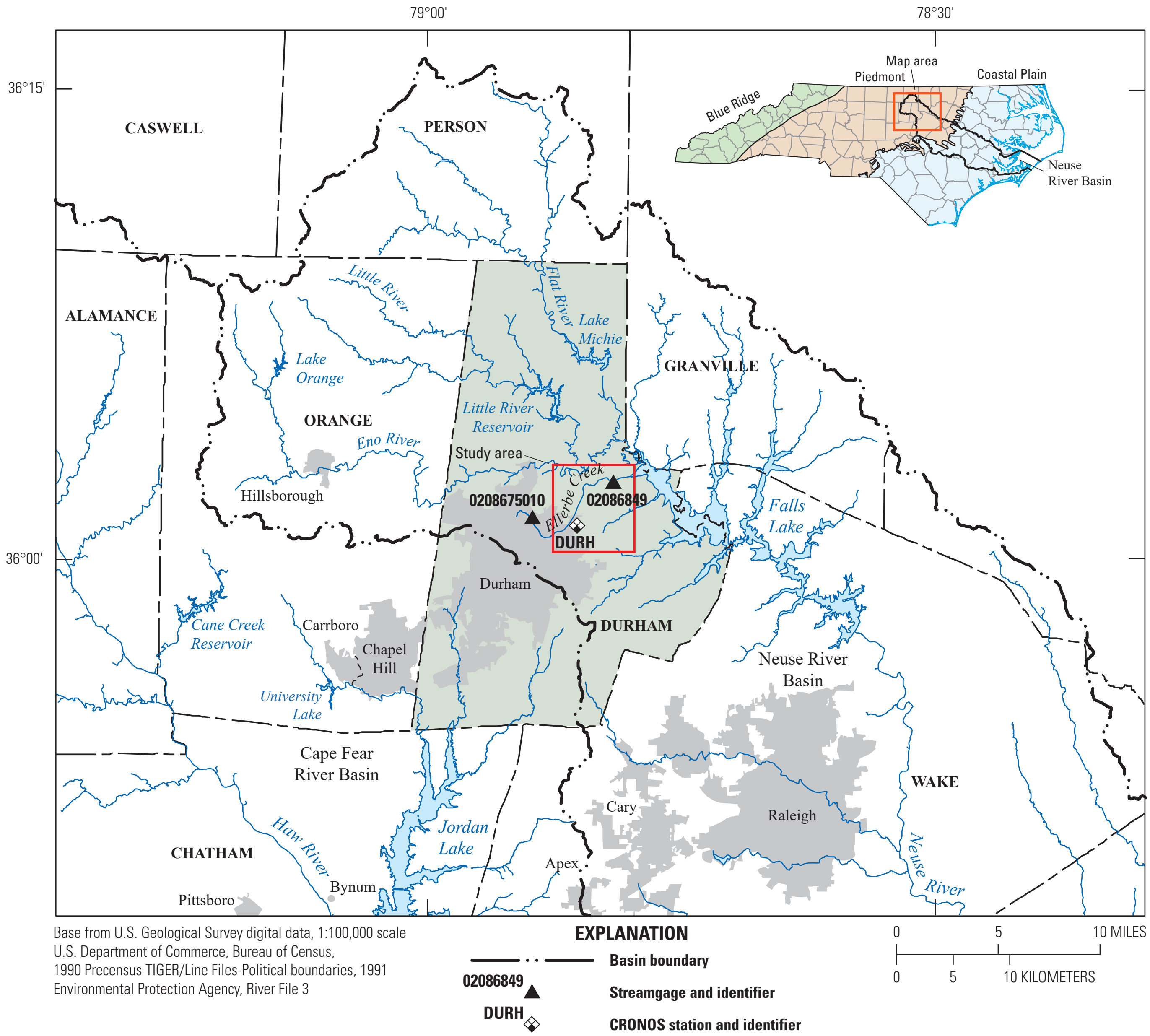

Figure 1. Map showing location of the study area in Durham, North Carolina, within the Piedmont physiographic province. Streamgage 0208675010 is site EC-1, and streamgage 02086849 is site EC-11. EC, Ellerbe Creek.

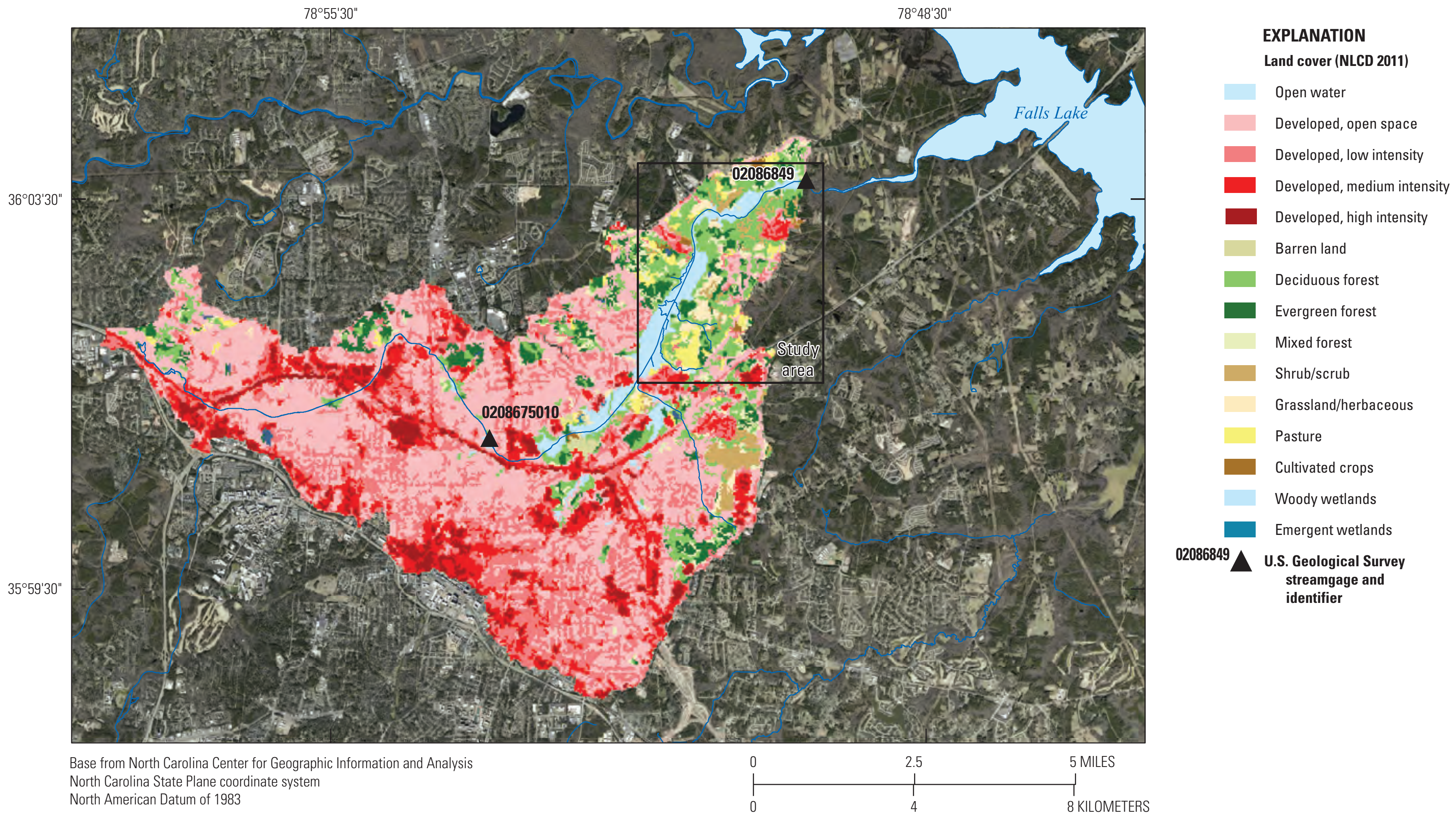

Figure 2. Map showing land cover within the Ellerbe Creek drainage area in Durham, North Carolina. Land-cover data are from the 2011 National Land Cover Database (NLCD 2011; Homer and others, 2015). Streamgage 0208675010 is site EC-1, and streamgage 02086849 is site EC-11. EC, Ellerbe Creek.

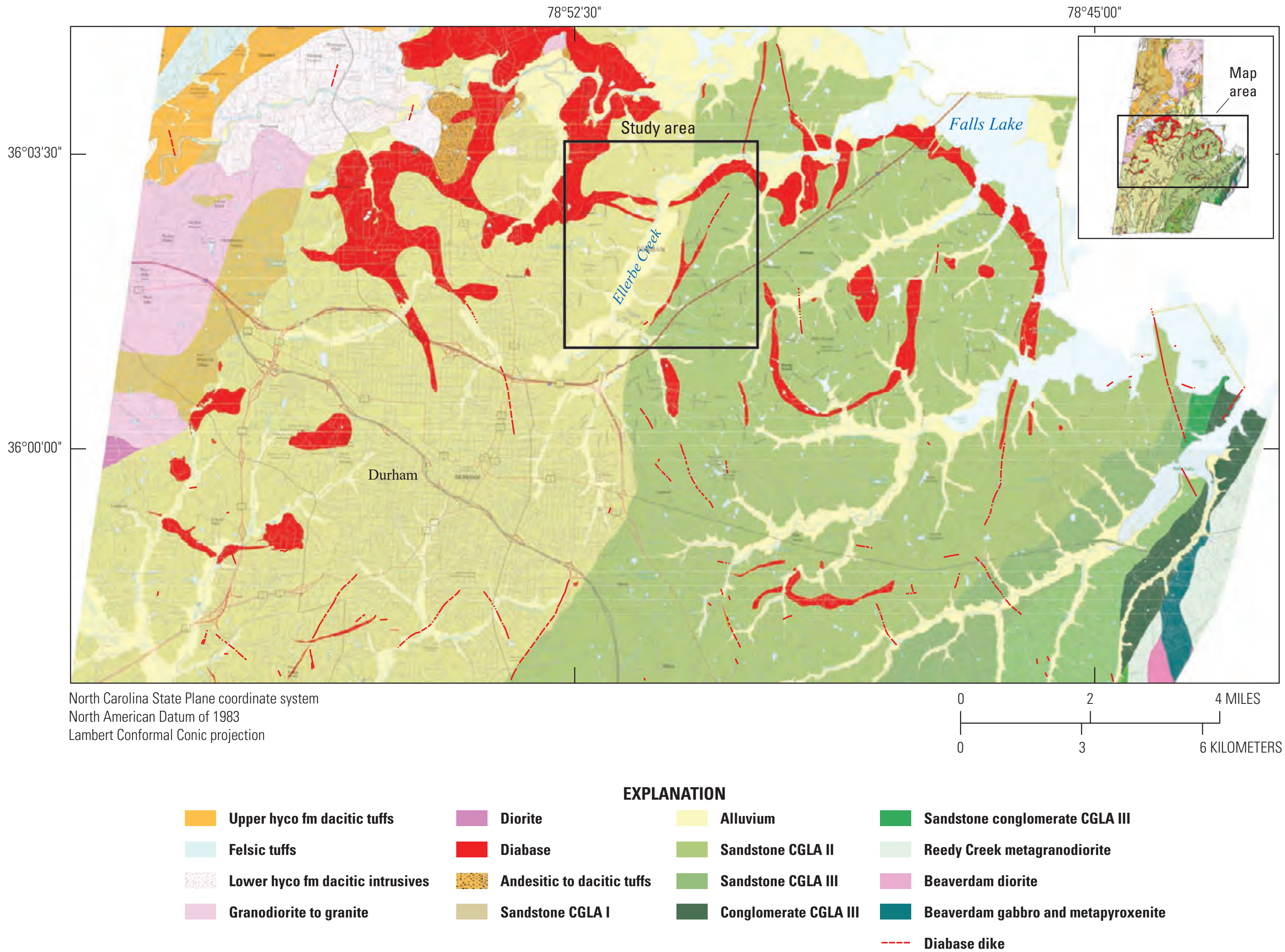

Figure 3. Map showing geology of the study area in Durham, North Carolina. The base map is modified from Hanna and Bradley (2016). Fm, formation; CGLA, Chatham Group Lithofacies Association.

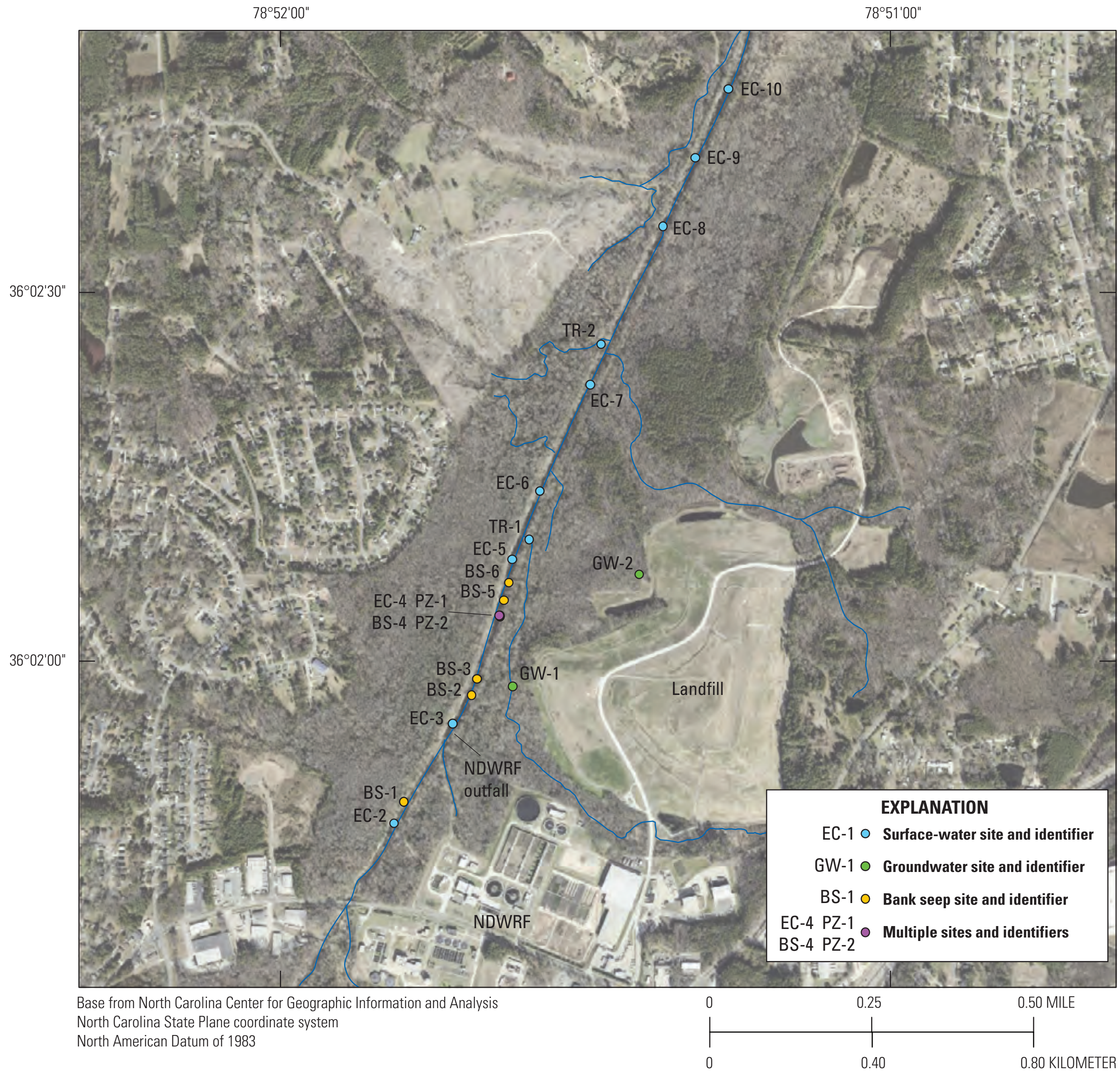

Figure 4. Map showing location of surface-water, groundwater, and bank seep sites in the Ellerbe Creek study area in Durham, North Carolina. Sites EC-1 and EC-11 are shown in figures 1 and 2. BS, bank seep; EC, Ellerbe Creek; GW, groundwater well; NDWRF, North Durham Water Reclamation Facility; PZ, piezometer.

