Effects of Culvert Construction on Streams and Macroinvertebrate Communities at Selected Sites in the East Gulf Coastal Plain of Alabama, 2010–19

Scientific Investigations Report 2021–5096

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

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By Aaron L. Pugh and Amy C. Gill

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
Length		
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.4047	square hectometer (hm^2)
acre	0.004047	square kilometer (km^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
Volume		
ounce, fluid (fl. oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
Flow rate		
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
Hydraulic gradient		
foot per mile (ft/mi)	0.3048	meter per day (m/d)

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)
kilometer (km)	0.5400	mile, nautical (nmi)
meter (m)	1.094	yard (yd)
Area		
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
Volume		
liter (L)	0.2642	gallon (gal)
Flow rate		
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

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

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as °C = (°F − 32) / 1.8.

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27).

Elevation, 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 constituents in water are given in milligrams per liter (mg/L).

Turbidity is the measure of relative clarity of a liquid and is measured in Nephelometric Turbidity Ratio Units (NTRU).

Abbreviations

ADEM   Alabama Department of Environmental Management

ALDOT   Alabama Department of Transportation

EPA   U.S. Environmental Protection Agency

EPT   Ephemeroptera, Plecoptera, and Trichoptera

IDAS   Invertebrate Data Analysis System

NAWQA   National Water-Quality Assessment

NWQL   National Water Quality Laboratory

MA   mega-annum (1 million years)

TV   tolerance value

USGS   U.S. Geological Survey

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Abstract

The U.S. Geological Survey, in cooperation with the Alabama Department of Transportation, evaluated the role of culvert construction in altering streams and habitats of benthic macroinvertebrate communities at selected study sites in the northern East Gulf Coastal Plain of Alabama during 2011–19. Analysis included examinations of changes in stream channel geometry, suspended sediment, turbidity, and benthic macroinvertebrate communities.

Topographic surveys of stream channel cross sections, upstream and downstream of the culvert, were conducted before and after construction. Changes in channel geometry (cross-sectional area, top width, mean depth, and thalweg slope) were assessed by using paired sample t-tests to compare before- and after-construction channel geometry measurements. Statistically significant changes in stream channel geometry between the before- and after-construction measurements were observed at four of the six study sites. Analysis of the channel geometry data indicates that 1 site had no measured changes, and thalweg reach slopes were inverted at 4 of the 12 study reaches—2 measured in before-construction reaches and 2 measured in after-construction reaches.

Surface-water samples were collected during selected storm events for suspended sediment and turbidity analyses. Samples were simultaneously collected upstream and downstream of the culvert construction reaches during all three phases of construction (before, during, and after). Analysis focused on the parity of upstream to downstream simultaneous samples. The mean upstream to downstream paired ratios of sediment concentrations and turbidity from the after-construction phase indicate that colloidal and noncolloidal sediments were passing through the construction reaches at two of the six sites, noncolloidal sediments were being trapped in the construction reaches at two sites, and colloidal and non-colloidal sediments were being removed from the construction reach at two sites.

Benthic macroinvertebrates were collected and identified at five of the six sites from instream habitats that were available in sampled areas both upstream and downstream of the culvert construction reaches. Differences between upstream and downstream reaches and the Wilcoxon rank sum statistic were used to examine changes in metrics of benthic macroinvertebrate communities between before- and after-construction phases. Benthic macroinvertebrate sampling results did not indicate that culvert construction caused impairment to communities at study sites. No tolerance metrics suggested a major change in the pollution tolerance of the communities. The same upstream to downstream patterns in abundance-weighted tolerance values were observed in the before- and after-construction periods at each site. At one site, the difference between upstream and downstream richness-based tolerance values increased, but the after-construction upstream and downstream richness-based tolerance values were lower (indicating a less pollution-tolerant macroinvertebrate community) than in the before-construction period.

Introduction

Physical characteristics of streams change during human-engineered modifications of stream channels (Lynch and others, 1977; Hahn, 1982; Brookes, 1988; Bolton and Shellberg, 2001; Jackson, 2003; Johansen, 2003). Reported changes include water temperature, turbidity, flow velocities, channel geometry, hydraulic flow regime, the amount and type of vegetation, the storage of organic matter, and the amount, size, and stability of suspended sediment and channel substrate.

The physical characteristics of streams form the habitat that aquatic biota require to thrive. Aquatic biota community growth, abundance, reproduction, and survival can change when physical stream characteristics change. The degree to which an aquatic community is affected, however, can vary with the type of channel modification and site characteristics.

The U.S. Geological Survey (USGS), in cooperation with the Alabama Department of Transportation (ALDOT), conducted a three-phase (before, during, and after construction) scientific assessment, over 10 years, to evaluate culvert effects on channel geometry, sediment concentration, turbidity, and benthic macroinvertebrate communities. Monitoring changes in channel geometry and sediment related to culvert installations can help to determine if stream conditions are stable

or if improvements to culvert designs are needed to support biotic communities after construction. The results of this study can be used by transportation managers to inform design of future culvert road crossings of streams. This work supports a major goal of the USGS Water Mission Area Science Strategy (Evenson and others, 2013) to "advance understanding of processes that determine water availability." The sampling and analyses done as part of this study add to the understanding of the effects human activities have on the quantity and quality of water to support local ecosystem needs.

Purpose and Scope

The two main objectives for this study were (1) to assess the degree and extent of changes in physical characteristics—channel geometry, suspended sediment concentrations, and turbidity—and in the benthic macroinvertebrate populations from data collected over 10 years, and (2) to identify any discernible and statistically significant relations among the observed changes. The before-construction phase measurements and samples established the baselines used to calculate deviations in the physical characteristics and benthic macroinvertebrate populations for the during- and after-culvert construction phases.

General Study Site Description

Six sites located in the northern East Gulf Coastal Plain Physiographic Section (hereinafter referred to as the Coastal Plain) of Alabama were selected for use in this study. The six sites are all within 50 miles of the Fall Line, which defines the northern boundary of the Coastal Plain, and these sites are spread across the State from Russell County, bordering Georgia, to Lamar County, bordering Mississippi (fig. 1; table 1). The current conditions of streams and their watersheds reflect the interactions among the local geology, soils, topography, hydrology, climate, and land cover over human and geological time scales.

Twelve USGS streamgage stations were established for this study (table 1). Two stations at each study site, one at the upstream end of the culvert construction reach and the second at the downstream end of the culvert construction reach. The streamflow and sediment information collected for this study is associated with the respective streamgage and is available through the USGS National Water Information System database (U.S. Geological Survey, 2020).

Alternative culvert designs developed to reduce the impact of stream roadway crossings on fish, sediment, and debris include buried or embedded inverts (inside bottom of the culvert) (National Academies of Sciences, Engineering, and Medicine, 2012). Constructing the culvert inverts below the adjacent upstream and downstream channel reaches allows the streambed through the culvert to aggregate and erode at

natural rates, greatly reducing the potential for perched inlets or outlets which often occur with culverts using traditional designs (National Academies of Sciences, Engineering, and Medicine, 2012). Buried culvert invert designs were used at the Tributary to Cahaba River (site 2) and the Tributary to Sandy Creek sites (table 2).

Geology and Soils

The geology underlying the six study sites consists of relatively young sedimentary rocks and unconsolidated sediments. During the Late Cretaceous period (approximately 70–65 mega-annum [MA] before present), the area was repeatedly inundated by shallow seas, resulting in an alternating sequence of marine and continental sediments. Subsequently, fluvial drainage networks were established and distributed continental sediments across the Coastal Plain. Most recently, during the Quaternary period (approximately 2.6 MA before present through the present), this drainage network continues to distribute sediments from the areas north of the Fall Line, and has redistributed existing sediments forming the hills, valleys, and terraces that exist today (fig. 2; table 3). The geologic units underlying the study sites slope southward at about 40 feet per mile and consist predominantly of chalk, sandstone, limestone, and claystone; the unconsolidated sediments are predominantly sands, silts, and clays (Hosman, 1991; Neilson, 2016).

The soils within the study basins have formed over time by the physical, chemical, and biological weathering of sedimentary rocks of Cretaceous age and the unconsolidated sediments of Cretaceous and Quaternary ages. The major soil series at the study sites include Smithdale, Luverne, and Savannah (table 4). These soils have either a loamy or clayey subsoil and a sandy loam or loam surface layer. Savannah soils have a fragipan (Mitchell and Loerch, 2008).

Topography

The subtle topography of the northern Coastal Plain consists of level to gently rolling hills, terraces, and prairies. The topography is governed by the rocks that underlie the surface and the erosional forces that have acted upon them. Because most of the sediments of Tertiary and Quaternary ages in the Coastal Plain fall into two major rock types, sandstone and shale, erosional processes have had similar effects throughout the area. The more resistant sand layers underlie ridges or cuestas, and the less resistant shale layers underlie the topographic lows or valleys (Hosman, 1991). In the Coastal Plain of Alabama, cuestas (hills or ridges where layered, harder sedimentary rock overlie softer sedimentary rock) trend east-west, with the gentle backslopes facing south and the steeper frontslopes facing north (Cotton, 1952).

Table 1. Site numbers and names with associated USGS streamgage stations, drainage area, locations, and stream order information.

[USGS, U.S. Geological Survey; mi², square mile; latitudes and longitudes are in degrees, minutes, seconds, referenced to the North American Datum of 1927; Trib, tributary; Ala., Alabama; Stream order less than (<)1, Stream is not mapped in the National Hydrography Dataset and therefore is smaller than a first-order stream]

Site number (fig. 1)	Abbreviated site name	USGS station number[1]	USGS station name[1]	Drainage area (mi²)	Latitude	Longitude	County	Highway or road near streamgage	Stream order
1	High Log Creek	02342870	High Log Creek (Site A) near Hatchechubbee, Ala.	13.7	32°16′21″	85°17′58″	Russell	State Highway 26	1
		02342871	High Log Creek (Site B) near Hatchechubbee, Ala.		32°16′20″	85°17′58″			
2	Tributary to Cahaba River	02423990	Tributary to Cahaba River (Site A) near Centreville, Ala.	0.39	32°57′23″	87°07′33″	Bibb	U.S. Highway 82 – State Route 6	<1
		02423991	Tributary to Cahaba River (Site B) near Centreville, Ala.		32°57′24″	87°07′33″			
3	Tributary to Sandy Creek	02424013	Tributary to Sandy Creek (Site A) near Vick, Ala.	1.34	32°56′23″	87°04′27″	Bibb	U.S. Highway 82 – State Route 6	<1
		02424014	Tributary to Sandy Creek (Site B) near Vick, Ala.		32°56′22″	87°04′27″			
4	Oakmulgee Creek	02424750	Oakmulgee Creek (Site A) near Lawley, Ala.	12.5	32°50′34″	86°57′30″	Bibb	U.S. Highway 82 – State Route 6	2
		02424751	Oakmulgee Creek (Site B) near Lawley, Ala.		32°50′34″	86°57′31″			
5	Northington Branch	02439159	Northington Branch near Detroit, Ala., Site A	6.22	34°00′58″	88°11′50″	Lamar	County Road 5 – Sipsey Fork Road	1
		02439160	Northington Branch near Detroit, Ala., Site B		34°00′58″	88°11′51″			
6	Lye Branch	02465390	Lye Branch (Site A) near Duncanville, Ala.	16.4	33°05′07″	87°23′35″	Tuscaloosa	Hargrove Road	3
		02465391	Lye Branch (Site B) near Duncanville, Ala.		33°05′06″	87°23′35″			

[1]USGS National Water Information System database (U.S. Geological Survey, 2020.
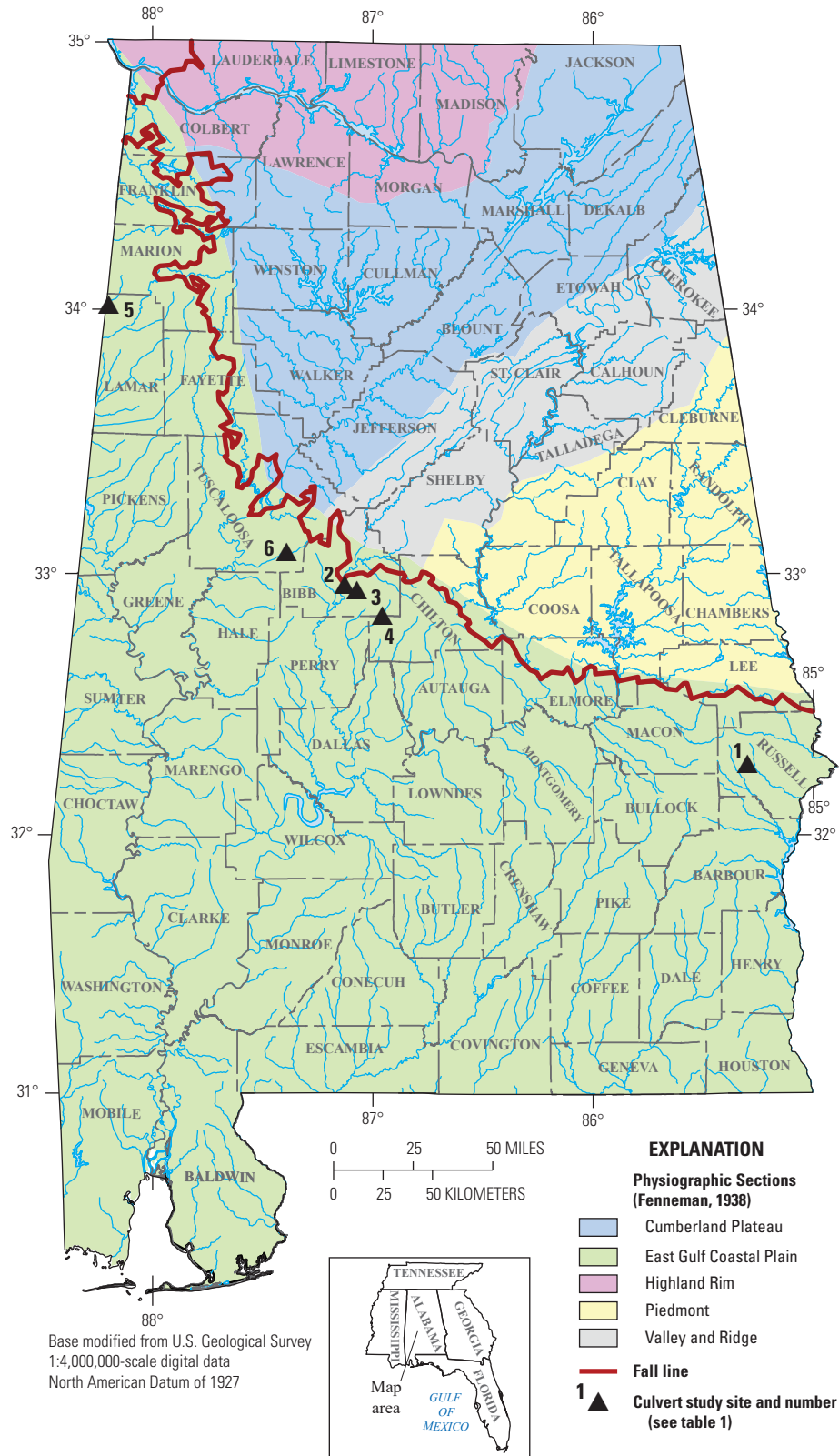
Figure 1.   Locations of sites used in the culvert study and Physiographic Sections of Alabama. The culvert site number in the figure references table 1 where site 1 is High Log Creek, site 2 is Tributary to Cahaba River, site 3 is Tributary to Sandy Creek, site 4 is Oakmulgee Creek, site 5 is Northington Branch, and site 6 is Lye Branch.

Table 2. Alabama Department of Transportation construction information for culverts at six sites in Alabama.

[Construction dates shown in month/day/year format; BW×BH×BL, barrel width × barrel height × barrel length; ft, foot; BIN, Bridge Identification Number; CIP, cast in place; CT, triple barrel culvert; CS, single barrel culvert; CQ, quadruple barrel culvert; NA, not applicable; Note: construction information provided by the Alabama Department of Transportation]

Site number (fig. 1; table 1)	Abbreviated site name	Construction start date	Construction end date	Type of culvert	Culvert dimensions, BW×BH×BL (ft)	Buried invert culvert design	BIN	Project number
1	High Log Creek	8/28/2013	9/28/2016	CIP concrete	CT16×14×78	No	20483	BR-0026(502)
2	Tributary to Cahaba River	11/2/2010	8/16/2013	Precast box culvert	CS10×6×229	Yes	NA	NHF-0006(530)
3	Tributary to Sandy Creek	11/2/2010	8/16/2013	CIP concrete	CT12×7×286	Yes	20354	NHF-0006(530)
4	Oakmulgee Creek	10/29/2013	3/26/2015	CIP concrete	CT16×14×44	No	20562	BRF-0006(541)
5	Northington Branch	10/5/2011	4/1/2013	CIP concrete	CT12×8×42	No	20506	BRZ-3800(209)
6	Lye Branch	11/6/2013	12/13/2018	CIP concrete	CQ14×8×60	No	20673	BRZ-6300(220)

Table 3.   Surficial geology mapped within selected stream reach drainage basins in Alabama.

[Fm, Formation; From Szabo and others, 1988]

		Site number and abbreviated name (fig. 2; table 1)					
		1	**2**	**3**	**4**	**5**	**6**
		High Log Creek	**Tributary to Cahaba River**	**Tributary to Sandy Creek**	**Oakmulgee Creek**	**Northington Branch**	**Lye Branch**
System	**Series**	**Unit name**					
Quaternary	Holocene			Alluvium	Alluvium	Alluvium	Alluvium
.	Pleistocene			Terrace deposits	Terrace deposits	Terrace deposits	Terrace deposits
Cretaceous	.	Mooreville Chalk, Blufftown Fm	Coker Fm	Coker Fm	Gordo Fm, Coker Fm	Eutaw Fm, Gordo Fm	Coker Fm
Pennsylvanian							Pottsville Fm

Hydrology

Stream order is a positive number indicating the position of a stream in the hierarchy of tributaries (Leopold, 1994). Stream order is an effective way to classify streams and assist in understanding and managing the many differences between streams of different sizes. The Horton-Strahler stream order system is a "top down" system (Horton, 1945; Strahler, 1957). First- through third-order streams are headwater streams that have formed on steeper slopes and have faster flows and smaller volumes. Fourth- through sixth-order streams are medium streams with less slope, slower flows, and larger volumes. Stream orders greater than sixth are large rivers; for example, the Ohio River is an 8th-order stream, and the Mississippi River is a 10th-order stream. The stream orders for the streams at the selected study sites were determined by using the Horton-Strahler method and the National Hydrography Dataset (1:24,000 scale) (U.S. Geological Survey, 2017). All the streams at the selected study sites are headwater streams of third-order or less with drainage areas from 0.39 to 16.4 square miles (mi^2) (table 1).

Hydrologic units and the associated watershed boundary datasets are used to delineate the areal extent of surface-water drainage in the United States. A hierarchical classification system is used to subdivide river basins into successively smaller basins (Seaber and others, 1987). At least one study reach is within each of the three subregional hydrologic units that drain the northern part of the Coastal Plain in Alabama (fig. 3; table 5). High Log Creek (site 1) is within the Apalachicola subregion. Cahaba River (site 2), Sandy Creek (site 3), and Oakmulgee Creek (site 4) are within the Alabama subregion, and Northington Branch (site 5) and Lye Branch (site 6) are within the Mobile-Tombigbee subregion.

Culvert design is predominantly based on the estimated peak streamflow that the structure is designed to convey (Norman and others, 2005). Streamflow estimates for floods having recurrence intervals of 1.5, 2, 5, 10, 25, 50, 100, 200, and 500 years were made by using USGS regional flood-frequency relations for Alabama (Hedgecock, 2004; Hedgecock and Feaster, 2007).

To facilitate comparisons among the different sites, only the 2-year peak streamflow estimates were used. The 2-year peak streamflow estimates for the six study reaches range from 94.0 cubic feet per second (ft^3/s) for the Tributary to Cahaba River (site 2) to 1,060 ft^3/s at the Lye Branch site (table 6).

Climate

The Coastal Plain has a generally warm, humid climate resulting from its mid-latitude location and proximity to the Gulf of Mexico. This location produces turbulent weather patterns that regularly bring tornadoes and hurricanes. Alabama is classified as being in the Humid Subtropical region according to the Koppen classification system, where the climate is characterized by relatively mild winters, hot summers, and year-round precipitation (Chaney, 2013). The average annual precipitation in the Coastal Plain is between 52 and 56 inches with an average annual temperature between 60 and 64 degrees Fahrenheit. The length of the growing season for agricultural production varies from approximately 200 to 220 days per year (University of Alabama, 2017).
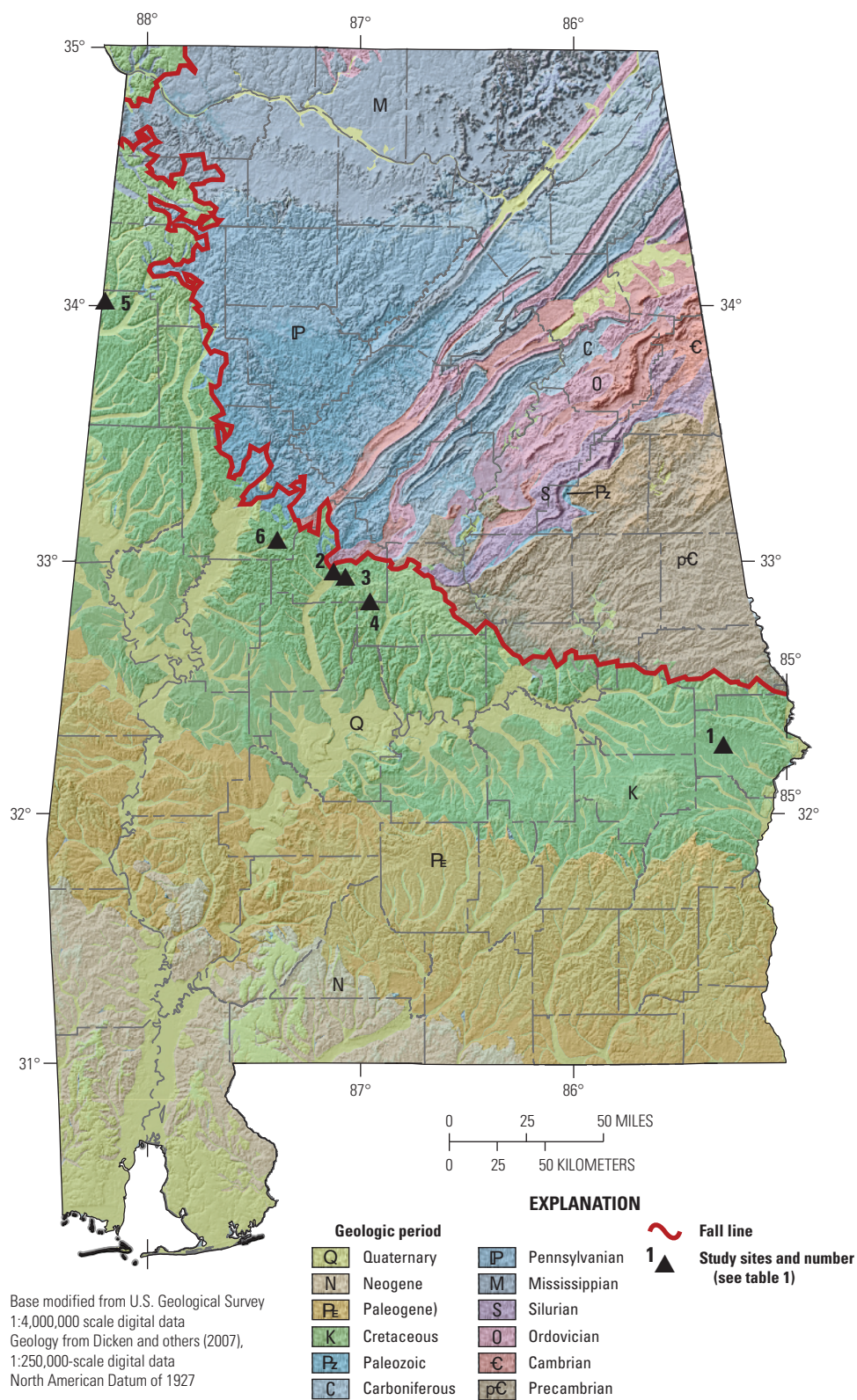
Figure 2. Locations of sites used in the culvert study and generalized surficial geology of Alabama. The culvert site number in the figure references table 1 where site 1 is High Log Creek, site 2 is Tributary to Cahaba River, site 3 is Tributary to Sandy Creek, site 4 is Oakmulgee Creek, site 5 is Northington Branch, and site 6 is Lye Branch.

