Prepared in cooperation with the U.S. Department of Agriculture Forest Service

Streamflow Gain and Loss, Hydrograph Separation, and Water Quality of Abandoned Mine Lands in the Daniel Boone National Forest, Eastern Kentucky, 2015–17

Scientific Investigations Report 2019–5006

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

Cover photograph. Downstream view at Rock Creek near Yamacraw, Kentucky (U.S. Geological Survey station 03410590). Photograph by Mac A. Cherry, U.S. Geological Survey, May 2015.

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DAVID BERNHARDT, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2019

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Conversion Factors

U.S. customary units to International System of Units

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

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

$$°F = (1.8 \times °C) + 32.$$

Datum

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

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

Abbreviations

AMD	acid mine drainage
AML	abandoned mine land
BFI	base-flow index computer program
DO	dissolved oxygen
EPA	U.S. Environmental Protection Agency
Forest Service	U.S. Department of Agriculture Forest Service
GW Toolbox	Groundwater Toolbox
OLC	open limestone channel
ppm	parts per million
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
YSI	Yellow Springs Instruments

Streamflow Gain and Loss, Hydrograph Separation, and Water Quality of Abandoned Mine Lands in the Daniel Boone National Forest, Eastern Kentucky, 2015–17

By Mac A. Cherry

Abstract

During 2015–17, the U.S. Geological Survey, in cooperation with the U.S. Department of Agriculture Forest Service (Forest Service), carried out a study to characterize the hydrology and water chemistry in two study areas within the Daniel Boone National Forest. One study area was within the Rock Creek drainage and the other study area included the Wildcat and Addison Branch drainages. Both study areas historically were mined for coal prior to the Surface Mining Control and Reclamation Act of 1977 and contain abandoned coal mine sites that have since been the focus of remediation efforts. Synoptic surveys of streamflow and water-quality properties (water temperature, pH, specific conductance, and dissolved oxygen) of Rock Creek were done during November 2015 and May 2016, and surveys of Wildcat and Addison Branches were done during June 2016 and May 2017. Streamflow measurements were used to quantify contributions from tributaries and to compute streamflow gain and loss in designated reaches. Discrete measurements of water temperature, pH, specific conductance, and dissolved oxygen were used to evaluate conditions during a short timeframe and for comparison between study areas. Study designs for the two study areas differed because there was an operating streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590) where streamflow and water-quality properties (water temperature, specific conductance, pH, dissolved oxygen, and turbidity) were monitored continuously, while Addison and Wildcat Branches were ungaged. Several hydrograph separation methods were used to estimate base flow and runoff at the Rock Creek gage. These data will be used by the Forest Service to evaluate the current (2018) conditions and plan remediation efforts.

The water quality at Rock Creek was less affected by acid mine drainage (AMD) than the Wildcat or Addison Branches. Appreciable losing reaches, where water flowed underground, were identified in both study areas. All losing reaches coincided with karst topography. Streamflow increased in areas with openings to underground mine tunnels, known as portals.

Six hydrograph separation methods (Base-flow index [BFI; standard and modified], HYSEP [fixed interval, sliding interval, and local minimum], and PART) were applied to daily mean streamflow collected from August 2015 to August 2017 at station number 03410590. The hydrograph separation methods partition total streamflow into base flow and streamflow that originated from surface runoff. Base flow typically reacts slowly to precipitation infiltration and is largely sustained by groundwater discharge. The estimated daily base flow and runoff made with the different separation methods are not highly different. On average, base flow accounted for more total streamflow than surface runoff during the study period, irrespective of method.

Water temperature, pH, dissolved oxygen, specific conductance, and turbidity values were measured from July 2016 through July 2017 with a continuous monitor installed at station number 03410590. Nearly neutral pH values that ranged from 6.8 to 7.9 standard units likely limited metal solubility in the surface water. The continuous specific conductance values ranged between 30 and 259 microsiemens per centimeter at 25 degrees Celsius. The previous remediation efforts are likely continuing to improve the effect of AMD in the study area.

Introduction

The Rock Creek and Wildcat/Addison Branch drainages (fig. 1) (hereafter referred to as the Rock Creek and Wildcat/Addison Branch study areas) in the Daniel Boone National Forest contain abandoned mine lands (AMLs) (U.S. Department of Agriculture Forest Service, 2015 and 2016). Mines began operating in both study areas in the early to mid-1900s and used a combination of surface and underground mining practices to extract the coal (U.S. Department of Agriculture, Forest Service, 2016). Many of the mining operations took place prior to the Surface Mining Control and Reclamation Act of 1977, which regulated coal mines but also aimed to reclaim AMLs. As a consequence of mining, coal waste piles accumulated throughout the study areas, and many of the underground mines were left open and entrances to underground mines

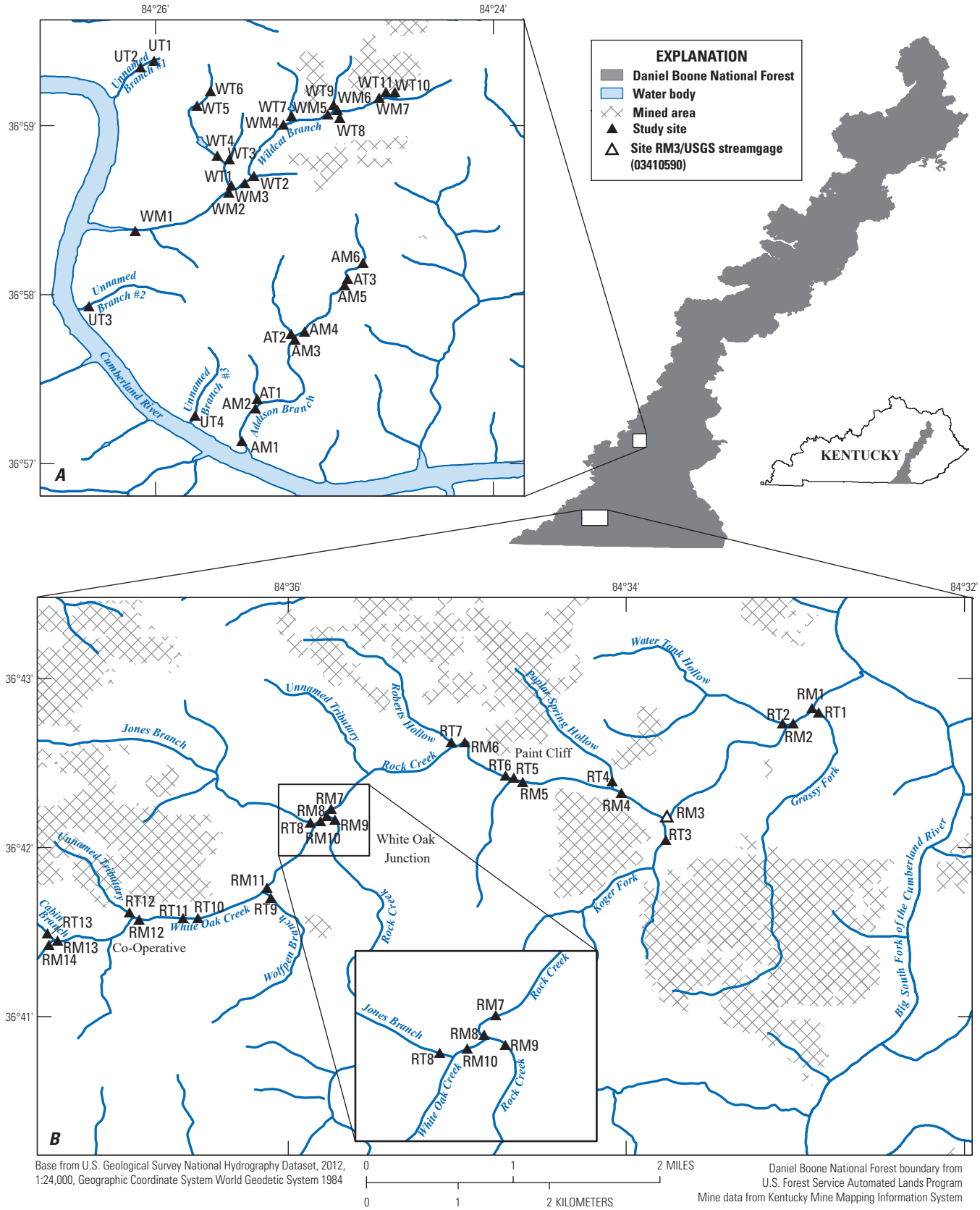


Figure 1. Location of study sites within the Daniel Boone National Forest, eastern Kentucky. *A*, Wildcat/Addison Branch study area. *B*, Rock Creek study area.

(called portals) collapsed (URS Group, Inc., 2017). The coal mining resulted in acid mine drainage (AMD) throughout the landscape (Carew, 2002). The acidification of mine drainage is caused by the oxidation of sulfur-bearing minerals in coal after contact with oxygen and water which leads to increased acidity and transport of soluble metals, such as aluminum and iron (Gluskoter, 1977; Jin and others, 2007).

Remediation efforts have been made in the Rock Creek and Wildcat/Addison Branch study areas in the past (U.S. Environmental Protection Agency [EPA], 2005). In the mid-1990s, coal waste piles in the Wildcat/Addison Branch study area were treated with agricultural lime and topped with soil and vegetation to neutralize the high acidity, and sediment ponds were constructed with limestone drains that connected the ponds to the main streams (Carew, 2002). The Wildcat/Addison Branch study area remediation efforts were evaluated in 2015, and it was concluded that many of the treatments were no longer effective because of lack of maintenance and the continued flow of highly contaminated leachate through the coal waste piles had exceeded the capacity of the method to neutralize AMD (U.S. Department of Agriculture Forest Service, 2016). A surface-flow wetland was constructed in the Rock Creek study area in 1989 (and renovated in 1995) that treated the high-metal load AMD in Jones Branch (Barton and Karathanasis, 1999). After a 19-month post-renovation period, the authors noted changes in soluble iron from 39 to 787 milligrams per liter (mg/L), pH from 3.4 to 6.5 standard units, and acidity as calcium carbonate equivalent from 199 to 2,240 mg/L. Portions of White Oak Creek, Lower Rock Creek, and their tributaries were dosed with limestone sand in 2000, which changed the water chemistry from net acidic to net alkaline (Carew, 2002). In 2000, open limestone channels (OLCs) were installed in select tributaries in the Rock Creek study area. The OLCs at the town of Co-Operative (fig. 1) changed the ranges of pH from 2.8 to 6.1 standard units before construction to 6.7 to 7.6 standard units after construction and at Roberts Hollow from 2.7 to 4.9 standard units before construction to 4.9 to 7.9 standard units after OLC construction (Carew, 2002). A modified vertical flow system was installed in the Paint Cliff area and resulted in a change from net acidic to net alkaline discharge at the mouth of Rock Creek (Carew, 2002; URS Group, Inc., 2017).

Staff from the U.S. Department of Agriculture Forest Service (Forest Service) Region 8 and the Daniel Boone National Forest are proposing to improve water quality by performing multiple remediation actions. It is necessary for the hydrology and chemistry of the study area to be characterized so the areas can be assessed and remediated within the bounds of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA). To help address that requirement, the U.S. Geological Survey (USGS), in cooperation with the Forest Service, carried out a study to characterize the hydrology and water chemistry in the Rock Creek and Wildcat Branch/Addison Branch areas of the Daniel Boone National Forest. The results of this study will augment the Engineering Evaluation/Cost Analysis (EE/CA) process.

Purpose and Scope

The purpose of this report is to describe the results of a study done to characterize water quality with respect to AMD influences and determine whether selected stream reaches were gaining or losing water during non-runoff periods in two study areas within the Daniel Boone National Forest in eastern Kentucky. The study areas included portions of the Rock Creek drainage and the Wildcat and Addison Branch drainages. Six different hydrograph separation techniques were used to estimate the contribution of groundwater discharge to total streamflow at a streamflow gaging station in the Rock Creek study area, and continuous water-quality data established baseline conditions during the study period. Data collection occurred between November 2015 and May 2017.

Description of Study Areas and Site Selection

This study was done in two separate areas, on tributaries to the Big South Fork of the Cumberland River and Cumberland River in southwestern Daniel Boone National Forest (fig. 1). The southernmost study area includes Rock Creek and its tributaries that drain to the Big South Fork of the Cumberland River (fig. 1*B*); the second study area, about 19 miles to the northeast, includes Wildcat Branch, Addison Branch, and three unnamed branches (fig. 1*A*) that drain to the Cumberland River. The Daniel Boone National Forest, located in eastern Kentucky, is owned and managed by the Forest Service. The streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590; herein referred to as Rock Creek streamgage) is at the confluence of Rock Creek and Koger Fork (site RM3; fig. 1*B*).

Rock Creek

The Rock Creek study area is located in McCreary County, Ky. (not shown), and includes lower Rock Creek (after the confluence with White Oak Creek), White Oak Creek, and their tributaries (fig. 1*B*). The entire Rock Creek basin is approximately 62.7 square miles. Approximately 64 percent of the Rock Creek basin is owned and managed by the Forest Service.

The bedrock underlying the Rock Creek study area is from the Mississippian and Pennsylvanian systems (Pomerene, 1964) (fig. 2*B*). The Paragon Formation consists of distinctly grayish-red or olive green shale, yellowish-brown to greenish-brown sandstone, and grey to yellowish-brown limestone. The sandstone is calcareous or argillaceous and weathers from carbonate leaching. The upper slopes are from the coal-containing lower-Pennsylvanian Series.