Methods of Investigation

This section provides a discussion of the methods used for describing the groundwater/surface-water interaction in Ellerbe Creek, including streamflow and groundwater data collection, water-quality sampling, and a distributed temperature survey. Map names for all study sites are used in place of USGS station names to make references concise within the text and figures (table 1).

Streamflow Data Collection

Streamflow data were collected at eight sites within Ellerbe Creek in July 2016 by using a handheld SonTek FlowTracker acoustic Doppler velocimeter (ADV) and a Teledyne RD Instruments StreamPro acoustic Doppler current profiler (ADCP) deployed from a tethered moving boat. The FlowTracker ADV instantaneous streamflow measurements were made by using the USGS midsection method (Young, 1950). The StreamPro ADCP allows three-dimensional velocities to be measured from approximately 1.0 ft beneath the water surface to within 6 percent of the depth to the bottom. The ADCP velocity, streamflow, and depth data were collected using standard USGS techniques (Mueller and others, 2013). Streamflow measurement locations were selected for gain-loss surveys to bracket tributary inflows and reaches suspected to contain shallow groundwater seeps. Hourly discharge data for the NDWRF effluent outfall from July 2014 to July 2018 were provided by the Durham Department of Water Management for reference (John Dodson, Durham Department of Water Management, written commun., 2018).

Table 1. Site information and map names for surface-water, bank seep, and groundwater sites in the Ellerbe Creek study area in Durham, North Carolina.

[NC, North Carolina; EC, Ellerbe Creek; Q, discharge; CR, Creek; RD, Road; NR, near; WQ, water quality; MI, mile; SR, Secondary Road; WL, water level; UT, unnamed tributary; BLW, below; TR, tributary; BL, below; BS, bank seep; MW, monitoring well; GW, groundwater well; PZBK, bank piezometer; PZ, piezometer; PZST, stream piezometer]

Site number	Station name	Map name	Latitude (decimal degrees)	Longitude (decimal degrees)	Data type collected
0208675010	ELLERBE CREEK AT CLUB BOULEVARD AT DURHAM, NC	EC-1	36.01938889	−78.89477	Q
0208682450	ELLERBE CR BELOW SECONDARY RD 1669 NR WEAVER, NC	EC-2	36.02983	−78.863694	Q, WQ
02086833	ELLERBE CREEK 0.33 MI BELOW SR1669 NR WEAVER, NC	EC-3	36.03206	−78.86206	Q, WQ
02086834	ELLERBE CR 0.51 MILE BELOW SR1669 NEAR WEAVER, NC	EC-4	36.03448	−78.860771	WL
02086835	ELLERBE CREEK 0.59 MI BELOW SR1669 NR WEAVER, NC	EC-5	36.03572	−78.86042	Q, WQ
02086837	ELLERBE CREEK 0.71 MI BELOW SR1669 NR WEAVER, NC	EC-6	36.03725	−78.85964	Q, WQ
02086839	ELLERBE CREEK 0.89 MI BELOW SR1669 NR WEAVER, NC	EC-7	36.03961	−78.85817	Q, WQ
02086841	ELLERBE CREEK AT WEAVER, NC	EC-8	36.04319	−78.85628	Q, WQ
02086843	ELLERBE CREEK 1.28 MI BELOW SR1669 NR WEAVER, NC	EC-9	36.04469	−78.85536	Q, WQ
02086845	ELLERBE CREEK 1.39 MI BELOW SR 1669 NR WEAVER, NC	EC-10	36.04625	−78.8545	Q, WQ
02086849	ELLERBE CREEK NEAR GORMAN, NC	EC-11	36.05956	−78.832534	Q, WQ
360211078513701	UT TO ELLERBE CR 0.63 MI BLW SR1669 NR WEAVER, NC	TR-1	36.03626	−78.86018	WQ
360226078512801	UT TO ELLERBE CR 1.04 MI BLW SR1669 NR WEAVER, NC	TR-2	36.04058	−78.85767	WQ
360149078514801	DR-073 ELLERBE LB-1 0.18 MI BL SR1669 NR WEAVER NC	BS-1	36.03028	−78.86333	WQ
360158078514201	DR-076 ELLERBE RB-4 0.35 MI BL SR1669 NR WEAVER NC	BS-2	36.03278	−78.86167	WQ
360159078514101	DR-074 ELLERBE RB-2 0.40 MI BL SR1669 NR WEAVER NC	BS-3	36.03306	−78.86139	WQ
360204078513901	DR-075 ELLERBE RB-3 0.51 MI3BL SR1669 NR WEAVER NC	BS-4	36.03444	−78.86083	WQ
360205078513801	DR-077 ELLERBE RB-5 0.50 MI BL SR1669 NR WEAVER NC	BS-5	36.03472	−78.86056	WQ
360207078513801	DR-078 ELLERBE RB-6 0.55 MI BL SR1669 NR WEAVER NC	BS-6	36.03528	−78.86056	WQ
360159078513801	DR-081 (MW-10) NEAR WEAVER, NC (REGOLITH)	GW-1	36.03289	−78.860399	WL, WQ
360207078512501	DR-082 (MW-2) NEAR WEAVER, NC (REGOLITH)	GW-2	36.03531	−78.856826	WL, WQ
360204078513902	DR-079 ELLERBE PZBK 0.51 MI BL SR1669 NR WEAVER NC	PZ-1	36.03448	−78.860744	WL, WQ
360204078513903	DR-080 ELLERBE PZST 0.51 MI BL SR1669 NR WEAVER NC	PZ-2	36.03448	−78.860771	WL, WQ

Groundwater-Level Monitoring

Groundwater-level measurements were collected at two piezometers (PZ-1 and PZ-2) and two monitoring wells (GW-1 and GW-2) in the study area to identify general flow direction and hydraulic gradients at the stream bank (table 2). The streambank piezometer (PZ-1) was installed to a depth of 3.4 ft below land surface, and the stream piezometer (PZ-2) was installed to a depth of 5.5 ft below the streambed. The lateral distance between the two piezometers was 10 ft. This section of the stream was selected for water-level monitoring due to the presence of and accessibility to a persistent bank seep (BS-4). The wells GW-1 and GW-2, part of a long-term monitoring network at the nearby unlined landfill, are about 600 ft and 1,100 ft, respectively, from the piezometer sites (fig. 4).

Measurements were made from the top of the well casing with an electric water-level tape or a steel tape, using techniques described by Cunningham and Schalk (2011). The measuring points at PZ-1 and PZ-2 were surveyed in relation to a locally established bench mark to determine the altitude difference between the two sites. Land-surface altitudes at the locally established bench mark and two monitoring well sites were derived from 1-meter (m) high-density light detection and ranging (lidar) data (National Oceanic and Atmospheric Administration, 2015) with a mean vertical accuracy of 0.04 m and were reported in feet above the North American Vertical Datum of 1988 (NAVD 88). The distance from the land surface to the measuring point was then measured with an engineer's rule to determine the measuring point altitude. Continuous water levels were measured in piezometers at sites PZ-1 and PZ-2 from December 2017 to March 2018 by using internally logging unvented pressure transducers. Stream water level was measured at site EC-4 also using an internally logging unvented pressure transducer, which was secured to the downstream side of the piezometer at site PZ-2. These datasets are available to the public through the USGS National Water Information System database (U.S. Geological Survey, 2018).

Weather and Climate Data

Hourly precipitation and air temperature data were collected by a North Carolina Climate Retrieval and Observations Network of the Southeast (CRONOS) station located at the NDWRF (CRONOS station DURH). A collaboration between State and Federal agencies, the CRONOS database contains weather and climate observations for 41 stations across 33 counties in North Carolina and is publicly available at https://climate.ncsu.edu/cronos.

Hydrograph Separation

Hydrograph-separation methods were used to estimate base flow within the 21.9-mi^2 drainage area of site EC-11 (USGS streamgage 02086849), as well as within the 6.0-mi^2 drainage area of the upstream site, EC-1 (USGS streamgage 0208675010), for comparison. Base flow is the component of streamflow largely sustained by groundwater discharge along the stream reach and is distinct from direct surface runoff. For the study area, base-flow estimates include natural base flows of steady groundwater discharge to Ellerbe Creek and its small tributary inflows, as well as anthropogenic inflows that have a relatively consistent discharge, such as effluent from the NDWRF. Hydrograph separation was done using the USGS Groundwater (GW) Toolbox, which is a software program that allows hydrograph analysis using six hydrograph-separation methods to calculate several components of the water budget, including base flow and surface-water runoff (Barlow and others, 2015). Two methods were used in the current study to determine lower and upper estimates of base flow; specifically, the base-flow index (BFI) and PART methods, respectively.

Table 2. Discrete water levels measured in November and December 2017 and March 2018 at groundwater and surface-water sites in the Ellerbe Creek study area in Durham, North Carolina.

[ft, foot; NADV 88, North American Vertical Datum of 1988; PZ, piezometer; GW, groundwater well; —, not measured; EC, Ellerbe Creek]

Site number	Map name	Land-surface altitude (ft above NAVD 88)	Altitude of top of casing (ft above NAVD 88)	Total well depth (ft)	Screened interval (ft)	Casing diameter (inches)	Water-level altitude (ft above NAVD 88) 11/29/17	Water-level altitude (ft above NAVD 88) 12/1/17	Water-level altitude (ft above NAVD 88) 12/7/17	Water-level altitude (ft above NAVD 88) 3/29/18
360204078513902	PZ-1	271.2	271.80	3.4	1	1	269.19	269.52	270.46	270.39
360204078513903	PZ-2	268.0	269.53	5.5	1	1	269.03	269.13	269.28	269.38
360159078513801	GW-1	279.7	281.55	14.5	10	2	—	—	—	274.65
360207078512501	GW-2	283.8	285.52	18.0	10	2	—	—	—	281.91
02086834	EC-4	268.0	269.53	—	—	—	269.01	269.1	269.14	269.25

The BFI method (Institute of Hydrology, 1980a, b; Wahl and Wahl, 1995) partitions the streamflow hydrograph into intervals of *N* days to determine minimum flows within each interval. If 90 percent of the minimum of interest is less than adjacent minimums, then the flow is determined to be a “turning point” and is connected with other turning points to complete the base-flow hydrograph. The PART method (Rutledge, 1998) designates days that are unaffected by surface runoff as those that are preceded by *N* days of continuous recession and linearly interpolates between these days to determine the base-flow hydrograph. For the current study, the period of analysis was October 1982 to January 2018 for USGS streamgage 02086849 (site EC-11) and July 2008 to January 2018 for streamgage 0208672010 (EC-1). The separation method parameters were set to a partition length of $N = 5$ days, a turning point test factor of $F = 0.90$, and a daily recession index of $K = 0.97915$.

Water-Quality Sampling

Water-quality samples were collected at four groundwater sites, six bank seeps, and 11 surface-water sites in July and August 2016, July 2017, and March 2018. Sampling methods followed those outlined in the USGS “National Field Manual for the Collection of Water-Quality Data” (U.S. Geological Survey, 2006). Surface-water sampling was conducted at 10 sites in July 2016, concurrent with stream-discharge measurements. Three of these sites were again sampled in March 2018, along with downstream site EC-11, about 3 mi downstream from the NDWRF. Water samples were collected at observable bank seeps using a drive-point piezometer connected to a peristaltic pump in August 2016 and in July 2017. The July 2017 sampling event coincided with the deployment of the fiber-optic distributed temperature sensing (FO-DTS) system described in the “Water-Temperature Surveys” section.

Groundwater, bank seep, and surface-water sites were sampled for nutrients, including nitrite, nitrate, and ammonia. Groundwater and surface-water sites were also sampled for major ions, iron, and manganese. All samples were analyzed at the USGS National Water Quality Laboratory in Denver, Colorado, using methods outlined in Fishman (1993).

Water-Quality Control Samples

Five field blanks and three sample replicates were also collected throughout the sampling process to address quality assurance and quality control (QA/QC). The blanks and replicates provide information regarding the accuracy and precision, respectively, of the water-quality data presented in this report. The QA/QC samples were collected in accordance with USGS policies and procedures documented in the National Field Manual (U.S. Geological Survey, 2006).

Statistical Analysis of Water-Quality Data

The water-quality data were summarized using Piper (trilinear) diagrams and box plots. Charge-balance errors calculated for the major cation and anion data of all samples were found to have less than a 10-percent difference, which was determined acceptable for statistical evaluation (U.S. Geological Survey, 1992). Piper diagrams are trilinear plots used to visually describe and compare the major ion composition of multiple samples of water on one graph. Ternary diagrams for both cations and anions are projected onto a diamond plot, where samples can be divided into hydrochemical facies or groups of samples with similar chemical characteristics as a result of similar hydrogeochemical processes (Piper, 1953). Using this approach, distinct source waters and the mixing relationships that exist between them can be identified, as well as any water-rock interactions that may occur along the groundwater flow path. Box plots also provide a way to visually compare datasets by displaying the statistical spread of the data (Sincich, 1993). The box encompasses the interval between the first and third quartiles (25th and 75th percentiles), with the median (50th percentile) represented by a horizontal line within the rectangular box. Lines and whiskers drawn from the first and third quartiles represent the values of the 10th and 90th percentiles of the dataset, respectively. For datasets that contained censored data for non-detection of a constituent (for example, nitrate), the rank method was used to determine summary statistics for the construction of boxplots. This method does not involve any assumption about the underlying distribution and is a simple and appropriate method for small datasets that have only one censoring value present (Bonn, 2008).