Table 4.   Soil series mapped within selected stream reach drainage basins in Alabama.

[From Soil Survey Staff, Natural Resources, United States Department of Agriculture]

Setting	Site number and abbreviated name (fig. 2; table 1)					
	1	2	3	4	5	6
	High Log Creek	Tributary to Cahaba River	Tributary to Sandy Creek	Oakmulgee Creek	Northington Branch	Lye Branch
Frequently flooded	Kinston, Mantachie, and Iuka	Bibb-Iuka complex	Bibb-Iuka complex	Mantachie, Iuka, and Kinston soils	Iuka-Mantachie complex	Iuka-Mantachie complex
Occasionally flooded				Columbus loam	Mantachie loam	
Rarely flooded	Dogue fine sandy loam, Maxton loamy sand, Lynchburg loamy fine sand		Cahaba sandy loam			
2 to 5 percent slope			Cahaba sandy loam		Savannah loam	
3 to 8 percent slope	Conecuh loam					
15 to 35 percent slope		Luverne-Smithdale complex		Luverne-Smithdale complex		Smithdale-Luverne complex

Table 5.   Hydrologic units in which selected study sites are located in Alabama.

[Hydrologic units are from Seaber and others (1987)]

| Site number (fig. 3; table 1)	Abbreviated site name	Hydrologic unit number and basin name			
		Cataloging unit (8-digit number)	Accounting unit (6-digit number)	Subregion (4-digit number)	Region (2-digit number)
1	High Log Creek	03130003 — Middle Chattahoochee - Walter F. George Reservoir	031300 — Apalachicola	0313 — Apalachicola	03 — South Atlantic-Gulf
2	Tributary to Cahaba River	03150202 — Cahaba	031502 — Alabama	0315 — Alabama	
3	Tributary to Sandy Creek				
4	Oakmulgee Creek				
5	Northington Branch	03160103 — Buttahatchee	031601 — Black Warrior-Tombigbee	0316 — Mobile-Tombigbe	
6	Lye Branch	03160113 — Lower Black Warrior			
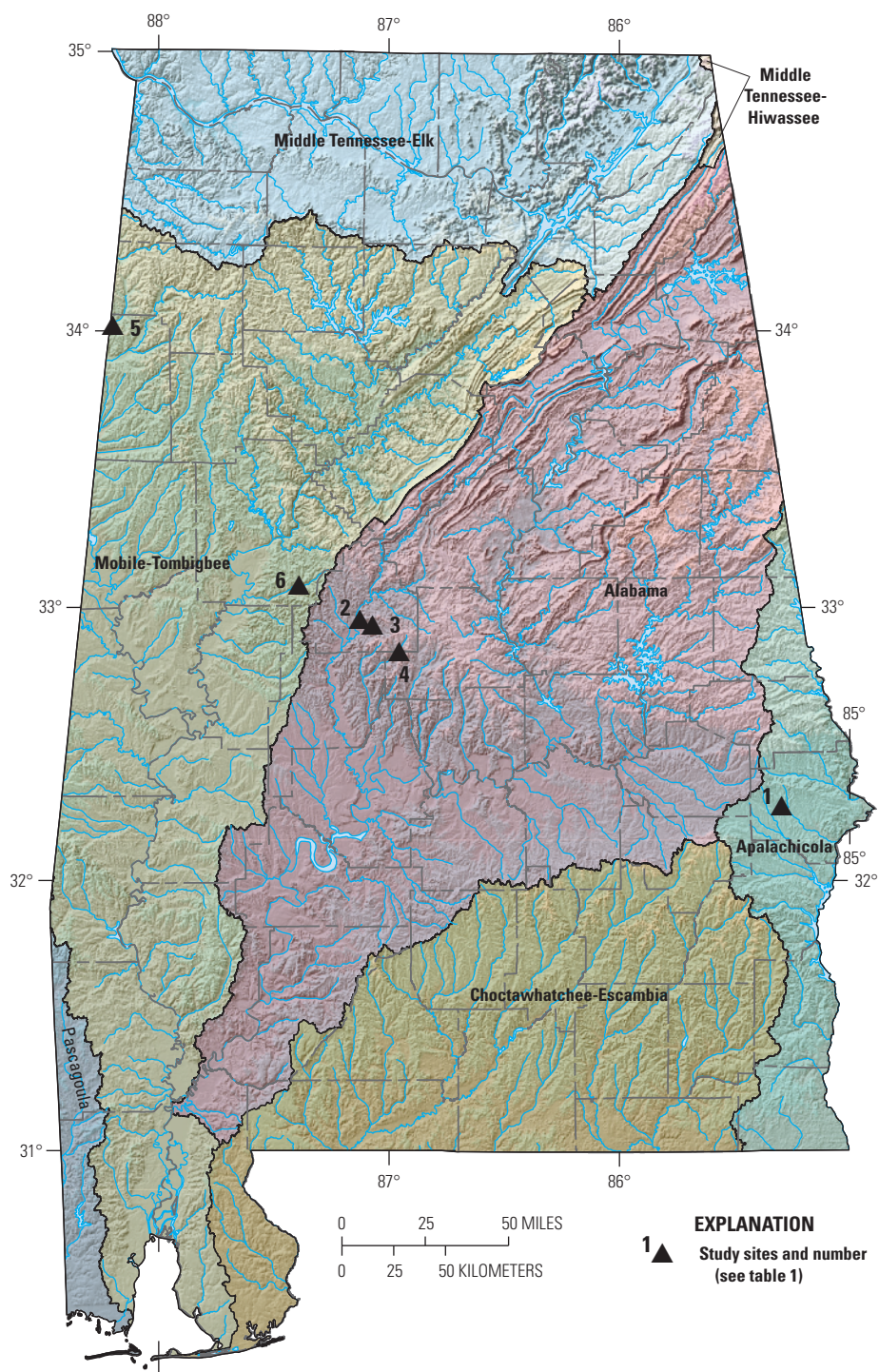
Figure 3.   Locations of sites used in the culvert study and hydrologic subregions of Alabama. The culvert site number in the figure references table 1 where site 1 is High Log Creek, site 2 is Tributary to Cahaba River, site 3 is Tributary to Sandy Creek, site 4 is Oakmulgee Creek, site 5 is Northington Branch, and site 6 is Lye Branch.

Table 6.   Estimates of peak streamflow from regional regression relations at six study sites in Alabama.

[Ala., Alabama; mi^2, square mile; ft^3/s, cubic foot per second; %, percent; N/A, not applicable]

	Site number (fig. 1; table 1) and abbreviated site name					
	1	**2**	**3**	**4**	**5**	**6**
	High Log Creek[1]	**Tributary to Cahaba River[2]**	**Tributary to Sandy Creek[2]**	**Oakmulgee Creek[1]**	**Northington Branch[1]**	**Lye Branch[1]**
Drainage area (mi^2)	13.7	0.39	1.34	12.5	6.22	16.4
Flood region(s) and percentage of watershed within region	4–100%	Statewide - 100%	Statewide - 100%	2–100%	2–100%	1–1% and 2–99%
1.5-year peak flood (ft^3/s)	728	N/A	N/A	672	423	813
2-year peak flood (ft^3/s)	956	94.0	235	879	555	1,060
5-year peak flood (ft^3/s)	1,720	166.1	410	1,510	958	1,820
10-year peak flood (ft^3/s)	2,330	225.6	556	2,020	1,280	2,430
25-year peak flood (ft^3/s)	3,190	314	776	2,710	1,730	3,270
50-year peak flood (ft^3/s)	3,910	389	962	3,260	2,080	3,920
100-year peak flood (ft^3/s)	4,700	471.9	1,166	3,850	2,460	4,630
200-year peak flood (ft^3/s)	5,560	565.2	1,395	4,500	2,890	5,410
500-year peak flood (ft^3/s)	6,780	703.9	1,735	5,500	3,530	6,600

[1]Peak streamflow estimated by using Hedgecock and Feaster (2007).

[2]Peak streamflow estimated by using Hedgecock (2004).

Land Cover

Land cover is the physical material covering the earth's surface. The land cover of the Coastal Plain is predominantly a mosaic of cropland, pasture, woodland, and forest. The woodlands and forest are mostly oak-hickory-pine and Southern mixed forest (Griffith and others, 2001). The drainage basins above sites 2–6 are within the Fall Line Hills Ecoregion and are mostly forests of mixed oak-hickory-pine and pine plantations with areas of pasture and hay and minor areas of cultivated cropland of corn, soybeans, and cotton (Griffith and others, 2001). The drainage basin above High Log Creek (site 1; fig. 1) is within the Flatwoods Ecoregion, which is a lowland area of little relief, deep soils, and dry woodlands of post oak (*Quercus stellata* Wangenh.), shortleaf pine (*Pinus echinata* Mill.), and loblolly pine (*Pinus taeda* L.) (Griffith and others, 2001).

Data from the National Land Cover Database (U.S. Geological Survey, 2011) was used to determine the land cover on each of the drainage basins above the selected study reaches and used to help evaluate the potential for anthropogenic activities affecting the stream channel (tables 7 and 8). Forest and grassland/shrub are the dominant land cover classes, on average covering 69.5 and 20.3 percent, respectively, of the drainage basins above the study reaches. The five remaining land cover classes—open water, urban, barren, agriculture, and wetlands—each on average covered less than 5 percent of the study reaches' drainage basins. The large percentages of forest and grassland/shrub land cover and the small percentages of urban and agriculture land cover suggest that the watersheds are minimally affected by anthropogenic activities above the selected study reaches.

Table 7.   Land cover within the drainage basins above the selected study sites in Alabama.

[mi², square mile; Land cover from National Land Cover Database (U.S. Geological Survey, 2011). The classification system used by the National Land Cover Database (U.S. Geological Survey, 2011) is modified from the Anderson Land Classification System (Anderson and others, 1976)]

Site number (fig. 1)	Abbreviated site name	Drainage area (mi²)	Level I land cover class within watershed (percent) (see table 8)						
			Open water	Urban	Barren	Forest	Grassland/ Shrub	Agriculture	Wetlands
1	High Log Creek	13.70	0.2	2.0	0.0	66.0	24.5	4.1	3.3
2	Tributary to Cahaba River	0.39	2.5	6.2	0.0	79.7	10.9	0.2	0.5
3	Tributary to Sandy Creek	1.34	0.6	1.7	0.0	83.8	10.5	3.5	0.0
4	Oakmulgee Creek	12.50	0.3	3.5	0.0	54.3	30.1	8.8	3.1
5	Northington Branch	6.22	0.0	3.1	0.1	66.9	21.2	7.7	0.9
6	Lye Branch	16.40	0.7	3.4	0.1	66.2	24.6	2.6	2.4
Average:			0.7	3.3	0.0	69.5	20.3	4.5	1.7

Table 8.   Land cover class descriptions associated within the drainage basins above the selected study sites in Alabama.

[Land cover from National Land Cover Database (U.S. Geological Survey, 2011). The classification system used by National Land Cover Database (U.S. Geological Survey, 2011) is modified from the Anderson Land Classification System (Anderson and others, 1976)]

Land cover class	Description
Open water	All areas of open water, generally with less than 25 percent vegetation or soil cover.
Urban	Includes developed open spaces with a mixture of some constructed materials, but mostly vegetation in the form of lawn grasses such as large-lot single-family housing units, parks, golf courses, and vegetation planted in developed settings for recreation, erosion control, or aesthetic purposes. Also included are lands of low, medium, and high intensity with a mixture of constructed materials and vegetation, such as single-family housing units, multifamily housing units, and areas of retail, commercial, and industrial uses.
Barren	Barren areas of bedrock, desert pavement, scarps, talus, slides, volcanic material, glacial debris, sand dunes, strip mines, gravel pits, and other accumulations of earthen material. Generally, vegetation accounts for less than 15 percent of total cover.
Forest	Areas dominated by trees generally taller than 5 meters, and greater than 20 percent of total vegetation cover. Includes deciduous forest, evergreen forest, and mixed forest.
Grassland/Shrub	Grassland areas dominated by graminoid or herbaceous vegetation and shrub/scrub areas dominated by shrubs less than 5 meters tall with shrub canopy typically greater than 20 percent of total vegetation, including true shrubs, young trees in an early successional stage, or trees stunted due to harsh environmental conditions. Management techniques that associate soil, water, and forage-vegetation resources are more suitable for rangeland management than are practices generally used in managing pastureland. Some rangelands have been or may be seeded to introduced or domesticated plant species.
Agriculture	Cultivated crops and pasture/hay—Cultivated crops are described as areas used for the production of annual crops, such as corn, soybeans, vegetables, tobacco, and cotton, and also perennial woody crops such as orchards and vineyards. This class also includes all actively tilled land. Pasture/Hay is described as grasses, legumes, or grass-legume mixtures planted for livestock grazing or the production of seed or hay crops, typically on a perennial cycle.
Wetlands	Woody wetlands and herbaceous wetlands—Areas where forest or shrubland vegetation accounts for greater than 20 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water. This class also includes areas where perennial herbaceous vegetation accounts for greater than 80 percent of vegetative cover and the soil or substrate is periodically saturated with or covered with water.

Methods

The following discussions describe the site selection process and sampling methods used at each study site. Types of samples and data collected included stream geometry surveys, suspended sediment and turbidity sampling, streamflow measurements, and benthic macroinvertebrate community sampling.

Site Selection

To maximize the homogeneity of stream features, all sites were located within the northern East Gulf Coastal Plain Physiographic Section in Alabama (Fenneman, 1938) (fig. 1). The streams of the Coastal Plain were considered the most likely to be affected by culvert construction because of the loose, shifting sand composing the streambed and banks.

The initial list of candidate sites was developed in consultation with ALDOT personnel. Selection criteria included candidate sites that had proposed box culverts, with no internal drop structures, relatively small drainage areas, and minimal human development (tables 1, 2, 7, and 8). Choosing sites with minimal anthropogenic influences maximizes the potential that observed changes are the result of culvert construction and not from other human activities.

During the fall of 2009, thorough field assessments were conducted at each candidate site to assess in-stream habitat and stream channel and riparian stability and to determine if site-specific modifications to data collection methods would be required. Choosing stable streams maximizes the potential that observed changes are the result of culvert construction and not a pre-existing instability. The final site selection was based on the site selection criteria and the observations made during site visits.

Stream Channel Geometry Surveys

Topographic surveys of 22 stream channel cross sections, 11 upstream and 11 downstream of the culvert construction, were conducted prior to culvert construction to provide a baseline to compare to the effects culvert construction may have on the stream channel beds, banks, and slopes. These topographic surveys were conducted outside of the right-of-way boundaries to avoid possible effects of construction. The cross sections were evenly distributed along a stream reach length of approximately 20 times the channel width. These same cross sections were resurveyed approximately 2 years after culvert construction was completed. Topographic survey data and map view plots of the survey data for each study site are available from Gill and Pugh (2021).

Analysis of data in this report includes comparisons of data from the upstream and the downstream reaches to evaluate the construction reach. The upstream reach is defined as the stream reach containing the 11 cross sections upstream of the culvert construction. The construction reach is defined as the stream reach between the right-of-way boundaries where culvert construction occurred. The downstream reach is defined as the stream reach containing the 11 cross sections downstream of the culvert construction.

A paired sample t-test of the mean cross-sectional parameters (cross-sectional area, top width, and mean depth) was used to assess before- and after-construction changes (table 9). The means of the before-construction, upstream, cross-sectional parameters were compared to the means of the after-construction, upstream, cross-sectional parameters, where the hypothesized mean difference was 0 and the alpha was 0.05. This technique was also used to assess the change between the before- and after-construction, downstream cross-sectional parameters.

A paired sample t-test for slopes of regression lines was used to assess the change between before- and after-construction channel thalweg slopes (table 10). The thalweg is defined as a line connecting the lowest points of successive cross sections along the stream (fig. 4). The slope of the before-construction, upstream thalweg was compared to the slope of the after-construction, upstream thalweg, where the hypothesized mean difference was 0 and the alpha was 0.05. This technique was also used to assess the change between the before- and after-construction, downstream thalweg slopes.

A statistically significant result for the differences between before- and after-construction observations indicates a high probability that the difference was real and not due to chance. It also means there is a 5-percent ($\alpha=0.05$) probability that the difference is due to chance. A statistically significant result only indicates that there is a difference, not the magnitude of the difference.

Suspended Sediment and Turbidity Sampling

Suspended sediment samples were collected at each study site during multiple storm runoff events, both upstream and downstream of the culvert construction reach, at the same time steps throughout each storm event. Discrete samples were collected at various stream stages representing the rising, peaking, and falling stages of the storm hydrograph. Some samples could not be collected because of lack of access to the stream cross sections during high-flow conditions. During flashy storm events with rapidly changing streamflow, sediment analyses did not always include a direct simultaneous measurement of streamflow. Because streamflow could not be accurately determined for each set of samples, data analysis focused on the parity of the upstream and downstream sediment concentrations for each discrete sample collection time. Suspended sediment samples were collected by using equal-width increment methods as described in Techniques of Water-Resources Investigations of the U.S. Geological Survey, book 3, chapter C2 (Edwards and Glysson, 1999). For some events, multiple sample bottles were collected for a discrete time step and composited in a churn splitter. The churn splitter was used to homogenize the composite sample and fill a single

Table 9.   Results of paired sample t-tests of mean area, width, and depth at cross sections to determine significant differences between the before- and after-construction parameters at selected study sites in Alabama.

[Δ XS area, difference between before- and after-construction cross-sectional areas; Δ top width, difference between before- and after-construction top widths; Δ mean depth, difference between before- and after-construction mean depths; ft², square foot; ft, foot; n, sample size; Std dev; standard deviation; %, percent; CI, confidence interval. Null Hypothesis (H₀): there is no significant difference between the means of the before- and after-construction cross-section indices. Alternate Hypothesis (H_A): there is a significant difference between the means of the before- and after-construction cross-section indices. H₀: μ0 = 0, H_A: μA ≠ 0. Hypothesized mean difference: 0, Alpha = 0.05]

	Upstream			Downstream		
	Δ XS area (ft²)	Δ Top width (ft)	Δ Mean depth (ft)	Δ XS area (ft²)	Δ Top width (ft)	Δ Mean depth (ft)
High Log Creek, site 1						
n	10	10	10	10	10	10
Mean	−12.85	2.30	−0.52	2.37	0.90	−0.10
Std dev	15.45	3.23	0.33	11.87	1.87	0.30
t Stat	2.50	2.14	4.72	0.60	1.45	0.98
Two-tail p	0.03	0.06	0.00	0.56	0.18	0.35
T alpha half 95% CI	2.26	2.26	2.26	2.26	2.26	2.26
Lower 95% CI	−23.90	−0.01	−0.76	−6.12	−0.44	−0.32
Upper 95% CI	−1.80	4.61	−0.29	10.87	2.24	0.12
H₀ or H_A	H_A	H₀	H_A	H₀	H₀	H₀
Tributary to Cahaba River, site 2						
n	14	14	14	11	11	11
Mean	3.15	0.00	0.21	1.30	−0.09	0.09
Std Dev	4.28	1.69	0.24	1.84	0.79	0.13
t Stat	−2.66	0.00	−3.07	−2.24	0.36	−2.24
Two-tail p	0.02	1.00	0.01	0.05	0.72	0.05
T alpha half 95% CI	2.16	2.16	2.16	2.23	2.23	2.23
Lower 95% CI	0.68	−0.98	0.07	0.06	−0.62	0.00
Upper 95% CI	5.62	0.98	0.35	2.54	0.44	0.18
H₀ or H_A	H_A	H₀	H_A	H_A	H₀	H_A
Tributary to Sandy Creek, site 3						
n	10	10	10	10	10	10
Mean	−2.07	−0.90	−0.03	−0.10	1.50	−0.12
Std Dev	8.15	3.39	0.19	12.00	5.00	0.18
t Stat	0.76	0.80	0.49	0.02	−0.90	2.01
Two-tail p	0.47	0.45	0.64	0.98	0.39	0.08
T alpha half 95% CI	2.26	2.26	2.26	2.26	2.26	2.26
Lower 95% CI	−7.89	−3.32	−0.16	−8.68	−2.08	−0.25
Upper 95% CI	3.76	1.52	0.10	8.49	5.08	0.01
H_O or H_A	H₀	H₀	H₀	H₀	H₀	H₀
Oakmulgee Creek, site 4						
n	11	11	11	11	11	11
Mean	−1.77	0.36	−0.06	9.31	−2.82	0.56
Std Dev	20.35	4.21	0.43	44.67	4.20	0.90
t Stat	0.28	−0.27	0.41	−0.66	2.12	−1.95
Two-tail p	0.79	0.79	0.69	0.52	0.06	0.08
T alpha half 95% CI	2.23	2.23	2.23	2.23	2.23	2.23

Table 9. Results of paired sample t-tests of mean area, width, and depth at cross sections to determine significant differences between the before- and after-construction parameters at selected study sites in Alabama.—Continued

[Δ XS area, difference between before- and after-construction cross-sectional areas; Δ top width, difference between before- and after-construction top widths; Δ mean depth, difference between before- and after-construction mean depths; ft^2, square foot; ft, foot; n, sample size; Std dev; standard deviation; %, percent; CI, confidence interval. Null Hypothesis (H_0): there is no significant difference between the means of the before- and after-construction cross-section indices. Alternate Hypothesis (H_A): there is a significant difference between the means of the before- and after-construction cross-section indices. H_0: $\mu 0 = 0$, H_A: $\mu A \neq 0$. Hypothesized mean difference: 0, Alpha = 0.05]

	Upstream			Downstream		
	Δ XS area (ft^2)	Δ Top width (ft)	Δ Mean depth (ft)	Δ XS area (ft^2)	Δ Top width (ft)	Δ Mean depth (ft)
Oakmulgee Creek, site 4—Continued						
Lower 95% CI	−15.44	−2.46	−0.35	−20.70	−5.64	−0.05
Upper 95% CI	11.90	3.19	0.23	39.31	0.00	1.17
H_0 or H_A	H_0	H_0	H_0	H_0	H_0	H_0
Northington Branch, site 5						
n	11	11	11	11	11	11
Mean	1.41	0.82	−0.09	−9.79	−0.73	−0.20
Std Dev	6.99	2.52	0.31	18.18	2.38	0.27
t Stat	−0.64	−1.03	0.90	1.70	0.97	2.38
Two-tail p	0.54	0.33	0.39	0.12	0.36	0.04
T alpha half 95% CI	2.23	2.23	2.23	2.23	2.23	2.23
Lower 95% CI	−3.28	−0.87	−0.29	−22.00	−2.32	−0.38
Upper 95% CI	6.11	2.51	0.12	2.42	0.87	-0.02
H_0 or H_A	H_0	H_0	H_0	H_0	H_0	H_A
Lye Branch, site 6						
n	11	11	11	10	10	10
Mean	3.56	−0.45	0.14	−13.77	2.30	−0.70
Std Dev	28.22	6.10	0.59	34.45	5.64	0.80
t Stat	−0.40	0.24	−0.76	1.20	−1.22	2.62
Two-tail p	0.70	0.82	0.47	0.26	0.25	0.03
T alpha half 95% CI	2.23	2.23	2.23	2.26	2.26	2.26
Lower 95% CI	−15.40	−4.55	−0.26	−38.42	−1.73	−1.27
Upper 95% CI	22.52	3.64	0.54	10.88	6.33	−0.13
H_0 or H_A	H_0	H_0	H_0	H_0	H_0	H_A

sample bottle to be analyzed for that time step. Suspended sediment samples were analyzed by the USGS Kentucky Sediment Laboratory to determine suspended sediment concentrations (table 11; U.S. Geological Survey, 2020).