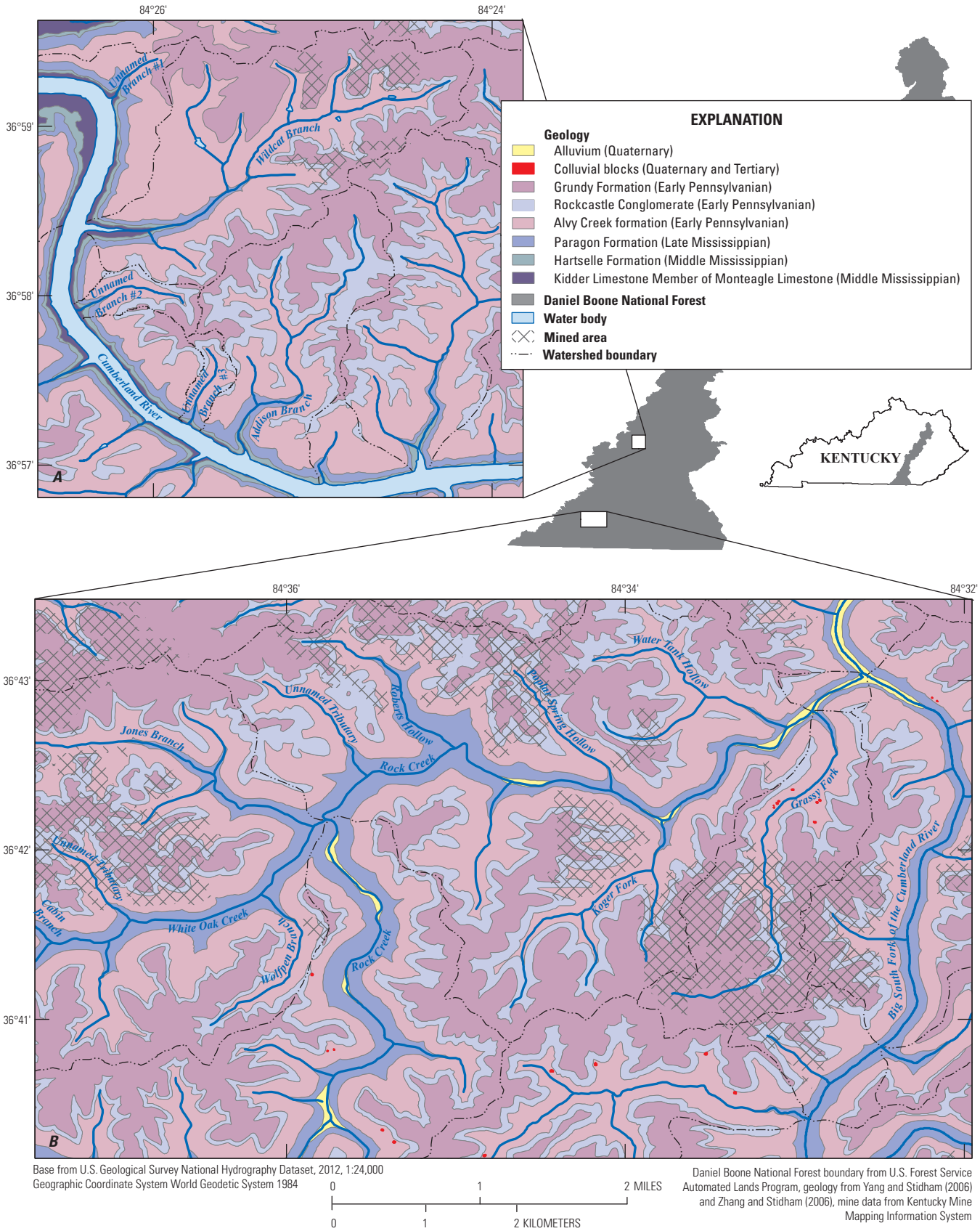


Figure 2. Geology within the Daniel Boone National Forest, eastern Kentucky. *A*, Wildcat/Addison Branch study area. *B*, Rock Creek study area.

There is a distinct difference between the land use in upper and lower Rock Creek. Above the confluence with White Oak Creek, Rock Creek is relatively undisturbed from coal mining, designated as a State Wild River, and is a stocked trout fishery (Kentucky Department of Fish and Wildlife Resources, 2017; URS Group, Inc., 2017). Many of the mines along White Oak Creek left behind open underground mine portals, coal waste piles, and other sources of AMD (Carew, 2002). White Oak Creek has been documented as contributing large quantities of AMD to the lower portion of Rock Creek (U.S. Department of Agriculture Forest Service, 2016).

Site selection was based on recommendations from the Forest Service Region 8 staff, with input from the USGS (table 1), to target sites that helped define gaining and losing reaches, and locations of known geologic importance or with known mining activities. Water-quality data from Rock Creek, previously collected by the USGS, were published in Carew (2002) and used in this report for comparisons to previous conditions. Sites were generally chosen on tributaries and the main stem after the confluence of each respective tributary. The main stem sites were selected far enough downstream from the tributary confluence to avoid backwater.

Wildcat and Addison Branches

The Wildcat/Addison Branch study area is located in Pulaski County, Ky. (not shown), with streams draining to the Cumberland River, a popular fishing and recreation area (fig. 1*A*). The study area includes Wildcat Branch, Addison Branch, and their major tributaries. The study area also includes three nearby unnamed branches, which have relatively small drainage areas that flow directly into the Cumberland River. The entire study area is over 2,600 acres and is mostly contained in the Daniel Boone National Forest.

The Wildcat/Addison Branch study area bedrock is from two different geologic systems: Mississippian and Pennsylvanian (fig. 2*A*) (Smith and others, 1973). Underlying the main channel streambeds and confluences are rocks of Mississippian age that generally are composed of shale, dolomite, limestone, and sandstone from the Paragon Formation. The confluence areas of all study streams with the Cumberland River contain limestone and shale from the Kidder Limestone Member. This limestone and shale feature is characterized by steep bluffs and karst topography (McDowell, 1983). The bedrock underlying the high gradient, headwater streams is Pennsylvanian age and contains shale from the Alvy Creek formation along the mid slopes and Rockcastle Conglomerate and Grundy Formation on the ridges. The shale is medium to yellowish gray and grayish brown. The siltstone and sandstone is light gray to olive gray and the sandstone is very fine-grained quartzose and contains mica and iron- and magnesium-containing minerals and thin bands of coal.

Surface and underground mining in the Wildcat/Addison Branch study area began in the early 1900s and continued through the 1970s (U.S. Department of Agriculture Forest Service, 2015). A few of the underground mine entry portals remain open and act as conduits, contributing AMD directly to the streams. Water samples have been collected in the study area that contained high levels of sulfate and dissolved aluminum, iron, and other heavy metals (U.S. Department of Agriculture Forest Service, 2015). Wildcat Branch has been identified by the State Unified Watershed Assessment as a priority watershed /subbasin and is listed in the 2012 Kentucky 305(b) Report to Congress as a 303(d)-listed stream as “impaired” for its intended uses (U.S. Department of Agriculture Forest Service, 2015). The listing was assigned because of low pH, heavy metals loading, and stream sedimentation resulting in nonsupport of aquatic resources and other beneficial uses. Additionally, the Nature Conservancy classifies this basin as a “Critical Watershed” to conserve at-risk fish and mussel species (U.S. Department of Agriculture Forest Service, 2015).

Similar to the Rock Creek study area, sites were selected to help define reaches that gain or lose water under non-runoff conditions. The geology of the Wildcat/Addison Branch study area was not as well known as Rock Creek, so no sites were chosen based on geology. Maps of mined areas were not available for the Addison Branch basin. Several sites in the Wildcat/Addison Branch study area were selected only to provide the Forest Service with information on water quality and the relative contribution of streamflow at locations expected to be important for future remediation strategies (sites UT1–4; table 1).

Methods

Streamflow measurements and discrete water-quality data were collected during two synoptic surveys in each of two study areas: Rock Creek and Wildcat/Addison Branches. Synoptic survey streamflow measurements were used to compute reach-specific streamflow gain and loss, and discrete water temperature, pH, specific conductance, and dissolved oxygen (DO) measurements were used to evaluate basin-scale conditions over a short timeframe. The Rock Creek streamgage (site RM3; table 1, fig. 1*B*) provided continuous streamflow, water temperature, pH, specific conductance, DO, and turbidity data. Hydrograph separation techniques were used to characterize the contribution of groundwater discharge relative to total streamflow at the Rock Creek streamgage. Data were collected from 2015 to 2017 and are available as a USGS data release (Cherry, 2019).

Table 1. Sites in the Rock Creek and Wildcat/Addison Branch study areas where streamflow and discrete water-quality properties were measured during synoptic surveys, eastern Kentucky, 2015–17.

[R, Rock Creek; M, main stem; °, degree; ‘, minute; ‘’, second; T, tributary; W, Wildcat Branch; A, Addison Branch; U, unnamed]

Map identifier (fig. 1)	U.S. Geological Survey station identifier	U.S. Geological Survey station description	Latitude	Longitude	Date of first survey	Date of second survey
		Rock Creek study area				
RM1	364250084325400	Rock Creek main stem below Grassy Fork, Kentucky	36° 42’ 49.7”	–84° 32’ 54.1”	November 5, 2015	May 18, 2016
RT1	364247084325400	Grassy Fork tributary at mouth before Rock Creek, Kentucky	36° 42’ 47.6”	–84° 32’ 54.0”	November 5, 2015	May 18, 2016
RM2	364244084330100	Rock Creek main stem below Watertank Hollow, Kentucky	36° 42’ 44.2”	–84° 33’ 00.8”	November 5, 2015	May 18, 2016
RT2	03410594	Water Tank Hollow at culvert at mouth before Rock Creek, Kentucky	36° 42’ 43.8”	–84° 33’ 03.3”	November 5, 2015	May 18, 2016
RM3	03410590	Rock Creek near Yamacraw, Kentucky	36° 42’ 11.8”	–84° 33’ 44.2”	November 5, 2015	May 18, 2016
RT3	03410585	Koger Fork tributary at mouth before Rock Creek, Kentucky	36° 42’ 02.9”	–84° 33’ 45.9”	November 5, 2015	May 18, 2016
RM4	364227084340500	Rock Creek main stem below Poplar Spring, Kentucky	36° 42’ 19.4”	–84° 34’ 01.6”	November 4, 2015	May 19, 2016
RT4	03410578	Poplar Spring tributary at mouth before Rock Creek, Kentucky	36° 42’ 22.2”	–84° 34’ 05.2”	November 4, 2015	May 19, 2016
RM5	364222084343500	Rock Creek main stem below Paint Cliff #1 and #2, Kentucky	36° 42’ 22.6”	–84° 34’ 35.0”	November 4, 2015	May 18, 2016
RT5	03410575	Paint Cliff #1 tributary above pond, Kentucky	36° 42’ 25.3”	–84° 34’ 33.6”	November 4, 2015	May 19, 2016
RT6	364225084343300	Paint Cliff #2 tributary above pond, Kentucky	36° 42’ 27.0”	–84° 34’ 38.0”	November 5, 2015	May 18, 2016
RM6	364238084334500	Rock Creek main stem below Roberts Hollow, Kentucky	36° 42’ 37.4”	–84° 34’ 57.4”	November 4, 2015	May 19, 2016
RT7	03410571	Roberts Hollow tributary at mouth before Rock Creek, Kentucky	36° 42’ 37.5”	–84° 35’ 01.7”	November 4, 2015	May 19, 2016
RM7	364237084350100	Rock Creek main stem below White Oak Creek and Junction, Kentucky	36° 42’ 10.4”	–84° 35’ 44.3”	November 4, 2015	May 19, 2016
RM8	364210084354500	Rock Creek main stem at White Oak Junction , Kentucky	36° 42’ 09.7”	–84° 35’ 43.4”	November 4, 2015	May 19, 2016
RM9	03410559	Rock Creek main stem above White Oak Creek and Junction, Kentucky	36° 42’ 08.9”	–84° 35’ 42.0”	November 4, 2015	May 19, 2016
RM10	03410557	White Oak Creek main stem at mouth before Rock Creek, Kentucky	36° 42’ 09.1”	–84° 35’ 50.0”	November 4, 2015	May 19, 2016
RT8	03410555	Jones Branch tributary above White Oak Creek, Kentucky	36° 42’ 08.8”	–84° 35’ 50.4”	November 4, 2015	May 19, 2016
RM11	364143084360800	White Oak Creek main stem below Wolfpen Branch, Kentucky	36° 41’ 44.0”	–84° 36’ 08.7”	November 4, 2015	May 19, 2016
RT9	364138084360400	Wolfpen Branch tributary above White Oak Creek, Kentucky	36° 41’ 43.4”	–84° 36’ 08.9”	November 4, 2015	May 19, 2016
RT10	364135084363200	Co-Operative South tributary above White Oak Creek, Kentucky	36° 41’ 35.6”	–84° 36’ 32.1”	November 4, 2015	May 19, 2016
RT11	03410547	Big Momma tributary above White Oak Creek, Kentucky	36° 41’ 35.0”	–84° 36’ 37.4”	November 4, 2015	May 19, 2016
RM12	364134084365400	White Oak Creek main stem below Unnamed Tributary, Kentucky	36° 41’ 34.4”	–84° 36’ 52.9”	November 4, 2015	May 18, 2016
RT12	364134084365500	Unnamed tributary above White Oak Creek, Kentucky	36° 41’ 37.0”	–84° 36’ 56.5”	November 4, 2015	May 18, 2016
RM13	364126084372300	White Oak Creek main stem below Cabin Branch, Kentucky	36° 41’ 27.0”	–84° 37’ 23.0”	November 3, 2015	May 18, 2016
RT13	03410542	Cabin Branch tributary at mouth before White Oak Creek, Kentucky	36° 41’ 29.8”	–84° 37’ 24.9”	November 3, 2015	May 18, 2016
RM14	364125084372400	White Oak Creek main stem above Cabin Branch, Kentucky	36° 41’ 26.9”	–84° 37’ 21.7”	November 3, 2015	May 18, 2016

Table 1. Sites in the Rock Creek and Wildcat/Addison Branch study areas where streamflow and discrete water-quality properties were measured during synoptic surveys, eastern Kentucky, 2015–17.—Continued

[R, Rock Creek; M, main stem; °, degree; ‘, minute; ‘’, second; T, tributary; W, Wildcat Branch; A, Addison Branch; U, unnamed]

Map identifier (fig. 1)	U.S. Geological Survey station identifier	U.S. Geological Survey station description	Latitude	Longitude	Date of first survey	Date of second survey
		Wildcat/Addison Branch study area				
WM1	365822084260700	Wildcat Branch main stem at mouth before conflunce with Cumberland River, Kentucky	36° 58’ 22.7”	–84° 2’6 07.10”	June 9, 2016	May 9, 2017
WM2	365836084253300	Wildcat Branch main stem below Unnamed Tributary #2, Kentucky	36° 58’ 36.2”	–84° 25’ 33.9”	June 9, 2016	May 9, 2017
WT1	365838084253300	Unnamed Tributary #2 above confluence with Wildcat Branch, Kentucky	36° 58’ 38.7”	–84° 25’ 33.0”	June 9, 2016	May 9, 2017
WT2	365842084252500	Unnamed Tributary #3 before confluence with Wildcat Branch, Kentucky	36° 58’ 42.0”	–84° 25’ 25.0”	June 9, 2016	May 9, 2017
WM3	365841084252800	Wildcat Branch main stem below confluence with unnamed tributary #3, Kentucky	36° 58’ 41.1”	–84° 25’ 28.4”	June 9, 2016	May 9, 2017
WT3	365849084253800	East Unnamed Tributary #2 above confluence with East Branch, Kentucky	36° 58’ 49.9”	–84° 25’ 32.6”	Not measured	May 10, 2017
WT4	365849084253200	West Unnamed Tributary #2 above confluence with West Branch, Kentucky	36° 58’ 49.2”	–84° 25’ 38.0”	Not measured	May 10, 2017
WT5	365907084254500	West Unnamed Tributary #2 below pond at Hwy 122C, Kentucky	36° 59’ 07.0”	–84° 25’ 45.2”	June 8, 2016	May 9, 2017
WT6	365912084254000	East Unnamed Tributary #2 above pond at Hwy 122C at seep, Kentucky	36° 59’ 12.3”	–84° 25’ 40.3”	June 8, 2016	May 9, 2017
WT7	365903084251100	Unnamed Tributary #4 above confluence with Wildcat Branch, Kentucky	36° 59’ 03.5”	–84° 25’ 11.6”	June 8, 2016	May 10, 2017
WM4	365900084251400	Wildcat Branch main stem below confluence with Unnamed Tributary #4, Kentucky	36° 59’ 00.3”	–84° 25’ 14.6”	June 8, 2016	May 10, 2017
WM5	365903084245800	Wildcat Branch main stem between Unnamed Tributaries #4 and #5, Kentucky	36° 59’ 03.9”	–84° 24’ 58.8”	June 8, 2016	May 8, 2017
WT8	365904084245600	Outfall from settling pond before confluence with Wildcat Branch, Kentucky	36° 59’ 10.9”	–84° 25’ 43.0”	June 8, 2016	May 8, 2017
WM6	365905084245500	Wildcat Branch main stem below beaver pond at Hwy 5148, Kentucky	36° 59’ 05.4”	–84° 24’ 55.3”	June 8, 2016	May 8, 2017
WT9	365907084245700	Unnamed Tributary #5 above confluence with Wildcat Branch at beaver pond, Kentucky	36° 59’ 07.2”	–84° 24’ 56.7”	June 8, 2016	May 8, 2017
WT10	365911084243800	West pond above Wildcat Branch main stem, Kentucky	36° 59’ 11.1”	–84° 24’ 38.7”	June 8, 2016	May 8, 2017
WT11	365910084243700	East pond above Wildcat Branch, Kentucky	36° 59’ 10.7”	–84° 24’ 37.8”	June 8, 2016	May 8, 2017
WM7	365909084244000	Wildcat Branch main stem above Unnamed Tributary #5, Kentucky	36° 59’ 09.6”	–84° 24’ 40.0”	June 8, 2016	May 8, 2017
AM1	365708084252900	Addison Branch main stem at mouth above Cumberland River, Kentucky	36° 57’ 08.1”	–84° 25’ 29.3”	June 29, 2016	May 10, 2017
AM2	365721084252200	Addison Branch main stem above unnamed tributary, Kentucky	36° 57’ 10.3”	–84° 25’ 30.9”	June 29, 2016	May 10, 2017
AT1	365722084252000	Unnamed tributary at mouth above Addison Branch, Kentucky	36° 57’ 21.6”	–84° 25’ 22.3”	June 29, 2016	May 10, 2017
AM3	365744084251000	Addison Branch main stem below confluence of East and West Branches, Kentucky	36° 57’ 22.9”	–84° 25’ 20.3”	June 28, 2016	May 10, 2017
AT2	365746084251100	Addison Branch West at mouth above confluence with East Branch, Kentucky	36° 57’ 44.1”	–84° 25’ 10.4”	June 28, 2016	May 10, 2017