Water-Temperature Surveys

Temperature has been shown to be an effective tracer of groundwater movement near streams (Stonestrom and Constantz, 2003). The interaction of shallow groundwater with surface water can be assessed by contrasting the natural variations in stream water temperature resulting from seasonal and meteorological changes with the relatively stable groundwater temperatures. In a gaining stream reach during the summer, the relatively cooler thermal signature of discharging groundwater may be seen within the warmer surface water. The methods used for this study ensure measurement of distinct temperature differences, but these methods cannot be used to distinguish between no-flow and losing reaches.

An initial reconnaissance survey in March 2016 and a subsequent survey in July 2016 were conducted to identify possible groundwater discharge points along the stream reach by using a forward-looking infrared (FLIR) camera in seasonal extremes. The high-resolution FLIR T620 and T640 thermal imaging cameras capture the emitted infrared radiation of the objects in view. Recent studies using similar ground-based thermal infrared imaging techniques have been successful in qualitatively locating groundwater discharge along discrete features, such as fractures and faults, as well as diffuse seepage along stream banks (Deitchman and Loheide, 2009; Pandey and others, 2013). Sites of interest were those where temperature differences were observed between the stream surface and points of streambank inflow, specifically where warmer groundwater was observed flowing from the streambank into the relatively cooler stream during the winter and where cooler groundwater was entering the relatively warmer stream during the summer.

FO-DTS can be used to determine differences in the temperature of surface water along a profile. With FO-DTS, surface-water temperatures are measured for several days along a fiber-optic cable that may extend more than a kilometer with a spatial resolution of less than 3 ft. Temperature precisions of 0.1 degree Celsius (°C) and a temporal resolution of 90 seconds can be obtained (Selker and others, 2006). The measured temperature differences can often denote locations of groundwater discharge along a reach.

From July 18 to 25, 2017, an FO-DTS survey was completed by using a Sensornet ORYX distributed temperature sensing (DTS) system to delineate areas of groundwater discharge along Ellerbe Creek, just upstream from the NDWRF outfall to downstream from the closed municipal landfill. About 975 m of fiber-optic cable was deployed on the right bank (closest to the landfill) in the bed of the stream channel. Global Positioning System (GPS) location measurements were collected every 30 ft along the cable during deployment, and a trolling SonTek RiverSurveyor M9 ADCP with a differentially corrected Global Positioning System (DGPS) receiver collected depth and location data every 1.6 ft during cable retrieval to georeference the location of the cable. The DGPS received differential corrections from a Wide Area Augmentation System (WAAS) and is specified by the manufacturer to be accurate to 3.3 ft at two standard deviations. Hourly air temperature was collected at the CRONOS DURH station located at the NDWRF.

Temperature data obtained by using the ORYX DTS system were collected between 18:39 on July 18, 2017, and 04:26 on July 25, 2017. Data were recorded every 15 minutes at intervals of about 3 ft along the length of the fiber-optic cable. Ten consecutive temporal measurements made by the FO-DTS system over a 15-minute period were averaged to obtain 1 temperature measurement, for a total of 641 measurements collected over about 7 days. Analysis of the thermal data was done by using the DTS graphical user interface (GUI) program, currently under development by the USGS (Martin Briggs, U.S. Geological Survey, oral commun., 2018). The DTS GUI is a Python-based internal data visualization code that provides tools to import and view FO-DTS data in geospatial format.

Groundwater/Surface-Water Interactions

Groundwater/surface-water interactions were characterized by synoptic streamflow measurements, hydraulic gradients derived from water-level monitoring, and continuous streambed temperature using FO-DTS. The regolith aquifer is the principal hydrogeologic unit that interacts with surface-water features in the study area. Under typical conditions, when the water table follows the local topography, groundwater stored within the regolith aquifer would flow downgradient through the alluvium and discharge to the stream across miles of the entire stream reach. The discharge and recharge rates are dependent on the hydraulic gradient that exists between the groundwater system and the stream.

Streamflow Gains and Losses

To characterize the bulk exchange of water between the stream and surficial groundwater system, a streamflow gain-loss survey was conducted in Ellerbe Creek on July 12, 2016, at eight sites along the stream reach. According to data collected at USGS streamgage 02086849 (EC-11; location shown in figs. 1 and 2), the stream was under base-flow conditions during all discharge measurements. Streamflow ranged from 17.0 to 24.2 cubic feet per second (ft^3/s), and stage ranged from 1.58 to 1.68 ft above NAVD 88 before a rainfall event occurred post-survey, during the evening (fig. 5). According to data provided by the NDWRF, the effluent discharge ranged from 7.8 to 18.9 ft^3/s over the course of the survey. The survey covered about 1.4 mi of Ellerbe Creek, starting at a site 740 ft upstream from the NDWRF outfall (fig. 6). The remaining seven discharge sites were upstream and downstream from major inflows to the stream, including two culverts, multiple small creeks, and a nearby surface-water impoundment.

The gain or loss in streamflow is estimated as the difference between inflow to the reach and outflow from the reach. A stream reach was classified as gaining or losing if the difference between the upstream and downstream discharge measurements exceeded the uncertainty error of both measurements. A meaningful streamflow gain within a reach was attributed to unmeasured tributary inflow and groundwater discharge to the stream. A meaningful seepage loss within a reach was assumed to be recharge to the groundwater system. Errors for each discharge measurement were based on measurement statistics generated by the ADV or ADCP data processing software. The total uncertainty in a discharge measurement includes uncertainty in cross-sectional area measurements, water-velocity profile measurements and assumptions, extrapolations for unmeasured areas, and random or systematic errors (Turnipseed and Sauer, 2010).

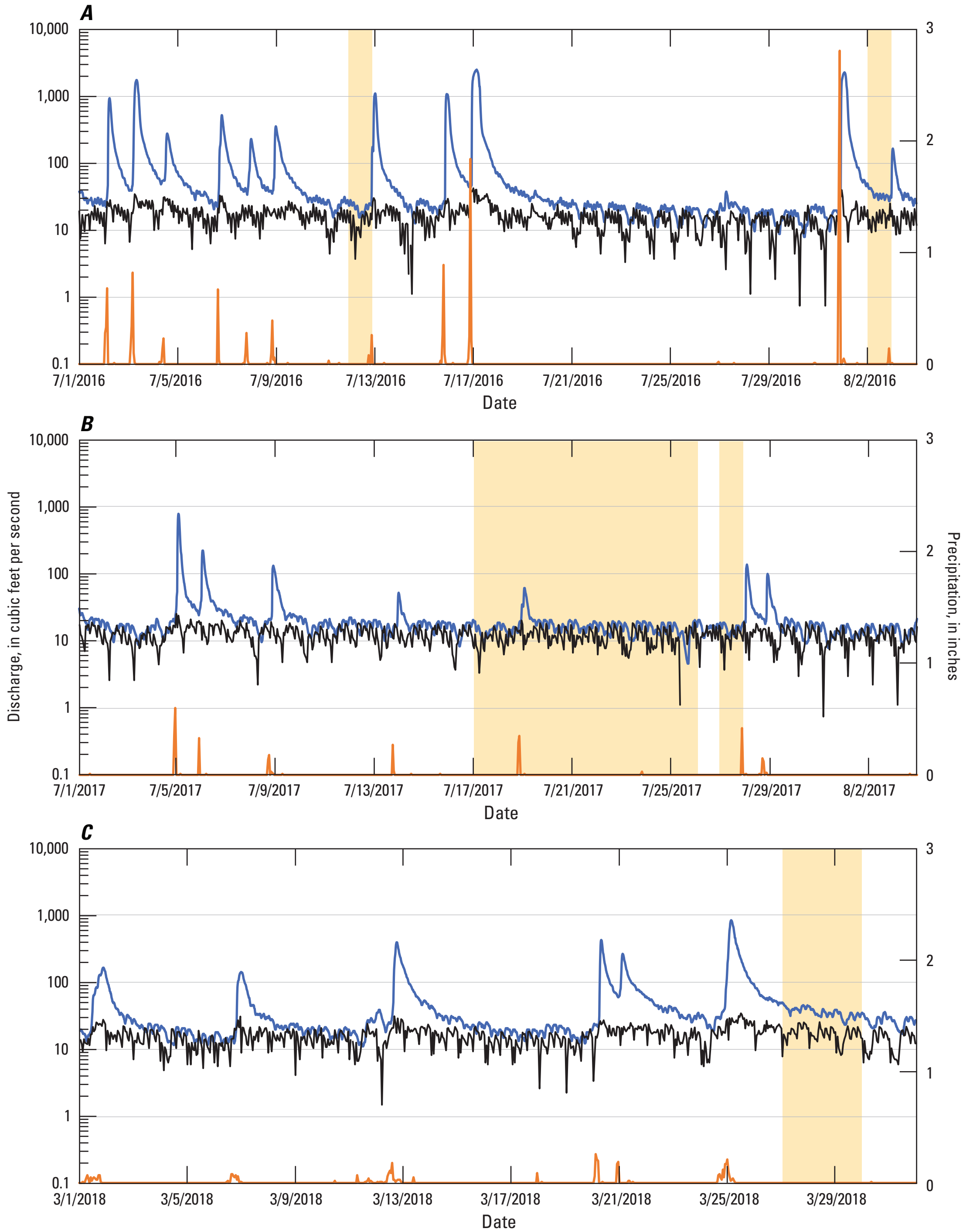

Figure 5. Graphs showing discharge at U.S. Geological Survey streamgage 02086849 (EC-11) (blue lines), North Durham Water Reclamation Facility effluent discharge (black lines), and precipitation at the Climate Retrieval and Observations Network of the Southeast DURH site (orange lines) during (*A*) a streamflow survey on July 12, 2016, and water-quality sampling on August 2, 2016; (*B*) a fiber-optic distributed temperature sensing survey from July 18 to 25, 2017, and water-quality sampling on July 27, 2017; and (*C*) water-quality sampling from March 27 to 29, 2018, at Ellerbe Creek, Durham, North Carolina. Yellow highlights indicate measurements made during the given sampling and survey dates.

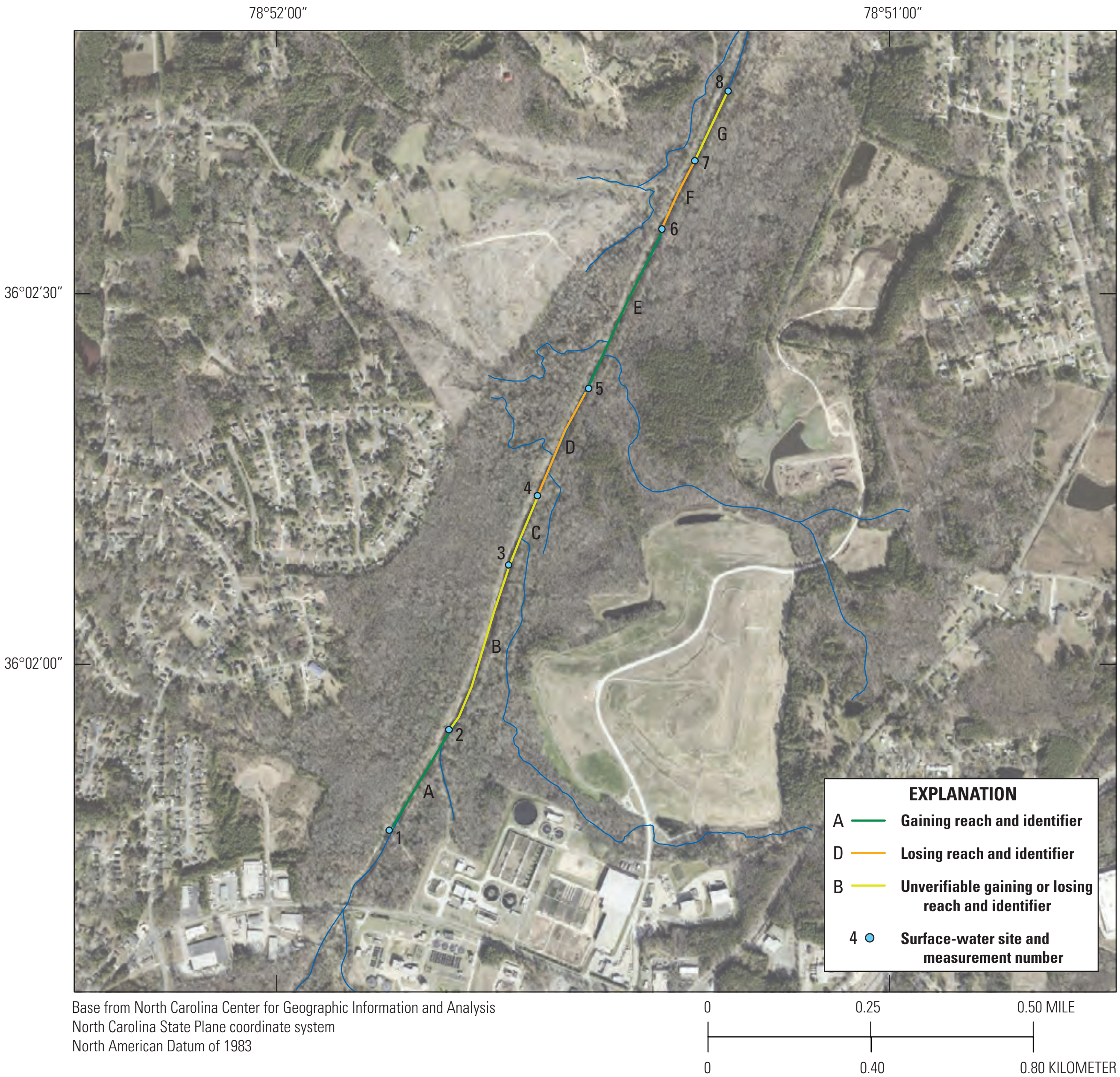

Figure 6. Map showing stream reaches measured for a streamflow gain-loss survey on July 12, 2016, in Ellerbe Creek in Durham, North Carolina.