Concurrent with suspended sediment sampling, turbidity samples were collected in the main section of streamflow, away from eddies and the streambanks. Samples were transported to the Montgomery, Alabama, USGS laboratory for analysis. Samples were stored in a dark refrigerator for varying time periods (a few days to several months) between collection and analysis. Samples were gently inverted back and forth at least 20 times to resuspend particulate matter, and the turbidity values were measured in three separately analyzed

aliquots by using a Hach 2100P turbidimeter. The median of the three measured concentrations was reported as the sample turbidity (table 11; U.S. Geological Survey, 2020).

The Techniques of Water-Resources Investigations of the U.S. Geological Survey, chapter A5, section 6.7 states "Turbidity measurement is time sensitive and therefore should be completed on-site (preferably in situ) to avoid effects from (a) biodegradation, growth, settling, or sorption of particulates in the sample; or (b) precipitation of humic acids and minerals (carbonates and hydroxides, for example) caused by changes in sample pH during transport and holding. If temporary storage of samples is necessary, collect samples in clean amber bottles, keep samples out of sunlight, and chilled at or below 4°C to prevent biodegradation of solids or biological growth.

Table 10.   Results of paired sample t-tests to determine the difference between the before- and after-construction thalweg slopes at selected study sites in Alabama.

[n, sample size; slope, thalweg slope; SE(reg), standard error of regression; SE(slope), standard error of slope; Difference(slope), difference in slopes; SE(Difference), standard error of difference in slopes; t stat, t statistic; df, degrees of freedom. Null Hypothesis (H_0): there is no significant difference between the before- and after-construction thalweg slopes. Alternate Hypothesis (H_A): there is a significant difference between the before- and after-construction thalweg slopes. H_0: $\mu_0 = 0$, H_A: $\mu_A \neq 0$. Hypothesized Mean Difference: 0, Alpha = 0.05]

	Upstream thalweg slope		Downstream thalweg slope	
	Before construction	**After construction**	**Before construction**	**After construction**
High Log Creek, site 1				
n	11	10	11	10
Slope	−0.0007	0.0038	−0.0012	−0.0025
SE(reg)	0.1685	0.9750	0.1063	0.2320
SE(slope)	0.0005	0.0031	0.0003	0.0008
Difference(slope)	0.0045		−0.0013	
SE(Difference)	0.0031		0.0008	
t stat	1.4566		1.4705	
df	17		17	
Two-tail p	0.1635		0.1597	
H_0 or H_A	H_0		H_0	
Tributary to Cahaba River, site 2				
n	12	11	11	11
Slope	−0.0057	−0.0055	−0.0084	−0.0080
SE(reg)	0.3908	0.3881	0.3319	0.4275
SE(slope)	0.0022	0.0025	0.0020	0.0024
Difference(slope)	0.0002		0.0004	
SE(Difference)	0.0033		0.0031	
t stat	0.0736		0.1492	
df	19		18	
Two-tail p	0.9421		0.8831	
H_0 or H_A	H_0		H_0	
Tributary to Sandy Creek, site 3				
n	15	10	11	10
Slope	−0.0028	−0.0070	−0.0018	0.0003
SE(reg)	0.4276	0.2129	0.8126	0.6666
SE(slope)	0.0015	0.0014	0.0048	0.0045
Difference(slope)	−0.0042		0.0021	
SE(Difference)	0.0021		0.0065	
t stat	2.0204		0.3156	
df	21		17	
Two-tail p	0.0563		0.7562	
H_0 or H_A	H_0		H_0	
Oakmulgee Creek, site 4				
n	11	11	12	12
Slope	−0.0022	−0.0001	−0.0090	−0.0077
SE(reg)	0.3009	0.7942	1.2566	1.7238
SE(slope)	0.0009	0.0023	0.0030	0.0042

Table 10. Results of paired sample t-tests to determine the difference between the before- and after-construction thalweg slopes at selected study sites in Alabama.—Continued

[n, sample size; slope, thalweg slope; SE(reg), standard error of regression; SE(slope), standard error of slope; Difference(slope), difference in slopes; SE(Difference), standard error of difference in slopes; t stat, t statistic; df, degrees of freedom. Null Hypothesis (H_0): there is no significant difference between the before- and after-construction thalweg slopes. Alternate Hypothesis (H_A): there is a significant difference between the before- and after-construction thalweg slopes. H_0: $\mu 0 = 0$, H_A: $\mu A \neq 0$. Hypothesized Mean Difference: 0, Alpha = 0.05]

	Upstream thalweg slope		Downstream thalweg slope	
	Before construction	**After construction**	**Before construction**	**After construction**
Oakmulgee Creek, site 4—Continued				
Difference(slope)	0.0021		0.0013	
SE(Difference)	0.0025		0.0052	
t stat	0.8299		0.2577	
df	18		20	
Two-tail p	0.4175		0.7993	
H_0 or H_A	H_0		H_0	
Northington Branch, site 5				
n	11	11	11	11
Slope	0.0006	−0.0022	−0.0023	−0.0021
SE(reg)	0.4310	0.2842	0.3905	0.4203
SE(slope)	0.0015	0.0010	0.0014	0.0015
Difference(slope)	−0.0028		0.0002	
SE(Difference)	0.0018		0.0020	
t stat	1.5219		0.0807	
df	18		18	
Two-tail p	0.1454		0.9366	
H_0 or H_A	H_0		H_0	
Lye Branch, site 6				
n	11	11	11	10
Slope	−0.0029	0.0014	0.0004	−0.0046
SE(reg)	0.3483	0.1976	1.1609	0.3138
SE(slope)	0.0012	0.0007	0.0041	0.0012
Difference(slope)	0.0044		−0.0050	
SE(Difference)	0.0014		0.0043	
t stat	3.1009		1.1751	
df	18		17	
Two-tail p	0.0062		0.2562	
H_0 or H_A	H_A		H_0	

The holding time must not exceed 24 hours" (Anderson, 2005, p. 33). The samples collected for this study did not strictly follow the prescribed methods as described in that samples were not analyzed within 24 hours of collection.

Ratios of the paired upstream to downstream suspended sediment concentrations and turbidity values were examined for each study reach by culvert construction phases (table 12). Ratios of upstream to downstream sediment concentrations and turbidity show differences as deviations from 1.00. For the purposes of this study, ratio values of 1.00, plus or minus 0.10 (0.90–1.10) were considered equal. Ratio values greater than 1.10 indicate the downstream sediment measurement was larger, and conversely, ratio values less than 0.90 indicate the upstream sediment measurement was larger. If a culvert had little effect on sediment transport, sediment concentrations and turbidity were expected to be unchanged from upstream to downstream.
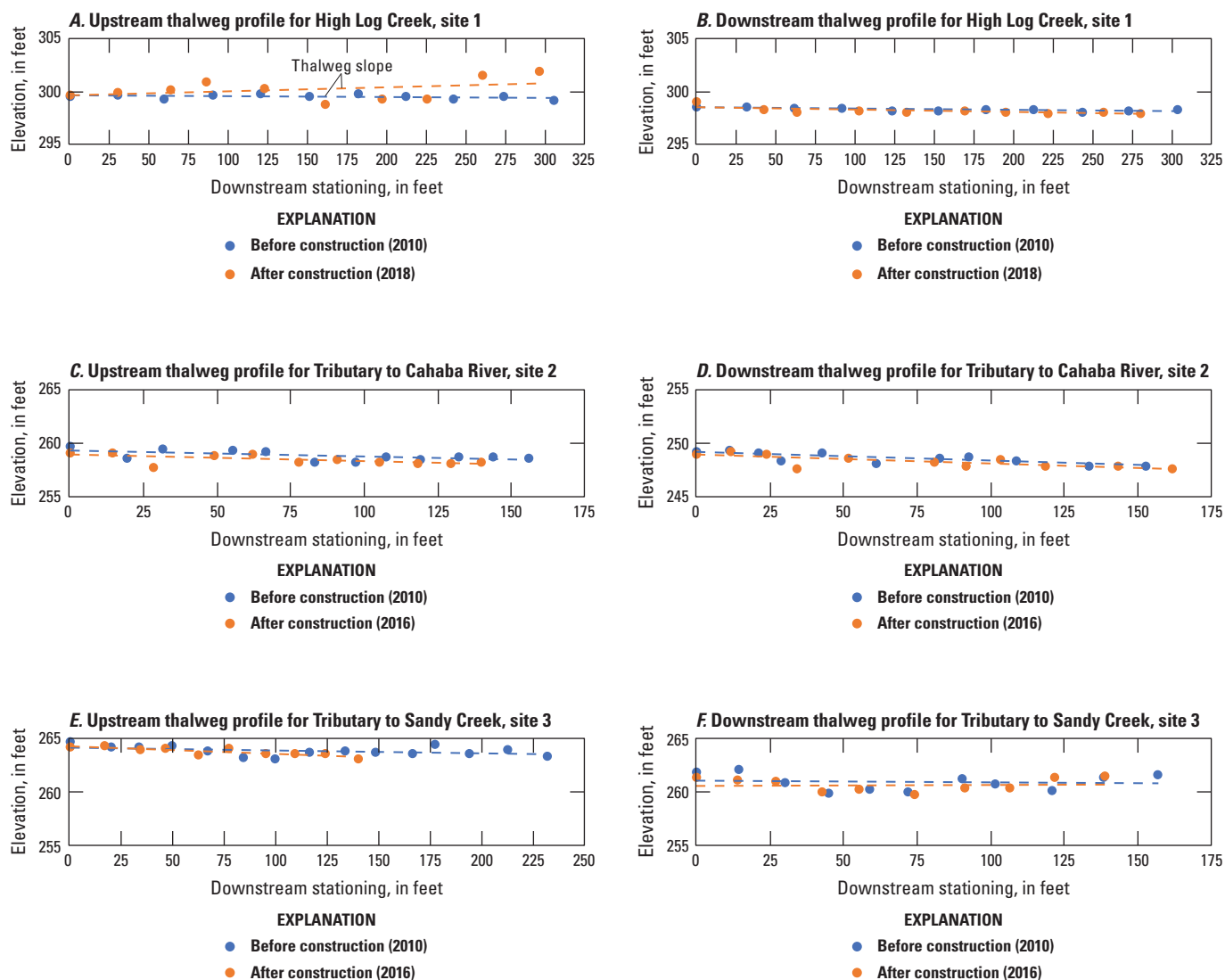
Figure 4. Longitudinal profiles of before- and after-construction thalwegs, upstream and downstream of selected study sites in Alabama.
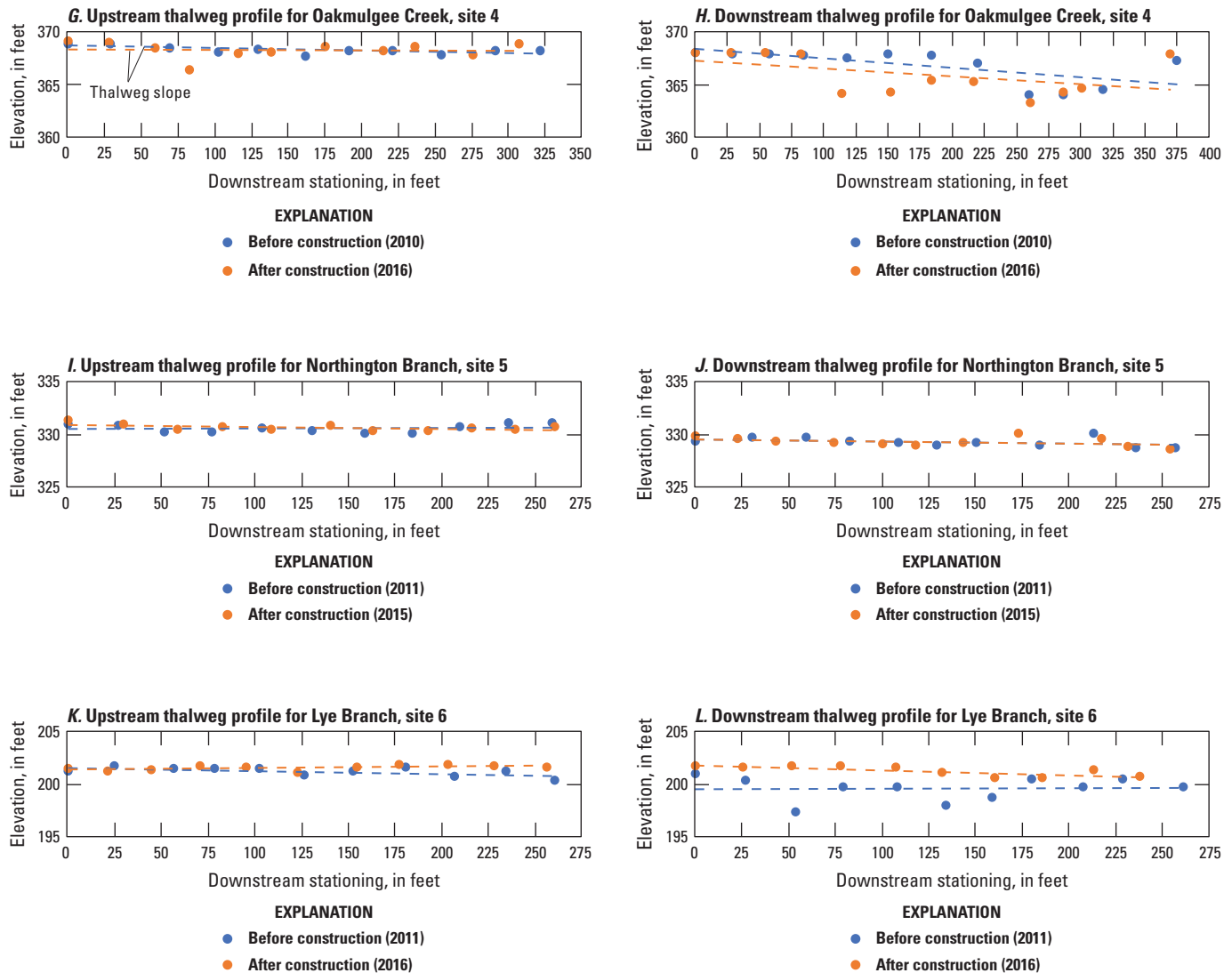
Figure 4.   Longitudinal profiles of before- and after-construction thalwegs, upstream and downstream of selected study sites in Alabama.—Continued

Streamflow Measurements

Stormflows measured as a part of this study varied considerably. To help determine if samples for sediment analysis were collected during similar flow conditions in each of the three construction phases, the maximum measured streamflow, the change in stage, and the storm duration for each event were summarized by site and storm date (table 13). Streamflow measurements were made upstream and downstream of culvert locations during each of the culvert construction phases at each site during multiple storm runoff events. Streamflow measurements were made by using prescribed methods as described in Turnipseed and Sauer (2010). These streamflow values are available through the USGS National Water Information System (U.S. Geological Survey, 2020). Stage-streamflow relations (rating tables) were not developed for any of the selected study reaches because of the limited number of streamflow measurements.

Table 11. Ratios of paired upstream to downstream suspended sediment concentrations and turbidity values collected during storm events measured before, during, and after construction at selected study sites in Alabama.

[mg/L, milligrams per liter; NTRU, Nephelometric Turbidity Ratio Units; BC, before construction; DC, during construction; AC, after construction; dates are in month/day/year format; ratios less than 0.9 indicate downstream values are greater; ratios between 0.9 and 1.1 indicate nearly equal values; ratios greater than 1.1 indicate upstream values are greater; --, no data]

Construction phase	Date of sample collection	Time of sample collection	Limb of storm hydrograph	Upstream of culvert		Downstream of culvert		Ratio of upstream to downstream suspended sediment concentrations	Ratio of upstream to downstream turbidity values
				Suspended sediment concentration (mg/L)	Turbidity (NTRU)	Suspended sediment concentration (mg/L)	Turbidity (NTRU)		
High Log Creek, site 1									
BC	7/15/2011	2315	Peak	1,580	470	1,540	180	1.03	2.61
BC	7/16/2011	0010	Falling	1,880	610	1,950	620	0.96	0.98
BC	2/25/2013	1135	Rising	343	56	481	61	0.71	0.92
BC	2/25/2013	1215	Rising	474	66	453	79	1.05	0.84
BC	2/25/2013	1500	Rising	548	100	503	140	1.09	0.71
DC	4/15/2014	0630	Peak?	784	250	748	250	1.05	1.00
DC	4/15/2014	0805	Falling	626	210	587	220	1.07	0.95
DC	4/15/2014	0930	Falling	487	190	1,010	190	0.48	1.00
DC	5/26/2015	1740	Rising	215	54	136	89	1.58	0.61
DC	5/26/2015	1835	Rising	2,360	270	2,610	140	0.90	1.93
AC	2/7/2018	1450	Rising	70	63	67	58	1.04	1.09
AC	2/7/2018	1605	Falling	83	47	71	72	1.17	0.65
AC	3/6/2018	1630	Falling	221	150	370	140	0.60	1.07
AC	10/10/2018	1910	Rising	345	360	528	300	0.65	1.20
AC	10/10/2018	2020	Rising	285	240	268	260	1.06	0.92
AC	10/10/2018	2220	Rising	679	310	597	320	1.14	0.97
AC	10/10/2018	2335	Rising	1,100	570	1,010	560	1.09	1.02
Tributary to Cahaba, site 2									
DC	4/4/2011	2125	Rising	93	57	604	910	0.15	0.06
DC	4/4/2011	2216	Peak?	48	55	280	320	0.17	0.17
DC	4/4/2011	2317	Peak?	38	39	100	91	0.38	0.43
DC	4/5/2011	0050	Falling	29	49	61	82	0.48	0.60
AC	12/8/2018	1645	Falling, from previous peak	77	48	61	53	1.26	0.91
AC	12/8/2018	1910	Falling	909	89	288	110	3.16	0.81
AC	4/18/2019	2235	Falling	240	54	52	58	4.62	0.93

Table 11. Ratios of paired upstream to downstream suspended sediment concentrations and turbidity values collected during storm events measured before, during, and after construction at selected study sites in Alabama.—Continued

[mg/L, milligrams per liter; NTRU, Nephelometric Turbidity Ratio Units; BC, before construction; DC, during construction; AC, after construction; dates are in month/day/year format; ratios less than 0.9 indicate downstream values are greater; ratios between 0.9 and 1.1 indicate nearly equal values; ratios greater than 1.1 indicate upstream values are greater; --, no data]

| Construction phase | Date of sample collection | Time of sample collection | Limb of storm hydrograph | Upstream of culvert | | Downstream of culvert | | Ratio of upstream to downstream suspended sediment concentrations | Ratio of upstream to downstream turbidity values |
				Suspended sediment concentration (mg/L)	Turbidity (NTRU)	Suspended sediment concentration (mg/L)	Turbidity (NTRU)		
				Tributary to Cahaba, site 2—Continued					
AC	4/18/2019	2315	Rising	46	51	37	49	1.24	1.04
AC	4/19/2019	0015	Peak	191	94	266	84	0.72	1.12
AC	4/19/2019	0055	Falling	169	110	177	100	0.95	1.10
AC	4/19/2019	0140	Falling	93	86	105	96	0.89	0.896
				Tributary to Sandy Creek, site 3					
DC	1/30/2013	0940	Rising	109	96	157	210	0.69	0.46
DC	1/30/2013	1012	Peak	147	94	120	170	1.23	0.55
DC	1/30/2013	1047	Falling	178	180	107	130	1.66	1.38
AC	12/8/2018	1725	Rising	119	42	250	27	0.48	1.56
AC	12/8/2018	1900	Rising	44	47	125	28	0.35	1.68
AC	12/8/2018	1935	Rising	57	56	137	36	0.42	1.56
AC	12/8/2018	2020	Rising	70	66	172	40	0.41	1.65
AC	12/8/2018	2145	Peak	87	99	81	53	1.07	1.87
AC	4/18/2019	2150	Falling	--	120	98	92	--	1.30
AC	4/18/2019	2245	Falling	101	88	126	83	0.80	1.06
AC	4/19/2019	0039	Rising	75	56	75	72	1.00	0.78
AC	4/19/2019	0130	Peak	51	54	77	60	0.66	0.90
				Oakmulgee Creek, site 4					
BC	3/30/2011	2015	Rising	230	110	181	91	1.27	1.21
BC	3/30/2011	2230	Peak	149	83	222	99	0.67	0.84
BC	3/31/2011	0130	Falling	127	62	109	66	1.17	0.94
BC	7/31/2012	1000	Rising	938	540	934	550	1.00	0.98
BC	7/31/2012	1045	Peak?	2,000	440	749	430	2.67	1.02
DC	4/6/2014	1905	Rising	383	130	220	110	1.74	1.18
DC	4/6/2014	2040	Rising?	811	200	240	110	3.38	1.82
DC	9/15/2014	1920	Rising	362	240	292	220	1.24	1.09
DC	9/15/2014	2030	Falling	347	350	331	280	1.05	1.25