Table 1. Sites in the Rock Creek and Wildcat/Addison Branch study areas where streamflow and discrete water-quality properties were measured during synoptic surveys, eastern Kentucky, 2015–17.—Continued

[R, Rock Creek; M, main stem; °, degree; ‘, minute; ‘’, second; T, tributary; W, Wildcat Branch; A, Addison Branch; U, unnamed]

Map identifier (fig. 1)	U.S. Geological Survey station identifier	U.S. Geological Survey station description	Latitude	Longitude	Date of first survey	Date of second survey
Wildcat/Addison Branch study area—Continued						
AM4	365744084251100	Addison Branch main stem at mouth above confluence with West Branch, Kentucky	36° 57’ 44.8”	–84° 25’ 11.0”	June 28, 2016	May 10, 2017
AM5	365809084253200	Addison Branch main stem below seep, Kentucky	36° 58’ 09.9”	–84° 25’ 32.2”	June 29, 2016	May 11, 2017
AT3	365756084245700	Seep on Addison Branch East, Kentucky	36° 58’ 05.9”	–84° 24’ 51.8”	June 29, 2016	May 11, 2017
AM6	365756084245600	Addison Branch main stem above seep, Kentucky	36° 58’ 11.3”	–84° 24’ 46.1”	June 29, 2016	May 11, 2017
Unnamed tributaries						
UT1	365922084260000	Unnamed Branch #1 above pond, Kentucky	36° 59’ 22.8”	–84° 26’ 00.4”	June 8, 2016	May 9, 2017
UT2	365920084260500	Unnamed Branch #1 below pond, Kentucky	36° 59’ 20.8”	–84° 26’ 05.3”	June 8, 2016	May 9, 2017
UT3	365756084262300	Unnamed Branch #2 before Cumberland River, Kentucky	36° 57’ 56.0”	–84° 26’ 23.5”	June 7, 2016	May 11, 2017
UT4	365740084253900	Unnamed Branch #3 before Cumberland River, Kentucky	36° 57’ 40.4”	–84° 25’ 39.0”	June 29, 2016	May 11, 2017

Streamflow and Discrete Water-Quality Data Collection

Streamflow and discrete water-quality measurements were made following USGS policies and methods (Rantz and others, 1982; Wilde and Radtke, 1998; Wagner and others, 2006; Turnipseed and Sauer, 2010; U.S. Geological Survey, variously dated). In most instances, water velocity was measured with Sontek acoustic velocity meters and streamflow was computed by means of the mid-section method (Sontek/YSI, 2007; Turnipseed and Sauer, 2010). In all other instances, streamflow was measured with the volumetric method (Rantz and others, 1982) or was estimated if flow was too low to measure.

The errors in the streamflow measurements were rated qualitatively (excellent, good, fair, or poor) by the field technician according to guidelines established by Sauer and Meyer (1992). The errors associated with excellent, good, fair, and poor measurements were considered to be 2, 5, 8, and 10 percent of the true streamflow, respectively. The error is based on assessments of streambed and velocity uniformity, streambed materials, and other stream characteristics that may affect the measurement accuracy. Streamflow measurement error, in cubic feet per second, was calculated by multiplying the value of streamflow by the assigned qualitative rating error. For example, a measured streamflow of 1.24 cubic feet per second (ft^3/s) rated fair (plus or minus 8 percent) would have a potential measurement error of plus or minus 0.10 ft^3/s.

Discrete water quality was measured with Yellow Springs Instruments (YSI) EXO multiparameter monitors (YSI, 2017). The monitors were equipped with water temperature, pH, DO, and specific conductance probes. Water-quality monitors were calibrated and operated according to manufacturer recommendations (YSI, 2017).

Streamflow Gain and Loss Computation

The timing of the synoptic surveys used for gain and loss computations was intended to capture variability in base-flow conditions, with a survey in the spring and autumn when the duration of antecedent dry conditions are generally shorter and longer, respectively. Logistics determined that the surveys were not always carried out as designed. Synoptic surveys were done at the Rock Creek study area in November 2015 and May 2016, and at the Wildcat/Addison study area in June 2016 and May 2017. The timing of synoptic surveys was intended to select periods not associated with a storm event; rather when streams were in “assumed” base-flow conditions based on the streamflow at the streamgage on Rock Creek and precipitation data from a nearby weather station for the ungaged Wildcat and Addison Branches. The synoptic surveys did not follow a precipitation event large enough to cause large changes in streamflow. No synoptic surveys were made during direct precipitation events.

Streamflow gains and losses were computed by separating a stream into reaches and determining the differences in flow between upstream and downstream boundaries. A gaining reach has groundwater that discharges to surface water, resulting in a downstream increase in flow; conversely, a losing reach has surface water that discharges to groundwater, resulting in a downstream decrease in flow. Other factors that can affect the net change in flow within a stream reach include tributary inflow, stream diversions, return flows from point sources, and evapotranspiration. Streamflow gains and losses (Turco and others, 2007) were computed as

$$G = Q_D - Q_U - I + D - R + E, \tag{1}$$

where

G is streamflow gain or loss,
Q_D is streamflow measured at the downstream reach,
Q_U is streamflow measured at the upstream reach,
I is measured tributary inflows,
D is measured stream diversions (outflows),
R is return flows, and
E is evapotranspiration. (All units are cubic feet per second.)

Numerous tributary inflows were measured during the study. There were no diversions or return flows. Evapotranspiration was not measured and was assumed negligible (Slade and others, 2002; Turco and others, 2007). All the individual measurement errors were summed to determine the potential total error associated with each reach, and the reach is considered verified if the error associated with the reach does not exceed the gain or loss value (Turco and others, 2007).

Hydrograph Separation Computations

Hydrograph separation involves partitioning a streamflow record into base flow and runoff components. Base flow is the component of total streamflow that persists in absence of runoff, reacts slowly to precipitation infiltration, and is largely sustained by groundwater discharge (Eckhardt, 2008).

Surface runoff includes water (from precipitation) that travels over the land surface and through channels to a stream plus water that infiltrates the soil surface that travels above the main groundwater level to a stream by means of gravity. The USGS Groundwater Toolbox (GW Toolbox; Barlow and others, 2015) was used to partition the total streamflow into surface runoff and base flow and to calculate the base-flow index (the ratio of base flow to total streamflow). Hydrograph separation analyses were done using daily mean streamflow data from the Rock Creek gage for the period August 2015 to August 2017. The analyses were done with each of six methods: Base-flow index (BFI) (standard and modified), HYSEP (fixed interval, sliding interval, and local minimum), and PART. Each method was used because they are available in the GW Toolbox, which aggregates several hydrograph-separation

programs. Barlow and others (2015) suggest using several hydrograph separation methods and comparing the results because each method works best in different conditions. Daily mean streamflow data from the Rock Creek streamgage were obtained from the USGS National Water Information System (NWIS) and used for hydrograph separation (U.S. Geological Survey, 2018).

Wahl and Wahl (1995) developed the original BFI program based on a procedure created by the Institute of Hydrology (1980). The original BFI program divided streamflow into intervals of N-days; the minimum streamflow during each N-day interval is compared to adjacent minimum, and turning points are determined. By default, the original BFI set the day interval (N) and the turning point test factor (f) to 5 and 0.9, respectively (Nelms and others, 2015). When f is set to 0.9, if 90 percent of a given N-day minimum is less than both adjacent N-day minimums, that minimum is considered a turning point. Turning points are connected by straight lines to create the base-flow hydrograph. The BFI-modified method replaces f with the daily recession index (K′):

$$K' = f^{\left(\frac{1}{N}\right)} \tag{2}$$

and equals 0.979 when the defaults of N=5 days and f=0.9 are used. For this analysis, an N-day interval of 2 was used for both BFI methods. Wahl and Wahl (1995) suggested an N value should be consistent with the duration of time required for surface runoff to typically cease. An N value of 2 was used because surface runoff generally ended within 1–2 days after peak runoff during the study period. The other values used were f=0.90 and K'=0.9487.

Additional base-flow analyses were done using the HYSEP methods (Sloto and Crouse, 1996). HYSEP uses three separation methods originally developed by Pettyjohn and Henning (1979): fixed interval, sliding interval, and local minimum. Annual base-flow estimates are typically more reliable than monthly or daily estimates with the HYSEP method, and long-term records are more reliable because they capture a wider range of climatic conditions than short-term records (Sloto and Crouse, 1996). HYSEP is more reliable in natural flow regimes compared to streams that have diversions or are regulated from reservoirs (Sloto and Crouse, 1996); none of the study streams in the Rock Creek study area had diversions or significant storage from ponds or reservoirs.

Base flow was also analyzed using the PART method, which was originally developed by Rutledge (1998). Base flow is estimated with PART by interpolating between streamflows on days estimated to be unaffected by surface runoff determined on the basis of antecedent streamflow recession criteria. The recommended lower and upper limits for drainage area are 1 and 500 square miles, respectively, for the PART method. Geologic heterogeneity, such as the karst geology in the study area, can bias the results (Rutledge, 1998).

Continuous Water-Quality Data Collection

Water-quality properties (water temperature, pH, DO, specific conductance, and turbidity) were measured continuously at the Rock Creek streamgage from July 2016 through July 2017. Water-quality data were measured with a YSI 6-series multiparameter water-quality monitor (YSI, 2012). The water-quality monitor was suspended from the bridge and placed near the thalweg of the stream (fig. 3). USGS protocols were used during the operation and maintenance of the multiparameter water-quality monitors and computation of continuous water-quality records (Wagner and others, 2006). According to criteria described in Wagner and others (2006), the periods of water-quality records for all parameters were rated good except some periods associated with high flow were deleted because the sonde was not heavy enough to remain submerged during high velocities. To prevent that problem, a weight was added to the suspended water-quality well on May 27, 2017 (fig. 3).

Results and Discussion

This section describes the results of the synoptic surveys from both study areas (Rock Creek and Wildcat/Addison Branches). Gaining and losing stream reaches were identified, and water quality measurements were taken across the entire study area in a short time span. From the Rock Creek streamgage, the results of the hydrograph separation analyses and continuous water-quality parameters are presented.

Synoptic Surveys and Streamflow Gains and Losses

Low pH and high specific conductance values from many of the Wildcat Branch sites during both synoptic surveys indicated that the study area was likely affected by AMD during the study period (table 2, fig. 4). The pH of AMD is usually 2.0 to 4.0 standard units (Nordstrom, 2011), and 68 percent of all the pH measurements in the Wildcat Branch study area were below 4.0 standard units (table 2). The highest measurement of specific conductance in the Wildcat Branch study area was at site WT6 (mean of values from 2016 and 2017 of 2,540 microsiemens per centimeter at 25 degrees Celsius [µS/cm]). Site WT6 was a seep in the hillside that discharged groundwater directly into the headwaters of Wildcat Branch (fig. 5). The DO was not measured during the first survey at site WT6 because the DO probe malfunctioned, but the water from the site was anoxic (0.1 mg/L) during the second survey.

A streamgage was not available at the Wildcat/Addison Branch study area, so precipitation measured at a nearby weather station was used to estimate when streams were at base flow conditions. During the preceding 14, 7, and 2 days

Figure 3. Picture of the pipe that contains and protects the continuous water-quality monitor at the U.S. Geological Survey streamgage Rock Creek near Yamacraw, Kentucky (station number 03410590).

Table 2. Streamflow and discrete water-quality results from synoptic surveys made June 2016 and May 2017 at Wildcat Branch, Daniel Boone National Forest, eastern Kentucky.