All reaches evaluated for streamflow gains or losses in this stretch of Ellerbe Creek are depicted in figure 6 and summarized in tables 3 and 4. Of the seven reaches assessed during the survey, reaches A and E had verifiable streamflow gain and reach F showed slight losing conditions. Reaches B and G did not have verifiable streamflow gain because the uncertainty errors exceed the inflow and outflow difference. Reach C had a relatively larger seepage loss, but upon consideration of the magnitude of uncertainty error coupled with an effluent discharge decrease of 2.4 ft^3/s between the inflow and outflow reach measurements, the observed loss is not meaningful. Flow from the tributary within reach C was not measured; however, the flow velocity was estimated to be between 1 and 2 feet per second through the 4-ft culvert at a depth near 0.5 ft, and the inflow to the stream during the survey was estimated to be between 1 and 2 ft^3/s.

Table 3. Measurements from the July 2016 gain-loss survey for reaches in Ellerbe Creek in Durham, North Carolina.

[ft/s, foot per second; ft^3/s, cubic foot per second; NDWRF, North Durham Water Reclamation Facility; ADV, acoustic Doppler velocimeter; —, not measured; ADCP, acoustic Doppler current profiler]

Site number	Measurement number	Method	Date and time	Mean velocity, ft/s	Discharge, ft^3/s	Uncertainty, percent	Uncertainty, ft^3/s (+/–)	Change in NDWRF discharge during measurement, ft^3/s	Change in NDWRF discharge from upstream measurement, ft^3/s
0208682450	1	ADV	7/12/2016 10:31	0.34	5.5	2.7	0.1	—	—
02086833	2	ADCP	7/12/2016 12:25	0.40	26.3	5.3	1.4	−0.3	—
02086835	3	ADCP	7/12/2016 13:06	0.41	26.9	23.0	6.2	−0.6	0.0
02086837	4	ADV	7/12/2016 14:12	0.56	19.7	2.5	0.5	−1.9	−2.4
02086839	5	ADV	7/12/2016 14:53	0.63	18.0	3.2	0.6	−1.9	0.0
02086841	6	ADV	7/12/2016 16:37	0.46	25.6	4.0	1.0	1.7	1.5
02086843	7	ADV	7/12/2016 15:37	0.27	21.1	3.1	0.7	−0.9	0.4
02086845	8	ADV	7/12/2016 16:08	0.26	21.2	4.9	1.0	−0.9	0.0

Table 4. Summary of gain-loss determinations during the July 2016 gain-loss survey for reaches in Ellerbe Creek in Durham, North Carolina.

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

Reach name	Associated measurements	Gain or loss, ft^3/s	Total uncertainty, ft^3/s (+/–)	Reach distance, ft	Averaged velocity, ft/s	Travel time, minutes
A	1, 2	20.8	1.5	965	0.37	43.5
B	2, 3	0.6	7.6	815	0.41	33.5
C	3, 4	−7.18	6.7	605	0.49	20.8
D	4, 5	−1.768	1.1	965	0.60	27.0
E	5, 6	7.6	1.6	1,380	0.55	42.2
F	6, 7	−4.514	1.7	610	0.37	27.9
G	7, 8	0.1	1.7	620	0.27	39.0

Reach A contains the NDWRF outfall, which likely accounts for much of the measured gain for the reach. A streamflow gain of 7.6 ft^3/s in reach E was attributed to both groundwater discharge and the two small, unmeasured tributaries flowing into the stream within the reach. A seepage loss of 1.8 ft^3/s measured in reach D indicates the combined contributions of groundwater discharge within the reach, and inflow from a small unmeasured tributary was exceeded by seepage loss to the groundwater system. Reach F also showed a meaningful seepage loss to the groundwater system of 4.5 ft^3/s.

Calculations from the streamflow gain-loss survey showed that Ellerbe Creek has both gaining and losing reaches within the study area. Only reaches A and E had verifiable streamflow gain (20.8 ft^3/s and 7.6 ft^3/s, respectively), which cannot be attributed solely to groundwater because small tributaries flow into the stream within both reaches, as well as NDWRF effluent inflow within reach A. Reach D showed a small but verifiable seepage loss despite containing two tributary inflows. Though the discharge from the NDWRF outfall fluctuated throughout the survey, the observed seepage losses were not related to decreases in effluent flow to the stream. Both inflow and outflow measurements in reach D were completed under stable effluent discharge conditions, whereas the volume of effluent discharge increased by 0.4 ft^3/s between the inflow and outflow measurements for reach F, which would slightly reduce the observed seepage loss (table 2). Diabase dikes cut across the bedrock underlying the alluvial sediments in this area of Ellerbe Creek (fig. 3), particularly within reach F (fig. 6). Though diabase dikes are not permeable and may act as an impermeable boundary to groundwater discharge (McSwain and others, 2009), preferential pathways along the weathered contact areas may divert groundwater along the dike. Weaver and McSwain (2013) observed no-flow or losing stream conditions in the Cape Fear River near Raven Rock State Park in North Carolina that coincided with the presence of diabase dikes intersecting the reach.

Groundwater and Surface-Water Levels

Continuous groundwater levels within two piezometers (PZ-1 and PZ-2) were recorded concurrently with continuous stream-level readings at site EC-4 between December 1, 2017, and March 28, 2018, to calculate hydraulic gradients in Ellerbe Creek during the wet season (fig. 7). Surface-water levels ranged from 268.65 to 273.54 ft above NAVD 88, and groundwater levels ranged from 268.71 to 273.20 ft above NAVD 88. Groundwater levels typically were higher than surface-water levels across the monitoring period, except during storm events when stream levels rose above groundwater levels. The hydrographs for both surface water and groundwater show similar patterns, likely because of hydrostatic pressure from the stream having direct communication to the shallow groundwater system through the alluvial sediments.

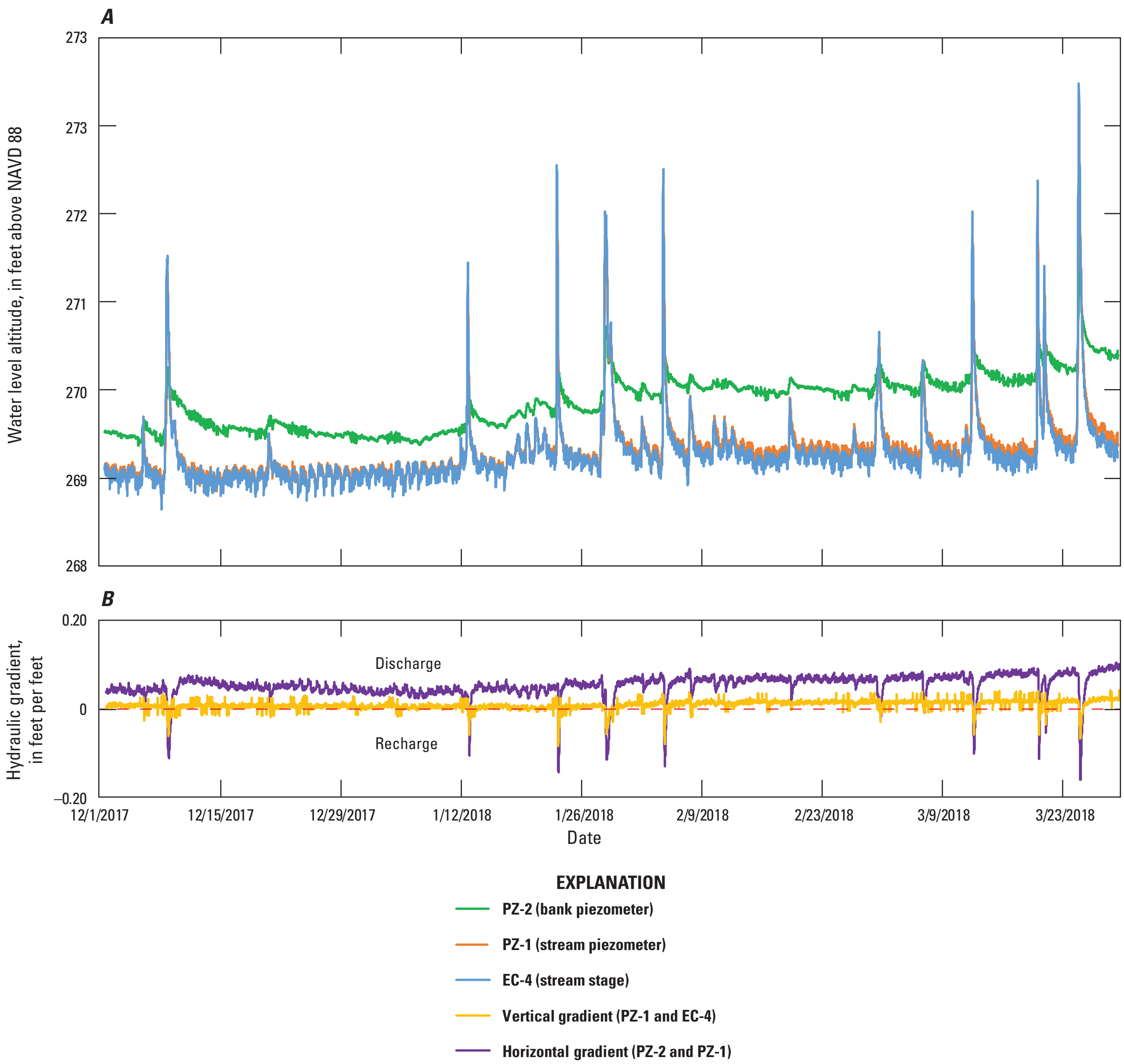

Figure 7. Graphs showing (*A*) continuous groundwater levels at sites PZ-1 and PZ-2 and surface-water level at site EC-4 and (*B*) hydraulic gradients measured between December 1, 2017, and March 29, 2018, within Ellerbe Creek in Durham, North Carolina. EC, Ellerbe Creek; NAVD 88, North American Vertical Datum of 1988; PZ, piezometer.

Positive vertical gradients indicate upward flow of groundwater discharge to the stream and negative gradients indicate downward flow, or groundwater recharge. Vertical gradients between the groundwater system beneath the stream and the stream level ranged from −0.08 to 0.04 foot per foot (ft/ft), with the mean near 0.01 ft/ft. The higher negative gradients coincided with storm events and had a duration of less than 4 hours. Horizontal gradients were computed between the piezometer within the stream and the stream bank piezometer with a range of −0.16 to 0.11 ft/ft, where positive values reflect groundwater movement into the stream and negative values reflect streamflow into bank storage. The mean horizontal gradient was 0.05 ft/ft, and the negative values coincided with storm events for short durations. Groundwater levels, showing a seasonal change, began to slowly rise during the monitoring period, with overall increases of about 0.9 ft within the bank piezometer and about 0.3 ft within the groundwater system beneath the stream.

Base-Flow Estimates

GW Toolbox was used to calculate base flow along Ellerbe Creek using streamflow records for USGS streamgages EC-10 and EC-11 from October 1982 to December 2017, with a median streamflow of 41 ft^3/s for the 35-year period. Gaps in the continuous streamflow record exist from May 1989 to September 1991, June 1994 to August 1994, and October 1995 to January 2006. The GW Toolbox program calculates base flow using all available data within periods between the data gaps, but the output files will not include the partial month or years with missing data in the results. Both the BFI and PART methods yielded annual and monthly estimates of base flow and surface runoff for the 35-year period.

The BFI method estimated an average annual rate of base flow of 14.0 ft^3/s and a base-flow index range of 0.21 to 0.49, which means that base flow contributes between 21 and 49 percent of total streamflow annually. Estimates for base flow computed by using the PART method were less conservative, with an average annual rate of base flow of 17.7 ft^3/s and a maximum base-flow index of 0.57. Annual and monthly fluctuations within the basin can be seen across the portion of the analyzed period shown in figure 8, with the highest flows in 2009 and low flows during the drought period of 2011. The base-flow estimates using the PART method show peaks that may include interflow because they coincide with high flows attributed to frequent storm events. The average annual rate of surface runoff was estimated to be near 23 ft^3/s for an average contribution of nearly 60 percent of streamflow.

On the basis of provided discharge records for effluent flow from the NDWRF from 2014 to 2018, the median discharge into Ellerbe Creek is 13 ft^3/s. Given these data, the average effluent discharge to Ellerbe Creek contributes slightly more than 30 percent of the total mean streamflow measured at the downstream USGS streamgage EC-11. On June 21, 2016, the discharge from the NDWRF outfall was stopped for about 3 hours, and the measured discharge at the USGS EC-11 streamgage dropped from 12.2 to 3.7 ft^3/s about 6 hours later, given the distance downstream from the outfall. The effluent discharge averaged 9.1 ft^3/s in the 6 hours prior to the shutoff, and the downstream EC-11 gage measured between 9.7 and 14 ft^3/s before flow began to decline. These data provide some insight into the natural base-flow contribution to streamflow from groundwater discharge and small tributary inflows within Ellerbe Creek, which is likely near 3.7 ft^3/s under similar hydrologic conditions.

Water-Temperature Survey Results

As stated previously, the interaction of shallow groundwater with surface water can be assessed by contrasting the variations in surface-water temperature resulting from seasonal and meteorological changes with the relatively stable groundwater temperature. Water-temperature surveys used to assess groundwater/surface-water interactions in Ellerbe Creek included the use of thermal imagery for locating persistent seeps along the stream bank and FO-DTS along the streambed. All data are publicly available online in Antolino (2018).

Reconnaissance of Bank Seeps Using Thermal Imaging

Reconnaissance surveys of Ellerbe Creek using a handheld FLIR camera were conducted on March 2, 2016, and July 18, 2016, to identify potential areas of groundwater discharge during seasonal extremes. The FLIR camera captures high-resolution images of real-time variations in stream and bank seep water temperature (fig. 9). During the March 2016 survey, the median surface temperatures recorded by the FLIR camera were 12.4 °C for bank inflow and 11.6 °C for the stream. During the July 2016 survey, several additional bank seeps were measured, with median surface temperatures of 23.3 °C for bank inflow and 26.5 °C for the stream. The temperature differences between bank inflow and the stream ranged from 1.3 to 2.8 °C for the March survey and from 1.5 to 8.3 °C for the July survey. The processed thermal images indicate six sites of potential groundwater input into the stream from the streambank where temperature differences were greater than 1.2 °C (BS-1, BS-2, BS-3, BS-4, BS-5, and BS-6; see fig. 4. for site locations). The surveys were used to identify areas of groundwater discharge for FO-DTS deployment, as well as to select water-quality sampling locations.