Table 11. Ratios of paired upstream to downstream suspended sediment concentrations and turbidity values collected during storm events measured before, during, and after construction at selected study sites in Alabama.—Continued

[mg/L, milligrams per liter; NTRU, Nephelometric Turbidity Ratio Units; BC, before construction; DC, during construction; AC, after construction; dates are in month/day/year format; ratios less than 0.9 indicate downstream values are greater; ratios between 0.9 and 1.1 indicate nearly equal values; ratios greater than 1.1 indicate upstream values are greater; --, no data]

Construction phase	Date of sample collection	Time of sample collection	Limb of storm hydrograph	Upstream of culvert		Downstream of culvert		Ratio of upstream to downstream suspended sediment concentrations	Ratio of upstream to downstream turbidity values
				Suspended sediment concentration (mg/L)	Turbidity (NTRU)	Suspended sediment concentration (mg/L)	Turbidity (NTRU)		
				Oakmulgee Creek, site 4—Continued					
DC	10/14/2014	0021	Rising	1,540	480	1,010	710	1.52	0.68
AC	3/8/2017	0045	Falling, near peak	405	190	638	180	0.63	1.06
AC	4/3/2017	1100	Rising	512	250	698	200	0.73	1.25
AC	4/3/2017	1155	Peak?	583	240	476	220	1.22	1.09
AC	4/27/2017	1105	Falling	53	38	52	38	1.02	1.00
				Northington Branch, site 5					
BC	9/5/2011	1020	Rising	331	--	1,870	--	0.18	--
BC	9/5/2011	1110	Rising	288	200	561	250	0.51	0.80
BC	9/5/2011	1335	Peak	193	160	361	180	0.53	0.89
AC	4/10/2015	0745	Rising	57	46	75	55	0.76	0.84
AC	4/10/2015	0930	Rising	121	150	116	130	1.04	1.15
AC	4/10/2015	1035	Peak	102	100	98	110	1.04	0.91
AC	4/10/2015	1140	Falling	89	110	98	110	0.91	1.00
AC	11/18/2015	0800	Rising	153	130	415	390	0.37	0.33
AC	11/18/2015	0930	Rising	200	140	--	22	--	6.36
AC	11/18/2015	1115	Peak	250	190	234	180	1.07	1.06
AC	2/23/2016	2205	Rising	168	40	342	86	0.49	0.47
AC	2/23/2016	2300	Rising	410	70	705	180	0.58	0.39
AC	2/24/2016	0025	Peak	574	310	581	250	0.99	1.24
AC	2/24/2016	0120	Falling	--	140	378	150	--	0.93
				Lye Branch, site 6					
BC	4/15/2011	2145	Peak	385	230	376	230	1.02	1.00
BC	4/15/2011	2325	Falling	217	180	225	160	0.96	1.13
BC	12/20/2012	1115	Rising	93	53	85	41	1.09	1.29
BC	12/20/2012	1210	Rising	112	44	89	40	1.26	1.10
DC	1/13/2014	1520	Rising	217	6.3	99	8.3	2.19	0.76

[mg/L, milligrams per liter; NTRU, Nephelometric Turbidity Ratio Units; BC, before construction; DC, during construction; AC, after construction; dates are in month/day/year format; ratios less than 0.9 indicate downstream values are greater; ratios between 0.9 and 1.1 indicate nearly equal values; ratios greater than 1.1 indicate upstream values are greater; --, no data]

Construction phase	Date of sample collection	Time of sample collection	Limb of storm hydrograph	Upstream of culvert		Downstream of culvert		Ratio of upstream to downstream suspended sediment concentrations	Ratio of upstream to downstream turbidity values
				Suspended sediment concentration (mg/L)	Turbidity (NTRU)	Suspended sediment concentration (mg/L)	Turbidity (NTRU)		
				Lye Branch, site 6—Continued					
DC	1/13/2014	1612	Rising	41	6.5	74	8.7	0.55	0.75
DC	1/13/2014	1710	Rising	54	8.1	17	7.8	3.18	1.04
DC	1/13/2014	1805	Peak	20	7.8	181	11	0.11	0.71
DC	2/21/2014	1652	Rising	440	110	462	140	0.95	0.79
DC	4/6/2014	2358	Rising	267	110	255	100	1.05	1.10
DC	4/7/2014	0035	Rising	277	--	314	160	0.88	--
AC	3/7/2017	1910	Rising	378	150	266	150	1.42	1.00
AC	3/7/2017	2100	Rising	1,220	270	509	270	2.40	1.00
AC	3/7/2017	2235	Peak	461	250	404	250	1.14	1.00
AC	6/21/2017	1845	Rising	159	89	168	87	0.95	1.02
AC	6/21/2017	1945	Rising	171	85	166	85	1.03	1.00
AC	6/21/2017	2045	Peak	166	91	181	100	0.92	0.91
AC	8/8/2017	1828	Rising	720	310	574	260	1.25	1.19

Table 12. Analysis of ratios of paired upstream to downstream suspended sediment concentrations and turbidity values measured before, during, and after construction at selected study sites in Alabama.

[BC, before construction; DC, during construction; AC, after construction; <, less than; n< 0.9 indicates downstream values are greater than upstream values; 0.9<n<1.1 indicates nearly equal values; >, greater than; >1.1 indicates upstream values are greater than downstream values; n, number of sample pairs; --, no data]

Abbreviated site name and site number	BC					DC					AC				
	n	Mean	n<0.9	0.9<n<1.1	n>1.1	n	Mean	n<0.9	0.9<n<1.1	n>1.1	n	Mean	n<0.9	0.9<n<1.1	n>1.1
Ratio of upstream to downstream suspended sediment concentrations															
High Log Creek, site 1	5	0.97	1	4	0	5	1.02	1	3	1	7	0.96	2	4	1
Tributary to Cahaba River, site 2	--	--	--	--	--	4	0.30	4	0	0	7	1.83	2	1	4
Tributary to Sandy Creek, site 3	--	--	--	--	--	3	1.19	1	0	2	8	0.65	6	2	0
Oakmulgee Creek, site 4	5	1.36	1	1	3	5	1.79	0	1	4	4	0.90	2	1	1
Northington Branch, site 5	3	0.41	3	0	0	--	--	--	--	--	9	0.81	4	5	0
Lye Branch, site 6	4	1.09	0	3	1	7	1.27	3	2	2	7	1.30	0	3	4
All sites	17	1.01	5	8	4	24	1.15	9	6	9	42	1.07	16	16	10
All sites—All phases of construction						83	1.08	30	29	24					
Ratio of upstream to downstream turbidity															
High Log Creek, site 1	5	1.21	2	2	1	5	0.61	1	3	1	7	0.99	1	5	1
Tributary to Cahaba River, site 2	--	--	--	--	--	4	0.32	4	0	0	7	0.97	2	4	1
Tributary to Sandy Creek, site 3	--	--	--	--	--	3	0.80	2	0	1	9	1.37	1	2	6
Oakmulgee Creek, site 4	5	1.37	1	3	1	5	1.20	1	1	3	4	1.10	0	3	1
Northington Branch, site 5	2	0.84	2	0	0	--	--	--	--	--	11	1.33	4	4	3
Lye Branch, site 6	4	1.13	0	2	2	6	0.86	4	2	0	7	1.02	0	6	1
All sites	16	1.08	5	7	4	23	0.88	12	6	5	45	1.16	8	24	13
All sites—All phases of construction						84	1.07	25	37	22					

Table 13.   Storm events and maximum measured streamflow at selected study sites in Alabama.

[BC, before construction; DC, during construction; AC, after construction; hr:min, hours:minutes; ft, foot; Max streamflow, maximum measured streamflow; ft³/s, cubic feet per second; dates are in month/day/year format; time is in hour:minute format]

Construction phase	Date (and time) of start of storm event	Date (and time) of end of storm event	Elapsed time (hr:min)	Difference between maximum and minimum stage (ft)	Max streamflow (ft³/s)
High Log Creek, site 1					
BC	7/15/11 (23:15)	7/16/11 (2:30)	3:15	1.48	153
BC	2/25/13 (11:10)	2/25/13 (15:25)	4:15	0.64	104
DC	4/15/14 (6:00)	4/15/14 (9:45)	3:45	0.16	155
DC	5/26/15 (16:55)	5/26/15 (20:48)	3:53	2.4	182
AC	2/7/18 (14:00)	2/7/18 (16:25)	2:25	0.22	37.4
AC	3/6/18 (14:30)	3/6/18 (16:45)	2:15	0.28	49
AC	10/10/18 (18:40)	10/10/18 (23:35)	4:55	1.01	167
		Mean:	*3:31*	*0.88*	*121*
		Median:	*3:45*	*0.64*	*153*
Tributary to Cahaba River, site 2					
DC	4/4/11 (19:25)	4/5/11 (0:50)	5:25	0.25	2.95
AC	12/8/18 (16:05)	12/8/18 (20:20)	4:15	0.24	7.86
AC	4/18/19 (22:04)	4/19/19 (1:40)	3:36	0.53	12
		Mean:	*4:25*	*0.34*	*7.6*
		Median:	*4:15*	*0.25*	*7.86*
Tributary to Sandy Creek, site 3					
DC	1/30/13 (9:15)	1/30/13 (11:15)	2:00	0.66	16.4
AC	12/8/18 (15:19)	12/8/18 (21:49)	6:30	0.91	10.1
AC	4/18/19 (21:21)	4/19/19 (1:50)	4:29	0.28	7
		Mean:	*4:19*	*0.62*	*11.2*
		Median:	*4:29*	*0.66*	*10.1*
Oakmulgee Creek, site 4					
BC	3/30/11 (19:45)	3/31/11 (2:10)	6:25	0.32	78.6
BC	7/31/12 (9:35)	7/31/12 (11:30)	1:55	0.21	140
DC	4/6/14 (18:28)	4/6/14 (20:40)	2:12	0.04	128
DC	9/15/14 (19:08)	9/15/14 (20:40)	1:32	0.16	36.6
DC	10/13/14 (23:35)	10/14/14 (0:26)	0:51	2.34	--
AC	3/8/17 (0:38)	3/8/17 (1:52)	1:14	0.45	130
AC	4/3/17 (10:10)	4/3/17 (11:55)	1:45	1.9	193
AC	4/27/17 (11:05)	4/27/17 (11:45)	0:40	0.01	15.8
		Mean:	*2:04*	*0.68*	*103*
		Median:	*1:38*	*0.27*	*128*
Northington Branch, site 5					
BC	9/5/11 (7:50)	9/5/11 (14:00)	6:10	0.62	29.9
AC	4/10/15 (7:20)	4/10/15 (11:40)	4:20	0.29	27.9
AC	11/18/15 (8:00)	11/18/15 (11:34)	3:34	0.92	49.9
AC	2/23/16 (22:05)	2/24/16 (1:20)	3:15	1.12	42.7
		Mean:	*4:19*	*0.74*	*37.6*
		Median:	*3:57*	*0.77*	*36.3*

Table 13. Storm events and maximum measured streamflow at selected study sites in Alabama.—Continued

[BC, before construction; DC, during construction; AC, after construction; hr:min, hours:minutes; ft, foot; Max streamflow, maximum measured streamflow; ft³/s, cubic feet per second; dates are in month/day/year format; time is in hour:minute format]

Construction phase	Date (and time) of start of storm event	Date (and time) of end of storm event	Elapsed time (hr:min)	Difference between maximum and minimum stage (ft)	Max streamflow (ft³/s)
		Lye Branch, site 6			
BC	4/15/11 (20:25)	4/16/11 (1:05)	4:40	0.77	130
BC	12/20/12 (10:55)	12/20/12 (12:25)	1:30	0.15	--
DC	1/13/14 (14:22)	1/13/14 (18:20)	3:58	1.8	29.9
DC	2/21/14 (17:22)	2/21/14 (19:11)	1:49	0.91	179
DC	4/6/14 (22:07)	4/7/14 (1:08)	3:01	1.45	--
AC	3/7/17 (18:30)	3/7/17 (23:08)	4:38	1.46	117
AC	6/21/17 (18:45)	6/21/17 (21:20)	2:35	0.2	48.2
AC	8/8/17 (18:25)	8/8/17 (19:16)	0:51	0.05	--
			Mean:	*2:52*	*0.85*	*101*
			Median:	*2:48*	*0.84*	*117*

Benthic Macroinvertebrate Sampling

Benthic macroinvertebrates were collected from instream habitats upstream and downstream of the culvert construction reaches to assess the ecological effects of culvert construction. The benthic macroinvertebrate communities were considered suitable indicators of subtle changes to stream channel, flow, and water quality that may have been caused by culvert construction because different benthic macroinvertebrate organisms prefer specialized habitats in terms of flow, depth, organic material, water chemistry, and other stream characteristics (Voshell, 2002).

Benthic macroinvertebrate sample collection was planned once for the before-construction period and once for the after-construction period at all sites except the Tributary to Sandy Creek site, which was excluded because of frequent zero-flow conditions. In the summer of 2011, benthic macroinvertebrate communities were sampled to represent before-construction conditions at all sites except High Log Creek (site 1), which was not sampled in 2011 because of zero-flow conditions during the sampling period. At the Tributary to Cahaba River (site 2) in 2011, the culvert was already constructed, and road-building activities were ongoing. For this reason, the sample collected in 2011 from the Tributary to Cahaba River site is considered representative only of during-construction conditions. To represent after-construction conditions, samples were collected for analysis of benthic macroinvertebrate communities during 2014–18, depending on the schedule of culvert construction, with most samples collected during 2017 (table 14). During this study, discrete samples were collected from upstream and downstream reaches at each of the streams. Biological data for all sites are available in Gill and Pugh (2021).

Samples were collected from one or more of the richest-targeted habitats that were in common between the upstream and downstream reaches. Richest-targeted habitats are instream habitats that are considered most likely to support a diverse and abundant community of macroinvertebrates. Available habitat types varied from site to site and from time period to time period. Woody debris, riffles, roots, and undercut banks were the most commonly sampled habitats (table 14). Sample collection methods generally followed protocols established by the USGS National Water-Quality Assessment (NAWQA) Program (Moulton and others, 2002) and varied based on the type of sampled habitats. Woody snags were collected into D-frame or rectangular nets, riffle areas were sampled by using the Slack sampler, and root and undercut bank samples were collected by jabbing undercut banks with D-frame nets. Field processing for samples from all habitat types followed the NAWQA protocols (Moulton and others, 2002).

Field parameters used for measuring water quality were recorded at some sampling sites (table 14), and habitat scores were assigned for sites sampled in 2017 and 2018. Habitat assessments were made during after-construction sampling by using the U.S. Environmental Protection Agency's (EPA) Rapid Bioassessment Protocol II (Barbour and others, 1999). Habitat parameters and the ranges of scores associated with stream condition categories are summarized in table 15. Habitat scores assigned to the study streams (table 16) were used to analyze differences between upstream and downstream benthic macroinvertebrate communities.

Identification and enumeration of macroinvertebrates were determined by the USGS National Water Quality Laboratory (NWQL) Biological Group. Samples were sorted and processed using methods similar to those in the Alabama

Table 14.   Sampled instream habitats and after-construction water-quality field parameters at selected new culvert installation sites, Alabama.

[temp., temperature; °C, degrees Celsius; DO, dissolved oxygen; mg/L, milligrams per liter; SC, specific conductance; µS/cm, microsiemens per centimeter; AC, after construction; US, upstream; DS, downstream; DC, during construction; BC, before construction; m^2, square meter; dates are in month/day/year format; --, no data]

Construction phase	Reach	Date	Habitats sampled	Water temp. (°C)	DO (mg/L)	pH (standard units)	SC (µS/cm at 25 °C)
High Log Creek, site 1							
AC	US	5/9/2018	Woody snags (10)	--	--	--	--
	DS	5/9/2018	Woody snags (16)	20.4	8.9	--	104
Tributary to Cahaba River, site 2							
DC	US	6/30/2011	Root/bank; 3–5 pieces woody debris	--	--	--	--
	DS	6/30/2011	Root/bank; 1–3 pieces woody debris	--	--	--	--
AC	US	8/9/2017	1 riffle area; 4–5 root/bank jabs	23.1	8.1	6.2	35
	DS	8/9/2017	1 riffle area; 4–5 root/bank jabs	23.3	7.3	6.7	155
Oakmulgee Creek, site 4							
BC	US	6/30/2011	4–5 pieces woody debris; 10–12 linear feet overhanging root/bank; 1 woody snag in riffle section	--	--	--	--
	DS	6/30/2011	4 pieces woody debris; 9 linear feet root/bank; 1 woody snag in riffle section	--	--	--	--
AC	US	8/17/2017	Root/bank from three areas	25.2	7.2	6.4	45.5
	DS	8/17/2017	Root/bank from three areas	25.3	7.2	6.1	47.5
Northington Branch, site 5							
BC	US	7/13/2011	Submerged roots and woody debris	--	--	--	--
	DS	7/13/2011	Submerged roots and woody debris	--	--	--	--
AC	US	7/14/2014	Five 0.25-m^2 areas from riffles	29.8	8.8	6.2	46
		6/29/2017	Three 0.25-m^2 areas from each of three riffle areas	25.5	8.3	6.34	46
	DS	7/14/2014	Three 0.25-m^2 areas from riffles	29.7	8.0	6.4	46
		6/29/2017	Three 0.25-m^2 areas from each of three riffle areas	24.5	8.3	6.2	47
Lye Branch, site 6							
BC	US	6/24/2011	Woody snags (3 at downstream boundary); root/bank and submerged roots	--	--	--	--
	DS	6/24/2011	Woody snags (5–6); root/bank/overhanging roots	--	--	--	--
AC	US	6/28/2017	Woody snags (10)	--	--	--	--
	DS	6/28/2017	Woody snags (9)	--	--	--	--

Department of Environmental Management (ADEM) Standard Operating Procedures #6001 for sorting greater than or equal to 100 organisms (Alabama Department of Environmental Management, 2008). Sorted macroinvertebrates were identified using ADEM Standard Operating Procedures #6002 (Alabama Department of Environmental Management, 2007). The macroinvertebrate data are available in Gill and Pugh (2021) and were entered into the USGS Invertebrate Data Analysis System (IDAS) software (Cuffney and Brightbill, 2010).

USGS IDAS was used to calculate multiple community metrics from taxonomic data produced from the macroinvertebrate samples. The metric groups important to this study were measures of abundance, taxa richness, and average community tolerance to pollution. Metrics were based on genera or the lowest level of identification above genus. Metrics at all sites were examined before and after construction. Metrics were expected to be similar between upstream and downstream reaches before culvert construction. If the construction or presence of culverts caused changes in geomorphology, substrate, microflow patterns, vegetation, or other stream characteristics, these changes could affect the species composition of the benthic macroinvertebrate communities, which could potentially be reflected in changes in the community metric values.

Table 15. Habitat parameters and scores for condition category (Barbour and others, 1999).

Habitat parameters	Scores for condition category			
	Optimal	Suboptimal	Marginal	Poor
Epifaunal substrate/available cover	20–16	15–11	10–6	5–0
Pool substrate characterization	20–16	15–11	10–6	5–0
Pool variability	20–16	15–11	10–6	5–0
Sediment deposition	20–16	15–11	10–6	5–0
Channel flow status	20–16	15–11	10–6	5–0
Channel alteration	20–16	15–11	10–6	5–0
Channel sinuosity	20–16	15–11	10–6	5–0
Bank stability	10–9	8–6	5–3	2–0
Vegetative protection	10–9	8–6	5–3	2–0
Riparian vegetative zone	10–9	8–6	5–3	2–0
Range of score totals for condition category	200–166	153–113	100–60	47–0

Several methods have been developed to assign tolerance values (TVs) to benthic macroinvertebrate taxa based on their sensitivity to the presence and severity of pollutants or disturbances in the sampled waterbody (Barbour and others, 1999; Chang and others, 2014). For this study, TVs included with the IDAS software were used to examine average community tolerance. The IDAS software includes regional TVs developed by the EPA for the Rapid Bioassessment Protocol (Barbour and others, 1999; Cuffney and Brightbill, 2010) for individual taxa, though some regions do not have assigned TVs for all taxa. The IDAS uses the mean of all regional TVs for a taxon as a national TV for that taxon, and these existing national TVs were used in analyses for this study. For evaluation of differences in average community tolerance among sites, the following TV ranges were used: 0 to 4 for intolerant communities, 4 to 7 for moderately tolerant communities, and 7 or greater for tolerant communities.

Average community TVs were determined within IDAS based on the abundance of individuals within each taxon, or taxa richness. Abundance-weighted average TVs were calculated by using equation 1:

$$\sum_{i=1}^{N} TV_i A_i / N \qquad (1)$$

where
TV_i is the tolerance value of taxon "i,"
A_i is the abundance of taxon "i," and
N is the total number of benthic macroinvertebrates in the sample.

Richness-based average TVs were calculated by using equation 2:

$$\sum_{i=1}^{n} TV_i / n \qquad (2)$$

where
TV_i is the tolerance value of taxon "i," and
n is the number of taxa in the sample (Cuffney and Brightbill, 2010).

The Wilcoxon rank sum nonparametric statistical test was used to evaluate differences between upstream and downstream metrics before and after culvert construction. For example, for each construction period, taxa richness in the sample from the downstream reach was subtracted from taxa richness in the sample from the upstream reach for each site. The result was designated as the site's upstream to downstream difference in taxa richness for that construction period. If culvert construction had altered stream conditions enough to affect taxa richness, then the after-construction upstream to downstream difference would vary from the before-construction upstream to downstream difference. Before-construction upstream to downstream differences for all sites were pooled and compared to pooled after-construction differences by using an exact Wilcoxon rank sum test. Not all sites were sampled both before and after culvert construction. The group of before-construction samples contained three sample differences, and the group of after-construction samples included six sample differences. The sample collected in 2011 from the Tributary to Cahaba River (site 2) was not included in this analysis because it represented during-construction conditions.

To further examine the relations between upstream and downstream conditions, Bland-Altman plots were created for upstream to downstream differences for each of the metrics examined in this report. The Bland-Altman plot is an x-y scatter of the difference between pairs of data plotted against the means of the pairs. The mean difference between the pairs and the upper and lower limits of agreement (values at plus and minus two standard deviations of the mean) are graphed as horizontal lines to help identify any outliers in the differences (Bland and Altman, 1986, 1999; Glen, 2016).