[ft³/s, cubic foot per second; °C, degree Celsius; µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; W, Wildcat Branch; M, main stem; T, tributary; DRY, stream was at no flow; ±, plus or minus; %, percent; --, not available]

Map identifier (fig. 1)	U.S. Geological Survey station identifier	Date of synoptic survey	Streamflow (ft³/s)	Streamflow measurement rating	Water temperature (°C)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard units)
First survey								
WM1	365822084260700	June 9, 2016	DRY	DRY	DRY	DRY	DRY	
WM2	365836084253300	June 9, 2016	1.24	Fair±8%	16.1	720	--	3.3
WT1	365838084253300	June 9, 2016	0.10	Fair±8%	13.7	--	--	5.1
WT2	365842084252500	June 9, 2016	0.09	Poor±10%	13.4	716	--	3.0
WM3	365841084252800	June 9, 2016	1.12	Fair±8%	16.1	776	--	3.1
WT3	365849084253800	--	--	--	--	--	--	--
WT4	365849084253200	--	--	--	--	--	--	--
WT5	365907084254500	June 8, 2016	0.22	Poor±10%	21.9	1,800	--	4.5
WT6	365912084254000	June 8, 2016	0.10	Fair±8%	14.1	2,560	--	3.8
WT7	365903084251100	June 8, 2016	0.17	Fair±8%	21.5	801	--	3.8
WM4	365900084251400	June 8, 2016	1.11	Good±5%	19.4	798	--	3.1
WT8	365904084245600	June 8, 2016	0.02	Fair±8%	20.9	423	--	3.5
WM5	365903084245800	June 8, 2016	1.06	Fair±8%	23.4	778	--	3.0
WM6	365905084245500	June 8, 2016	0.84	Fair±8%	22.1	807	--	4.8
WT9	365907084245700	June 8, 2016	0.18	Poor±10%	18.8	1,160	--	3.1
WT10	365911084243800	June 8, 2016	0.54	Fair±8%	26.3	914	--	3.0
WT11	365910084243700	June 8, 2016	0.19	Poor±10%	27.4	114	--	4.3
WM7	365909084244000	June 8, 2016	0.50	Fair±8%	25.5	735	--	3.0
Second survey								
WM1	365822084260700	May 9, 2017	DRY	DRY	DRY	DRY	DRY	DRY
WM2	365836084253300	May 9, 2017	2.35	Good±5%	16.4	571	9.4	3.5
WT1	365838084253300	May 9, 2017	0.54	Fair±8%	17.4	802	9.3	4.6
WT2	365842084252500	May 9, 2017	0.11	Fair±8%	13.9	484	9.4	3.1
WM3	365841084252800	May 9, 2017	1.41	Fair±8%	16.5	569	9.4	3.4
WT3	365849084253800	May 10, 2017	0.07	Fair±8%	15.5	505	9.3	6.0
WT4	365849084253200	May 10, 2017	0.51	Fair±8%	17.7	956	8.9	4.3
WT5	365907084254500	May 9, 2017	0.21	Fair±8%	17.3	1,740	9.1	4.0
WT6	365912084254000	May 9, 2017	0.11	Poor±10%	14.0	2,520	0.1	4.1
WT7	365903084251100	May 10, 2017	0.20	Fair±8%	18.0	--	8.9	3.6
WM4	365900084251400	May 10, 2017	1.05	Fair±8%	17.4	664	9.0	3.3
WT8	365904084245600	May 8, 2017	0.06	Poor±10%	17.9	389	8.9	3.5
WM5	365903084245800	May 8, 2017	1.59	Fair±8%	17.9	447	9.0	3.4
WM6	365905084245500	May 8, 2017	1.36	Fair±8%	19.5	467	8.6	3.4
WT9	365907084245700	May 8, 2017	0.31	Fair±8%	15.3	1030	9.5	3.2
WT10	365911084243800	May 8, 2017	0.34	Fair±8%	20.0	494	8.7	3.2
WT11	365910084243700	May 8, 2017	0.73	Fair±8%	18.8	100	9.0	4.1
WM7	365909084244000	May 8, 2017	1.00	Fair±8%	18.2	457	9.0	3.2

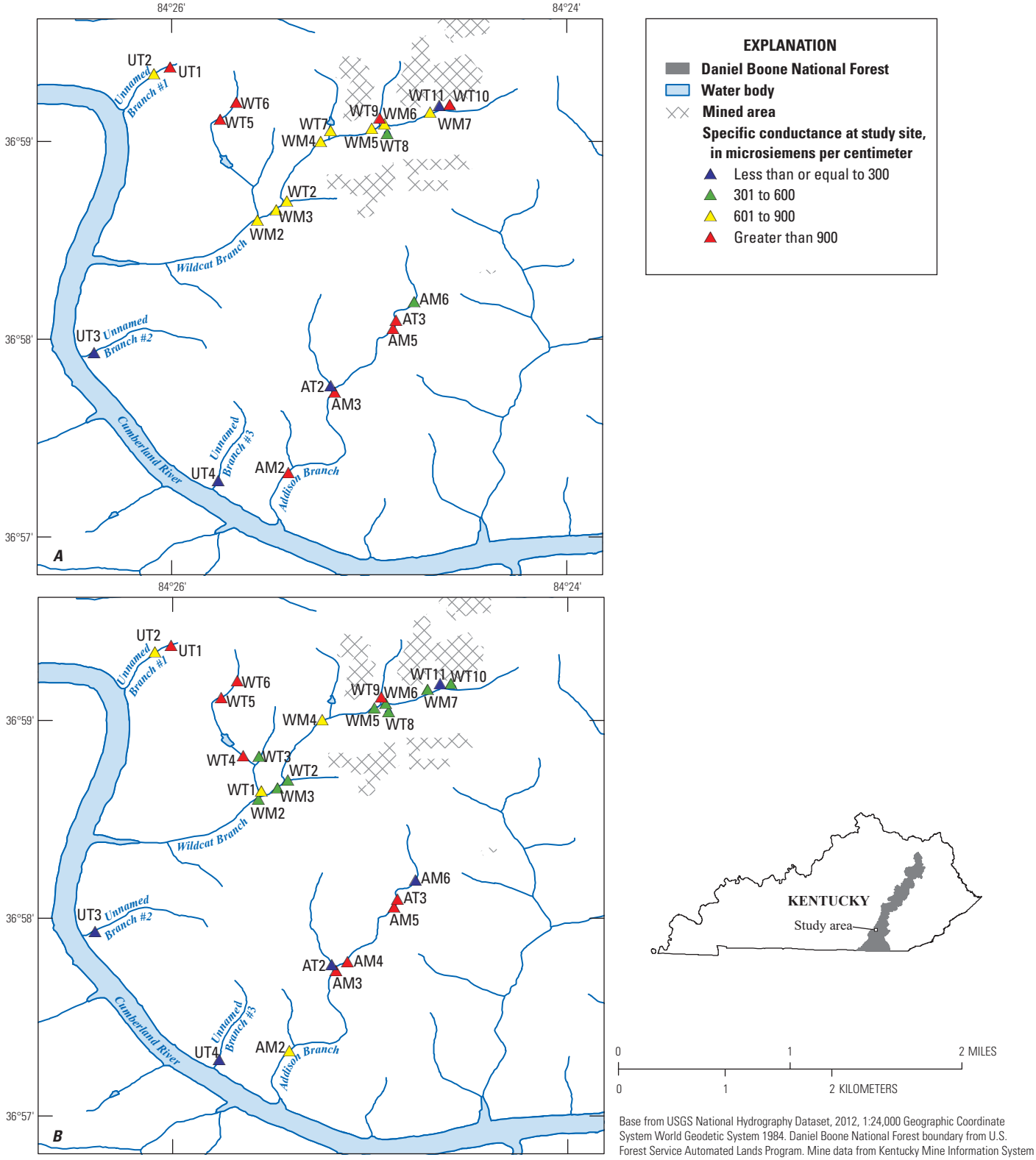


Figure 4. Specific conductance at study sites in the Wildcat/Addison Branch study area in Daniel Boone National Forest, eastern Kentucky. *A*, June 2016. *B*, May 2017. (Sites with no streamflows are not shown.)

Figure 5. Picture of the seep in the Wildcat Branch of the Wildcat/Addison Branch study area at site WT6 taken June 8, 2016, Daniel Boone National Forest, eastern Kentucky.

of the June 2016 survey, the study area received 2.17, 1.23, and 0.00 inches (in.) of cumulative precipitation, respectively, at nearby Williamsburg, Ky. (not shown on map; University of Kentucky, 2017). During the preceding 14, 7, and 2 days of the May 2017 survey, the study area received 2.59, 1.25, and 0.00 in. of cumulative precipitation, respectively.

Gaining and losing reaches were identified along the main stem of Wildcat Branch (table 3, fig. 6). Wildcat Branch reach 1, from upstream at site WM2 to downstream at WM1, was losing during both surveys, and the stream was dry at site WM1 during both surveys. Site WM1 is the last site on Wildcat Branch before the confluence with the Cumberland River. The Kidder Limestone Member underlies Wildcat Branch reach 1 (fig. 2*A*), so during the surveys the karst topography directed all the streamflow into the subsurface somewhere along Wildcat Branch reach 1.

The measured values of pH and specific conductance at Addison Branch sites indicated the study area, except the small basin draining at site AT2, was likely affected by AMD during the study period (table 4; fig. 4). The DO of the water at site AT3 was consistently the lowest among all Addison Branch sites and was anoxic during the first survey (0.2 mg/L; table 4). Site AT3 is an open mine portal that discharges groundwater directly to the surface. The values of pH from all Addison Branch sites except AT2 were below 4.0 standard units. Site AT2 consistently had the highest pH values and lowest specific conductance values. Site AT2 drained the west portion of the Addison Branch basin and had better water quality but less streamflow than AM4, the last site on the east portion of Addison Branch (table 4).

Gaining and losing reaches were identified along the main stem of Addison Branch (table 5; fig. 6). Similar to Wildcat Branch, Addison Branch reach 1 was the last reach before the confluence with the Cumberland River and was losing during both surveys. A large swallow hole that directed all the streamflow to the subsurface was found on Addison Branch reach 1 while performing the field work. Site AM4 was not measured during the June 2016 synoptic survey, so site AM4 was not used in the May 2017 reach 3 computation. Site AM5 was the upstream-most site in reach 3 for both computations.

Table 3. Results of streamflow gain and loss computations from synoptic surveys made June 2016 and May 2017 at Wildcat Branch, Daniel Boone National Forest, eastern Kentucky.

[ft³/s, cubic foot per second; W, Wildcat Branch; M, main stem; T, tributary; --, not available; ±, plus or minus; Underlined values of reach gain or loss exceed the potential error associated with the streamflow measurements, and are considered verified]

Reach	Map identifier (fig. 1)	Downstream streamflow (ft^3/s)	Upstream streamflow (ft^3/s)	Inflow streamflow (ft^3/s)	Reach gain or loss (ft^3/s)	[1] Maximum error associated with streamflow measurement (ft^3/s)	Maximum error associated with reach streamflow (ft^3/s)
First survey (June 8–9, 2016)							
1	WM1	0.00	--	--	–1.24	±0.00	0.10
1	WM2	--	1.24	--	--	±0.10	--
2	WM2	1.24	--	--	0.02	±0.10	0.20
2	WM3	--	1.12	--	--	±0.09	--
2	WT1	--	--	0.10	--	±0.01	--
3	WM3	1.12	--	--	–0.08	±0.09	0.16
3	WM4	--	1.11	--	--	±0.06	--
3	WT2	--	--	0.09	--	±0.01	--
4	WM4	1.11	--	--	–0.12	±0.06	0.15
4	WM5	--	1.06	--	--	±0.08	--
4	WT7	--	--	0.17	--	±0.01	--
5	WM5	1.06	--	--	0.02	±0.08	0.17
5	WM6	--	0.84	--	--	±0.07	--
5	WT8	--	--	0.02	--	±0.00	--
5	WT9	--	--	0.18	--	±0.02	--
Second survey (May 8–10, 2017)							
1	WM1	0.00	--	--	–2.35	±0.00	0.12
1	WM2	--	2.35	--	--	±0.12	--
2	WM2	2.35	--	--	0.40	±0.12	0.27
2	WM3	--	1.41	--	--	±0.11	--
2	WT1	--	--	0.54	--	±0.04	--
3	WM3	1.41	--	--	0.25	±0.11	0.20
3	WM4	--	1.05	--	--	±0.08	--
3	WT2	--	--	0.11	--	±0.01	--
4	WM4	1.05	--	--	–0.74	±0.08	0.23
4	WM5	--	1.59	--	--	±0.13	--
4	WT7	--	--	0.20	--	±0.02	--
5	WM5	1.59	--	--	–0.14	±0.13	0.27
5	WM6	--	1.36	--	--	±0.11	--
5	WT8	--	--	0.06	--	±0.01	--
5	WT9	--	--	0.31	--	±0.02	--

[1]The error associated with a streamflow measurement, in cubic feet per second, is the product of the measured streamflow and the qualitative rating error from table 2.

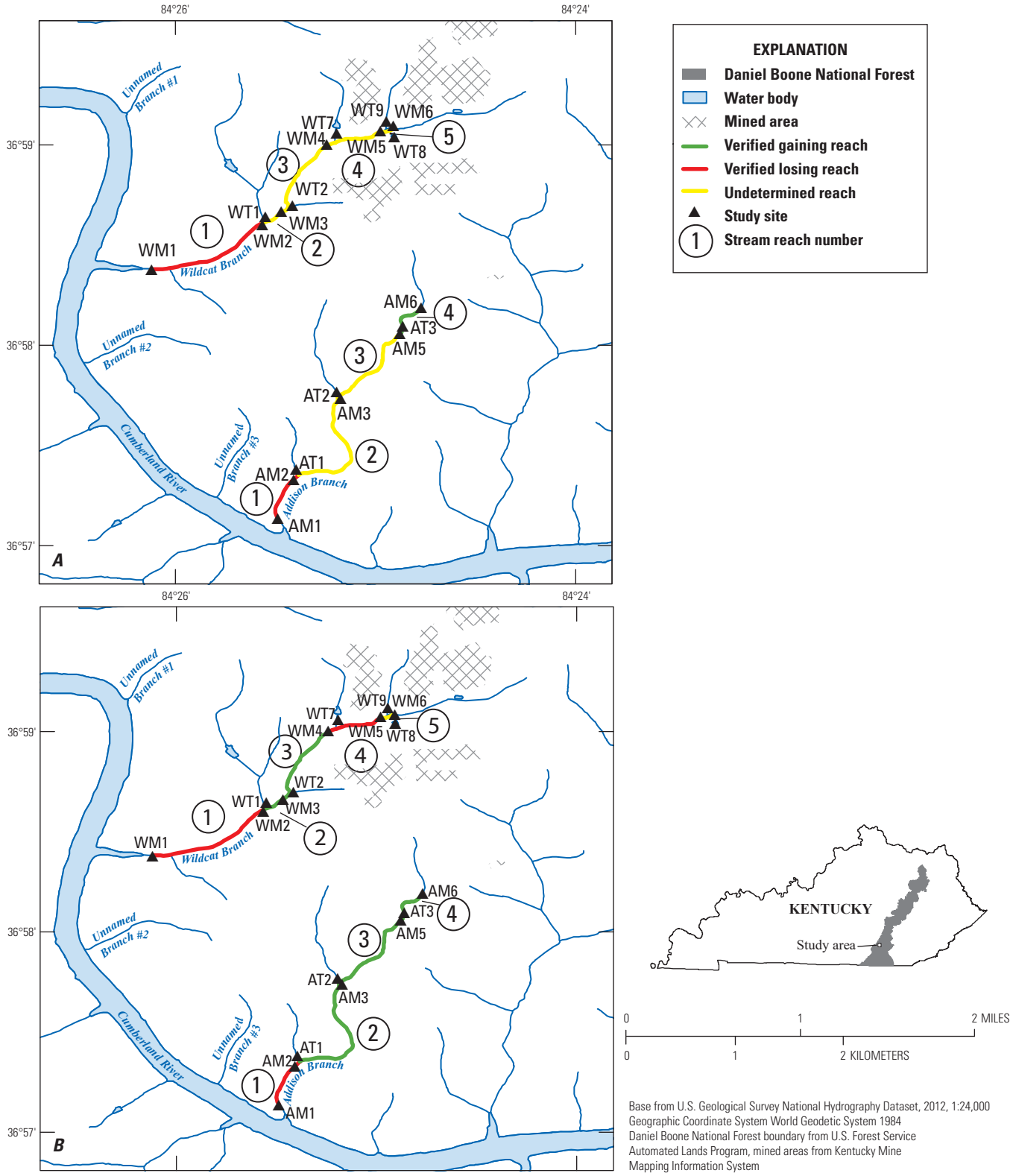


Figure 6. Gaining, losing, and undetermined stream reaches in the Wildcat/Addison Branch study area in Daniel Boone National Forest, eastern Kentucky. *A*, June 2016. *B*, May 2017. Undetermined reaches have the sum of errors associated with the streamflow measurements greater than the gain or loss value.