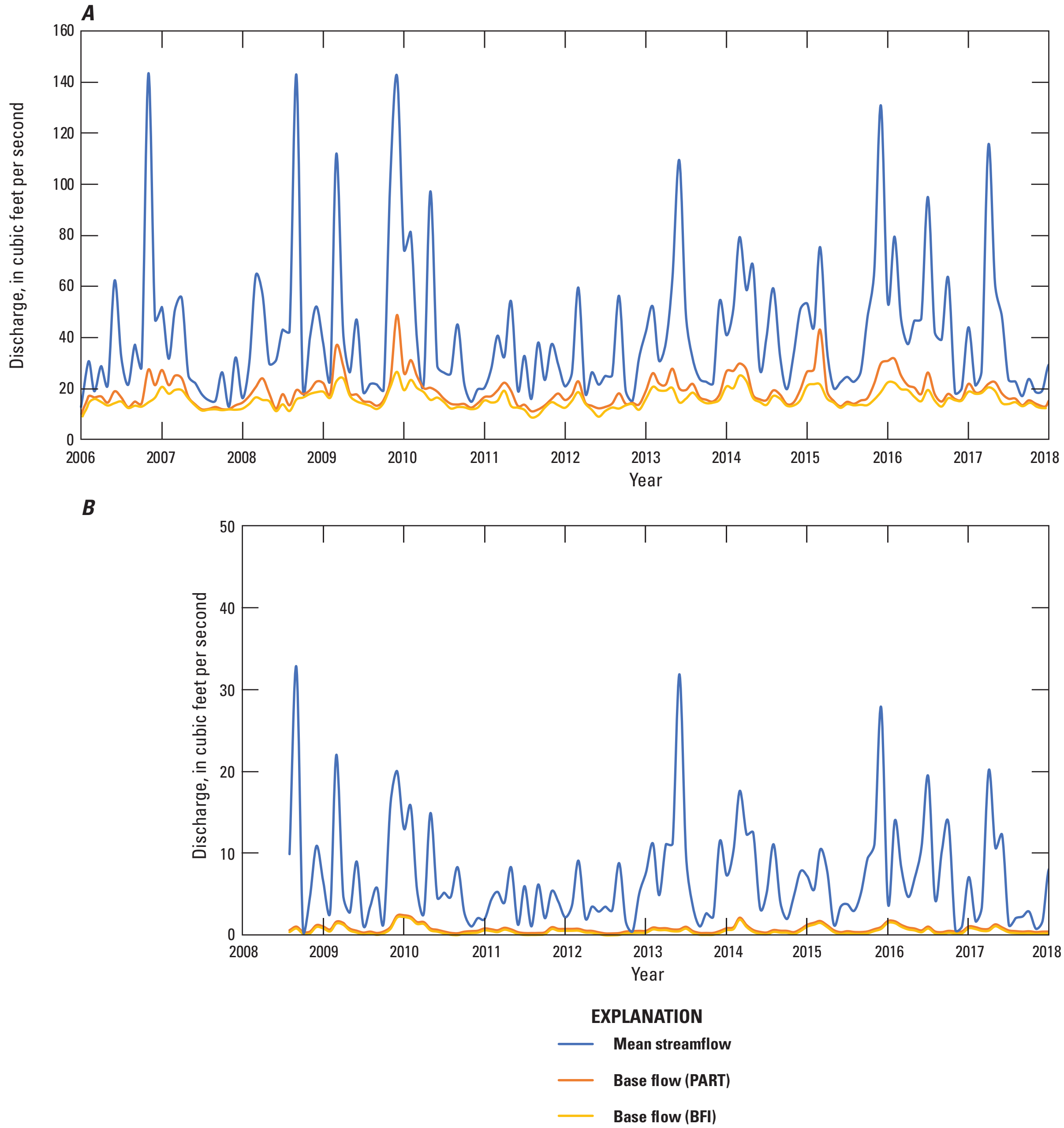

Figure 8. Graphs showing base flow estimated by using the base-flow index (BFI) and PART hydrograph separation methods for (*A*) U.S. Geological Survey (USGS) streamgage 02002086849 (site EC-11) and (*B*) USGS streamgage 0208675010 (site EC-1) in Ellerbe Creek in Durham, North Carolina.

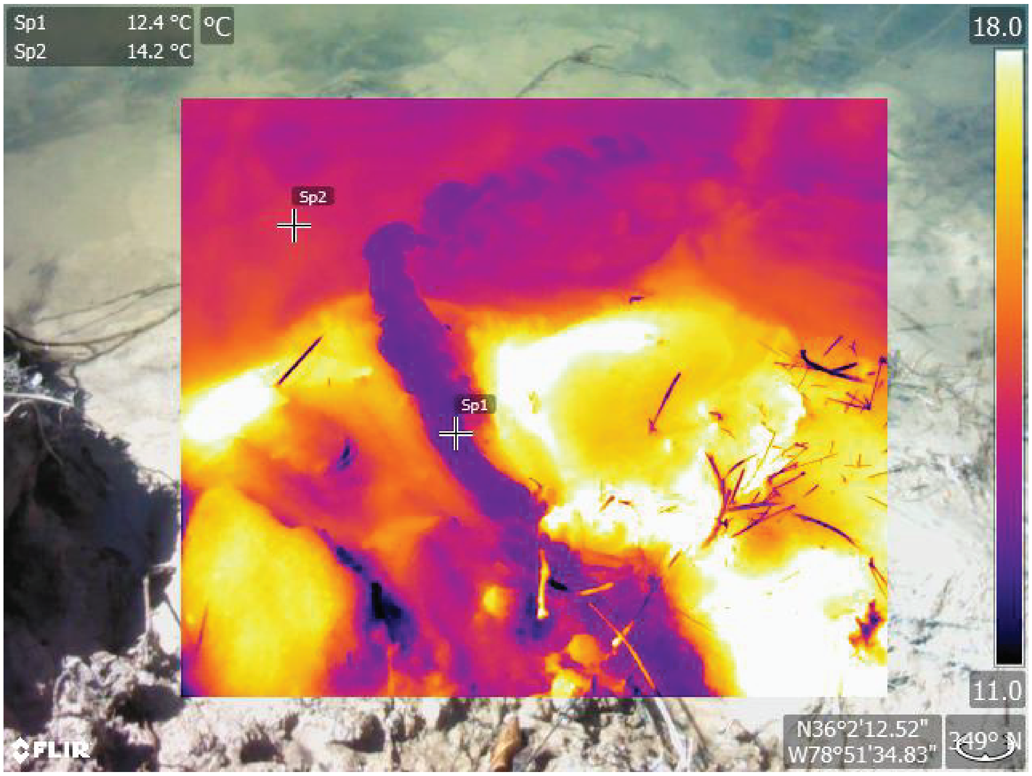

Figure 9. Example of a thermal image captured by the forward-looking infrared (FLIR) camera in March 2016 to determine stream surface and bank seep temperatures. The image was taken at bank seep BS-4 at Ellerbe Creek in Durham, North Carolina.

Thermal imagery identified several bank seeps along the study reach where water-quality samples could be taken. Temperature differences between the bank seeps and the stream were distinct enough in both winter and summer conditions to delineate inflow to Ellerbe Creek. Several of the bank seeps identified in the March 2016 survey were not observed in the July 2016 survey. Both surveys were conducted about a week after a rainfall event, so persistent groundwater seeps likely would have been flowing. During rainfall events, stream stage at the downstream USGS gage EC-11 can rise from 2 to 5 ft above base-flow conditions. These events inundate the high, sandy-silt channel walls and contribute to shallow groundwater and bank storage. Most bank seeps observed discharging to the stream within a week of sizeable runoff events likely are sourced predominantly from bank storage. Persistent bank seeps, such as BS-1 and BS-4, may have preferential flow pathways that yield a larger groundwater component that contributes to very small but constant flow in these areas.

Distributed Temperature Sensing Results

From July 18 to 25, 2017, an FO-DTS survey was conducted in Ellerbe Creek, beginning slightly upstream from the NDWRF outfall and extending downstream from the closed municipal landfill. The streambed is mostly sand and silt for much of the reach, with exposed bedrock and boulders at the downstream end of the survey reach. The fiber-optic cable was placed within the streambed along the right bank of Ellerbe Creek to capture any discharging groundwater that may have flow paths connected to the landfill.

Streamflow recorded at the downstream USGS streamgage EC-11 during the FO-DTS survey ranged from 4.6 ft^3/s on July 25 to 61.8 ft^3/s on July 19 (fig. 6). On the night of July 18, 2017, a rainfall event of 0.64 inch was recorded during the survey. According to data collected by the NDWRF, hourly discharge from the outfall ranged from 5.6 to 20.4 ft^3/s and daily effluent temperatures ranged from 26.60 to 27.10 °C during the FO-DTS survey. Local air temperature ranged from 18.8 °C on July 19 to 36.5 °C on July 23. The streambed temperatures measured along the reach by the FO-DTS system ranged from 21.54 to 28.53 °C. Diurnal fluctuations observed within the streambed temperature data were attributed to solar radiation warming the stream each afternoon followed by cooling during the night. Areas where thermal fluctuations were reduced were assumed to be possible evidence of groundwater discharge to the stream.

Thermal traces of streambed temperatures collected at 15-minute intervals were compared to determine areas of reduced diurnal fluctuations (fig. 10). Two ice baths were set up to quality-check the temperature readings at the upstream end of the cable (9–69 ft) and near the midpoint of the cable (1,870–2,025 ft); these areas where the cable left the streambed are shaded gray in the thermogram in figure 10. The effects of the rainfall event that occurred late on July 18 and into the morning of July 19 can be observed in cool streambed temperatures with distinct pulses of cool runoff into the stream. Areas farthest downstream, where the stream is most shallow, had the warmest temperature signatures and largest diurnal variance.

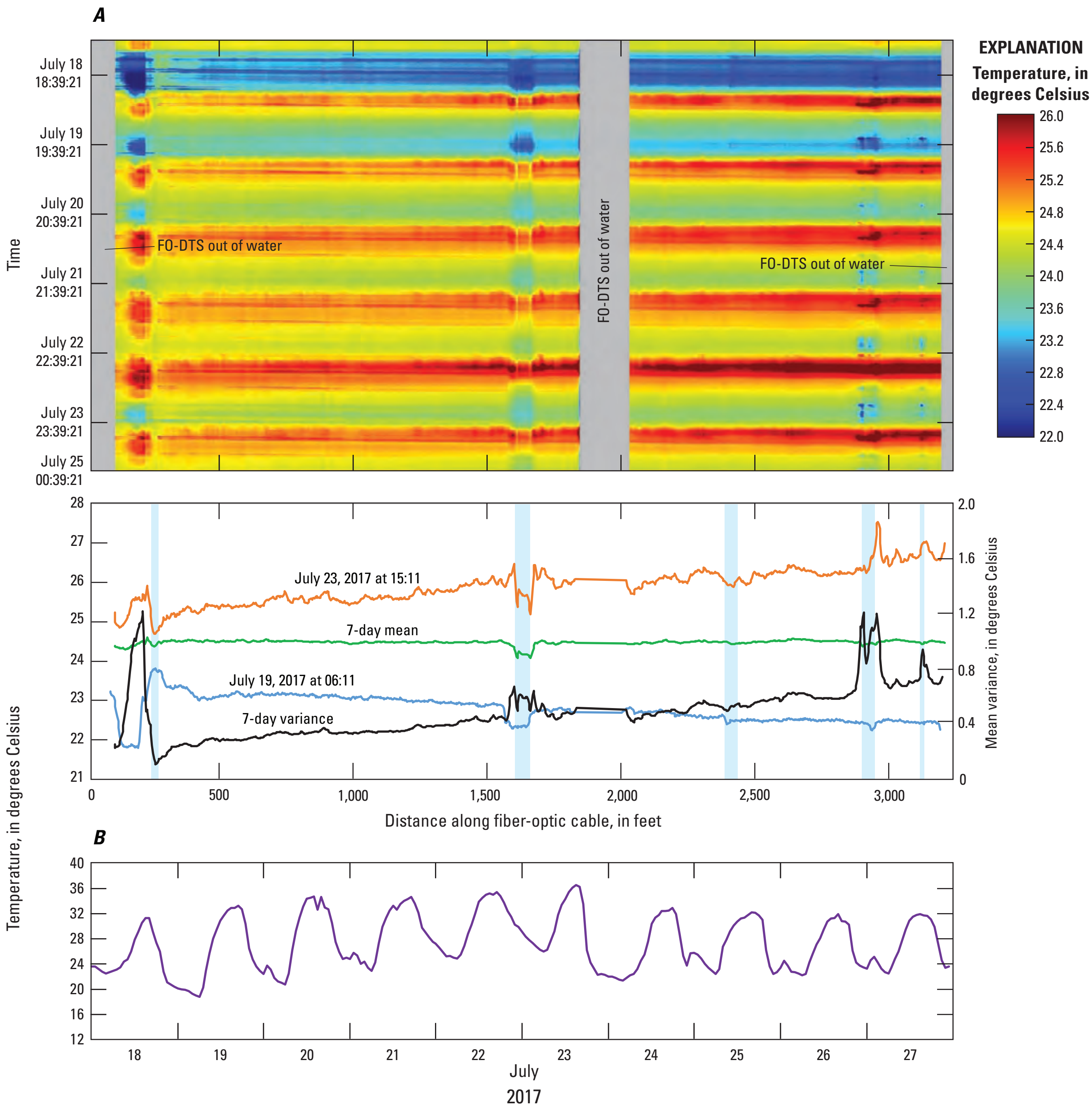

Figure 10. Distributed temperature sensing measurements collected from July 18 to 25, 2017, in Ellerbe Creek, Durham, North Carolina. *A*, Thermogram image of survey period and graph showing the 7-day mean surface-water temperature compared with warmest and coldest days/times (blue-shaded areas in the graph represent cooler inflow from groundwater or small tributaries). *B*, Graph showing recorded air temperature. FO-DTS, fiber-optic distributed temperature sensing.

The thermal traces for the coldest day and time (July 19 at 06:11) and the warmest day and time (July 23 at 15:11) were compared with the 7-day mean for each measurement location along the cable to visualize the temperature extremes within the data. Under typical conditions, areas with small temperature variation would be locations that are thermally buffered by consistent groundwater discharge. However, it is important to consider that warm water discharged from the NDWRF outfall near the upstream end of the cable (downstream from the 230-ft cable mark) can also obscure the natural diurnal signal in this reach of Ellerbe Creek. Additional consideration should be given regarding small downstream tributaries whose sources are unaffected by the warm outfall discharge. These inflows would appear as a steady flow of slightly cooler water at the stream confluence, yielding a similar signature to that of cooler groundwater discharge to the stream.