Table 16. Habitat scores for each reach at selected sites sampled for benthic macroinvertebrate communities, Alabama.

[USGS, U.S. Geological Survey; US, upstream; DS, downstream; dates are in month/day/year format; see table 14 for more information about habitat scores; protocols for assigning scores from Barbour and others (1999)]

Sample date		5/9/2018		8/9/2017		8/17/2017		6/29/2017		6/28/2017	
Site number		1		2		4		5		6	
Abbreviated site name		High Log Creek		Tributary to Cahaba River		Oakmulgee Creek		Northington Branch		Lye Branch	
USGS station number[1]		02342870	02342871	02423990	02423991	02424750	02424751	02439159	02439160	02465390	02465391
Sample reach		US	DS	US	DS	US	DS	US	DS	US	DS
Habitat parameters											
Epifaunal substrate/available cover		6	5	16	18	15	15	15	13	13	15
Pool substrate characterization		3	8	18	19	11	11	18	18	9	8
Pool variability		[2]13	10	15	19	16	14	3	8	14	13
Sediment deposition		7	5	11	13	8	8	10	13	8	11
Channel flow status		20	20	12	16	8	8	8	13	16	20
Channel alteration		13	15	18	14	19	13	8	14	13	12
Channel sinuosity		9	8	14	19	13	13	5	5	5	5
Bank stability	Left bank	9	7	6	8	7	8	8	7	7	6
	Right bank	8	7	8	8	7	8	8	7	7	6
Vegetative protection	Left bank	8	7	8	8	10	9	8	7	8	4
	Right bank	5	7	9	10	10	9	10	7	8	4
Riparian vegetative zone	Left bank	9	5	8	4	9	4	0	1	10	10
	Right bank	3	5	6	8	10	8	2	1	10	5
Total score		*100*	*109*	*149*	*164*	*143*	*128*	*103*	*114*	*128*	*119*

[1]USGS National Water Information System database (U.S. Geological Survey, 2020).

[2]Pool variability score affected by beaver activity that increased pools in the reach.

For Bland-Altman plots in this report, mean differences and limits of agreement were calculated without the sample collected in 2011 from the Tributary to Cahaba River site, but the scatter points for that data are plotted for comparison of during-construction data to before- and after-construction data.

Physical Parameters Analysis

Physical data, including channel geometry parameters, suspended sediment and turbidity, were analyzed for each of the six study reaches. The following sections of this report include a brief summary of the study reach and analysis of changes between the before- and after-construction channel geometry parameters (cross-sectional area, width, mean depth, and thalweg profile) and the before-, during-, and after-construction changes in suspended sediment and turbidity.

The suggested cause for the observed changes at each site could be one of many conceivable scenarios based on two or three observations. Because consideration of all possible scenarios would be cumbersome, only causes that are associated with culvert construction are presented here. Additional observations may help to refine the causes for the observed changes and to further the understanding of the effects these new culverts are having on streams.

High Log Creek Near Hatchechubbee – Site 1

The High Log Creek site is in Russell County, central Alabama, approximately 1.4 miles west of Hatchechubbee on State Highway 26 (figs. 1 and 5). The stream is part of the Apalachicola subregional hydrologic unit (fig. 3; table 5). The drainage area above the study site is 13.7 mi^2 (table 1); in 2011, 66.0 percent of the drainage area was forest, and 24.5 percent was grassland/shrub (tables 7 and 8). The estimated 2-year peak streamflow is 956 ft^3/s (table 6). Between August 2013 and September 2016, a triple barrel, cast-in-place, concrete box culvert was constructed at the site to replace an existing bridge (table 2).

In addition to the culvert construction, other anthropogenic activities occurred near the High Log Creek site. Comparison of the February 26, 2015, imagery from Google Earth, with imagery from February 16, 2013, indicates a large area of forest was cleared upstream of the culvert at the High Log Creek site. Google Earth images of the study reaches are available from Gill and Pugh (2021).

Stream Channel Geometry

At the High Log Creek site, the only statistically significant changes in the channel geometry parameters were for the upstream cross-sectional area (−12.85 ft^2) and mean depth (−0.52 ft) (table 10). It should be noted that the after-construction, upstream thalweg reach slope was inverted (positive slope; table 9) and the two after-construction,

upstream thalweg elevation measurements nearest the culvert were approximately 3 ft above the corresponding before-construction measurements (fig. 4A). A cofferdam made of steel sheet piling reinforced with stacked rip rap was built just upstream of the culvert during construction. Remnants of the cofferdam remained through the after-construction observations. The presence of the cofferdam and its remnants caused sediment deposition in the upstream reach, resulting in the observed inverted channel slope and reduced mean depth and cross-sectional area.

Streamflow, Sediment, and Turbidity

At the High Log Creek site, surface-water samples were collected during each of the construction phases at similar streamflows with the two lowest streamflows measured during the after-construction phase (table 13). The before-construction, upstream to downstream mean paired sample ratios indicate that suspended sediment concentrations were nearly equal (0.97), but turbidity was greater upstream (1.21) (table 12). This suggests that the construction reach was trapping colloidal sediment (silt, clay, and organic matter). The during-construction mean paired sample ratios indicate that suspended sediment concentrations were nearly equal (1.02), but turbidity was greater downstream (0.61) (table 12). This suggests that the colloidal sediment (silt, clay, and organic material) was mobilized as the stream passed through the construction reach. The after-construction mean paired sample ratios indicate that suspended sediment concentrations and turbidity were both nearly equal (0.96 and 0.99, respectively) (table 12), suggesting that the creek's sediment load was efficiently passing through the construction reach.

Tributary to Cahaba River Near Centreville – Site 2

The Tributary to Cahaba River site is in Bibb County, central Alabama, approximately 1.1 miles northeast of Centreville on U.S. Highway 82 (figs. 1 and 6). The tributary is part of the Alabama subregional hydrologic unit (fig. 3; table 5). The drainage area above the study site is 0.39 mi^2 (table 1); in 2011, 79.7 percent of the drainage area was forest, and 10.9 percent was grassland/shrub (tables 7 and 8). The estimated 2-year peak streamflow is 94.0 ft^3/s (table 6). Between November 2010 and August 2013, a single barrel precast concrete box culvert was constructed by using a buried culvert inverts design as part of the new U.S. Highway 82 corridor construction (table 2).

Stream Channel Geometry

At the Tributary to Cahaba River study site, statistically significant changes in the channel geometry parameters occurred in the upstream and downstream cross-sectional areas (3.15 ft^2 and 1.30 ft^2, respectively) and mean depths
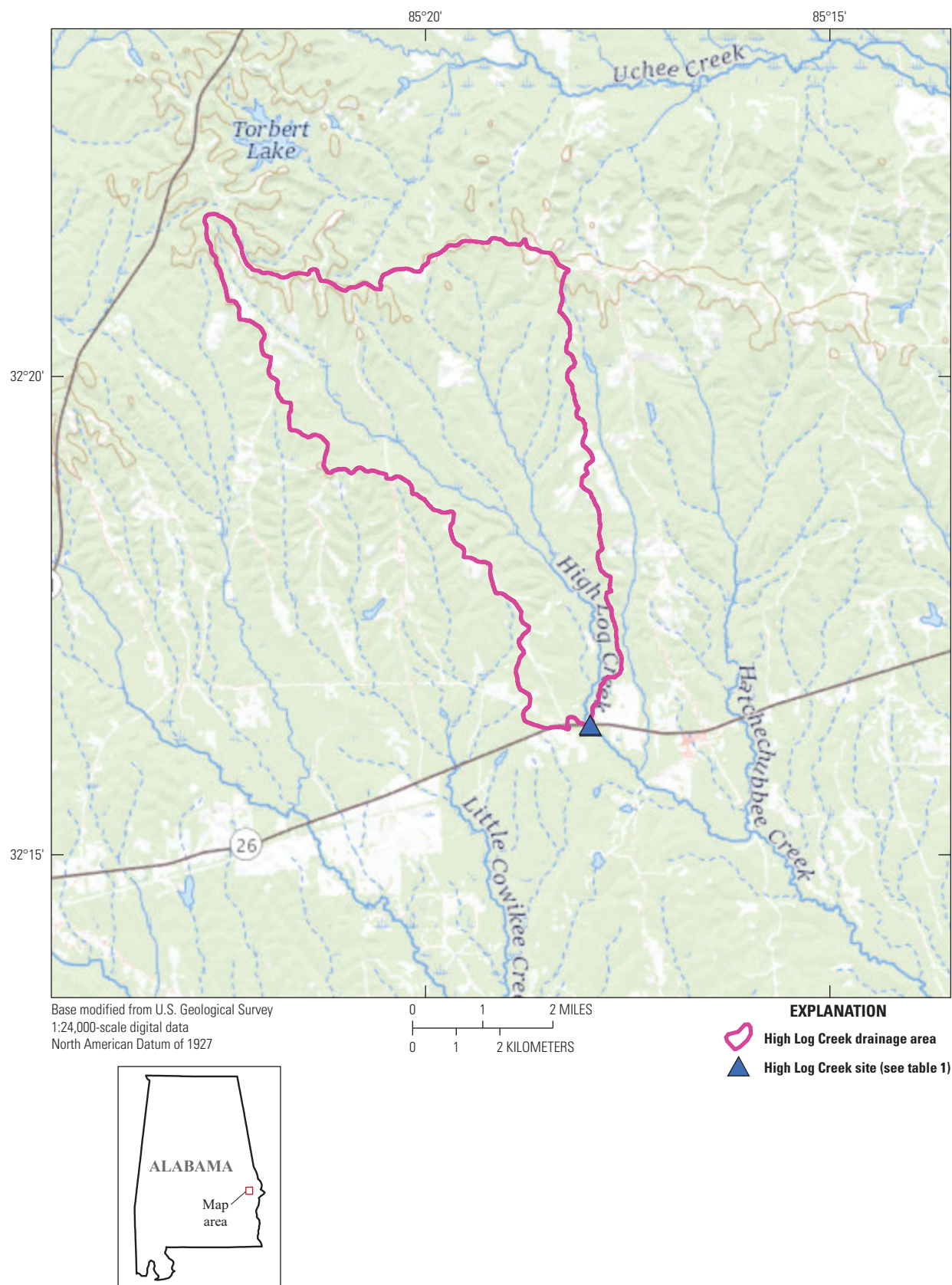
Figure 5.   Location of High Log Creek near Hatchechubbee (site 1) and the associated drainage area.
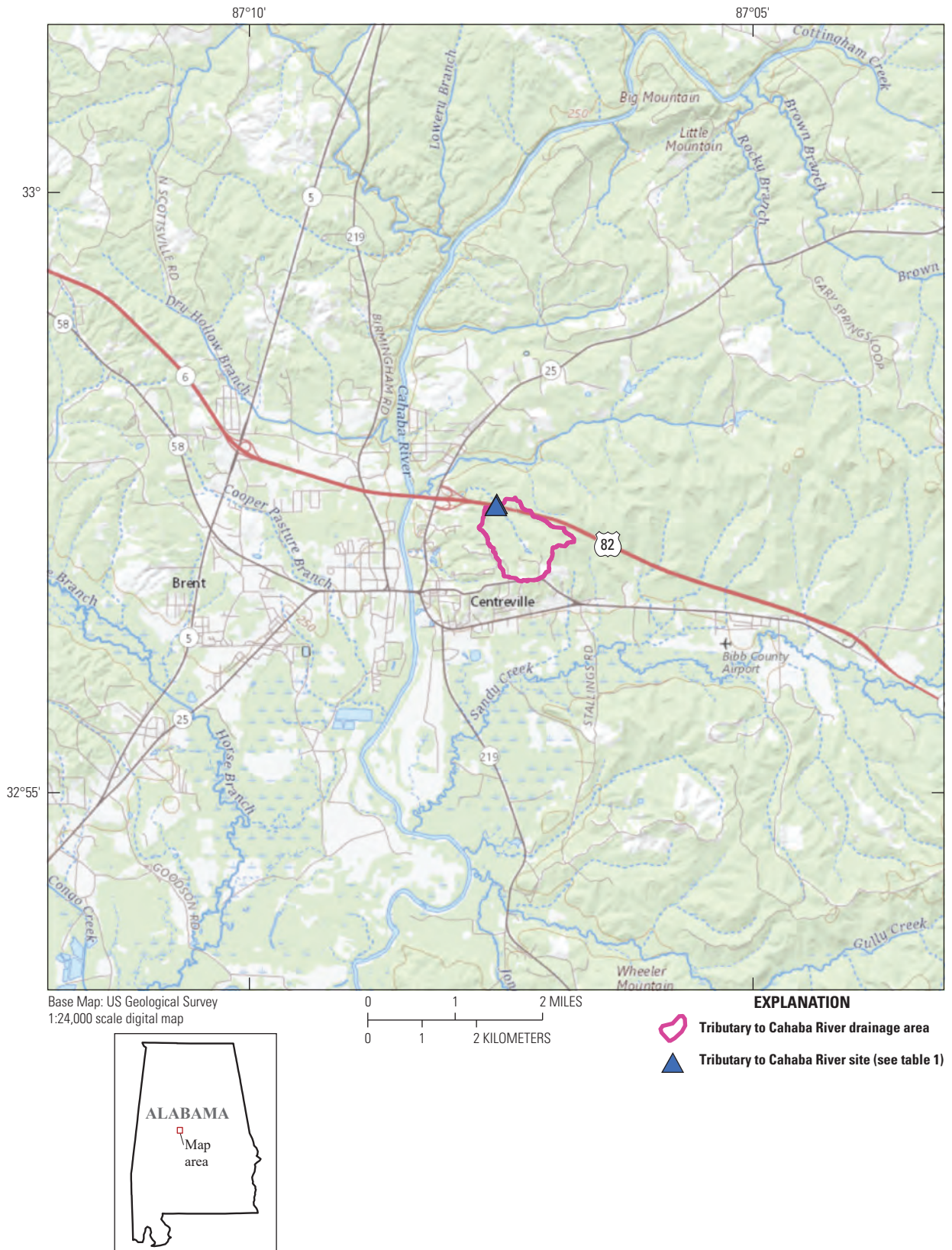
Figure 6.   Location of Tributary to Cahaba River near Centreville (site 2) and the associated drainage area.

(0.21 ft and 0.09 ft, respectively) (table 9). Although the thalweg slopes did not change significantly, the upstream and downstream thalweg elevations were lower in the after-construction phase (table 10; figs. 4C and 4D). This suggests that the culvert inverts were set at an elevation below the before-construction thalweg, thus inducing erosion in the upstream reach and increasing the cross-sectional areas and mean depths observed in the upstream reach. Erosion of the downstream reach indicates that the construction site's erosion control measures trapped sediment, resulting in sediment-free water exiting the site and eroding the upstream part of the downstream reach; the observed increases in the cross-sectional areas and mean depths in the downstream reach also support this conclusion.

Streamflow, Sediment, and Turbidity

At the Tributary to Cahaba River study site, samples were collected during three storm events; one was during construction, and two were after construction (tables 11 and 13). The during-construction, upstream to downstream mean paired sample ratios indicate suspended sediment concentrations and turbidity were greater downstream (0.30 and 0.32, respectively) (table 12), suggesting that sediment was mobilized as the stream passed through the construction reach. The after-construction mean paired sample ratios indicate that sediment concentrations were greater upstream (1.83), but turbidity was nearly equal (0.97) upstream and downstream (table 12). This suggests that the construction reach was trapping the larger sediment particles (sand), while the colloidal part of the suspended sediment (silt, clay, and organic material) passed through the construction reach. Together, the after-construction channel geometry and sediment data suggest that the thalweg of the stream was still adjusting to match the upstream and downstream channel reaches.

Tributary to Sandy Creek Near Vick – Site 3

The Tributary to Sandy Creek site is in Bibb County, central Alabama, approximately 0.5 mile east of Vick on U.S. Highway 82 (figs. 1 and 7). The tributary is part of the Alabama subregional hydrologic unit (fig. 3; table 5). The drainage area above the study site is 1.34 mi^2 (table 1). In 2011, 83.8 percent of the drainage area was forest, and 10.5 percent was grassland/shrub (tables 7 and 8). The estimated 2-year peak streamflow is 235 ft^3/s (table 6). Between November 2010 and August 2013, a triple barrel cast-in-place, concrete box culvert was constructed as part of the new U.S. Highway 82 corridor construction (table 2).

Stream Channel Geometry

At the Tributary to Sandy Creek study site, no statistically significant changes in the channel geometry parameters occurred (tables 9 and 10). Note that the after-construction,

downstream thalweg slope was inverted (table 10), and the after-construction, downstream thalweg elevations nearest the culvert were lower than the before construction elevations by approximately 0.3 foot (ft) (fig. 4F). In addition to the culvert, several other engineered structures were built within the construction reach. These structures included a temporary bypass channel to convey streamflow around the construction area, ditches on both sides of the new highway that drain into the creek, and an engineered energy dissipation basin at the outlet of the culvert. Together, the observed inverted downstream thalweg slope and lower downstream thalweg elevations suggest that sediment-free water exited the construction reach, eroding the streambed in the upper parts of the downstream reach.

Streamflow, Sediment, and Turbidity

At the Tributary to Sandy Creek site, no samples were collected during storm events before construction began, samples were collected during one storm event during construction, and samples were collected during two storm events after construction (table 13). The storm event with the maximum measured streamflow occurred in the during-construction phase (table 13). The during-construction, upstream to downstream mean paired sample ratios indicate sediment concentrations were greater upstream (1.19), but turbidity was greater downstream (0.80) (table 12). This suggests that the relatively larger particles of the suspended sediment load (sand) were being trapped within the construction reach while the relatively smaller colloidal sediment (silt, clay, and organic material) was being mobilized from the construction reach during construction. The after-construction mean paired sample ratios indicate that sediment concentrations were greater downstream (0.65) while turbidity was greater upstream (1.37) (table 12). This suggests that the relatively larger particles of suspended sediment (sand) were being mobilized within the construction reach while the relatively smaller colloidal particles (silt, clay, and organic material) were being trapped within the construction reach after construction.

Together, the channel geometry and sediment data suggest that after construction, the release of sediment-free water did not continue. Energy dissipation in the basin and the construction site's erosion control measures combined to prevent sediment from exiting the site during construction. Once the culvert construction was completed and the erosion control measures removed, the suspended sediment load returned to normal.

Oakmulgee Creek Near Lawley – Site 4

The Oakmulgee Creek site is in Bibb County, central Alabama, approximately 1.2 miles southwest of Lawley on U.S. Highway 82 (figs. 1 and 8). Oakmulgee Creek is part of the Alabama subregional hydrologic unit (fig. 3; table 5). The drainage area above the study site is 12.5 mi^2 (table 1).
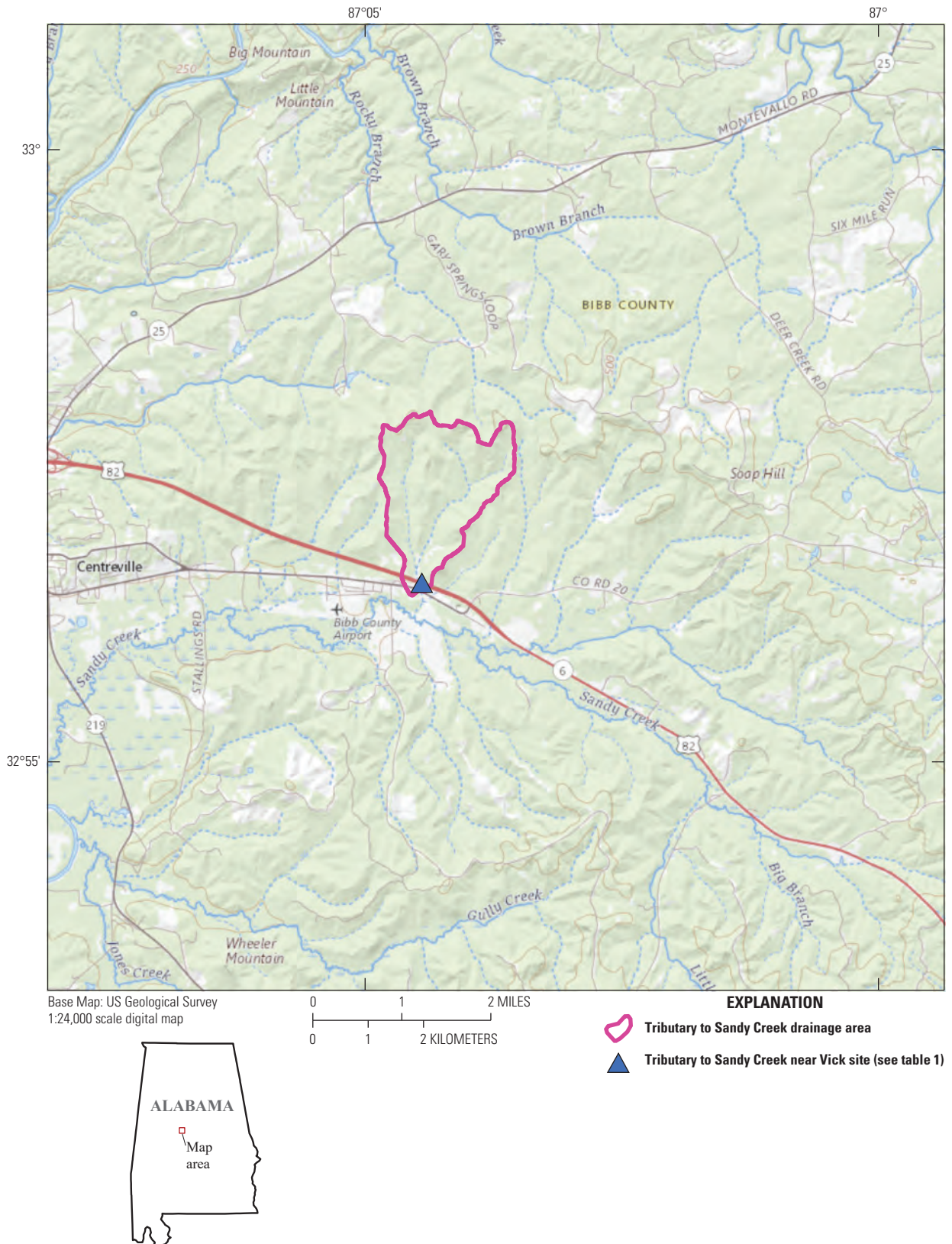
Figure 7.   Location of Tributary to Sandy Creek near Vick (site 3) and the associated drainage area.
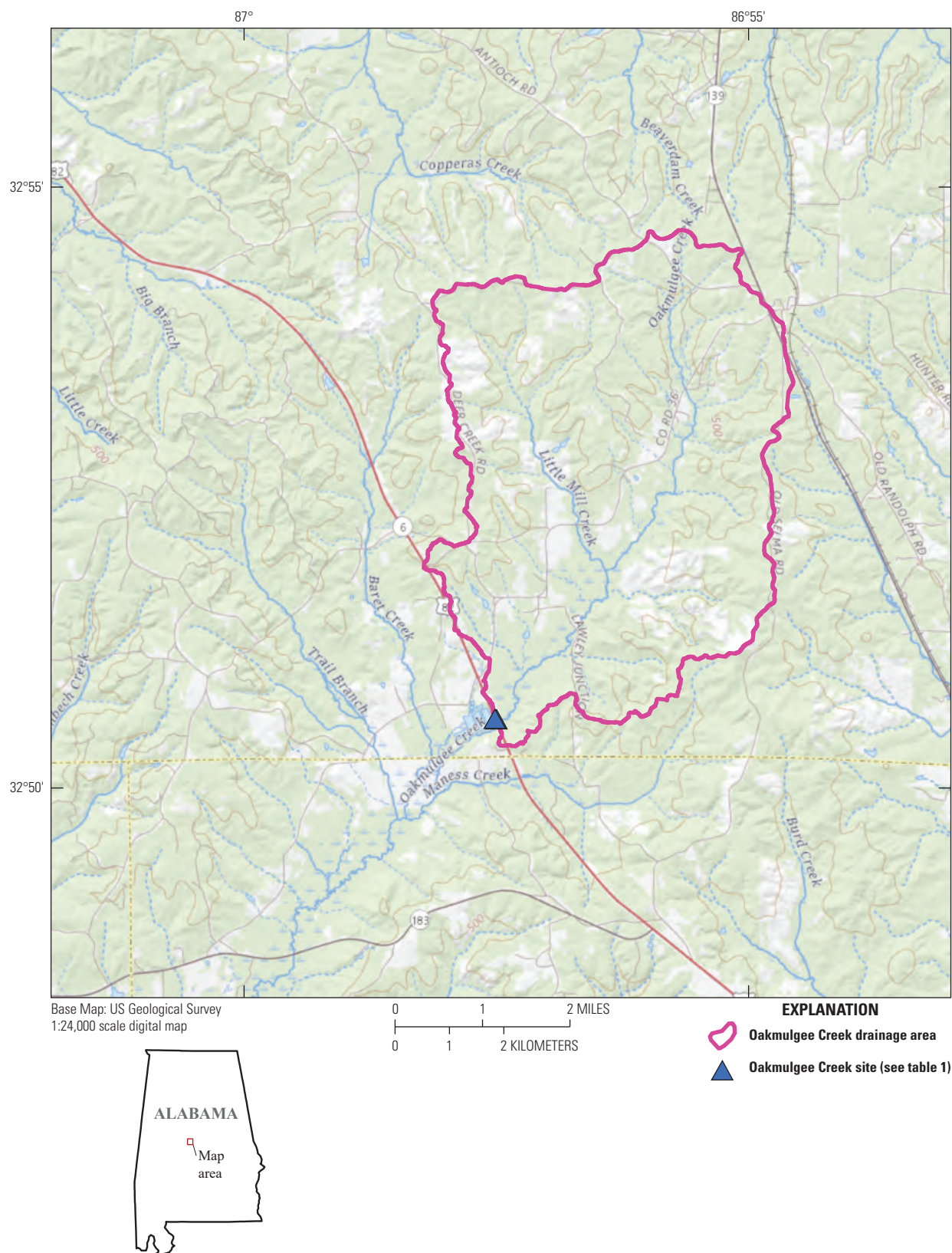
Figure 8.   Location of Oakmulgee Creek near Lawley (site 4) and the associated drainage area.