Table 4. Streamflow and discrete water-quality results from synoptic surveys made June 2016 and May 2017 at Addison Branch, Daniel Boone National Forest, eastern Kentucky.

[ft³/s, cubic foot per second; °C, degree Celsius; µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; A, Addison Branch; M, main stem; DRY, stream was at no flow; ±, plus or minus; %, percent; T, tributary; --, not available]

Map identifier (fig. 1)	U. S. Geological Survey station identifier	Date of synoptic survey	Streamflow (ft³/s)	Streamflow measurement rating	Water temperature (°C)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard units)
First survey								
AM1	365708084252900	June 29, 2016	DRY	DRY	DRY	DRY	DRY	DRY
AM2	365721084252200	June 29, 2016	0.46	Fair±8%	19.5	1,280	9.0	2.5
AT1	365722084252000	June 29, 2016	DRY	DRY	DRY	DRY	DRY	DRY
AM3	365744084251000	June 28, 2016	0.43	Fair±8%	20.6	1,280	8.5	2.6
AT2	365746084251100	June 28, 2016	0.13	Poor±10%	22.0	56	8.3	7.9
AM4	365744084251100	--	--	--	--	--	--	--
AM5	365809084253200	June 29, 2016	0.32	Fair±8%	16.6	1,780	8.5	2.4
AT3	365756084245700	June 29, 2016	0.16	Poor±10%	13.6	2,000	0.2	2.4
AM6	365756084245600	June 29, 2016	0.04	Poor±0%	18.1	412	2.7	3.0
Second survey								
AM1	365708084252900	May 10, 2017	DRY	DRY	DRY	DRY	DRY	DRY
AM2	365721084252200	May 10, 2017	1.81	Fair±8%	16.0	742	9.6	2.8
AT1	365722084252000	May 10, 2017	DRY	DRY	DRY	DRY	DRY	DRY
AM3	365744084251000	May 10, 2017	1.46	Good±5%	16.5	972	9.3	2.7
AT2	365746084251100	May 10, 2017	0.37	Fair±8%	16.8	38	9.2	5.3
AM4	365744084251100	May 10, 2017	0.88	Fair±8%	16.6	1,250	9.3	2.6
AM5	365809084253200	May 11, 2017	0.68	Fair±8%	15.6	1,370	9.3	2.6
AT3	365756084245700	May 11, 2017	0.39	Poor±10%	13.3	1,500	2.4	2.6
AM6	365756084245600	May 11, 2017	0.11	Fair±8%	15.0	297	6.2	3.2

Addison Branch reach 4 was gaining during both surveys (table 5). Site AT3 was a mine portal, an artifact from previous mining activity, and discharged groundwater directly to the surface and had 3 to 4 times more flow than the next upstream main stem site (site AM6; table 4).

The results of the synoptic surveys from June 2016 and May 2017 on various unnamed tributaries are listed in table 6. The unnamed tributaries were relatively small, so gains and losses were not computed. Site UT3 had the largest flows during both surveys and site UT4 had the lowest flows during both surveys. Sites UT3 and UT4 had the lowest specific conductance values (table 6).

Synoptic surveys were made November 2015 and May 2016 in the Rock Creek study area (table 7). The Rock Creek streamgage, located at site RM3, indicated streamflow was approximately steady during both surveys (fig. 7*A* and *B*). The streamflow during the May 2016 survey was about 3.5 times greater than the November 2015 survey at site RM1. It is beneficial to do synoptic surveys during different streamflow conditions, so groundwater and surface water interactions can be evaluated at different water-table depths.

Table 5. Results of streamflow gain and loss computations from synoptic surveys made June 2016 and May 2017 at Addison Branch, Daniel Boone National Forest, eastern Kentucky.

[ft^3/s, cubic foot per second; A, Addison Branch; M, main stem; T, tributary; --, not available; ±, plus or minus; Underlined values of reach gain or loss exceed the potential error associated with the streamflow measurements, and are considered verified]

Reach	Map identifier (fig. 1)	Downstream streamflow (ft^3/s)	Upstream streamflow (ft^3/s)	Inflow streamflow (ft^3/s)	Reach gain or loss (ft^3/s)	[1]Maximum error associated with streamflow measurement (ft^3/s)	Maximum error associated with reach streamflow (ft^3/s)
First survey (June 28–29, 2016)							
1	AM1	0.00	--	--	–0.46	±0.00	±0.04
1	AM2	--	0.46	--	--	±0.04	--
1	AT1	--	--	0.00	--	±0.00	--
2	AM2	0.46	--	--	0.03	±0.04	±0.07
2	AM3	--	0.43	--	--	±0.03	--
3	AM3	0.43	--	--	–0.02	±0.03	±0.07
3	AM5	--	0.32	--	--	±0.03	--
3	AT2	--	--	0.13	--	±0.01	--
4	AM5	0.32	--	--	0.12	±0.03	±0.05
4	AM6	--	0.04	--	--	±0.00	--
4	AT3	--	--	0.16	--	±0.02	--
Second survey (May 10–11, 2017)							
1	AM1	0.00	--	--	–1.81	±0.00	±0.14
1	AM2	--	1.81	--	--	±0.14	--
1	AT1	--	--	0.00	--	±0.00	--
2	AM2	1.81	--	--	0.35	±0.14	±0.21
2	AM3	--	1.46	--	--	±0.07	--
3	AM3	1.46	--	--	0.41	±0.07	±0.15
3	AM5	--	0.68	--	--	±0.05	--
3	AT2	--	--	0.37	--	±0.03	--
4	AM5	0.68	--	--	0.18	±0.05	±0.10
4	AM6	--	0.11	--	--	±0.01	--
4	AT3	--	--	0.39	--	±0.04	--

[1]The error associated with a streamflow measurement, in cubic feet per second, is the product of the measured streamflow and the qualitative rating error from table 4.

Table 6. Streamflow and discrete water-quality results from synoptic surveys made June 2016 and May 2017 at unnamed branches, Daniel Boone National Forest, eastern Kentucky.

[ft³/s, cubic foot per second; °C, degree Celsius; µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; U, unnamed; T, tributary; ±, plus or minus; %, percent; --, not available]

Map site identifier (refer to fig. 1)	U. S. Geological Survey station identifier	Date of synoptic survey	Streamflow (ft³/s)	Streamflow measurement rating	Water temperature (°C)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard units)
First survey								
UT1	365922084260000	June 8, 2016	0.05	Poor±10%	15.5	1,260	--	3.3
UT2	365920084260500	June 8, 2016	0.04	Poor±10%	18.5	880	--	3.6
UT3	365756084262300	June 7, 2016	0.16	Fair±8%	20.9	24	--	5.9
UT4	365740084253900	June 9, 2016	0.01	Poor±10%	19.1	20	8.8	6.7
Second survey								
UT1	365922084260000	May 9, 2017	0.02	Poor±10%	13.4	971	7.9	3.4
UT2	365920084260500	May 9, 2017	0.05	Fair±8%	15.2	825	9.2	3.7
UT3	365756084262300	May 11, 2017	0.10	Fair±8%	15.1	34	8.9	4.4
UT4	365740084253900	May 11, 2017	0.01	Poor±10%	15.6	19	9.0	4.8

Gaining and losing stream reaches were identified along White Oak Creek and lower Rock Creek (table 8; fig. 8). Eight reaches were verified as gaining or losing, with the gain or loss greater than the sum of streamflow measurement errors, during the November 2015 survey, but only four reaches were verified during May 2016. A substantial loss of flow was consistently observed in reach 8, where a limestone outcrop alongside the streambank allowed surface water to drain underground (table 8; fig. 9). It was not until after the confluence of Roberts Hollow (site RT7) and Rock Creek that a gaining reach was observed. The exact location where the stream resurfaced was not identified during the synoptic surveys.

Barton and Karathanasis (1999) renovated a constructed wetland on Jones Branch (site RT8) in 1990. The study objective was to treat AMD and they observed an increase in pH from 3.4 to 6.5 standard units during a 19-month study period. In the current study, site RT8 was dry in November 2015, but in May 2016 (when water was present), the pH was 7.5 standard units (table 7). Measurements for pH were not available for most sites during the first synoptic survey in November 2015 because the pH probe malfunctioned, but during the second synoptic survey in May 2016, pH values were above 6.5 standard units at 21 of 26 sites (81 percent; table 7). The pH values were generally more alkaline in the Rock Creek study area than in the Wildcat/Addison Branch study area, where pH was measured above 6.5 standard units at 2 of 26 sites (8 percent) during the first synoptic survey in June 2016 (tables 2, 4, and 6). The near-neutral values of pH measured in the Rock Creek study area indicated the previous remediation efforts at Rock Creek likely continued to mitigate the AMD.

There are numerous sites in the Rock Creek study area where a ferric hydroxide precipitate (also known as "yellow-boy") armored the natural or limestone-lined streambed (fig. 10). The armoring on the limestone rocks limits the neutralizing capacity of the rock. The formation of ferric hydroxide precipitate is pH dependent, forming if the pH is above about 3.5 standard units (Hem and Cropper, 1959).

The spatial distribution of specific conductance values at the Rock Creek study area can be seen in figure 11. A specific conductance benchmark for evaluating aquatic life has been developed for central Appalachian streams (EPA, 2011). The report established a chronic aquatic life benchmark of 300 µS/cm that applies to parts of West Virginia and Kentucky, which includes the study area. The synoptic survey made at Rock Creek in May 2016 is temporally close to the June 2016 survey made at Wildcat/Addison and serves as a comparison; twenty-three percent of the Rock Creek sites were above the 300 µS/cm benchmark, where 81 percent of the Wildcat/Addison sites were above the threshold.

Table 7. Streamflow and discrete water-quality results from synoptic surveys made November 2015 and May 2016 at Rock Creek study area, Daniel Boone National Forest, eastern Kentucky.

[ft³/s, cubic foot per second; °C, degree Celsius; µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; R, Rock Creek; M, main stem; ±, plus or minus; %, percent; --, not available; T, tributary; DRY, stream was at no flow]

Map identifier (fig. 1)	U.S. Geological Survey station identifier	Date	Streamflow (ft³/s)	Streamflow measurement rating	Water temperature (°C)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard units)
First survey								
RM1	364250084325400	November 5, 2015	14.6	Good±5%	15.4	162	9.2	--
RT1	364247084325400	November 5, 2015	0.01	Poor±10%	14.7	127	7.0	--
RM2	364244084330100	November 5, 2015	14.0	Good±5%	15.3	166	9.4	--
RT2	03410594	November 5, 2015	0.03	Fair±8%	14.2	59	9.5	--
RM3	03410590	November 5, 2015	14.5	Good±5%	15.8	166	9.6	--
RT3	03410585	November 5, 2015	0.17	Fair±8%	14.1	343	9.5	--
RM4	364227084340500	November 4, 2015	11.6	Good±5%	--	--	--	--
RT4	03410578	November 4, 2015	0.03	Poor±10%	--	--	--	--
RM5	364222084343500	November 4, 2015	14.0	Fair±8%	16.4	208	9.0	--
RT5	03410575	November 4, 2015	0.02	Poor±10%	18.6	3,440	7.3	--
RT6	364225084343300	November 5, 2015	0.81	Fair±8%	--	--	--	--
RM6	364238084334500	November 4, 2015	14.2	Good±5%	16.1	143	9.0	--
RT7	03410571	November 4, 2015	0.08	Fair±8%	17.5	976	8.2	--
RM7	364237084350100	November 4, 2015	0.58	Fair±8%	18.1	311	8.9	--
RM8	364210084354500	November 4, 2015	0.29	Fair±8%	17.5	174	8.0	7.6
RM9	03410559	November 4, 2015	12.6	Good±5%	16.2	116	9.3	7.2
RM10	03410557	November 4, 2015	0.64	Fair±8%	16.5	287	9.5	7.
RT8	03410555	November 4, 2015	DRY	DRY	DRY	DRY	DRY	DRY
RM11	364143084360800	November 4, 2015	1.02	Poor±10%	15.2	287	9.2	7.1
RT9	364138084360400	November 4, 2015	0.06	Poor±10%	14.3	110	9.1	7.3
RT10	364135084363200	November 4, 2015	0.07	Fair±8%	15.2	477	8.1	6.9
RT11	03410547	November 4, 2015	0.26	Good±5%	14.8	582	9.9	6.8
RM12	364134084365400	November 4, 2015	0.73	Good±5%	15.0	148	9.1	8.2
RT12	364134084365500	November 4, 2015	0.04	Poor±10%	14.9	359	9.0	8.0
RM13	364126084372300	November 3, 2015	0.56	Fair±8%	15.4	--	--	7.0
RT13	03410542	November 3, 2015	0.10	Fair±8%	17	435	8.4	--
RM14	364125084372400	November 3, 2015	0.67	Fair±8%	16.6	75	8.1	6.6
Second survey								
RM1	364250084325400	May 18, 2016	50.6	Good±5%	14.3	127	9.1	7.4
RT1	364247084325400	May 18, 2016	50.6	Good±5%	14.3	127	9.1	7.4
RM2	364244084330100	May 18, 2016	50.6	Good±5%	14.3	127	9.1	7.4
RT2	03410594	May 18, 2016	1.31	Fair±8%	12.8	42	9.7	8.5
RM3	03410590	May 18, 2016	42.2	Good±5%	14.4	133	8.8	7.3
RT3	03410585	May 18, 2016	1.62	Poor±10%	12.7	115	9.4	7.0
RM4	364227084340500	May 19, 2016	39.1	Fair±8%	14.9	124	9.2	7.3
RT4	03410578	May 19, 2016	22	Poor±10%	13.5	449	9.3	3.5
RM5	364222084343500	May 18, 2016	40.6	Fair±8%	14.5	216	8.8	6.8
RT5	03410575	May 18, 2016	0.23	Poor±10%	15.8	1,150	8.7	3.7

Table 7. Streamflow and discrete water-quality results from synoptic surveys made November 2015 and May 2016 at Rock Creek study area, Daniel Boone National Forest, eastern Kentucky.—Continued

[ft³/s, cubic foot per second; °C, degree Celsius; µS/cm, microsiemen per centimeter at 25 °C; mg/L, milligram per liter; R, Rock Creek; M, main stem; ±, plus or minus; %, percent; --, not available; T, tributary; DRY, stream was at no flow]