Areas where the thermal signature shows small temperature variability are highlighted in blue in the plot below the thermogram in figure 10. The five most prominent of these areas on the thermogram were at distances of 255–272, 1,591–1,667, 2,395–2,408, 2,933–2,946, and 3,057–3,071 ft from the upstream end of the cable. The area between 255 and 272 ft corresponds with the NDWRF outfall, where the thermal signature shows a consistently warm inflow to the stream (fig. 11). At the area near the 1,591-ft mark, a small persistent seep was observed at the bank (BS-5), behind a sandbar formed during recent stormflow. Several loops of cable were wound at this location to ensure any temperature difference from the inflow was captured by the survey. This site is likely a small discharge point for shallow groundwater to the stream. Three small unnamed tributaries to Ellerbe Creek are at cable distances of 2,395–2,408, 2,933–2,946, and 3,057–3,071 ft. It appears that stream depth may explain the difference in variability of thermal signatures at these locations. The tributary at 2,395 ft enters the stream through a culvert where the stream depth is about 3.9 ft, whereas the tributaries farther downstream at 2,933 and 2,946 ft enter at a stream depth of only about 0.65 ft (fig. 11). Cooler inflow was observed at all three tributaries after the rain event on July 18, 2017. The farthest downstream tributaries were exposed to the air as stream stage dropped after the storm event, as can be seen in the increasing temperature extremes from day to night across the monitoring period shown on the thermogram.

Low levels of groundwater discharge to the stream may explain the lack of distinctive discharge areas captured in the FO-DTS survey data. The groundwater seep at the 1,591-ft mark likely was detected because of its location behind a sandbar, where it was shielded from the higher and warmer flows of the stream. Groundwater discharge from bank seeps is small compared to the overall streamflow; therefore, the FO-DTS survey was not able to resolve groundwater discharge through the streambed within Ellerbe Creek. Using the FO-DTS method, Briggs and others (2012) were able to resolve groundwater contributions along a 900-meter stream reach discharging at a rate near 5 percent of the overall streamflow. Lauer and others (2013) were able to resolve simulated groundwater inflow to a stream at a rate near 2 percent of the streamflow in a mountain creek. Likely, most of the remaining contributions to streamflow come from recently recharged shallow groundwater that discharges farther upgradient into the small tributaries along Ellerbe Creek.

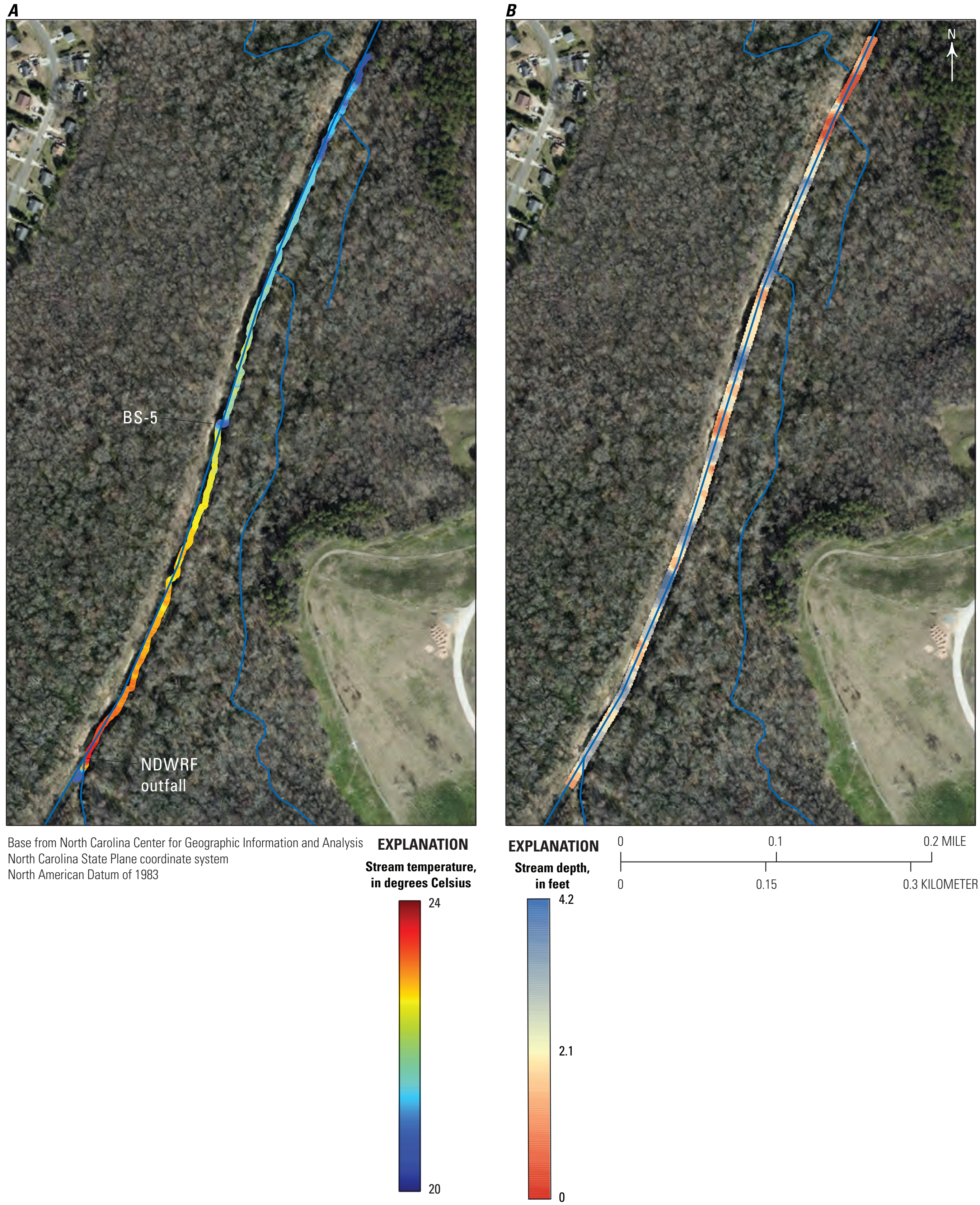

Figure 11. Maps showing (*A*) mean distributed temperature sensing measurements collected from July 18, 2017, to July 25, 2017, and (*B*) stream depth measurements collected with an acoustic Doppler current profiler during base-flow conditions on July 27, 2017, at Ellerbe Creek in Durham, North Carolina. BS, bank seep; NDWRF, North Durham Water Reclamation Facility.

Water-Quality Results

Water-quality sampling within the study area provided information to help identify possible sources of nutrients into Ellerbe Creek and ultimately Falls Lake. Periodic water-quality samples were collected at 11 sites along Ellerbe Creek during July 2016 and March 2018 (tables 5 and 6). Shallow groundwater seeps along the stream bank were sampled at six locations in August 2016 and July 2017. Two groundwater monitoring wells and two piezometers were sampled in March 2018. Quality-assurance sample results for the three replicates generally signified good analytical precision, with two of the replicates having less than a 10-percent difference from the original sample. Five blank samples were collected, and results were generally below reporting limits for all samples, except for one field blank sample collected in August 2016 that had a total nitrogen concentration of 0.11 mg/L. On the basis of guidelines provided in Mueller and others (2015), associated samples collected during the August 2016 sampling event were considered valid only if the concentration exceeded five times the amount detected in the blank, in this case, 0.55 mg/L of total nitrogen.

The temperature of surface-water samples ranged from 24.4 to 27.2 °C for the July 2016 sampling and 7.0 to 13.1 °C for the March 2018 sampling. The temperature of bank seep samples ranged from 21.6 to 28.8 °C during the summer sampling events in August 2016 and July 2017. The temperature of groundwater samples ranged from 13.1 °C in GW-2 to 22.8 °C in GW-1. Specific conductance values ranged from 29 microsiemens per centimeter (µS/cm) at the upstream surface-water site EC-2 to 461 µS/cm at the bank seep BS-3. The high specific conductance measured at BS-3 on August 2, 2016, may be attributed to high sodium and bicarbonate (or alkalinity) concentrations at the site, both of which were the highest concentrations of all samples collected in the study. Generally, the groundwater samples had noticeably lower specific conductance than the surface-water samples. Values for pH ranged from 5.1 to 7.4 and were generally higher within surface water than in groundwater. Dissolved oxygen ranged from 7.1 to 10.6 mg/L for the surface-water samples and 1.6 to 9.3 mg/L for the groundwater samples. Field measurements of dissolved oxygen for the bank seeps did not meet precision standards for inclusion in the study.

Relative distribution of major ions in water samples is shown on a Piper diagram (fig. 12). Water rich in calcium-bicarbonate upstream from the NDWRF outfall roughly trended toward water dominated by sodium-sulfate with a slight rise in chloride downstream from the outfall. Nitrate concentrations in surface-water samples increased slightly between July 2016 and March 2018. The three bank seeps sampled for major ions (BS-1, BS-3, and BS-4) represented a range of water types, with BS-4 being the most similar to the Ellerbe Creek samples. BS-4 had the highest sodium concentration of all samples collected during the study at 82.9 mg/L. The water types for the two groundwater monitoring wells differ from one another, with GW-1 containing higher concentrations of dissolved constituents, especially iron, and more than twice the amount of nutrients as seen in GW-2. This relative dilution observed in GW-2 may be due to some degree of hydraulic communication with a nearby retention pond that is upgradient from the well (fig. 4). GW-1 had the highest calcium, magnesium, bicarbonate, and chloride concentrations of all sampled sites at 33.4, 14.2, 102, and 39.2 mg/L, respectively. The sample collected from the small tributary 0.55 kilometer downstream from the outfall, site TR-1, shows a water type that plots near the midpoint of all surface-water samples.

Boxplots were constructed for specific conductance, pH, and nutrient concentrations of the surface-water, bank seep, and groundwater sites (fig. 13). Ammonia concentrations ranged from below the method detection level of 0.01 mg/L (BS-4, PZ-2, and GW-2) to 0.46 mg/L in bank seep BS-2. Concentrations of nitrate ranged from below the method detection level of 0.04 mg/L (bank seeps BS-1, BS-3, and BS-4) to 2.69 mg/L at surface-water site EC-3, 215 ft downstream from the NDWRF outfall (figs. 14–16). The median nitrate concentration in the surface-water samples was an order of magnitude higher than that of the groundwater samples.

Nitrate was detected in all surface-water samples, with the lowest concentration of 0.38 mg/L observed upstream from the NDWRF outfall. Surface-water samples collected in July 2016 did not have a strong spatial pattern. The March 2018 samples had higher nitrate concentrations near the NDWRF and became more diluted moving downstream. Samples collected from tributary inflows contained low levels of nitrate, with concentrations ranging from 0.16 to 0.41 mg/L. Samples collected from shallow bank seeps along the stream did not have elevated nitrate concentrations; several were below the method detection level, and the highest concentration was 0.406 mg/L. The bank seep BS-5, which was identified in the FO-DTS survey, had a nitrate concentration of 0.14 mg/L. The sample collected at the streambed piezometer (PZ-1) had a nitrate concentration of 1.04 mg/L, which is likely due to downward surface-water seepage through the streambed. Neither the groundwater monitoring wells nor the bank piezometer sample had nutrient concentrations over 0.10 mg/L. Higher nitrate concentrations are typically found within groundwater when ammonium and dissolved oxygen are abundant, whereas denitrification via bacteria within the aquifer can reduce nitrate to nitrogen gas when adequate amounts of dissolved oxygen are not available. The GW-1 and PZ-1 samples had ammonia concentrations between 0.10 and 0.02 mg/L, likely the result of natural organic matter decay along the flow path toward the stream. All samples had total nitrogen concentrations below the Falls Lake Nutrient Strategy Stage I mass limit of 3.09 mg/L, except for one stream sample (EC-3) immediately downstream from the NDWRF outfall, which had a total nitrogen concentration of 3.23 mg/L in March 2018.

Table 5. Temperature, specific conductance, dissolved oxygen, pH, and nutrient concentrations of water-quality samples collected at Ellerbe Creek, Durham, North Carolina, from July 2016 to March 2018.

[Locations of sample sites are shown in figure 4. °C, degree Celsius; mg/L, milligram per liter; µS/cm, microsiemens per centimeter; N, nitrogen; P, phosphorus; EC, Ellerbe Creek; TR, tributary; BS, bank seep; —, not measured; <, less than; PZ, piezometer; GW, groundwater well]

Station number	Site map name	Sample date	Sample time	Temperature, °C	Dissolved oxygen, mg/L	Dissolved oxygen saturation, percent	pH, standard units	Specific conductance, µS/cm	Ammonia, mg/L as N	Nitrate plus nitrite, mg/L as N	Nitrite, mg/L as N	Orthophosphate, mg/L as P	Total N, mg/L
0208682450	EC-2	7/12/2016	09:45	24.4	7.1	85.2	7.4	29	0.14	0.381	0.022	0.039	1.02
02086833	EC-3	7/12/2016	10:25	24.9	7.5	90.9	7.3	390	0.07	1.17	0.031	0.043	1.73
02086835	EC-5	7/12/2016	11:00	25.3	7.5	91.6	7.3	393	0.06	1.41	0.035	0.037	2.06
360211078513701	TR-1	7/12/2016	11:20	25.5	7.4	90.7	7.3	156	0.04	0.273	0.007	0.048	0.88
02086837	EC-6	7/12/2016	11:45	25.7	7.5	92.2	7.3	378	0.06	1.33	0.032	0.037	1.92
02086839	EC-7	7/12/2016	13:00	26.1	8	99.1	7.4	381	0.06	1.21	0.03	0.04	1.82
360226078512801	TR-2	7/12/2016	13:10	25.7	7.3	89.8	7.2	131	0.06	0.164	0.007	0.032	0.78
02086841	EC-8	7/12/2016	15:20	27.2	8.1	100	7.3	398	0.04	1.18	0.014	0.035	1.84
02086843	EC-9	7/12/2016	14:10	26.9	8	100	7.4	380	0.05	1.22	0.029	0.039	1.78
02086845	EC-10	7/12/2016	14:40	27.1	8	100	7.4	379	0.05	1.21	0.03	0.038	1.79
360149078514801	BS-1	8/2/2016	11:00	22.2	—	—	5.9	100	0.12	0.406	0.003	0.041	0.85
360159078514101	BS-3	8/2/2016	12:15	28.8	—	—	7.1	461	0.11	<0.040	0.001	0.065	0.39
360204078513901	BS-4	8/2/2016	12:45	21.6	—	—	5.6	147	<0.01	0.203	<0.001	0.01	0.28
360149078514801	BS-1	7/27/2017	13:15	26.2	—	—	6.7	117	0.1	<0.040	<0.001	0.019	—
360159078514101	BS-3	7/27/2017	10:15	27.1	—	—	6.6	170	0.05	0.062	0.002	0.007	—
360204078513901	BS-4	7/27/2017	10:50	26.1	—	—	5.9	150	0.03	0.111	0.002	0.011	—
360158078514201	BS-2	7/27/2017	09:40	26.4	—	—	6.5	160	0.46	<0.040	0.003	0.01	0.75
360205078513801	BS-5	7/27/2017	11:20	26.2	—	—	6.1	80	0.03	0.136	0.001	0.009	—
360207078513801	BS-6	7/27/2017	12:10	26.2	—	—	6	100	0.11	0.043	0.009	0.018	—
02086833	EC-3	3/27/2018	09:30	13.1	9.7	92.1	7.0	328	0.03	2.69	0.007	0.013	3.23
360211078513701	TR-1	3/27/2018	11:00	7.0	10.6	87.2	7.2	204	0.04	0.41	0.003	0.016	0.94
02086837	EC-6	3/27/2018	11:30	12.3	10	93.3	7.0	320	0.03	2.27	0.006	0.014	2.79
02086849	EC-11	3/27/2018	12:15	10.4	10.2	91.1	7.2	279	0.11	2.19	0.02	0.016	2.75
360204078513902	PZ-1	3/29/2018	15:20	21.3	9.3	100	6.1	144	0.19	0.067	0.002	0.023	0.51
360204078513903	PZ-2	3/29/2018	15:30	22.4	8.9	100	6.3	298	<0.01	1.04	<0.001	0.005	1.17
360159078513801	GW-1	3/29/2018	11:00	22.8	1.6	18.8	5.2	186	0.11	0.105	0.006	0.044	0.65
360207078512501	GW-2	3/29/2018	14:00	13.1	4.9	74.2	5.1	119	<0.01	0.048	<0.001	0.004	0.15

Table 6. Major ion concentrations in water-quality samples collected at Ellerbe Creek, Durham, North Carolina, from July 2016 to March 2018.