In 2011, 54.3 percent of the drainage area was forest, and 30.1 percent was grassland/shrub (tables 7 and 8). The estimated 2-year peak streamflow is 879 ft³/s (table 6). Between October 2013 and March 2015, a triple barrel cast-in-place, concrete box culvert was constructed at the site to replace an existing bridge (table 2).

Stream Channel Geometry

At the Oakmulgee Creek study site, no statistically significant changes in the channel geometry parameters occurred (tables 9 and 10). Note there was substantial change in the downstream thalweg profile shape and point elevations from before- to after construction. Differences in the downstream thalweg point elevations ranged from −0.6 ft to 3.5 ft. (fig. 4*H*). The change in downstream thalweg profile shape and point elevations (fig. 4*H*) indicate that a head cut was propagating upstream through the downstream reach. The 2010 thalweg elevations suggest a head cut had progressed upstream to between the 225-ft and 250-ft downstream stationing, and the 2016 thalweg elevations suggest the head cut had continued to propagate upstream to near the 100-ft downstream stationing (fig. 4*H*).

Streamflow, Sediment, and Turbidity

At the Oakmulgee Creek study site, streamflow was measured, and samples were collected during all three phases of construction, representing a variety of streamflow magnitudes (table 13). The before-construction, upstream to downstream mean paired sample ratios indicate that sediment concentrations and turbidity were both greater upstream (1.36 and 1.37, respectively) (table 12). This suggests that the construction reach was trapping sediment. The during-construction mean paired sample ratios indicate that sediment concentrations and turbidity were both greater upstream (1.79 and 1.20, respectively) (table 12), suggesting the construction reach was still trapping sediment. The after-construction mean paired sample ratios indicate that sediment concentrations and turbidity were nearly equal upstream and downstream (0.90 and 1.10, respectively) (table 12). This suggests that suspended sediment was efficiently passing through the construction reach after construction.

Northington Branch Near Detroit – Site 5

The Northington Branch site is in Lamar County, northwestern Alabama, approximately 1.8 miles west of Detroit, Ala., on County Road 5 (figs. 1 and 9). Northington Branch is part of the Mobile-Tombigbee subregional hydrologic unit (fig. 3; table 5). The drainage area above the study site is 6.22 mi² (table 1). In 2011, 66.9 percent of the drainage area was forest, and 21.2 percent was grassland/shrub (tables 7 and 8). The estimated 2-year peak streamflow is 555 ft³/s (table 6).

Between October 2011 and April 2013, a triple barrel cast-in-place, concrete box culvert was constructed to replace an existing bridge (table 2).

Stream Channel Geometry

At the Northington Branch site, the only statistically significant change in the channel geometry parameters was in the downstream mean depth (−0.20 ft) (tables 9 and 10). Note that the before-construction, upstream reach thalweg slope was inverted (table 10). The inverted before-construction, upstream reach thalweg slope suggests a streamflow obstruction in the upstream part of the construction reach, trapping sediment in the downstream part of the upstream reach. After construction, the upstream reach thalweg returned to a normal slope, suggesting the streamflow obstruction was removed during construction and sediments in the upstream reach mobilized. Concurrently, sediment was trapped in the downstream reach, resulting in the observed reduction in mean depth (table 9).

Streamflow, Sediment, and Turbidity

At the Northington Branch site, measurements and samples were collected during one storm event in the before-construction phase and three storm events in the after-construction phase (table 13). Maximum measured storm streamflows were similar for both phases of construction (table 13). The before-construction, upstream to downstream mean paired sample ratios indicate that sediment concentrations and turbidity were both greater downstream (0.41 and 0.84, respectively) (table 12). This suggests that sediment was being mobilized as the streamflow passed through the construction reach. The after-construction mean paired sample ratios indicate that sediment concentrations were greater downstream (0.81) while turbidity was greater upstream (1.33) (table 12). This suggests that the larger particles of suspended sediment (sand) were being mobilized within the construction reach while smaller colloidal particles (silt, clay, and organic material) were being trapped within the construction reach after construction.

Lye Branch Near Duncanville – Site 6

The Lye Branch site is in Tuscaloosa County, northwest central Alabama, approximately 3.5 miles northeast of Duncanville on Hargrove Road (figs. 1 and 10). Lye Branch is part of the Mobile-Tombigbee subregional hydrologic unit (fig. 3; table 5). The drainage area above the study site is 16.4 mi² (table 1). In 2011, 66.2 percent of the drainage area was forest, and 24.6 percent was grassland/shrub (tables 7 and 8). The estimated 2-year peak streamflow is 1,060 ft³/s (table 6). Between November 2013 and December 2018, a quadruple barrel cast-in-place, concrete box culvert was constructed to replace an existing bridge (table 2).
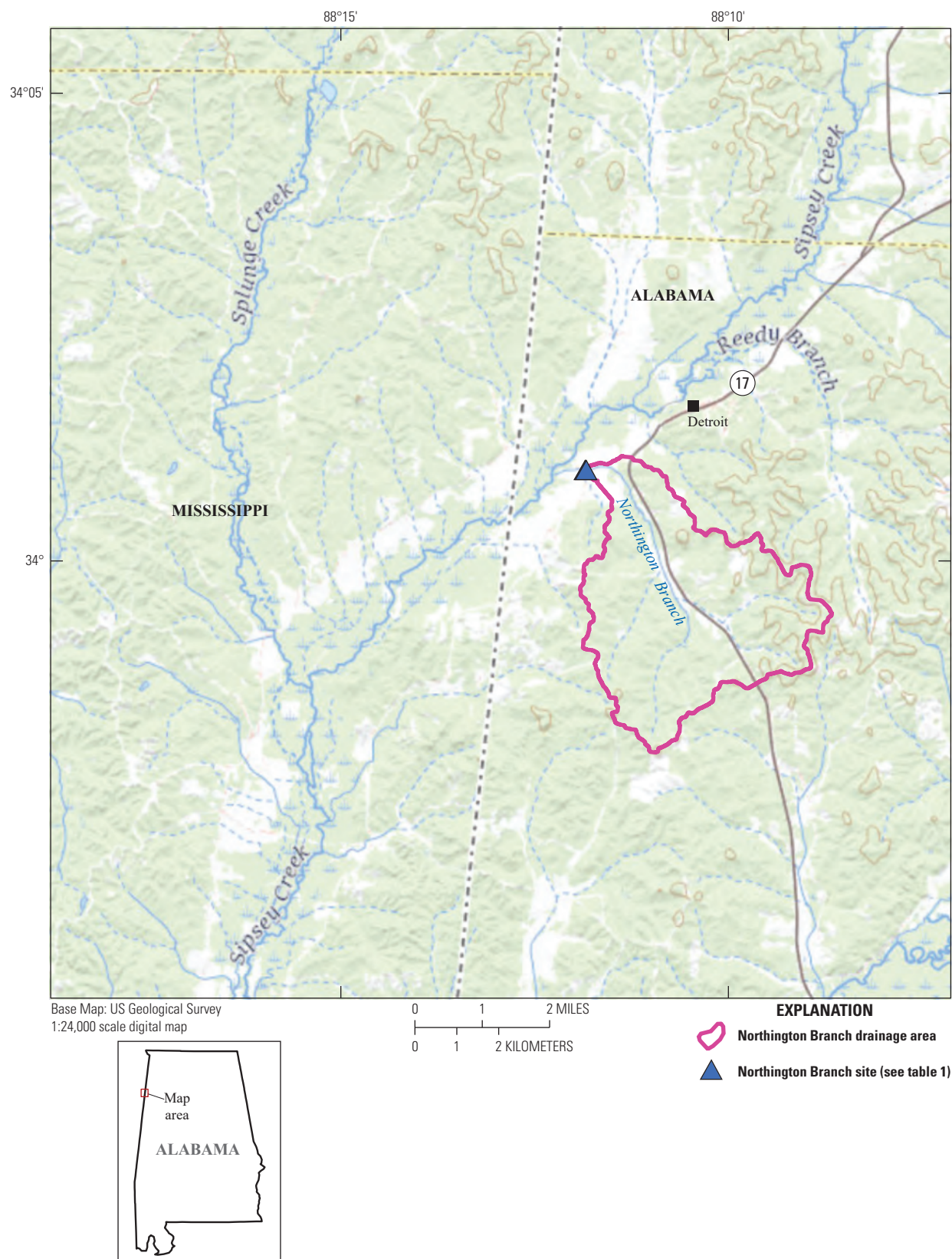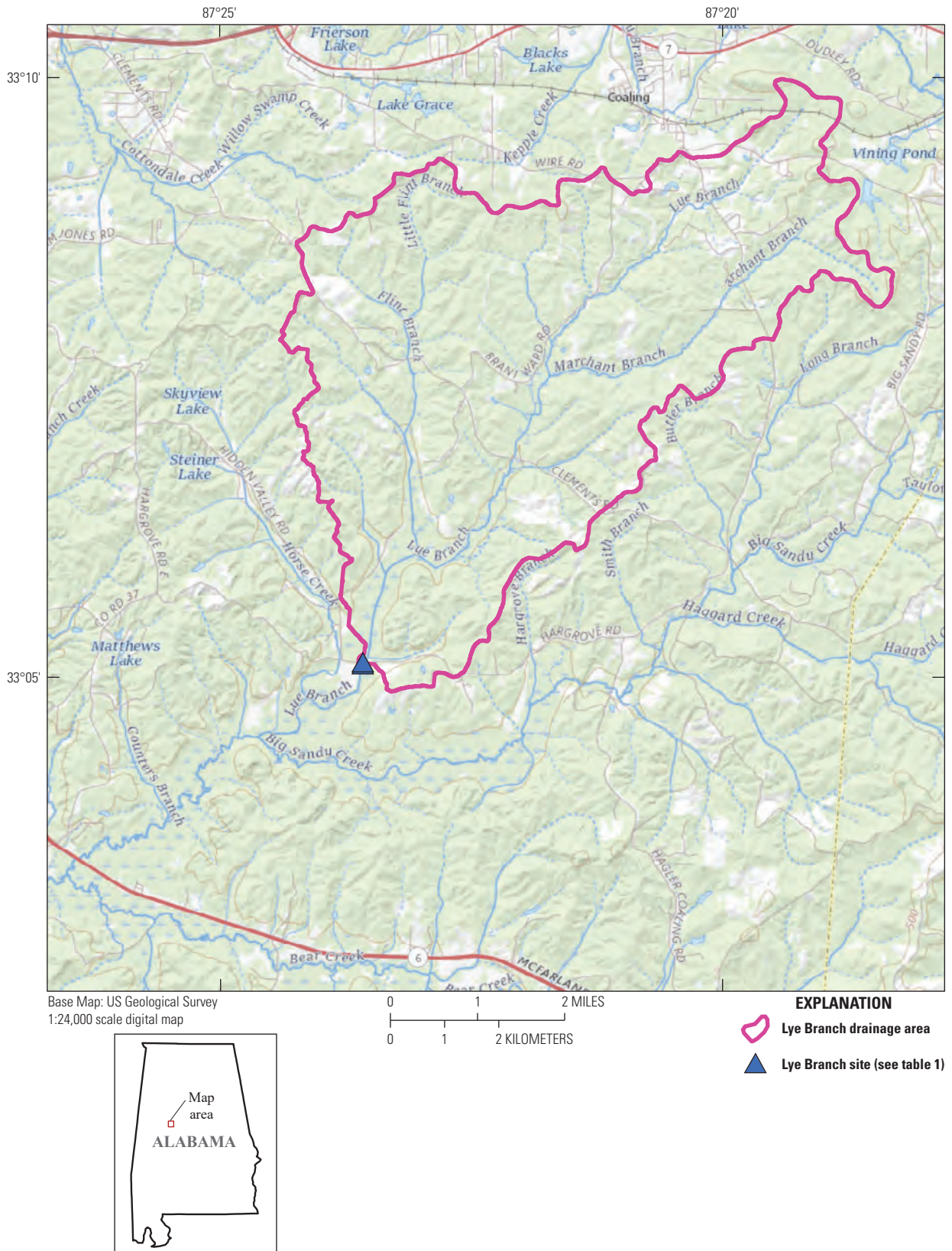
Figure 9. Location of Northington Branch near Detroit (site 5) and the associated drainage area.

Figure 10.   Location of Lye Branch near Duncanville (site 6) and the associated drainage area.

In addition to the culvert construction, other anthropogenic activities occurred near the Lye Branch site. Comparison of the May 5, 2014, imagery from Google Earth, with imagery from October 20, 2012, indicates that approximately 20 acres of forest were cleared upstream of the culvert and that the right bank of Lye Branch was cleared for approximately 500 ft downstream of the culvert. Google Earth images of the study reaches are available from Gill and Pugh (2021).

Stream Channel Geometry

At the Lye Branch study site, statistically significant changes in the channel geometry parameters occurred in the downstream mean depth (−0.70 ft) and the upstream thalweg slope (0.0044) (tables 9 and 10). Note that the before-construction, downstream reach and the after-construction, upstream reach thalweg slopes were inverted (table 10). The after-construction, upstream thalweg elevations measured closest to the culvert were approximately 0.75 ft higher than the before-construction elevations (fig. 4K). The after-construction, downstream thalweg elevations through the entire reach were approximately 1.3 ft higher than the before-construction elevations (fig. 4L). The inverted, before-construction, downstream reach thalweg slope suggests that a channel obstruction downstream of the downstream study reach caused sediment deposition in the lower part of the reach, resulting in the observed inverted reach thalweg slope. The increased thalweg elevations and inverted thalweg slope in the after-construction, upstream reach suggests a channel obstruction within the construction reach, possibly remnants of the temporary detour bridge built, used, and removed during the construction of the culvert. The increased thalweg elevations throughout the after-construction, downstream reach suggest that the channel obstruction downstream of the reach continued to cause sediment deposition, correcting the downstream reach thalweg slope and reducing the mean depth as noted in the stream geometry t-test results (table 9).

Streamflow, Sediment, and Turbidity

At the Lye Branch study site, samples were collected during eight storm events—two before construction, three during construction, and three after construction (table 13). Streamflow was not measured during three of the storm events, one in each of the construction phases. Measured maximum streamflows during storm events ranged from 29.9 to 179 ft³/s (table 13). The before-construction, upstream to downstream mean paired sample ratios indicate that sediment concentrations were nearly equal (1.09), but the turbidity was greater upstream (1.13) (table 12). This suggests the construction reach was trapping colloidal sediment (silt, clay, and organic matter) before construction. The during-construction mean paired sample ratios indicate that sediment concentrations were greater upstream (1.27), but the turbidity was greater downstream (0.86) (table 12). This suggests that the larger particles of suspended sediment (sand) were being trapped within the construction reach while smaller colloidal particles (silt, clay, and organic material) were being mobilized within the construction reach. The after-construction mean paired sample ratios indicate that sediment concentrations were greater upstream (1.30), and the turbidity was nearly equal (1.02) (table 12). This suggests that the larger sediment particles (sand) were mobilized from the construction reach after construction.

Benthic Macroinvertebrate Analysis

The analysis of benthic macroinvertebrate community metrics is organized into a project-wide evaluation and site-by-site evaluations. First, samples from all study sites were pooled into before- and after-construction groups to evaluate the project-wide consistency of community changes between the two periods. Second, because some of the observed variation in communities is a natural response to the unique habitat, flow, riparian zone, and other conditions of each stream, upstream to downstream comparisons for communities at each site were examined to determine if local effects of culvert construction were evident.

Macroinvertebrate abundance and taxa richness varied among the study sites. Total abundance of macroinvertebrates in a single sample ranged from a maximum of more than 1,000 organisms to a minimum of 33 individuals. Ephemeroptera, Plecoptera, and Trichoptera (EPT) abundance ranged from 3 to almost 600 individuals per sample (fig. 11; Gill and Pugh, 2021). Taxa richness at all sites ranged from 20 to 46 taxa per sample (fig. 12). EPT taxa richness ranged from a single taxon in one sample to a maximum of 14 taxa (fig. 12).

At least 81 percent of identified taxa in the study streams had IDAS-assigned national TVs, and at least 82 percent of benthic macroinvertebrate abundance from each sampled community was assigned a national TV. Average community TVs from all sites were between 4 and 7, which is considered moderately tolerant (fig. 13; Cuffney and Brightbill, 2010; Barbour and others,1999). Average abundance-weighted TVs for all reaches and all time periods ranged from 4.07 at the Oakmulgee Creek downstream reach to 6.95 at the Tributary to Cahaba upstream reach (fig. 13A). Average richness-based TVs ranged from a low of 4.47 at the Lye Branch upstream reach in the after-construction phase to a high of 6.20 at the Tributary to Cahaba upstream reach in the during-construction phase (fig. 13B).

The Wilcoxon rank sum test results indicated that there was little variation between before- and after-construction periods in the upstream to downstream difference in community metrics. Total abundance, total taxa richness, EPT abundance and taxa richness, and abundance-weighted and richness-based average tolerance values did not have statistically significant differences in the pooled analysis (table 17); however, graphs of these metrics (figs. 11–13) and related habitat and water-quality data (tables 14 and 16) reveal some differences in reach characteristics that are discussed individually for each site.

Table 17.   Metrics calculated by IDAS and Wilcoxon rank sum statistics to test for significance of differences between before-construction and after-construction variation for metric values in upstream and downstream reaches at selected sites in Alabama.

[IDAS, U.S. Geological Survey Invertebrate Data Analysis System (Cuffney and Brightbill, 2010); Wilcoxon rank sum statistics are not significant (p<0.5); %, percent]

Metric description	Metric abbreviation	Wilcoxon rank sum statistic	Metric abbreviation	Wilcoxon rank sum statistic
Abundance and percent abundance metrics				
	Abundance		%Abundance	
Total number of organisms in the sample	ABUND	14		
Abundance of Ephemeroptera, Plecoptera, and Trichoptera	EPT	15	EPTp	15
Richness and percent richness metrics				
	Richness		%Richness	
Total richness (number of taxa)	RICH	13		
Number of Ephemeroptera, Plecoptera, and Trichoptera taxa	EPTR	13.5	EPTRp	14
Tolerance metrics				
Mean of taxa tolerances: $\sum_{i=1}^{N} \dfrac{TVi}{N}$ where TVi is the tolerance value of taxon "i" and N is the number of taxa in the sample	RichTOL	17		
Abundance-weighted mean taxa tolerances: $\sum_{i=1}^{N} \dfrac{TViAi}{N}$ where TVi is the tolerance value of taxon "i," Ai is the abundance of taxon "i," and N is the number of taxa in the sample (Hilsenhoff biotic index)	AbundTOL	17		

Different richest-targeted habitats were chosen for the before-construction and after-construction samples because of site conditions. All before-construction samples included collections from overhanging or submerged roots, whereas many of the after-construction samples included collections from riffle areas and woody snags. The differences in richest-targeted habitats between the two sampling periods may explain the lack of a statistically significant change in upstream to downstream differences in community metrics between the before-construction and after-construction sampling periods. Future studies of these sites might benefit from the use of standardized artificial substrates to minimize the variability of sampled benthic communities within and between sites due to differences in sampled substrates.

Bland-Altman plots for the metrics reveal some overall patterns in upstream to downstream differences for a few metrics (figs. 14–16). In agreement with the Wilcoxon rank sum analysis (table 17), the plots show that for total abundance, total richness, EPT richness, and richness-based average tolerance, all differences between upstream and downstream for before- and after-construction periods were within the two standard deviations of the mean difference. Upstream to downstream differences in EPT abundance at the Northington Branch site in 2014 (fig. 14B) and in abundance-weighted tolerance at the Tributary to Cahaba River site in 2017 (fig. 16A) were outside of the limits of agreement.