Map identifier (fig. 1)	U.S. Geological Survey station identifier	Date	Streamflow (ft³/s)	Streamflow measurement rating	Water temperature (°C)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	pH (standard units)
Second survey—continued								
RT6	364225084343300	May 19, 2016	0.75	Poor±10%	14.9	3,140	3.3	5.4
RM6	364238084334500	May 19, 2016	37.2	Good±5%	14.1	107	9.0	7.7
RT7	03410571	May 19, 2016	0.64	Fair±8%	15.0	420	9.0	7.0
RM7	364237084350100	May 19, 2016	3.63	Good±5%	13.3	202	9.9	7.2
RM8	364210084354500	May 19, 2016	0.28	Poor±10%	12.9	201	10.0	7.2
RM9	03410559	May 19, 2016	29.2	Good±5%	13.6	86	9.2	7.6
RM10	03410557	May 19, 2016	4.21	Good±5%	11.9	189	10.0	6.9
RT8	03410555	May 19, 2016	0.86	Fair±8%	12.2	242	9.7	7.5
RM11	364143084360800	May 19, 2016	4.28	Good±5%	--	--	--	--
RT9	364138084360400	May 19, 2016	0.39	Fair±8%	11.1	96	9.4	7.1
RT10	364135084363200	May 19, 2016	0.48	Poor±10%	12.8	357	8.5	7.5
RT11	03410547	May 19, 2016	0.40	Fair±8%	12.6	459	9.6	6.6
RM12	364134084365400	May 18, 2016	3.15	Good±5%	13.1	95	9.4	6.5
RT12	364134084365500	May 18, 2016	0.32	Fair±8%	12.8	162	9.1	7.5
RM13	364126084372300	May 18, 2016	3.15	Fair±8%	13.0	101	9.0	7.1
RT13	03410542	May 18, 2016	1.04	Fair±8%	12.8	172	9.0	6.4
RM14	364125084372400	May 18, 2016	2.12	Fair±8%	--	58	9.0	7.6

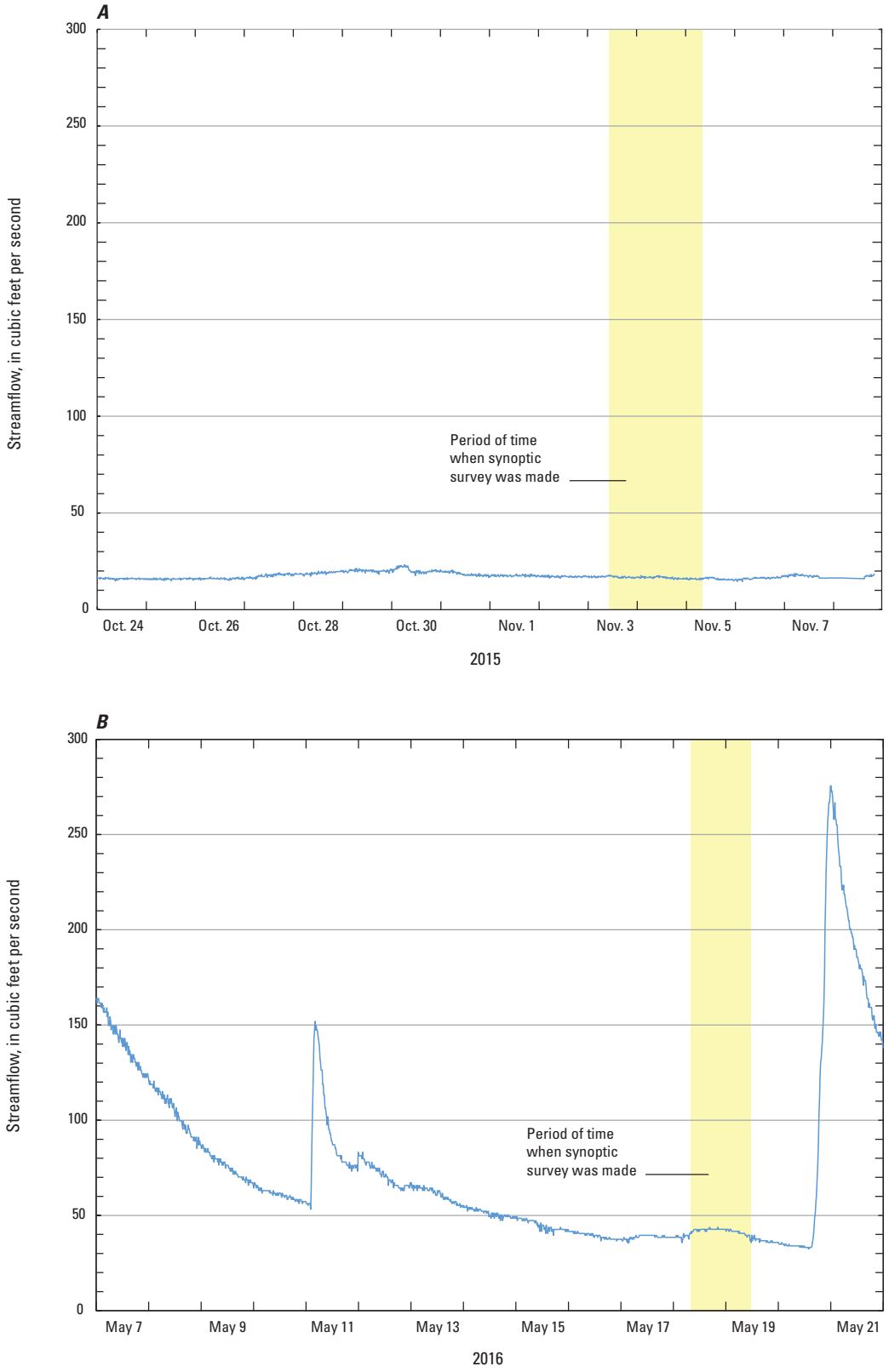


Figure 7. Instantaneous streamflow (15-minute) at the U.S. Geological Survey streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590). *A*, Survey 1, October 24–November 9, 2015. *B*, Survey 2, May 7–22, 2016.

Table 8. Results of the streamflow gain and loss computations from synoptic surveys made November 2015 and May 2016 at Rock Creek, Daniel Boone National Forest, eastern Kentucky.

[ft³/s, cubic foot per second; R, Rock Creek; M, main stem; --, not available; T, tributary; ±, plus or minus; Underlined values of reach gain or loss exceed the potential error associated with the streamflow measurements, and are considered verified]

Stream reach	Map identifier (fig. 1)	Downstream streamflow (ft³/s)	Upstream streamflow (ft³/s)	Inflow streamflow (ft³/s)	Reach gain or loss (ft³/s)	[1]Maximum error associated with streamflow measurement (ft³/s)	Maximum error associated with reach streamflow (ft³/s)
First survey (November 3–5, 2015)							
1	RM1	14.6	--	--	0.59	±0.73	±1.43
1	RM2	--	14.0	--	--	±0.70	--
1	RT1	--	--	0.01	--	±0.00	--
2	RM2	14.0	--	--	–0.53	±0.70	±1.42
2	RM3	--	14.5	--	--	±0.72	--
2	RT2	--	--	0.03	--	±0.00	--
3	RM3	14.5	--	--	2.73	±0.72	±1.31
3	RM4	--	11.6	--	--	±0.58	--
3	RT3	--	--	0.17	--	±0.01	--
4	RM4	11.6	--	--	–2.43	±0.58	±1.70
4	RM5	--	14.0	--	--	±1.12	--
4	RT4	--	--	0.03	--	±0.00	--
5	RM5	14.0	--	--	–1.03	±1.12	±1.89
5	RM6	--	14.2	--	--	±0.71	--
5	RT5	--	--	0.02	--	±0.00	--
5	RT6	--	--	0.81	--	±0.06	--
6	RM6	14.2	--	--	13.5	±0.71	±0.77
6	RM7	--	0.58	--	--	±0.05	--
6	RT7	--	--	0.08	--	±0.01	--
7	RM7	0.58	--	--	–0.35	±0.05	±0.12
7	RM10	--	0.64	--	--	±0.05	--
7	RM8	--	--	0.29	--	±0.02	--
8	RM8	0.29	--	--	–12.3	±0.02	±0.65
8	RM9	--	12.6	--	--	±0.63	
9	RM10	0.64	--	--	–0.38	±0.05	±0.15
9	RM11	--	1.02	--	--	±0.10	--
9	RT8	--	--	0.00	--	±0.00	--
10	RM11	1.02	--	--	–0.10	±0.10	±0.17
10	RM12	--	0.73	--	--	±0.04	--
10	RT9	--	--	0.06	--	±0.01	--
10	RT10	--	--	0.07	--	±0.01	--
10	RT11	--	--	0.26	--	±0.01	--
11	RM12	0.73	--	--	0.13	±0.04	±0.08
11	RM13	--	0.56	--	--	±0.04	--
11	RT12	--	--	0.04	--	±0.00	--
12	RM13	0.56	--	--	–0.21	±0.04	±0.10
12	RM14	--	0.67	--	--	±0.05	--
12	RT13	--	--	0.10	--	±0.01	--

Table 8. Results of the streamflow gain and loss computations from synoptic surveys made November 2015 and May 2016 at Rock Creek, Daniel Boone National Forest, eastern Kentucky.—Continued

[ft³/s, cubic foot per second; R, Rock Creek; M, main stem; --, not available; T, tributary; ±, plus or minus; Underlined values of reach gain or loss exceed the potential error associated with the streamflow measurements, and are considered verified]

Stream reach	Map identifier (fig. 1)	Downstream streamflow (ft³/s)	Upstream streamflow (ft³/s)	Inflow streamflow (ft³/s)	Reach gain or loss (ft³/s)	[1]Maximum error associated with streamflow measurement (ft³/s)	Maximum error associated with reach streamflow (ft³/s)
Second survey (May 18–19, 2016)							
1	RM1	50.6	--	--	4.63	±2.53	±6.21
1	RM2	--	44.4	--	--	±3.55	--
1	RT1	--	--	1.57	--	±0.13	--
2	RM2	44.4	--	--	0.89	±3.55	±5.76
2	RM3	--	42.2	--	--	±2.11	--
2	RT2	--	--	1.31	--	±0.10	--
3	RM3	42.2	--	--	1.48	±2.11	±5.40
3	RM4	--	39.1	--	--	±3.13	--
3	RT3	--	--	1.62	--	±0.16	--
4	RM4	39.1	--	--	–1.72	±3.13	±6.40
4	RM5	--	40.6	--	--	±3.25	--
4	RT4	--	--	0.22	--	±0.02	--
5	RM5	40.6	--	--	2.42	±3.25	±5.21
5	RM6	--	37.2	--	--	±1.86	--
5	RT5	--	--	0.23	--	±0.02	--
5	RT6	--	--	0.75	--	±0.08	--
6	RM6	37.2	--	--	32.9	±1.86	±2.09
6	RM7	--	3.63	--	--	±0.18	--
6	RT7	--	--	0.64	--	±0.05	--
7	RM7	3.63	--	--	–0.86	±0.18	±0.42
7	RM10	--	4.21	--	--	±0.21	--
7	RM8	--	--	0.28	--	±0.03	--
8	RM8	0.28	--	--	–28.9	±0.03	±1.49
8	RM9	--	29.2	--	--	±1.46	
9	RM10	4.21	--	--	–0.93	±0.21	±0.49
9	RM11	--	4.28	--	--	±0.21	--
9	RT8	--	--	0.86	--	±0.07	--
10	RM11	4.28	--	--	–0.14	±0.21	±0.48
10	RM12	--	3.15	--	--	±0.16	--
10	RT9	--	--	0.39	--	±0.03	--
10	RT10	--	--	0.48	--	±0.05	--
10	RT11	--	--	0.40	--	±0.03	--
11	RM12	3.15	--	--	–0.32	±0.16	±0.44
11	RM13	--	3.15	--	--	±0.25	--
11	RT12	--	--	0.32	--	±0.03	--
12	RM13	3.15	--	--	–0.01	±0.25	±0.50
12	RM14	--	2.12	--	--	±0.17	--
12	RT13	--	--	1.04	--	±0.08	--

[1]The error associated with a streamflow measurement, in cubic feet per second, is the product of the measured streamflow and the qualitative rating error from table 7.