[Locations of sample sites are shown in figure 4. mg/L, milligram per liter; $CaCO_3$, calcium carbonate; µg/L; microgram per liter; EC, Ellerbe Creek; —, not measured; BS, bank seep; TR, tributary; GW, groundwater well; <, less than]

Station number	Site map name	Sample date	Sample time	Dissolved solids, mg/L	Calcium, mg/L	Magnesium, mg/L	Potassium, mg/L	Sodium, mg/L	Chloride, mg/L	Sulfate, mg/L	Bicarbonate, mg/L	Alkalinity, mg/L as $CaCO_3$	Bromide, mg/L	Fluoride, mg/L	Iron, µg/L	Manganese, µg/L
0208682450	EC-2	7/12/2016	09:45	200	28.7	7.16	4.49	18.9	17.4	13.6	125.66	103	—	0.16	604	205
02086833	EC-3	7/12/2016	10:25	227	23.7	6.11	7.62	39.2	33	34.1	109.56	89.8	—	0.32	304	93.5
02086835	EC-5	7/12/2016	11:00	243	21.9	5.8	8.58	45.6	37.6	39.8	104.19	85.4	—	0.38	205	61.2
02086837	EC-6	7/12/2016	11:45	247	22.1	5.91	8.25	43.9	35.9	37.7	105.042	86.1	—	0.35	225	73.8
02086839	EC-7	7/12/2016	13:00	237	22.7	6.03	7.98	42.3	34.6	35.9	106.262	87.1	—	0.34	265	74.4
02086841	EC-8	7/12/2016	15:20	233	20.9	5.64	8.74	47	39.1	40.9	101.75	83.4	—	0.39	186	50.8
02086843	EC-9	7/12/2016	14:10	218	22.5	5.87	7.94	42	34.8	36.1	105.77	86.7	—	0.34	247	66.1
02086845	EC-10	7/12/2016	14:40	219	22.4	5.92	8.1	41.4	34.7	36.1	105.53	86.5	—	0.34	264	67.3
360149078514801	BS-1	8/2/2016	11:00	71	8.02	2.17	1.81	7.47	3.28	6.21	42.09	34.5	0.04	0.06	1,150	596
360159078514101	BS-3	8/2/2016	12:15	296	20.2	5.43	1.82	82.9	25.5	11.7	258.64	212	0.252	0.16	562	968
360204078513901	BS-4	8/2/2016	12:45	97	7.56	3.6	0.57	15.8	6.8	33	28.79	23.6	0.056	0.04	95.4	10.6
02086833	EC-3	3/27/2018	09:30	—	20.1	5.19	7.32	36.3	37.5	35.3	62.8	51.6	0.069	—	187	—
360211078513701	TR-1	3/27/2018	11:00	—	17.9	4.95	2.12	17.3	21.4	14.1	65.9	54.1	0.084	—	438	—
02086837	EC-6	3/27/2018	11:30	—	20.2	5.2	7.11	35.2	36.7	33.9	75.6	62.2	0.09	—	209	—
02086849	EC-11	3/27/2018	12:15	—	19.4	5.01	5.86	28.9	30.2	27.5	65.7	54	0.06	—	233	—
360159078513801	GW-1	3/29/2018	11:00	—	33.4	14.2	1.13	10.5	39.2	8.25	102	83.4	0.479	—	4,260	—
360207078512501	GW-2	3/29/2018	14:00	—	12.6	4.13	0.33	17.9	37	6.82	31.2	25.5	0.239	—	<10.0	—

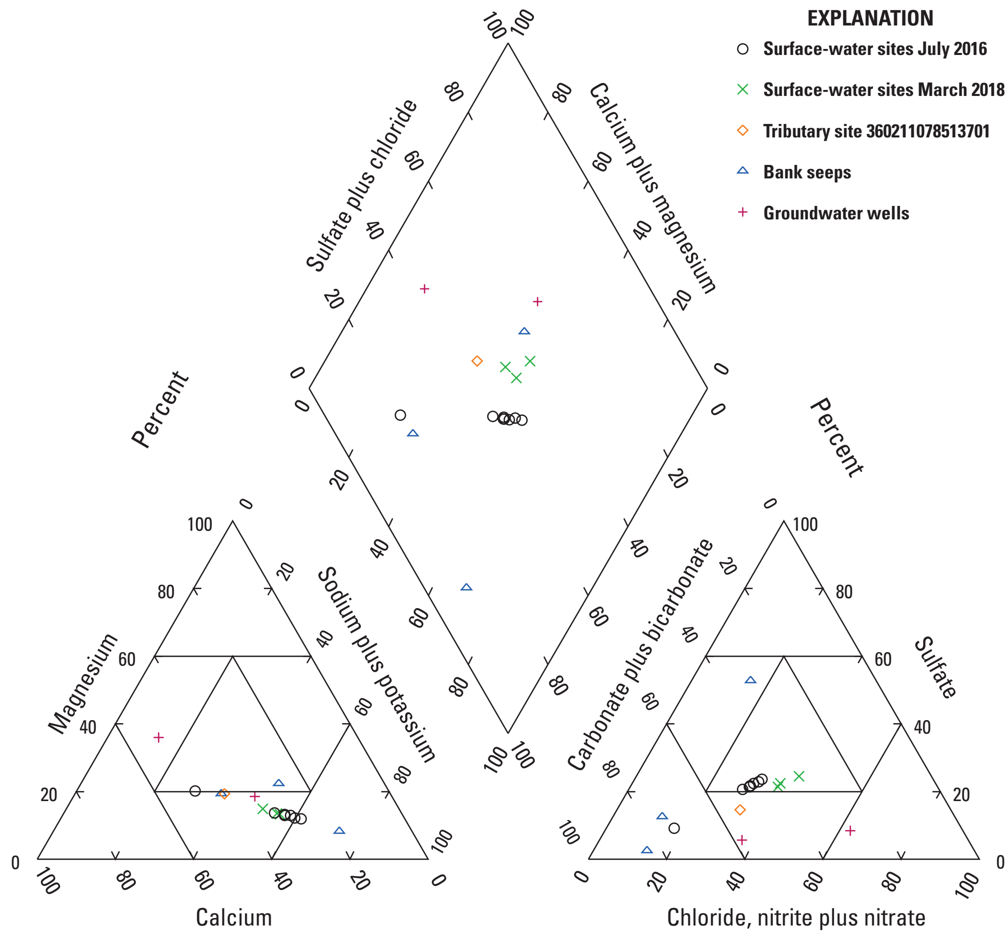

Figure 12. Trilinear Piper diagram showing water-chemistry data for water-quality samples collected in July 2016 and March 2018 at surface-water sites, bank seeps, and groundwater wells in the Ellerbe Creek study area, Durham, North Carolina.

On the basis of the low nitrate concentrations within the groundwater samples, the small source of nitrate observed within the bank seeps and tributaries may be attributed to Ellerbe Creek itself. In response to rainfall events, rising stage from storm flow recharges bank storage with diluted stream water and likely produces some degree of backwater within the tributaries. As stream stage falls and hydraulic gradients begin to reverse to base-flow conditions, the inundated banks discharge back into Ellerbe Creek. In other settings where stream waters do not contain elevated nitrate concentrations, discharge from bank storage can dilute the nutrient signature of the groundwater discharging to a stream. Given the nutrient concentrations within Ellerbe Creek, however, this likely is not the case. The bank storage component, which is filled from recent storm events, is more likely to contain the high nutrient concentrations. Similar studies have shown that where effluent discharge constitutes a majority of base flow, it may also exert a dominant influence on stream water-quality (Harden and others, 2013; Lambert and others, 2017).

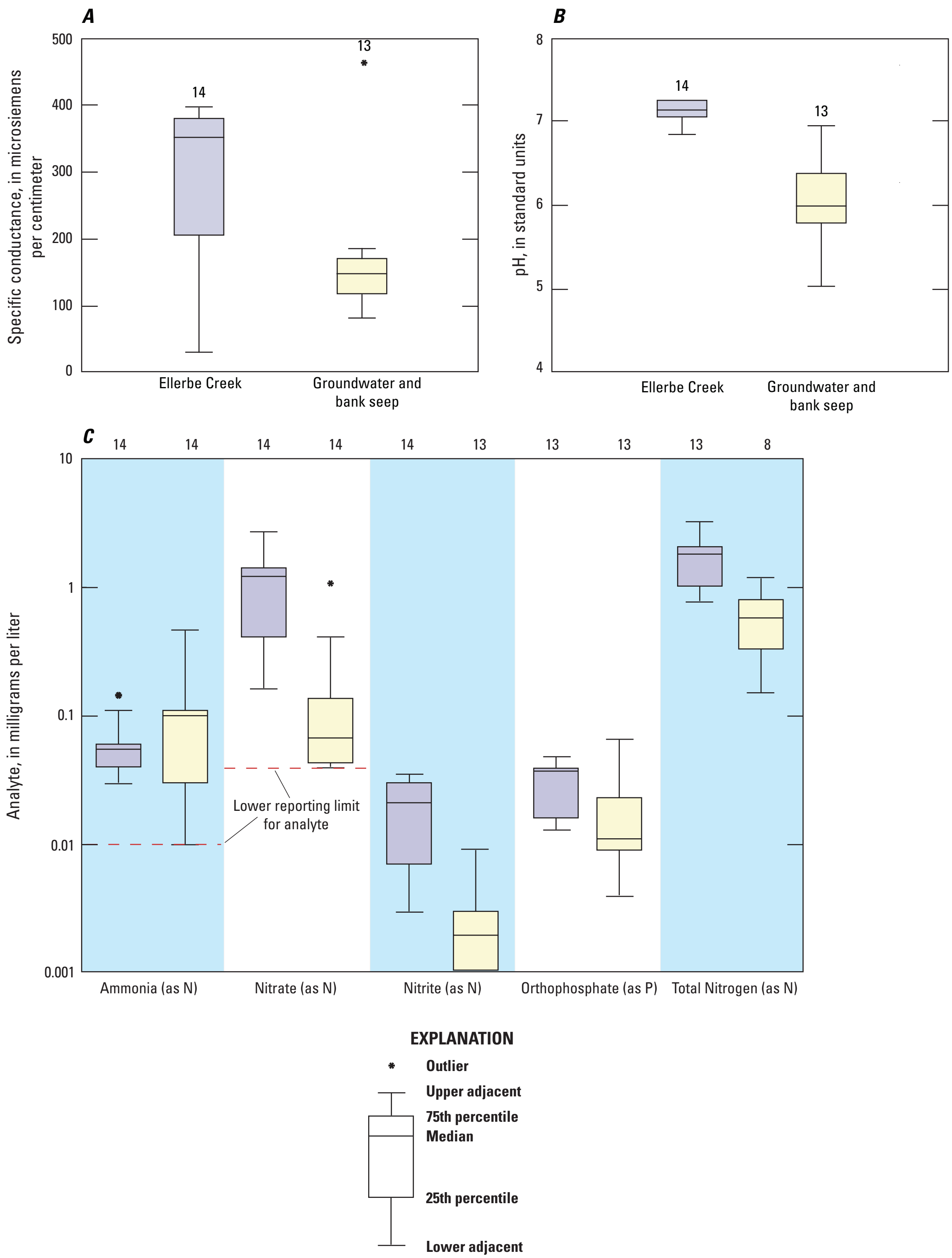

Figure 13. Boxplots showing range, median, and quartile statistical values for (*A*) specific conductance, (*B*) pH, and (*C*) nutrient concentrations of surface-water, groundwater, and bank seep samples collected in July and August 2016, July 2017, and March 2018 in the Ellerbe Creek study area in Durham, North Carolina. N, nitrogen; P, phosphorous.