In general, upstream to downstream differences in total abundance were near zero, with slightly more abundance in the upstream reaches for most sites and sampling periods (fig. 14A). Lye Branch had more organisms downstream than upstream in the before-construction sample and similar counts in both reaches in the after-construction sampling period. In 2014, Northington Branch had much more abundance in the upstream reach than in the downstream reach. EPT abundance was also similar between each set of reaches for almost all the sampling sites and time periods (fig. 14B). Only the EPT abundance in Northington Branch samples in 2014 differed greatly between reaches, with about 500 more EPT organisms in the upstream reach.

Total richness only varied by an average of 1.56 taxa between upstream and downstream reaches (fig. 15A). Northington Branch was the most variable site in terms of total taxa richness, having 10 more taxa in the downstream reach than in the upstream reach in 2014 and 16 more taxa in the upstream reach than in the downstream reach in 2017. Differences between upstream and downstream total richness at most other sites and sample sites were within five taxa (fig. 15A). EPT taxa richness was slightly greater in the upstream reaches than in the downstream reaches for almost all samples (fig. 15B), both before and after construction, which indicates that the differences were not related to new culvert construction.
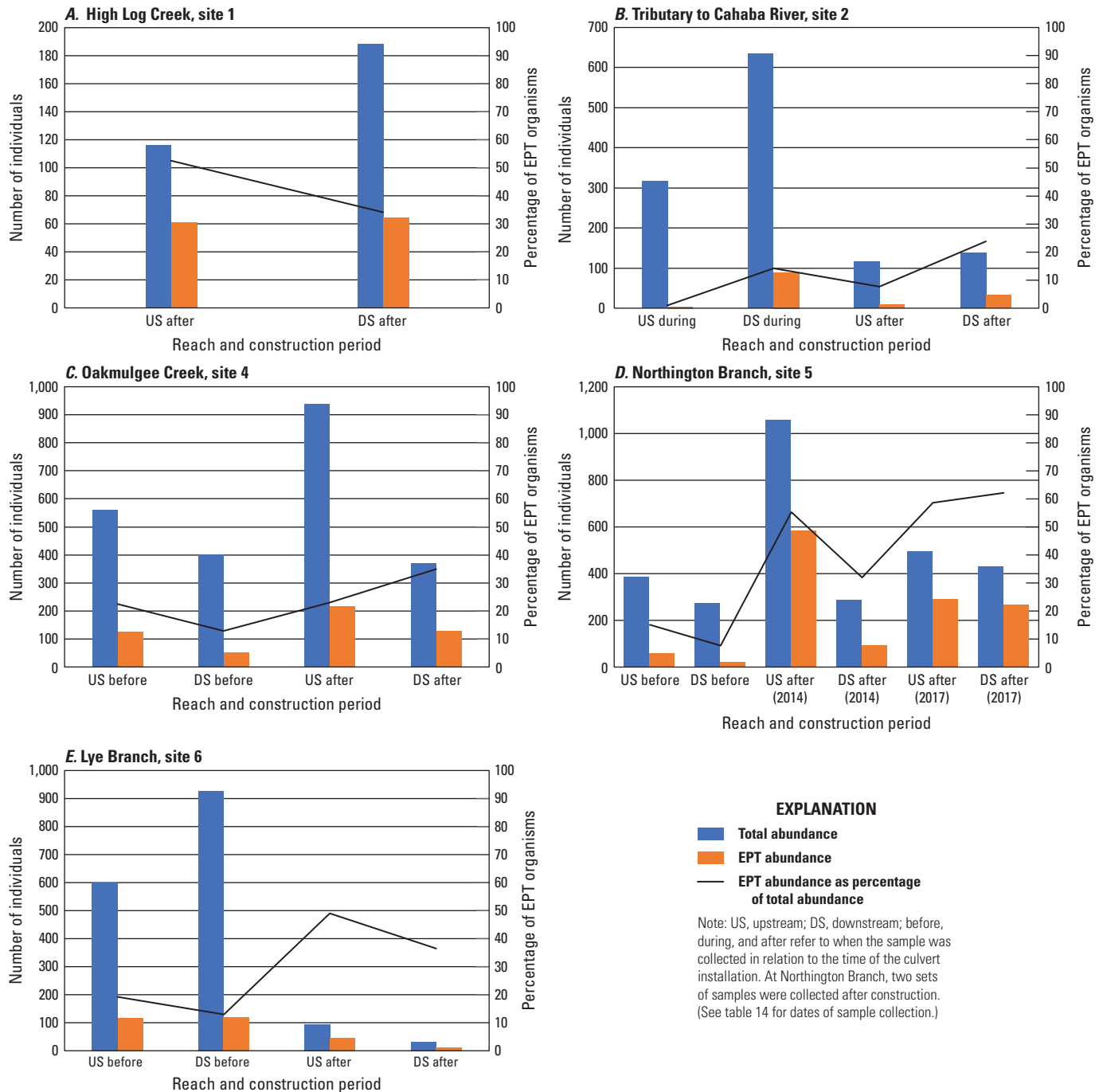
Figure 11. Total abundance of benthic macroinvertebrates, abundance of Ephemeroptera, Plecoptera, and Trichoptera (EPT) organisms, and EPT abundance as a percentage of total abundance in before-, during-, and after-construction samples collected from reaches upstream and downstream of new culvert installations at selected sites in Alabama.

Abundance-weighted TVs differed very little between upstream and downstream reaches, with a mean difference of nearly zero (fig. 16A). The samples collected from the Tributary to Cahaba River site (during and after construction) differed the most between reaches, with upstream average TVs slightly higher than downstream TVs. Richness-based average TVs were more likely to be higher downstream

than upstream, but the differences were small for most sites (fig. 16B). Richness-based TVs for the Tributary to Cahaba River site in 2011 (during construction) were higher upstream than downstream.

The upstream to downstream differences for the during-construction sample collected from the Tributary to Cahaba River site in 2011 plotted outside of the limits of agreement on
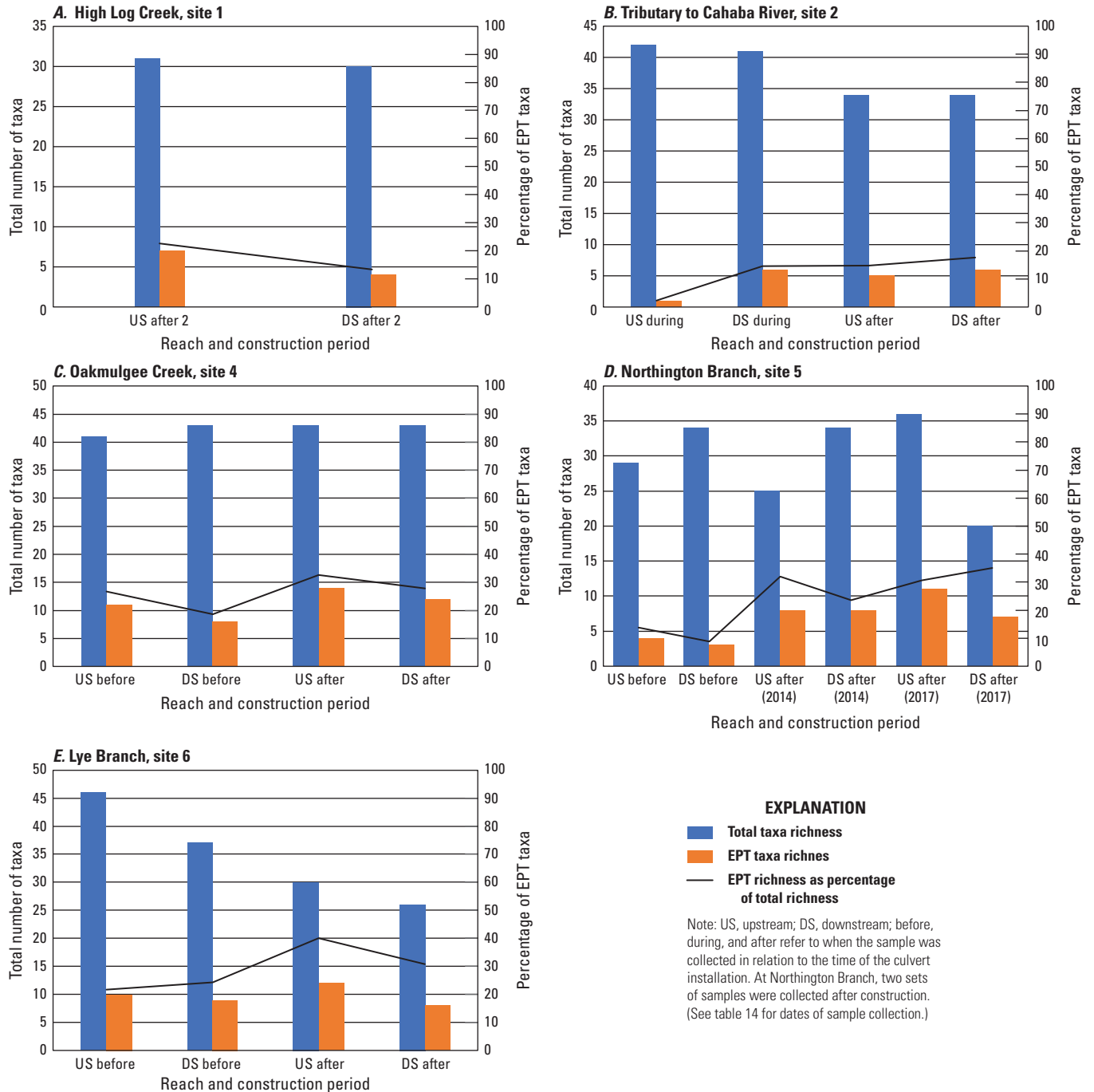
Figure 12.   Total taxa richness, Ephemeroptera, Plecoptera, and Trichoptera (EPT) taxa richness, and EPT richness as a percentage of total richness in before-, during-, and after-construction samples collected from reaches upstream and downstream of new culvert installations at selected sites in Alabama.

the EPT richness, abundance-weighted TV, and richness-based TV Bland-Altman plots (figs. 15*B*, 16*A* and *B*). The difference in EPT taxa richness plotted below the lower limit of agreement for EPT richness, and differences in both tolerance metrics were above their respective upper limits of agreement. These results indicate that during road construction at this site the benthic macroinvertebrate community at the downstream

reach had more EPT taxa and less tolerant taxa than the upstream reach. Sediment and water-quality control measures used during construction appear to have adequately prevented degradation to the benthic macroinvertebrate community in the downstream reach.
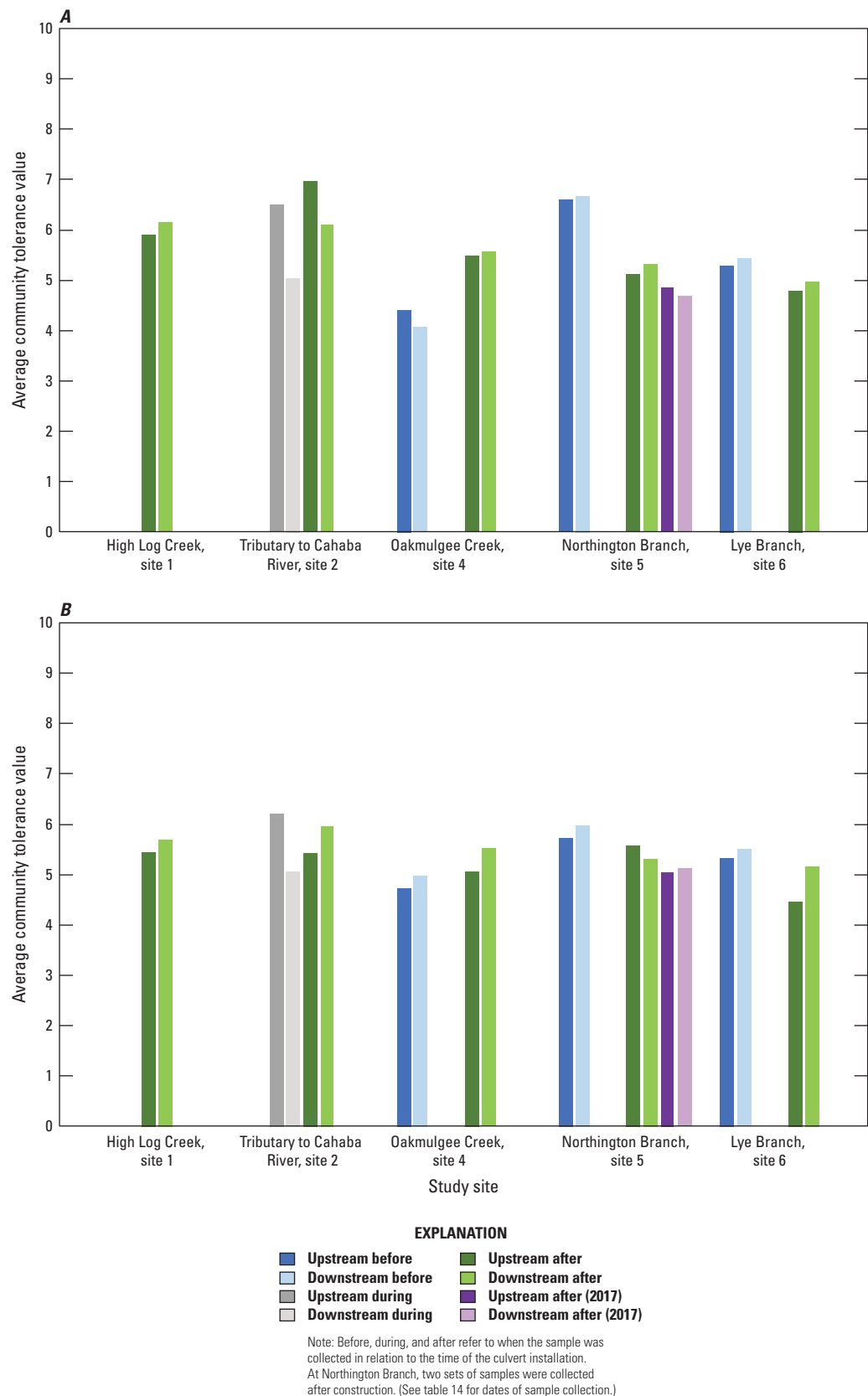
Figure 13.   Average community tolerance values based on *A*, total abundance and *B*, taxa richness in benthic macroinvertebrate community samples collected at selected culvert installation sites in Alabama.
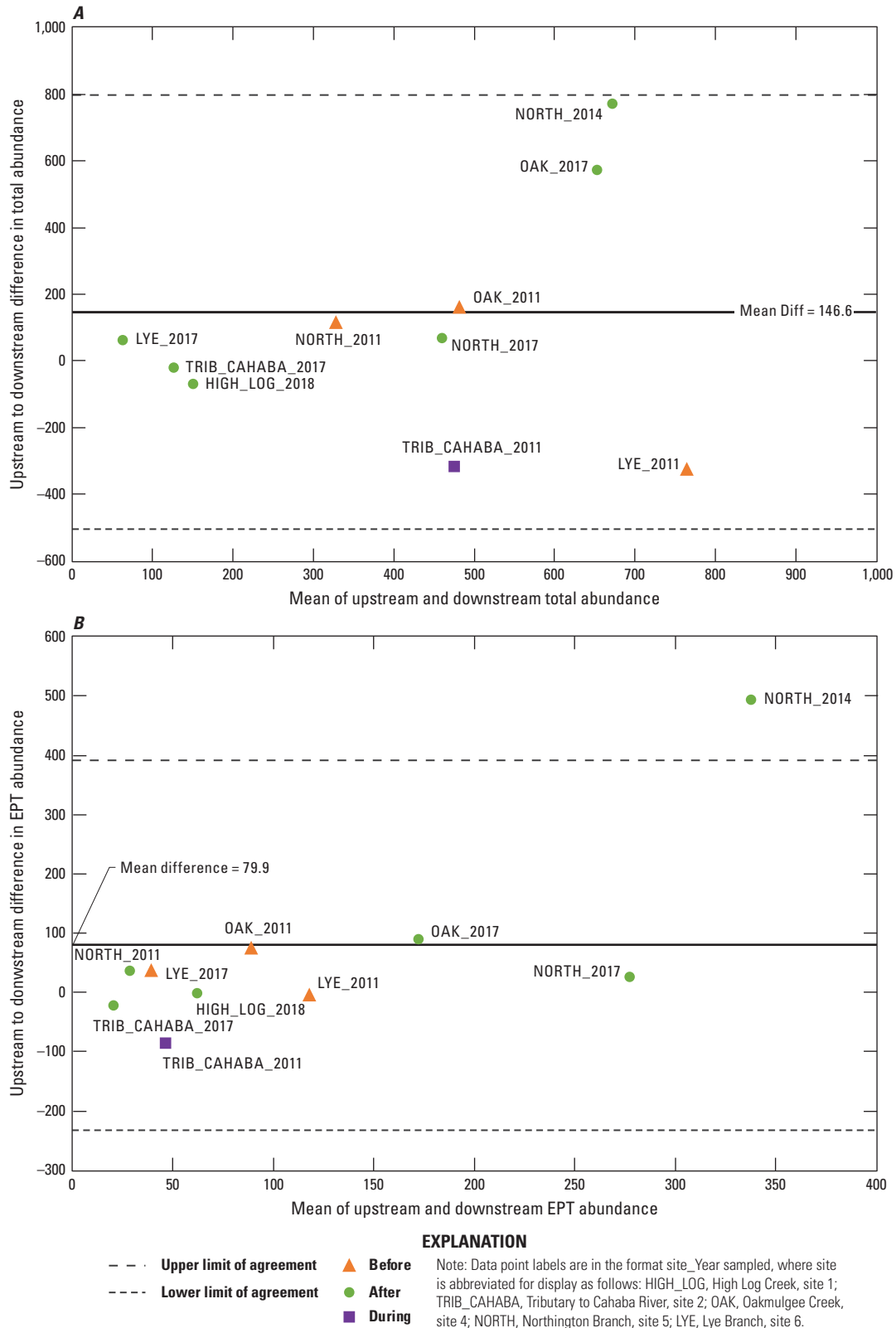
Figure 14.   Bland-Altman plots showing differences in *A*, total abundance and *B*, Ephemeroptera, Plecoptera, and Trichoptera (EPT) abundance in benthic macroinvertebrate samples collected before, during, and after culvert installation from upstream and downstream of selected culverts in Alabama.
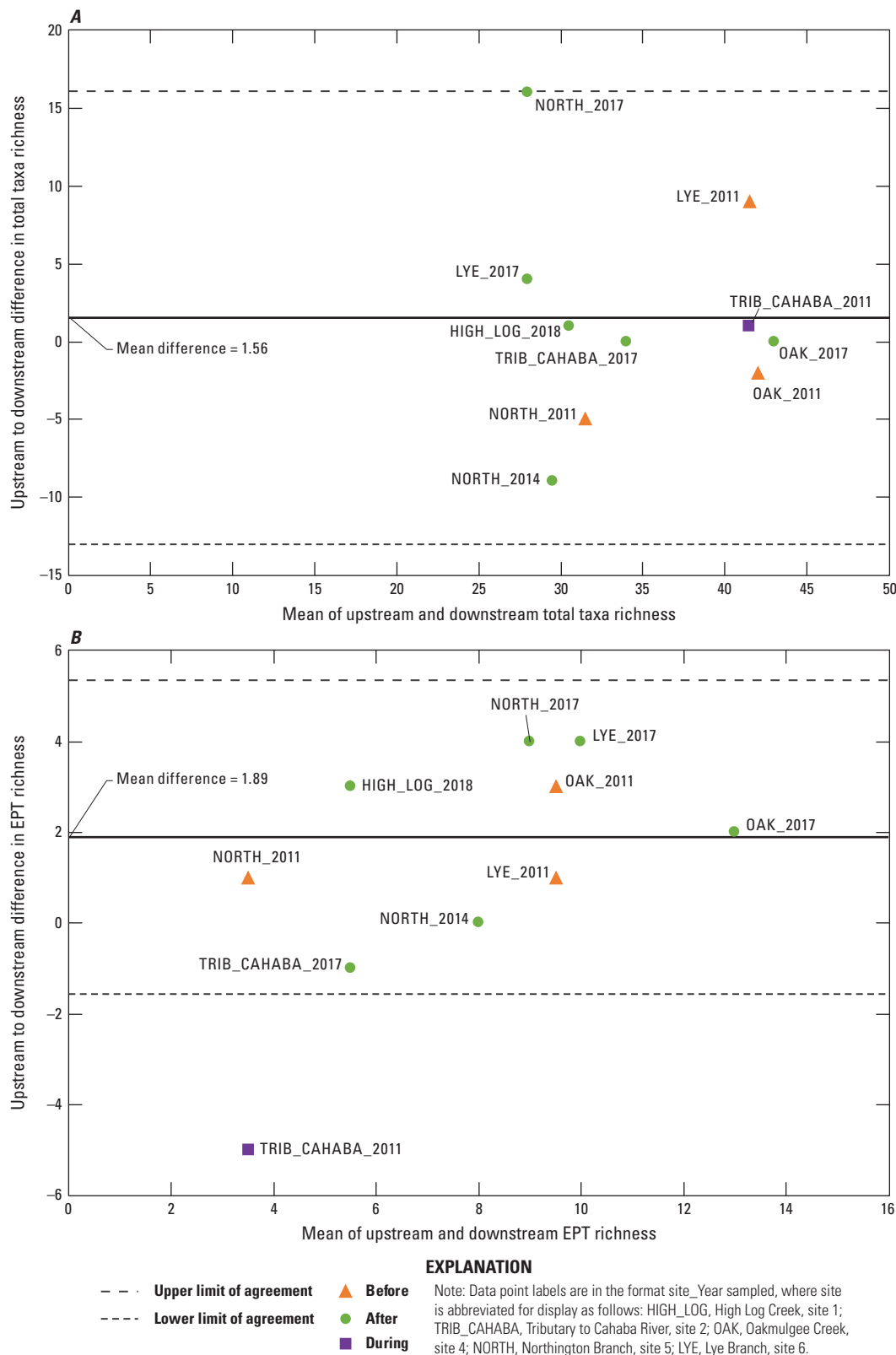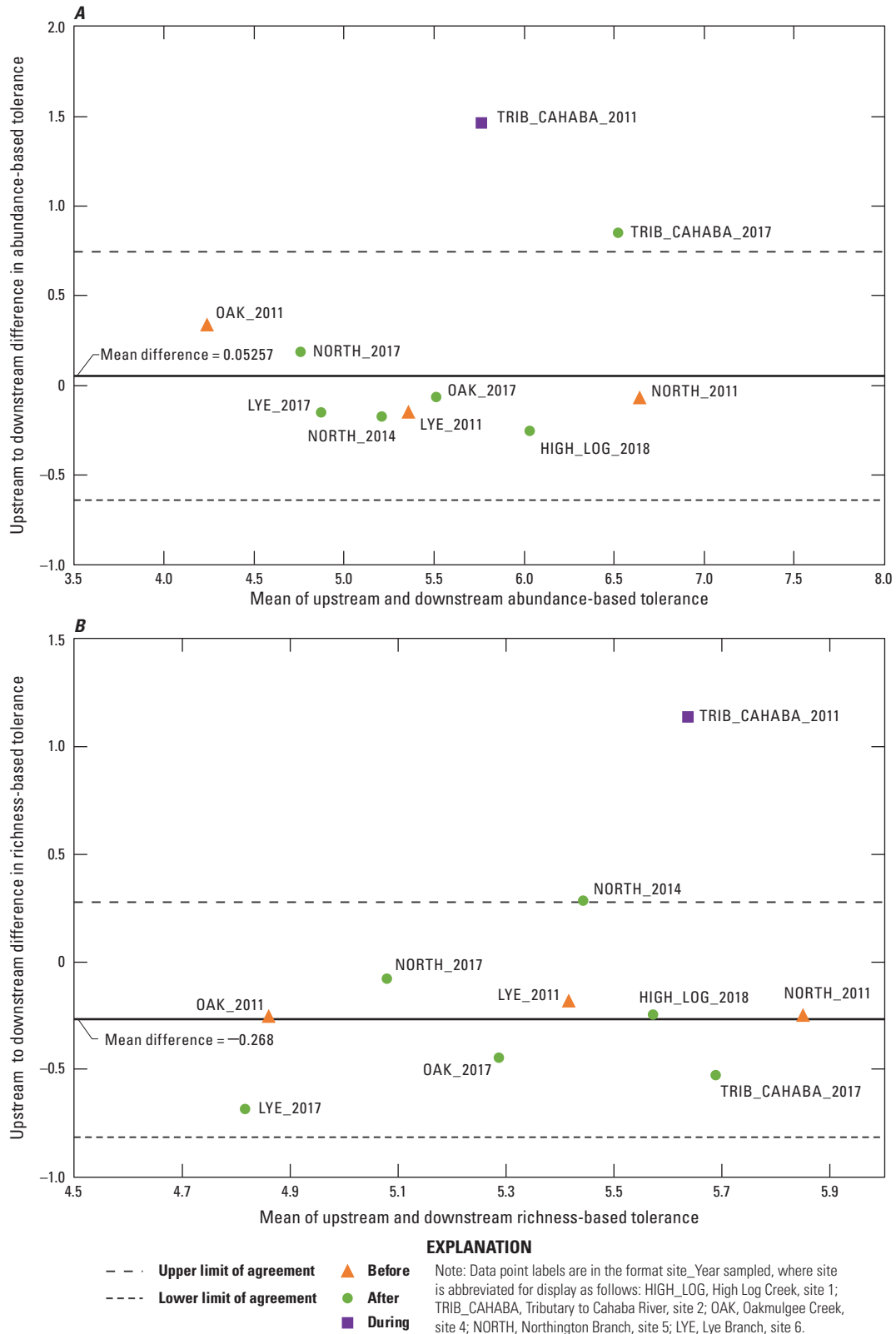
Figure 15.   Bland-Altman plots showing differences in *A*, total richness and *B*, Ephemeroptera, Plecoptera, and Trichoptera (EPT) richness in benthic macroinvertebrate samples collected before, during, and after culvert installation from upstream and downstream of selected culverts in Alabama.