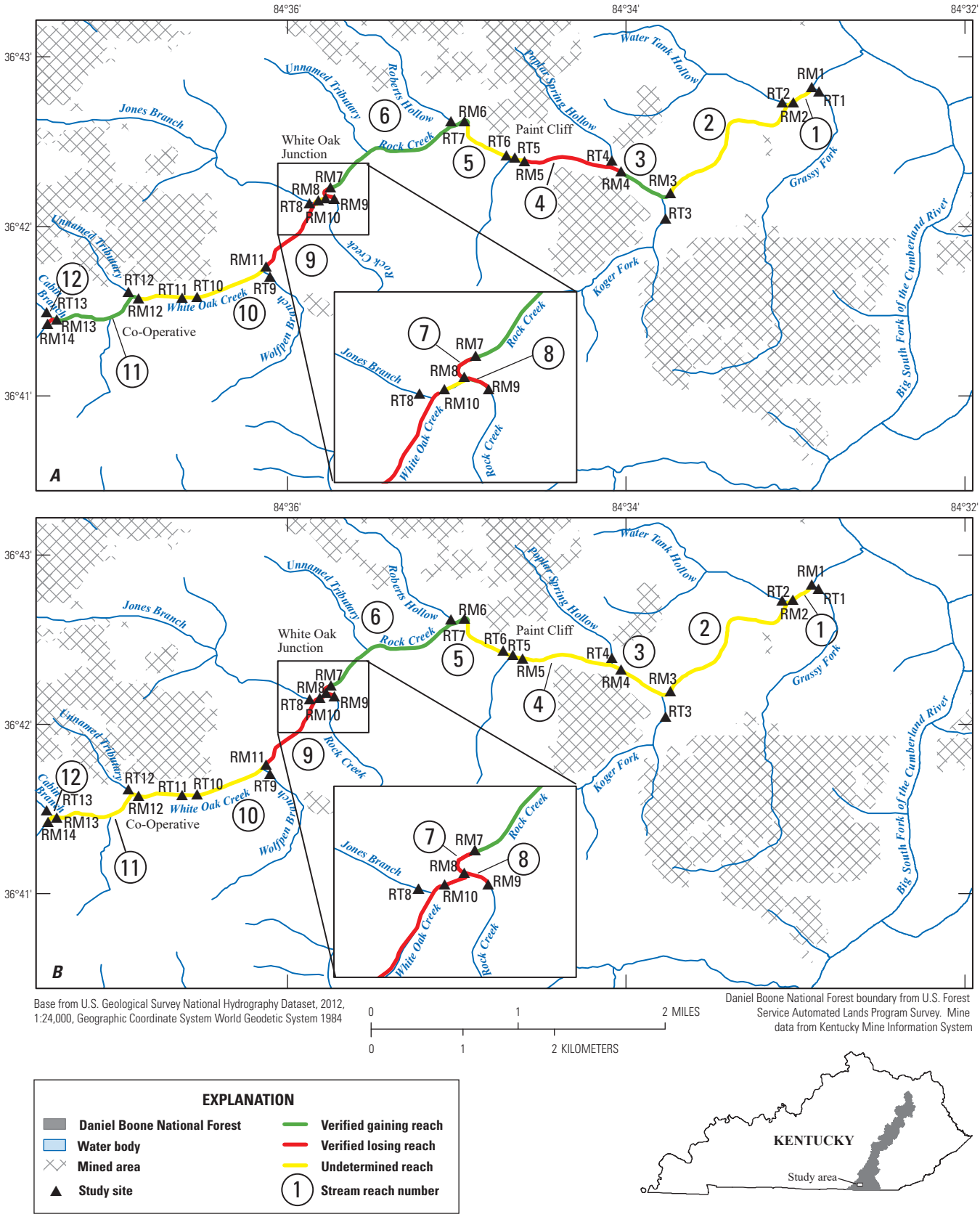
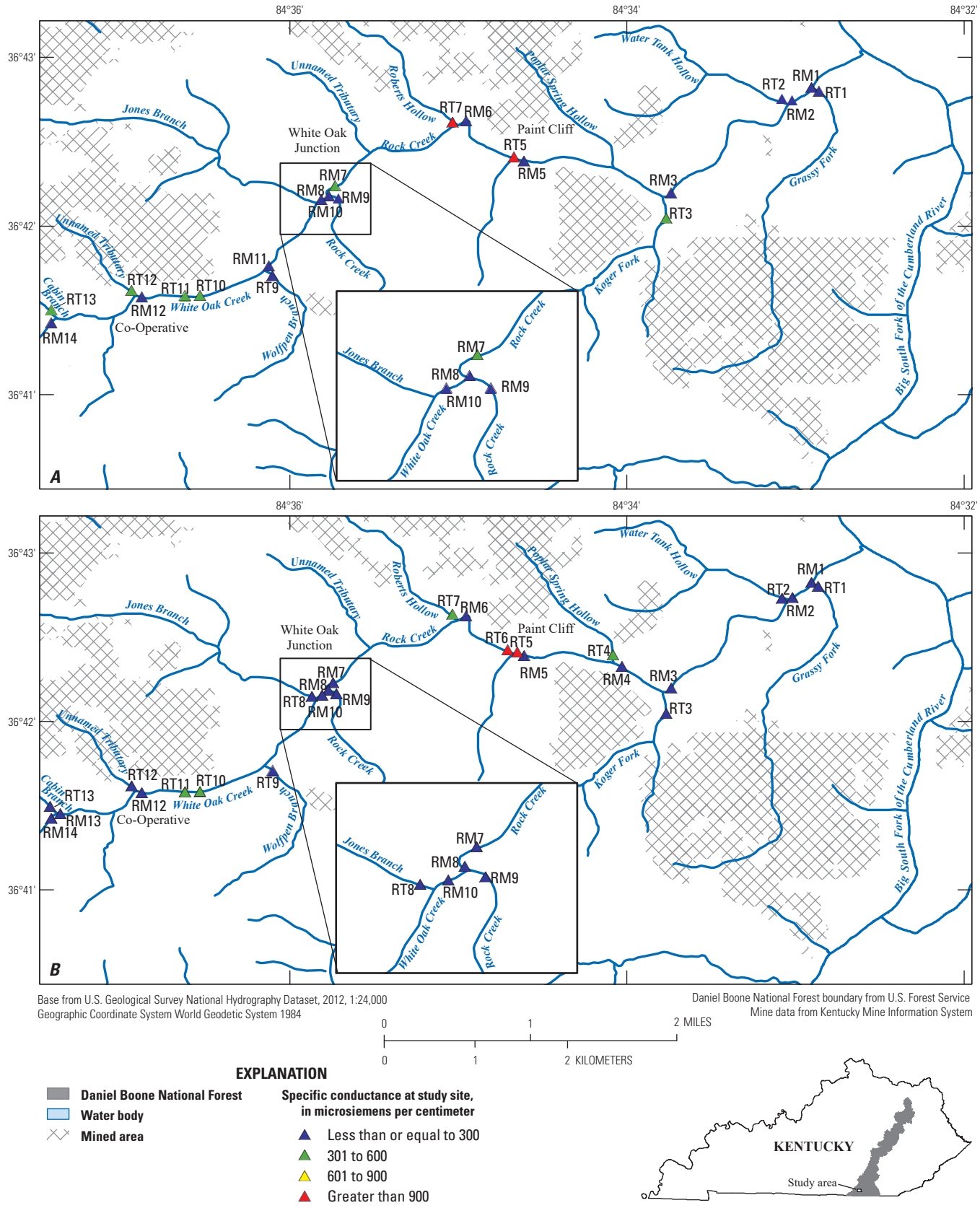


Figure 8. Gaining, losing, and undetermined stream reaches in the Rock Creek study area in Daniel Boone National Forest, eastern Kentucky. *A*, November 2015. *B*, May 2016. Undetermined reaches have the sum of errors associated with the streamflow measurements greater than the gain or loss value.

Figure 9. Picture of a cave between site RM8 and RM9 that caused the streamflow to go subsurface, reach 8, Rock Creek study area, Daniel Boone National Forest, eastern Kentucky.

Figure 10. Pictures of ferric hydroxide precipitant or "yellow boy" in the Rock Creek study area. *A*, Site RT4. *B*, Site RT6. *C*, Site RT8.



Base from U.S. Geological Survey National Hydrography Dataset, 2012, 1:24,000
Geographic Coordinate System World Geodetic System 1984

Daniel Boone National Forest boundary from U.S. Forest Service
Mine data from Kentucky Mine Information System

0 1 2 MILES

0 1 2 KILOMETERS

EXPLANATION

- Daniel Boone National Forest
- Water body
- Mined area

Specific conductance at study site, in microsiemens per centimeter

- Less than or equal to 300
- 301 to 600
- 601 to 900
- Greater than 900

Figure 11. Specific conductance at study sites in the Rock Creek study area in Daniel Boone National Forest, eastern Kentucky. *A*, November 2015. *B*, May 2016.

Hydrograph Separation

Six hydrograph separation methods were applied to daily mean streamflows from the Rock Creek streamgage (site RM3) for the period August 2015 to August 2017. Only partial streamflow record was available for the months of August 2015 and August 2017. Monthly mean streamflow for the period September 2015 through July 2017 ranged from 7.2 ft^3/s for October 2016 to 328 ft^3/s for February 2016 (table 9). On average, base flow accounted for more total streamflow than surface runoff during the study period, irrespective of method used for hydrograph separation.

Barlow and others (2015), caution against using the GW Toolbox where groundwater recharge is not uniformly distributed over the entire basin, which can be caused by losing reaches and where all groundwater recharge, except what is lost to evapotranspiration, does not discharge to the receiving stream. A major losing reach was identified upstream of the Rock Creek streamgage at reach 8 (fig. 8, table 8), so groundwater recharge was not uniformly distributed over the entire basin and may not entirely discharge to the receiving stream (Rock Creek). These shortcomings prevent the extrapolation of the hydrograph separation results from Rock Creek reach 3, to the entire upstream basin.

Summary statistics for base-flow index values calculated from six different methods are shown in table 10. The summary statistics were computed only for months with complete streamflow record. The mean base-flow index ranged from 0.681 using the PART method to 0.565 using the BFI Modified method. Barlow and others (2015) presented a 30-year dataset from a USGS streamgage on the Pawcatuck River at Wood River Junction, Rhode Island (station number 01117500) and determined the PART method generated the highest base-flow index and both BFI methods generated the lowest base-flow index. The methods that generated the highest and lowest base-flow indices from Barlow and others (2015) agree with the current study, but do not represent what the methods will yield from all streamgages.

Flow-duration curves were plotted so that results from hydrograph separation methods could be compared between each other (fig. 12). The flow duration curves were developed from daily mean streamflows, base flows, and runoff estimates and included partial-month record. The curves indicate the duration characteristics of estimated daily base flow and runoff made with the different separation methods are not highly different. Greater differences were observed between methods in base-flow duration characteristics at lower percent exceedance levels and greater differences in runoff duration characteristics at higher percent exceedance levels.

Continuous Water Quality

Summary statistics of continuous record for water temperature, pH, specific conductance, DO, and turbidity values measured July 15, 2016 through July 31, 2017 are presented in table 11. The water-quality information collected during the synoptic surveys provided a widespread view of the conditions across the study area, but the continuous data provided a detailed perspective of the water quality at a single location. Water quality results from discrete measurements made during the synoptic surveys were similar between site RM3 and the outlet of the study area (site RM1; table 7) during these low-flow conditions.

The continuous water-quality results were used to evaluate the presence of AMD at the outlet of the Rock Creek study area. Water samples were not collected during this study, but the pH values were near neutral at the Rock Creek streamgage (fig. 13). Barton and Karathanasis (1999) showed that by raising the pH to near-neutral values at site RT8, sulfate concentrations decreased by 56 percent, aluminum concentrations decreased by 98 percent, and iron concentrations decreased by 95 percent. The previous remediation efforts are likely continuing to improve the effect of AMD in the study area. The continuous specific conductance values ranged between 30 and 259 µS/cm (table 11). The range of specific conductance values were below the specific conductance aquatic life benchmark of 300 µS/cm (EPA, 2011). The minimum continuous DO during the study period was 7.5 mg/L (table 11). There was an inverse relationship between DO and pH values, and the diurnal fluctuations observed in both parameters was likely from biological activity (fig. 13).

Specific conductance is affected by AMD, even in areas where dilution occurs, so it is considered a good indicator for AMD (Gray, 1995). There is a general inverse relationship between streamflow and specific conductance (fig. 14). It is expected for specific conductance of streamflow to decrease during precipitation events because precipitation typically has relatively low specific conductance and the storm runoff dilutes the water in the stream. (fig. 14). A decrease in specific conductance was observed during storm events, but directly before the drop, there was a sharp spike (fig. 14). This response has been observed in karst areas and attributed to carbonate-rich water stored in the epikarst that was forced to the stream by storm-generated hydraulic head and then dropped to pre-storm levels from diluted storm water (Toran and others, 2006).

Table 9. Monthly mean streamflow at the U.S. Geological Survey streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590) for the period September 2015 through July 2017, with monthly base flows and base-flow indices calculated with six different hydrograph separation methods.

[ft³/s, cubic foot per second; PART, a computer program that partions streamflow to estimate base flow (Rutledge, 1998); HYSEP, a computer program that includes three methods to separate a streamflow hydrograph into components of base flow and surface runoff (Sloto and Crouse, 1996); BFI, a computer program that implements the procedures for base-flow separation that were established by the Institute of Hydrology (Wahl and Wahl, 1995); NA, not applicable]

Month	Number of days per month	Monthly mean streamflow (ft³/s)	PART base flow (ft³/s)	PART base-flow index	HYSEP fixed interval base flow (ft³/s)	HYSEP fixed interval base-flow index	HYSEP local minium base flow (ft³/s)	HYSEP local minium base-flow index	HYSEP sliding interval base flow (ft³/s)	HYSEP sliding interval base-flow index	BFI standard base flow (ft³/s)	BFI standard base-flow index	BFI modified base flow (ft³/s)	BFI modified base-flow index
Sep. 2015	30	23.3	21.1	0.905	19.4	0.833	17.5	0.753	19.1	0.820	18.8	0.808	18.4	0.791
Oct. 2015	31	27.9	21.1	0.757	23.3	0.838	19.8	0.711	21.6	0.774	20.1	0.720	19.9	0.714
Nov. 2015	30	40.6	20.1	0.494	25.6	0.629	16.3	0.401	17.9	0.440	16.8	0.412	16.7	0.410
Dec. 2015	31	226	95.9	0.424	120	0.531	59.2	0.262	105	0.464	92.0	0.407	59.2	0.262
Jan. 2016	31	116	94.1	0.814	80.4	0.696	80.8	0.699	84.1	0.728	90.1	0.779	80.7	0.698
Feb. 2016	29	328	174	0.532	154	0.468	129	0.394	165	0.504	139.0	0.424	129.1	0.394
Mar. 2016	31	91.4	85.0	0.931	78.0	0.854	74.8	0.819	76.9	0.841	76.6	0.839	74.7	0.818
Apr. 2016	30	58.7	53.9	0.919	50.6	0.861	47.8	0.815	49.7	0.847	52.4	0.892	47.8	0.815
May 2016	31	126	64.5	0.511	59.7	0.473	46.1	0.365	61.2	0.484	45.7	0.361	42.6	0.337
June 2016	30	35.5	25.1	0.707	22.1	0.622	20.4	0.574	23.1	0.650	22.5	0.634	21.5	0.606
July 2016	31	46.9	18.7	0.398	18.1	0.386	17.2	0.367	20.0	0.426	17.4	0.372	17.0	0.363
Aug. 2016	31	18.8	16.1	0.857	15.0	0.798	14.5	0.775	15.0	0.799	15.1	0.802	14.4	0.769
Sep. 2016	30	9.0	8.2	0.916	7.6	0.843	7.59	0.848	7.6	0.846	7.8	0.865	7.6	0.845
Oct. 2016	31	7.2	6.6	0.905	6.3	0.867	6.3	0.876	6.4	0.882	6.6	0.913	6.4	0.883
Nov. 2016	30	14.3	11.2	0.784	11.3	0.790	11.2	0.783	11.1	0.777	11.5	0.803	11.4	0.793
Dec. 2016	31	132	32.6	0.246	40.7	0.308	28.3	0.214	45.3	0.342	28.5	0.215	28.3	0.214
Jan. 2017	31	116	81.7	0.704	80.1	0.691	80.3	0.693	76.2	0.657	78.1	0.674	80.3	0.693
Feb. 2017	28	62.3	53.3	0.856	45.7	0.733	47.9	0.769	47.0	0.755	47.8	0.766	47.7	0.765
Mar. 2017	31	173	102	0.591	95.2	0.551	85.4	0.495	95.7	0.554	86.9	0.503	85.9	0.498
Apr. 2017	30	161	66.8	0.416	79.0	0.492	56.0	0.349	71.4	0.444	56.4	0.351	56.0	0.349
May 2017	31	154	71.5	0.463	67.7	0.439	68.2	0.442	71.8	0.465	68.2	0.442	68.2	0.442
June 2017	30	59.8	38.8	0.649	35.8	0.599	35.3	0.590	36.1	0.604	35.5	0.593	34.5	0.577
July 2017	31	13.3	12.0	0.900	11.5	0.862	11.3	0.848	11.7	0.877	NA	NA	NA	NA
Mean	NA	88.6	50.9	0.681	49.8	0.659	42.6	0.601	49.4	0.651	44.8	0.589	42.0	0.565

Table 10. Base-flow index summary statistics for the U.S. Geological Survey streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590) for the period September 2015 through July 2017.