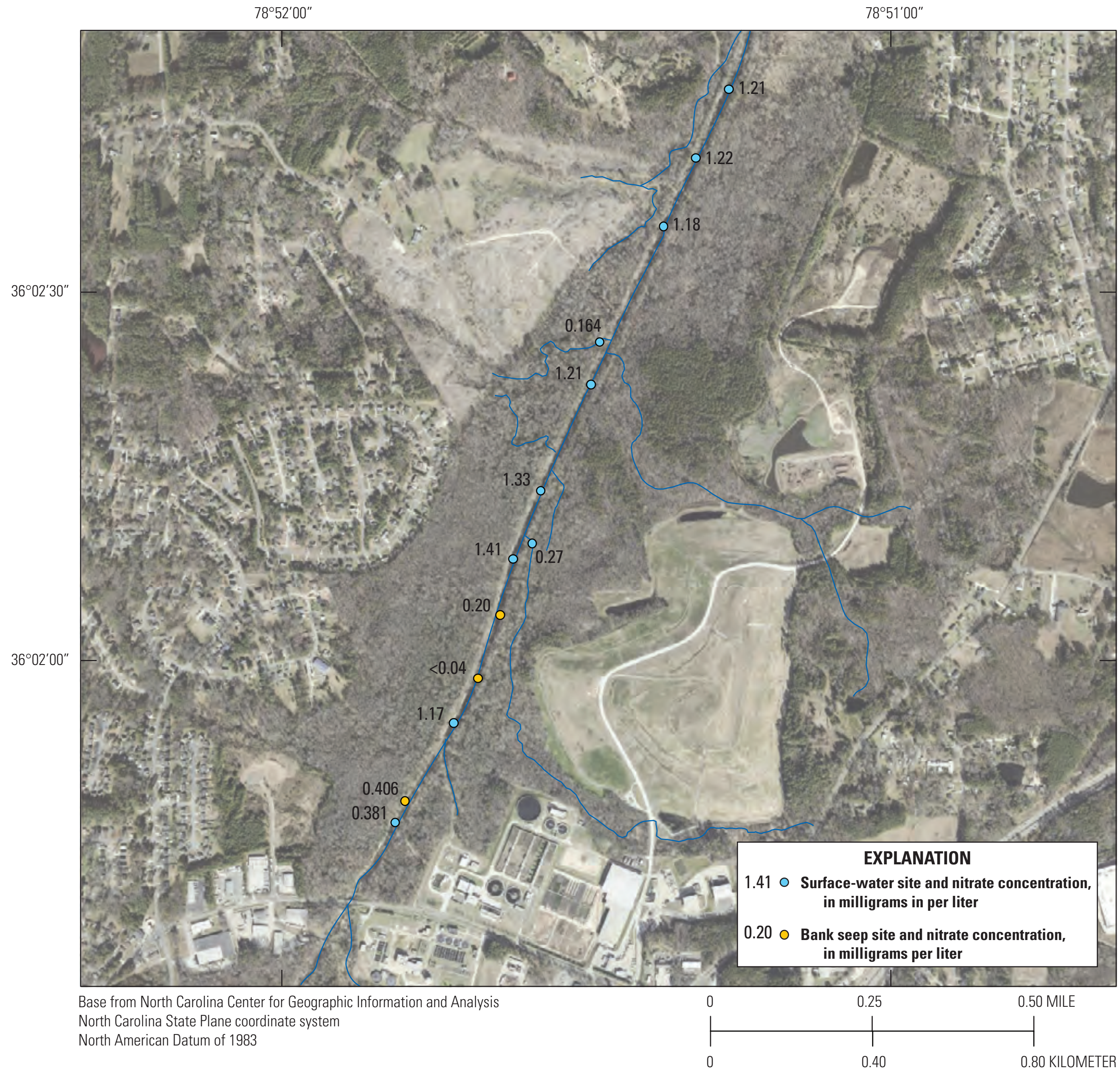

Figure 14. Map showing nitrate concentrations at surface-water and bank seep sites sampled in July and August 2016 in the Ellerbe Creek study area in Durham, North Carolina.

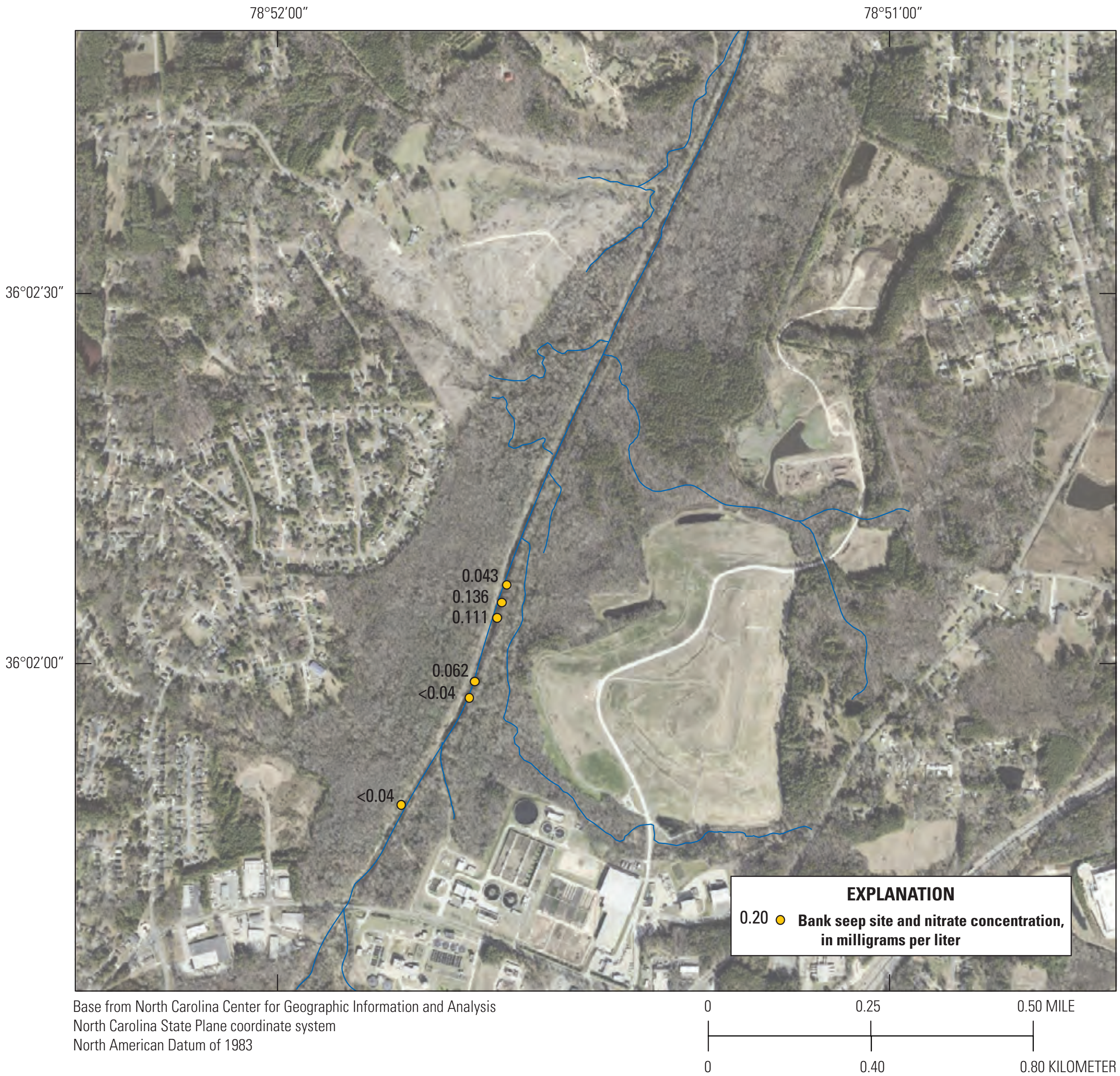

Figure 15. Map showing nitrate concentrations at bank seep sites sampled in July 2017 in the Ellerbe Creek study area in Durham, North Carolina.

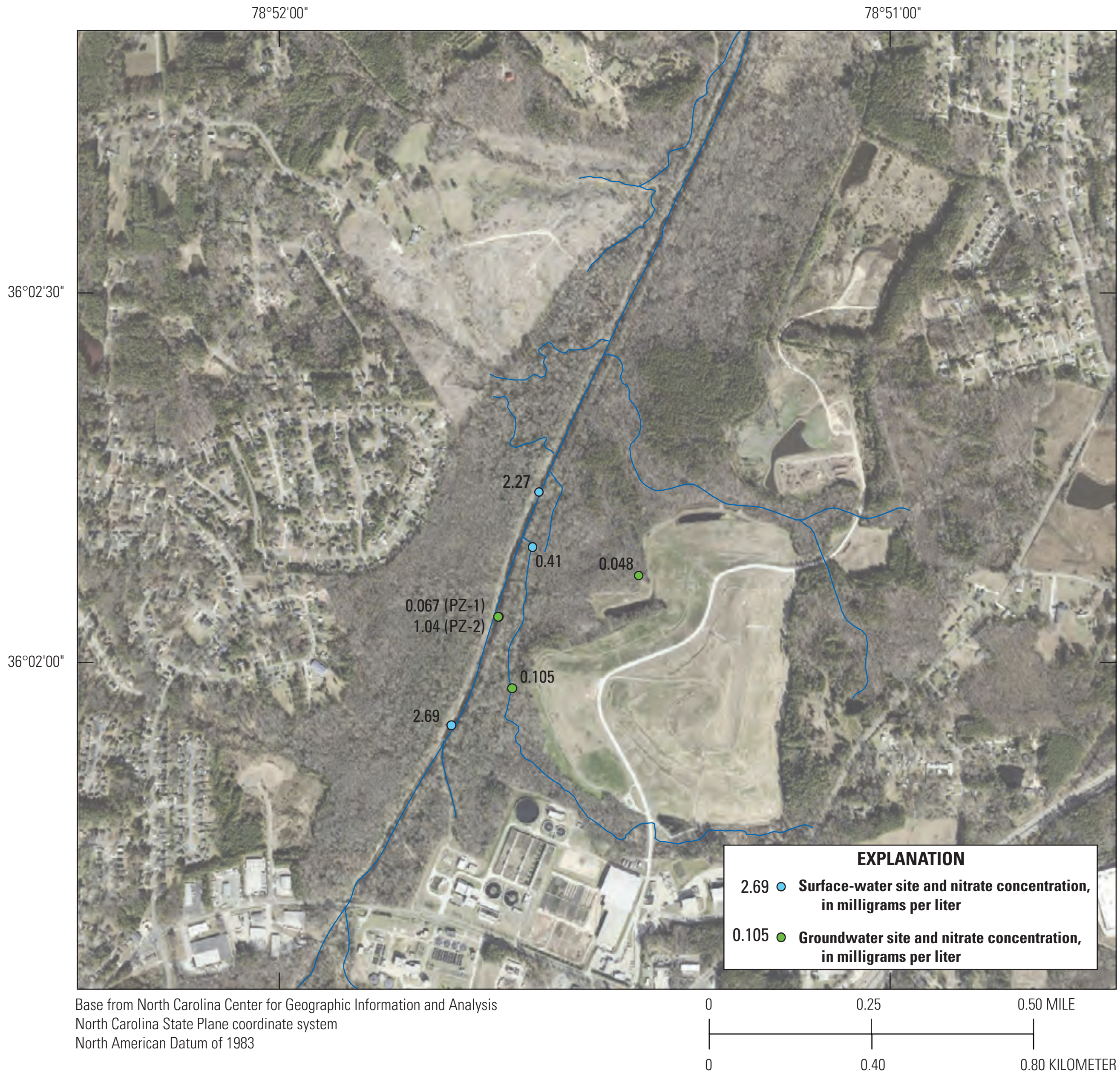

Figure 16. Map showing nitrate concentrations at surface-water and groundwater sites sampled in March 2018 in the Ellerbe Creek study area in Durham, North Carolina. PZ, piezometer.

Summary and Conclusions

An assessment of groundwater and surface-water interactions along Ellerbe Creek in Durham, North Carolina, was conducted from July 2016 to March 2018 using a multimethod approach to understand if groundwater discharge is a source of nitrate to the stream. A streamflow gain-and-loss survey showed that Ellerbe Creek has both gaining and losing reaches within the study area. Verifiable streamflow gain exists in reaches with surface-water inflows, such as from the North Durham Water Reclamation Facility (NDWRF) effluent outfall and small unnamed tributaries. Gains from groundwater generally were small—too small to quantitatively verify within the uncertainty limitations of the discharge measurement methods. Diabase dikes cut across the bedrock underlying the alluvial sediments in this area of Ellerbe Creek particularly within reach F. The diabase dikes may act as an impermeable boundary to groundwater discharge, and preferential pathways along the weathered contact areas may divert groundwater along the dike.

Continuous water-level data collected within the stream, banks, and streambed show that Ellerbe Creek is largely a gaining stream within the study area. Hydraulic gradients were highest in the horizontal direction into the stream, with observed horizontal gradients twice the magnitude of those in the vertical direction. During storm events when streamflow is high, gradients temporarily reverse, and recharge through the streambed sediments and bank storage occurs for short durations. Groundwater levels likely are highest in late spring, which would lead to an increase in groundwater discharge through both the stream bank and streambed.

Hydrograph-separation methods yielded base-flow estimates ranging from 14.0 to 17.7 cubic feet per second (ft^3/s), corresponding to contributions of up to 57 percent of streamflow in Ellerbe Creek in the study area. According to data provided by the NDWRF, average effluent discharge from the NDWRF is about 13 ft^3/s, which accounts for more than 30 percent of the mean streamflow and nearly 80 percent of base flow in this reach of Ellerbe Creek. Groundwater discharge and tributary inflows along the stream account for the small remaining component of base flow. An estimated 3.7 ft^3/s of natural base flow was observed when effluent discharge was stopped for several hours during the study period. This base flow would account for about 9 percent of streamflow, which agrees with upper base-flow estimates calculated by the PART method.

Thermal imagery surveys of bank seeps along the stream show few persistent seeps during early spring and late summer. Bank-storage discharge likely accounts for much of the observed seepage from the stream banks; however, distinct temperature differences indicate that some bank seeps contain a measurable component of discharging groundwater. The fiber-optic distributed temperature sensing (FO-DTS) survey was able to resolve discharge from only one of the persistent seeps, likely because the area was sheltered from direct streamflow by a sandbar. These results indicate that the quantity of groundwater discharge along the reach is such a small contribution to the overall streamflow that it cannot be resolved by the FO-DTS system under these conditions. On the basis of base-flow estimations and flow calculated from water-level data, the groundwater component in Ellerbe Creek is less than 2 percent of the mean streamflow.

Nitrate concentrations were higher in surface water compared to the bank seeps and groundwater, with the highest concentration of 2.69 milligrams per liter (mg/L) in the reach just downstream from the NDWRF outfall. In comparison, samples collected at landfill groundwater monitoring wells contained nitrate concentrations less than or equal to 0.11 mg/L and low concentrations of dissolved oxygen, suggesting that conditions favoring denitrification exist at depth. Denitrification could help account for the relatively low concentrations of nitrate observed at the groundwater sites. Elevated nitrate concentrations within the bank seep and stream piezometer samples were highest after a storm event. These samples may reflect a mixture of stream-recharged bank storage and shallow groundwater.

Groundwater within the proximity of Ellerbe Creek does not have a strong influence on the hydrology and, as a consequence, the water-quality of the stream in the study reach. Groundwater flowing from the landfill towards the stream was not observed to exert influence on nitrogen concentrations in the study reach. The data collected during this study indicate that surface-water inflows, including the effluent discharge from the NDWRF, are of much greater importance to the streamflow and a greater nutrient source than groundwater discharge along the study reach of Ellerbe Creek.

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