Figure 16. Bland-Altman plots showing differences in *A*, abundance-weighted tolerance values and *B*, richness-based tolerance values for samples collected before, during, and after culvert construction from upstream and downstream of selected culverts in Alabama.

High Log Creek Near Hatchechubbee – Site 1

High Log Creek was only sampled once, after construction, and only minimal differences in benthic macroinvertebrate community characteristics were observed between the upstream and downstream reaches at the site. Woody snags were identified as the richest habitat in common between the upstream and downstream reaches (table 14). Though overall habitat scores from the two reaches were similar, indicating marginal conditions (table 16), the upstream reach was mainly a large pooled area with slower, deeper water impounded by a beaver dam built on top of limestone riprap just upstream of the culvert. The impoundment and limestone were not present during a before-construction site visit. The only riffles present during the sample collection were caused by fill material near the road. Water-quality field parameters were measured only at the downstream reach and indicated well-oxygenated conditions and a specific conductance value that was higher than values measured at most of the other study sites (table 14).

Total abundance was slightly higher in the downstream reach than in the upstream reach, but EPT abundance was almost equal between the two reaches (fig. 11A). A total of 31 taxa were identified in the sample collected from the upstream reach, and 30 taxa were identified in the sample collected from the downstream reach (fig. 12A). EPT taxa richness was slightly greater in the sample from the upstream reach than in the sample from the downstream reach. The most abundant taxon in both samples was *Caenis* sp., a genus of mayfly.

Average TVs were similar for benthic macroinvertebrate communities in the upstream and downstream reaches. The downstream reach community had a slightly higher TV by both richness and abundance-weighted tolerance methods (fig. 13). The moderately tolerant class comprised about 75 percent of total abundance at both reaches (Gill and Pugh, 2021; Cuffney and Brightbill, 2010). Almost 15 percent of the total organisms at the upstream site were considered intolerant, while only about 10 percent of the total organisms at the downstream site were intolerant.

The benthic macroinvertebrate community at the High Log Creek site did not appear to be affected by the culvert construction. Even though differences in habitat and localized additions of road construction materials were observed onsite at High Log Creek, most differences in community structure and health metrics were minimal between the reaches upstream and downstream of the culvert. The upstream reach did have a few more EPT taxa than the downstream reach (fig. 12A), which was a pattern at most study sites both before and after culvert construction (fig. 15B).

Tributary to Cahaba River Near Centreville – Site 2

Samples were collected at the Tributary to Cahaba River site in 2011 and 2017. The samples collected in 2011 were considered during-construction samples because active roadbuilding was ongoing around the newly installed culvert. The samples collected in 2017 represented after-construction conditions. The total habitat scores recorded in 2017 were considered suboptimal and were greater for the reaches at the Tributary to Cahaba River site than at other study site (tables 15 and 16), indicating that habitat conditions may support a healthier macroinvertebrate community. Sampled instream habitats in 2011 were root/bank and woody debris, but in 2017, sampled habitats included riffles as well as root/bank jabs (table 14). Water-quality parameters recorded in 2017 indicated lower dissolved oxygen and higher specific conductance in the downstream reach than in the upstream reach (table 14). The change in specific conductance was likely due to the presence of limestone around the culvert and road installation.

Total abundance was much greater in the samples collected in 2011 than in the samples collected in 2017 and was greater in samples from the downstream site during both periods (fig. 11B). EPT abundance was very low at the upstream reach, both during and after construction, accounting for only about 1 percent of total abundance during road construction and less than 8 percent after construction. Total taxa richness was similar in samples from upstream and downstream reaches during each of the sampling periods but was greater in the samples collected during construction (fig. 12B). EPT richness was much lower in the sample from the upstream reach than in the sample from the downstream reach during construction, but in the after-construction samples, EPT richness was similar for samples collected upstream and downstream (fig. 12B).

Among all the study sites, the greatest differences in mean TVs between upstream and downstream reaches were measured in the during-construction phase at the Tributary to Cahaba River site (figs. 13 and 16). The richness-based and abundance-weighted TVs indicated a more tolerant benthic macroinvertebrate community upstream than downstream in the during-construction phase.

Richness-based and abundance-weighted TVs for after-construction samples still indicated differences between the upstream and downstream reaches, but richness-based TVs indicated a slightly more tolerant community downstream, while abundance-weighted TVs indicated the upstream community was more tolerant (figs. 13 and 16). The difference in abundance-weighted TVs between the upstream and downstream reaches at the Tributary to Cahaba River site in 2017 was more than 2 standard deviations from the mean reach difference for all before- and after-construction samples (fig. 16A). Though this reach difference was an outlier value, it represented lower tolerance in the downstream reach than in the upstream reach. Lower TVs downstream of the culvert indicate that the culvert is not detrimentally affecting benthic macroinvertebrate communities at the site.

Most measures of benthic community health in the upstream and downstream reaches at the Tributary to Cahaba River site after construction were the same or better in the reach downstream of the new culvert, indicating no

detrimental effects from the culvert construction. Richness-based TVs in this period, however, did indicate that the down-stream community may have changed to become more tolerant of disturbance. Interestingly, data collected in 2011 during roadbuilding also seem to indicate that active construction did not negatively affect the benthic communities; abundance and taxa richness were similar or greater than in samples collected after construction was complete.

Oakmulgee Creek Near Lawley – Site 4

Habitat scores at Oakmulgee Creek indicated overall suboptimal conditions in both reaches (tables 14 and 15). The upstream reach had slightly better conditions, including well-vegetated banks and a more intact riparian zone. Water-quality field parameters recorded in 2017 were nearly identical between the reaches (table 14).

Total abundance in the after-construction sample from the upstream reach was greater than in the before-construction sample. Total abundance in samples collected from the down-stream reach was similar in the before- and after-construction samples but was less than the total abundance in upstream samples during both before- and after-construction periods (fig. 11*C*). EPT abundance was also greater in upstream samples than the downstream samples but was slightly greater in both samples collected in the after-construction period (fig. 11*C*). The greater abundances in the upstream reach were consistent with the better habitat score (table 16) for the upstream reach than for the downstream reach.

Total taxa richness in the Oakmulgee samples were nearly identical in both reaches and time periods and ranged from 41 to 43 taxa (fig. 12*C*). The EPT taxa, which are commonly expected to be relatively intolerant to pollution, increased in taxa richness from the before-construction to the after-construction samples (fig. 12*C*). EPT taxa richness was greater in the upstream reach than in the downstream reach for both time periods (figs. 12*C* and 15*B*).

Community TVs at Oakmulgee Creek were similar in samples from upstream and downstream reaches during both periods but increased slightly in after-construction samples (fig. 13). Before construction, the Oakmulgee Creek site had the lowest abundance-weighted average TVs recorded for study sites. After construction, TVs were similar to TVs at other sites.

Macroinvertebrate communities and water-quality condi-tions in Oakmulgee Creek did not appear to be affected by the installation of the culvert. Water chemistry, total and EPT macroinvertebrate abundance, and taxa richness indicated only minor differences between samples collected before and after culvert construction. TVs increased for the after-construction samples, but these increases were in samples from both reaches.

Northington Branch Near Detroit – Site 5

Northington Branch was sampled three times during this study: before construction in 2011 and after construc-tion in 2014 and 2017 (table 14). After-construction sampling in 2014 was during a period of abnormally low streamflow, which affected the amount and type of available habitat, so a subsequent sample was collected in 2017 to ensure that the macroinvertebrate community was accurately assessed. In 2011, the habitats sampled were submerged roots and woody debris. Because of the low flows in 2014 and less available submerged woody debris in 2017, riffle areas were identified as richest available habitats in the after-construction samples.

Total habitat scores recorded at Northington Branch in 2017 were in the marginal category range in the upstream reach and in the lower suboptimal in the downstream reach (tables 15 and 16). The entire area in the vicinity of the culvert had been channelized before this study began, and effects of the channelization on instream habitat and riparian zones were noted as part of the habitat scores. Dissolved oxygen, pH, and specific conductance measurements were similar for the upstream and downstream reaches in 2017 (table 14).

Total and EPT abundance in the sample collected in 2017 were greater than in the before-construction sample collected in 2011 (fig. 11*D*). In 2014, EPT abundance in the sample from the upstream reach of Northington Branch exceeded the downstream sample's EPT abundance by about 500 organ-isms, and the difference between the reaches was more than 2 standard deviations from the mean reach difference in EPT abundance for all study sites (fig. 14*B*). Because the EPT abundance was similar in samples collected from upstream and downstream reaches in 2011 and 2017, the EPT abun-dance in samples collected in 2014 was most likely affected by other environmental factors and did not represent a lasting response to culvert construction. During sampling in 2014, lower streamflow affected the amount of available habitat, and more area was sampled upstream than downstream. This dif-ference in area sampled in 2014 may explain the much greater total and EPT abundance in the upstream sample (figs. 11*D* and 14). For all sampling periods, total and EPT abundance at Northington Branch were slightly greater in the upstream reach than in the downstream reach (figs. 11*D*, and 14*A, B*).

Before culvert construction, total taxa richness was slightly greater in the downstream reach than in the upstream reach. Total taxa richness was not consistent in the after-construction samples; richness was greater in the downstream reach in 2014 and greater in the upstream reach in 2017 (figs. 12*D* and 15*A*). The difference in total taxa richness between the reaches was also greater in the after-construction sampling periods, ranging from 25 taxa upstream to 34 taxa downstream in 2014 and from 20 taxa downstream to 36 taxa upstream in 2017 (figs. 12*D* and 15*A*). EPT taxa richness was greater in all samples collected after construction than in the samples collected before construction, possibly because of the difference in sampled habitat type (fig. 12*D*).

TVs based on abundance were considerably lower for the samples collected in 2014 and 2017 than for the samples collected in 2011, indicating a less pollution-tolerant community after construction (figs. 13 and 16*A, B*). Average TVs based on richness varied much less between time periods than those based on abundance. TVs were similar between upstream and downstream reaches for all time periods, indicating that neither the pre-existing bridge nor the new culvert affected the tolerance of the benthic macroinvertebrate communities.

Community measures at Northington Branch were highly variable. Despite the high variability, some apparent patterns in the data allow for an assessment of culvert construction effects. Generally total and EPT abundance were greater upstream than downstream during the before- and after-construction periods, indicating that this difference was caused by something other than the culvert. TVs were similar for benthic macroinvertebrate communities upstream and downstream in all sampling periods, but TVs were slightly lower in samples from the after-construction period. This suggests that stream conditions have not degraded because of culvert construction and are adequate to support a community of more intolerant organisms.

Lye Branch Near Duncanville – Site 6

Instream habitats at Lye Branch differed slightly between the before- and after-construction phases of this study. The stream has a sandy bottom throughout both reaches, and woody snags and submerged roots were the sampled habitats in the before-construction phase (table 14). Only woody snags were sampled after construction (table 14) because sand had shifted to cover some of the exposed root bank areas downstream. Total habitat scores recorded in the after-construction phase (table 16) were in the suboptimal category for both stream reaches, but the upstream reach scored slightly higher than the downstream reach because it had a more stable riparian zone.

Total abundance was much lower in the after-construction phase than in the before-construction phase, but the percentage of EPT abundance was much higher after construction (fig. 11*E*). Total taxa richness decreased in after-construction samples and was consistently greater in samples from the upstream reach than in samples from the downstream reach (fig. 12*E*). EPT taxa richness in samples collected from the upstream and downstream reaches before construction only differed by one taxon. After construction, the sample collected from the upstream reach contained 12 EPT taxa, and the sample collected from the downstream reach had eight EPT taxa (fig. 12*E*).

All TVs were lower for samples collected after construction than for samples collected before construction. Tolerance values were slightly lower in the upstream reach than in the downstream reach for all samples, but the difference was more pronounced for richness-based tolerance in the after-construction phase (fig. 13).

Metrics of the benthic macroinvertebrate community at Lye Branch did not show a clear response to culvert construction. Total and EPT abundance and total taxa richness were reduced in the after-construction samples (figs. 11*E* and 12*E*), but patterns of greater abundance and richness in the upstream reach than in the downstream reach were seen in both the before- and after-construction samples. Lower tolerance values in the after-construction samples indicate that the after-construction condition of the sampled reaches can support more intolerant organisms (fig. 13).

Limitations of This Study and Lessons Learned

The purpose of this study was to determine if culvert installations were having lasting measurable effects on stream channel geometry and instream habitats and biota. Challenges of real-world environmental conditions exposed limitations in the study design and methods. Slight changes in methods could provide a considerable improvement in potential future studies of culvert effects. Four changes are proposed: (1) improve topographic survey control, (2) add thalweg longitudinal profile measurements to the topographic survey, (3) collect continuous stage information, and (4) employ the use of artificial substrates for benthic macroinvertebrate collections.

Accurate measurement of stream channel geometry change depends on having a strict definition of site cross sections. The lack of permanent benchmarks at the ends of cross sections resulted in the misalignment of many of the paired, before- and after-construction, topographic surveys of the cross sections. Establishing permanent cross-section endpoints would allow for measurements to be made in exactly the same position each time a survey is made.

Stream channel longitudinal profiles are an important stream geometry parameter to measure. Longitudinal profiles of the thalweg define the channel sinuosity and slope and identify the distribution of streambed forms (for example, cascades, riffles, pools, and dunes). More accurate measurements could be obtained if longitudinal profile measurements were made concurrently with the cross-sectional topographic surveys and started above the most upstream cross section and run continuously through the construction reach, ending below the most downstream cross section.

Collection of continuous stage data based on a set datum for the duration of the study would allow for better distribution of sediment samples throughout storm hydrographs, comparisons of sediment concentration across multiple storm events, and, if a stage/streamflow relation is developed, calculation of sediment loading. A related suggestion for improving collection of stormflow data for sediment analysis is the use of automatic samplers. Some of the larger stream sites in this study became inaccessible at high flows, and samples were not

always collected to define the peak of the storm hydrograph. Properly sited automatic samplers could continue to collect data throughout storm events.

Ideally, benthic macroinvertebrate community samples would have been collected in replicate to define the inter-sample variability. Because of constraints in time, funding, and stream size, replicate samples were not collected during this study. Artificial substrates for benthic macroinvertebrate colonization could be used to increase comparable available habitat in the upstream and downstream reaches. The use of a standardized artificial substrate could minimize time spent sampling and provide ample habitat of the same type at each site. Artificial substrates could also provide enough habitat to allow for analysis of replicate samples at each site.

The planned timelines of the construction of culverts and other civil structures often change. Completion of such structures can be delayed or canceled because of changing funding priorities, contracting challenges, materials acquisition or quality issues, and (or) inclement weather. Studies depending on the construction of proposed civil structures may be more effective or efficient with a nimble, flexible timeline to account for the continually changing timelines of these projects.

Summary

To measure the effects of highway culvert construction on selected stream channel beds, banks, and slopes at six sites in Alabama, topographic surveys of the channel geometry (cross-sectional area, mean depth, top width, and thalweg slope) upstream and downstream of the culvert were conducted by the U.S. Geological Survey, in cooperation with the Alabama Department of Transportation, before and after culvert construction during 2011–19. At the High Log Creek site, the stream geometry data indicate sediment deposition related to the remnants of a cofferdam in the upstream reach. At the Tributary to Cahaba River site, the stream geometry data indicate erosion in the upstream and downstream reaches related to the buried culvert invert design. Erosion in the downstream reach of the Tributary to Sandy Creek site was related to sediment-free water exiting the site. Erosion in the downstream reach of the Oakmulgee Creek site increased as a head cut progressed upstream through the reach. Erosion in the upstream reach of the Northington Branch site helped the reach's slope return to normal; deposition in the downstream reach was evident as the stream continued to adjust to the removal of a pre-construction channel obstruction. Deposition in the upstream and downstream reaches at the Lye Branch site was related to channel obstructions.

To help assess the changes in channel geometry and aquatic ecology, surface-water samples were simultaneously collected for analyses of suspended sediment and turbidity; samples were collected upstream and downstream of the study sites during high-flow events in all three phases of culvert construction. Because streamflow could not be accurately determined during collection of the samples, data analysis focused on the parity of the upstream and downstream sediment concentrations and turbidity for each discrete sample collection time. The mean upstream to downstream paired ratios of sediment concentrations and turbidity data indicate that the High Log Creek construction reach was trapping colloidal particles before construction, mobilizing colloidal particles during construction, and efficiently transporting the creek's sediment load through the reach after construction. The data from the Tributary to Cahaba River site indicate that the construction reach was mobilizing colloidal and noncolloidal sediment during construction and trapping noncolloidal sediment after construction. At the Tributary to Sandy Creek site, the construction reach was trapping noncolloidal sediment and mobilizing colloidal particles during construction and was mobilizing noncolloidal sediment and trapping colloidal particles after construction. The construction reach at the Oakmulgee Creek site was trapping colloidal and noncolloidal sediment before and during construction, and colloidal and noncolloidal sediment was moving efficiently through the reach after construction. The construction reach at the Northington Branch site mobilized colloidal and noncolloidal sediment before construction and mobilized noncolloidal sediment and trapped colloidal sediment after construction. The construction reach at the Lye Branch site was trapping colloidal sediment before construction and was trapping noncolloidal sediment and mobilizing colloidal sediment during and after construction.

Benthic macroinvertebrate sampling results did not strongly indicate that culvert construction caused impairment to communities at study sites. Observed differences in benthic communities between upstream and downstream reaches were relatively small, and the Wilcoxon rank sum test indicated that upstream to downstream variations in total and Ephemeroptera, Plecoptera, and Trichoptera (EPT) abundance, total and EPT richness, and abundance-weighted and richness-based average tolerance values were not statistically different between the before- and after-construction sampling periods. For total abundance, total richness, EPT richness, and richness-based average tolerance, all individual differences between upstream and downstream metrics were within two standard deviations of the mean difference for all upstream to downstream reach pairs for before- and after-construction periods. Differences between upstream and downstream reaches were more than two standard deviations from the mean difference for EPT abundance at the Northington Branch site in 2014 and abundance-weighted tolerance at the Tributary to Cahaba River site in 2017, but neither of these outliers indicated detrimental effects of culvert construction.

Tolerance metrics indicated no major changes in the pollution tolerance of benthic macroinvertebrate communities. Average tolerance values indicated the pollution sensitivity of the benthic macroinvertebrate communities weighted by variation in total abundance and taxa richness. Tolerance values at study sites ranged from about 4 to 7 and indicated moderately pollution-tolerant macroinvertebrate communities. Samples were collected from the Oakmulgee Creek, Northington

Branch, and Lye Branch sites before and after construction for analysis of benthic macroinvertebrates. Abundance-weighted tolerance values at Oakmulgee Creek were slightly greater for the after-construction samples from both reaches, while after-construction values at the Northington Branch and Lye Branch sites were somewhat lower than before-construction values. Upstream to downstream patterns in abundance-weighted tolerance values, however, remained the same between the before-construction and after-construction sampling periods, indicating no evidence of detrimental effects from culvert construction. For richness-based tolerance values at Lye Branch, the difference between upstream and downstream values became more pronounced in the after-construction period with greater average tolerance downstream. The observed increase in tolerance values downstream provides some evidence for potential negative effects from culvert construction at Lye Branch, but both upstream and downstream tolerance values were lower after construction than before.

Changes in the available types of in-stream habitat for before-, during-, and after-construction sampling periods may explain some of the observed variance in measures of benthic macroinvertebrate community composition. Future studies of benthic macroinvertebrate communities at these sites or other sites with new culvert installations could benefit from the use of standardized artificial substrates, more sample replicates during each construction phase, and more frequent and detailed habitat scoring.

Acknowledgments

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