[PART, a computer program that partions streamflow to estimate base flow (Rutledge, 1998); HYSEP, a computer program that includes three methods to separate a streamflow hydrograph into components of base flow and surface runoff (Sloto and Crouse, 1996); BFI, a computer program that implements the procedures for base-flow separation that were established by the Institute of Hydrology (Wahl and Wahl, 1995)]

	PART	HYSEP fixed interval	HYSEP local minimum	HYSEP sliding interval	BFI standard	BFI modifed
Mean	0.681	0.659	0.601	0.651	0.589	0.565
Maximum	0.931	0.867	0.876	0.882	0.913	0.883
Minimum	0.246	0.308	0.214	0.342	0.215	0.214
Spread	0.684	0.559	0.662	0.54	0.698	0.669

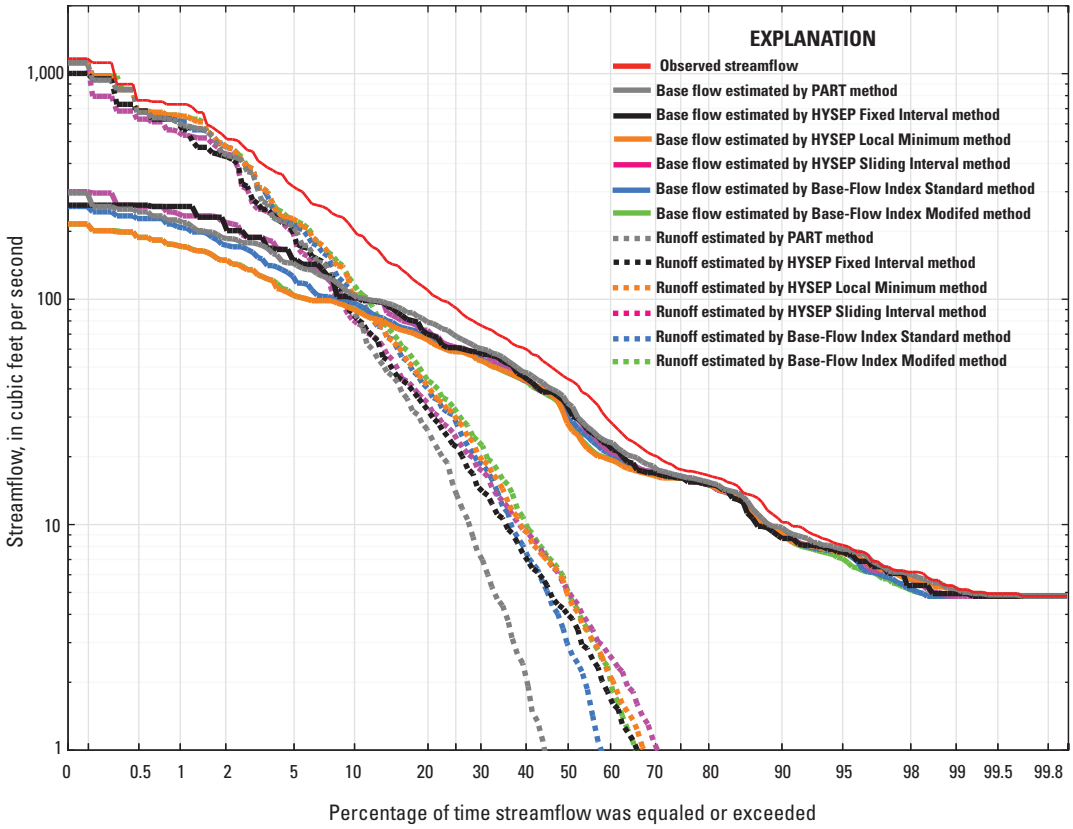


Figure 12. Flow duration curves for observed streamflow, and base flow and surface runoff calculated with six hydrograph separation methods for the U.S. Geological Survey streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590) for the period August 2015 to August 2017.

Table 11. Summary statistics for continuous water-quality parameters recorded at the U.S. Geological Survey streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590) for the period July 15, 2016 to July 31, 2017.

[°C, degree Celsius; µS/cm, micosiemen per centimeter; mg/L, milligram per liter; FNU, formazine nephelometric unit]

Statistic	Water temperature (°C)	pH (standard units)	Specific conductance (µS/cm)	Dissolved oxygen (mg/L)	Turbidity (FNU)
Maximum	27.6	7.9	259	14.1	1,060
75th percentile	21.8	7.6	183	11.0	5
Median	16	7.4	119	9.3	3
25th percentile	9.1	7.3	81	8.5	2
Minimum	0.5	6.8	30	7.5	0
Mean	15.4	7.4	132	9.7	5

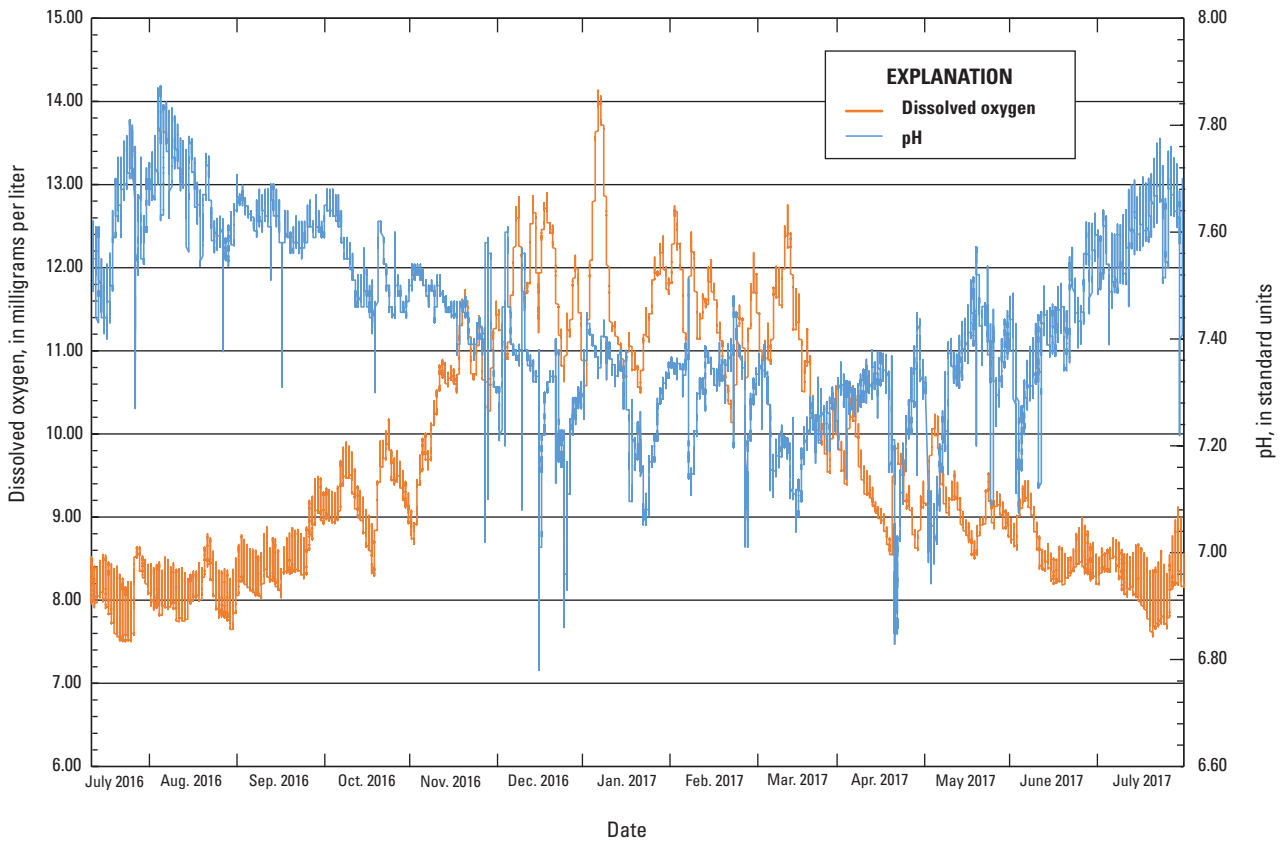


Figure 13. Continuous dissolved oxygen and pH at the U.S. Geological Survey streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590), from July 15, 2016 to July 31, 2017.

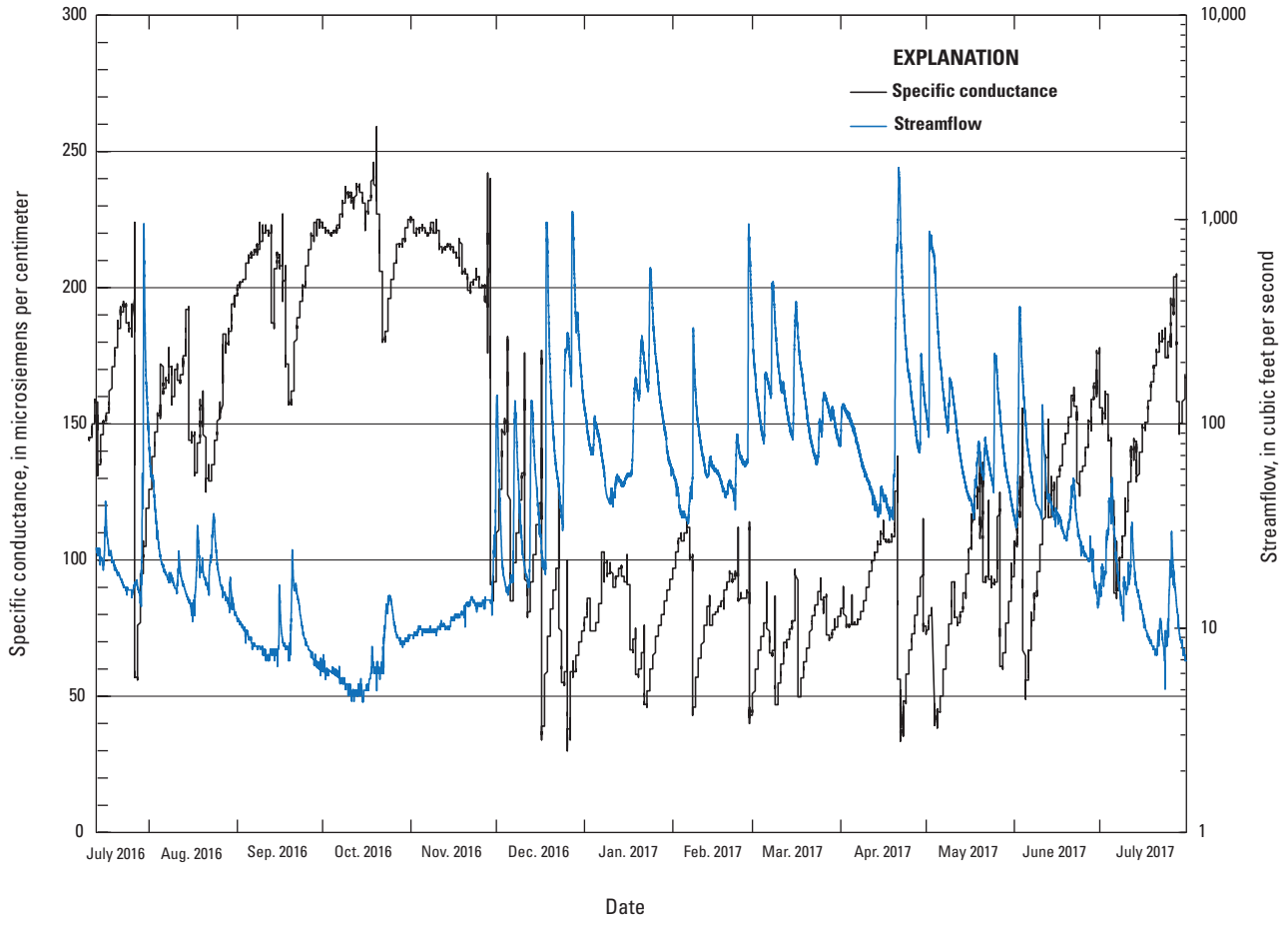


Figure 14. Specific conductance and streamflow at the U.S. Geological Survey streamgage on Rock Creek near Yamacraw, Kentucky (station number 03410590), from July 15, 2016 to July 31, 2017.

A substantial part of the streamflow in Rock Creek goes underground in reach 8 and resurfaces downstream in reach 6 (table 8). The maximum specific conductance for the 12-month period at the Rock Creek streamgage was 259 µS/cm (table 11). Because the pH is near neutral at the Rock Creek streamgage, much of the aluminum and iron are likely precipitating out and not being carried downstream in the dissolved form. Anecdotal evidence of metal mineral precipitation was observed as iron staining at several sites in the Rock Creek study area (fig. 10). Based on the 300 µS/cm benchmark, the specific conductance results indicated the effect of AMD at the Rock Creek streamgage was minimal.

Summary

During 2015–17, the U.S. Geological Survey, in cooperation with the U.S. Department of Agriculture Forest Service, carried out a study to characterize the hydrology and water chemistry in the Rock Creek and Wildcat and Addison Branches of the Daniel Boone National Forest. The Rock Creek and Wildcat/Addison Branch study areas contain abandoned mine lands. Mines began operating in both areas in the early to mid-1900s and used a combination of surface and underground mining practices to extract the coal. Many of the mining operations took place prior to the Surface Mining Control and Reclamation Act of 1977, which regulated coal mines but also aimed to reclaim abandoned mine lands. As a consequence of mining, coal waste piles accumulated throughout the study areas, and many of the underground mines were inadequately reclaimed, leaving open and collapsed underground mine portals.

Streamflow measurements and field measurements of water-quality properties were made during two synoptic surveys in both study areas. Additionally, continuous water-quality and streamflow data were collected at the Rock Creek near Yamacraw, Kentucky (station number 03410590; herein referred to as Rock Creek streamgage, and continuous streamflow data were used for hydrograph separation analyses. Not all sites measured during the synoptic surveys were used to compute gains and losses, some were instead used to determine the relative contributions of tributaries. Sites were established on Rock Creek, Wildcat Branch, Addison Branch, their major tributaries, and three unnamed tributaries. Sites were typically established on major tributaries and on the main stem downstream of the tributaries.

The study results indicated the water quality in the Rock Creek study area was generally better than the Wildcat/Addison Branch study area. Wildcat and Addison Branches both contained seeps (sites WT6 and AT3) that were included in the synoptic surveys. Sites WT6 and AT3 that had the highest specific conductance and lowest pH values in the Wildcat Branch and Addison Branch study areas, respectively. Site WT6 was a seep that fed Wildcat Branch. Site AT3 is an entrance to a mine portal that discharges groundwater directly to Addison Branch. Most of the Addison Branch sites had pH values at or below 3.0 standard units, except for site AT2. Site AT2 drained an area of the Addison Branch basin that had relatively good water quality during the study.

Reach 1 of Wildcat and Addison Branches was losing during both surveys. The stream was dry at sites WM1 and AM1 during both surveys, and both were the last site on their respective branches before the confluence with the Cumberland River. The Kidder Limestone Member underlies both reaches, so the karst topography likely directed all the streamflow subsurface somewhere along the reach.

Six hydrograph separation methods were applied to daily mean streamflow from the Rock Creek streamgage for the period August 2015 to August 2017. The six methods were chosen because they were all included in the U.S. Geological Survey Groundwater Toolbox. The PART and ase-flow index modified methods produced the highest and lowest mean base-flow index values, respectively. The curves indicate the duration characteristics of estimated daily base flow and runoff made with the different separation methods are not highly different. Each of the hydrograph separation methods are limited by losing stream reaches, so the losing stream reaches on Rock Creek prevented extrapolating the results computed at site RM3 to the entire upstream basin.

Continuous water temperature, pH, dissolved oxygen, specific conductance, and turbidity values were measured from July 2016 through July 2017. The near-neutral pH values measured at the Rock Creek streamgage likely caused much of the aluminum and iron to precipitate out, causing them not to be carried downstream in the dissolved form. The specific conductance results indicated the effect of acid mine drainage at the streamgaging station was minimal, taking into consideration the upstream contributions of acid mine drainage.

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