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Effects of Box Culverts on Stream Habitat, Channel Morphology, and Fish and Macroinvertebrate Communities at Selected Sites in South Carolina, 2016–18

Scientific Investigations Report 2020–5021

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

Front cover: *Left*, Box culvert on Enoree Creek at South Carolina Highway 49, near Cross Anchor, S.C. Photograph by Jeff Riley.
Right, Sampling crew collecting fish with backpack electrofisher at box culvert Sadler Swamp on SC 122 near St. Matthews, S.C. (Left to right: Karen Beaulieu, Steve Walsh, Jeff Riley, Ryan Rasmussen.) Photograph by Alan Cressler, U.S. Geological Survey.

Back cover: Photographs of box culverts in South Carolina. Photographs by Jeff Riley.
Top, Tributary to Alison Creek at SC 236, near Clover, S.C.
Middle, Bishop Branch at SC 49, near Cross Anchor, S.C.
Bottom, Kennedy Creek at Unites States Highway 176, near Pacolet, S.C.

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DAVID BERNHARDT, Secretary

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

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Conversion Factors

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
micrometer (µm)	0.00003937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
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	
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	1.308	cubic yard (yd^3)
	Flow rate	
meter per second (m/s)	3.281	foot per second (ft/s)

Datum

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

Abbreviations

2D	two dimensional
3D	three dimensional
ANOSIM	analysis of similarities
BEST	Bio-Env + Stepwise
C/f	catch per unit effort
GCU	geomorphic channel unit
LWD	large woody debris
nMDS	nonmetric multidimensional scaling
PRIMER	Plymouth Routines in Multivariate Ecological Research
RI	recurrence interval
SCDHEC	South Carolina Department of Health and Environmental Control
SCDOT	South Carolina Department of Transportation
SIMPROF	similarity profile
S–W	Shannon-Wiener diversity index
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

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Abstract

Much attention has been placed on the role that under-roadway culverts may have in inhibiting upstream fish movement because of altered hydrology and unsuitable conditions for accessing or swimming through the culvert. Other culvert effects related to habitat alterations or disturbance to macroinvertebrate communities have received relatively little attention. Entities responsible for culverts or other stream crossing structures are required to follow the U.S. Army Corps of Engineers guidelines for compensatory mitigation should any disturbance result from an engineering activity. One factor considered in the scoring of mitigation requirements is culvert length. Except for shading a longer length of stream, it is unknown whether longer culverts result in greater disturbance to stream habitat or the biotic communities than shorter culverts. The U.S. Geological Survey, in cooperation with the South Carolina Department of Transportation, evaluated the role of culverts in altering physical habitat and community structure of fish and macroinvertebrates at 20 sites in South Carolina. Culvert sites were categorized by length (either greater than 30.5 meters or less than or equal to 30.5 meters) and physiographic province (Piedmont or Upper Coastal Plain). This study design allowed for a regional assessment to determine if culverts may have different effects on habitat and biotic communities in different physical settings. The results indicated considerable variation in physical habitat characteristics within and among the culvert sites from all categories. A consistent finding was that channel cross-sectional area tended to increase in reaches downstream from culverts in the Upper Coastal Plain. The primary dimension of change was vertical, that is, incision of the streambed. This change, however, did not seem to coincide with a deleterious effect on the fish community. Increased habitat complexity and greater taxonomic richness were observed at most sites with downstream incision. Macroinvertebrate communities were highly variable and did not tend to cluster along any of the culvert categories, which may reflect the variability of microhabitats within each site. In contrast, fish communities were largely segregated by physiographic province but did not show any other significant clustering on the basis of upstream or downstream reach or culvert length. Given the small within-group sample size, extrapolation of results should be done carefully, acknowledging the physiographic and group characteristics.

Introduction

Culverts are ubiquitous features on the modern landscape and are especially prevalent where roadways traverse hilly topography with numerous low-order streams and swales. In South Carolina, there are more than 9,000 culverts of varying types and sizes. Research on the ecological effects of culverts has been relatively limited, such as studies that evaluated the role of substandard culverts in inhibiting fish movement because of culvert outlets perched above the streambed, high velocities caused by under-sized culverts, and shallow water depths (Gibson and others, 2005; Kemp and Williams, 2008; Evans and others, 2015; Birnie-Gauvin and others, 2019; Johnson and others, 2019). There is a general need for more detailed investigation on the effects of culverts on aquatic environments to assist agencies charged with assessing and mitigating deleterious effects to stream ecosystems from engineering activities.

Culverts may affect habitats and associated biota directly by interrupting stream connectivity or by altering localized stream velocity and hydraulics. An issue that has received considerable attention, albeit primarily at bridge locations, is contraction scour (Richardson and Richardson, 1999). Contraction scour results when the natural flow area of a stream channel is reduced or constricted and the floodplain is blocked by the roadway. This type of scour is especially relevant to culverts because they may constrict the cross-sectional stream area and, with an immobile bed (unlike with bridges), energy may be further increased and transferred to the channel below the culvert outlet. The bed and banks can be eroded when water exits the culvert with excessive velocity, resulting in effects to channel stability, aquatic habitat, and associated biota (Merrill and Gregory, 2004; Merrill, 2005; Khan and Colbo, 2008). Bouska and others (2010) noted that in Kansas prairie streams, bankfull depths and width-to-depth ratios were lower upstream from box culverts compared to downstream, possibly due to culvert-induced scour and incision. In addition to constricting the channel, culverts may also be installed with a slope that exceeds that of the prevailing streambed. Steep culvert slopes can have similar effects as constriction but may be even more disruptive because the steeper slope leads to higher water velocities, increasing scour potential even during lower flow conditions. For both constricted channels and steep culvert slopes, instream habitat and biota may be directly affected by the increased velocity and associated stream power that can erode and transport sediment. Increased energy over a limited longitudinal scale may interrupt sediment continuity, large wood transport, and general habitat conditions.

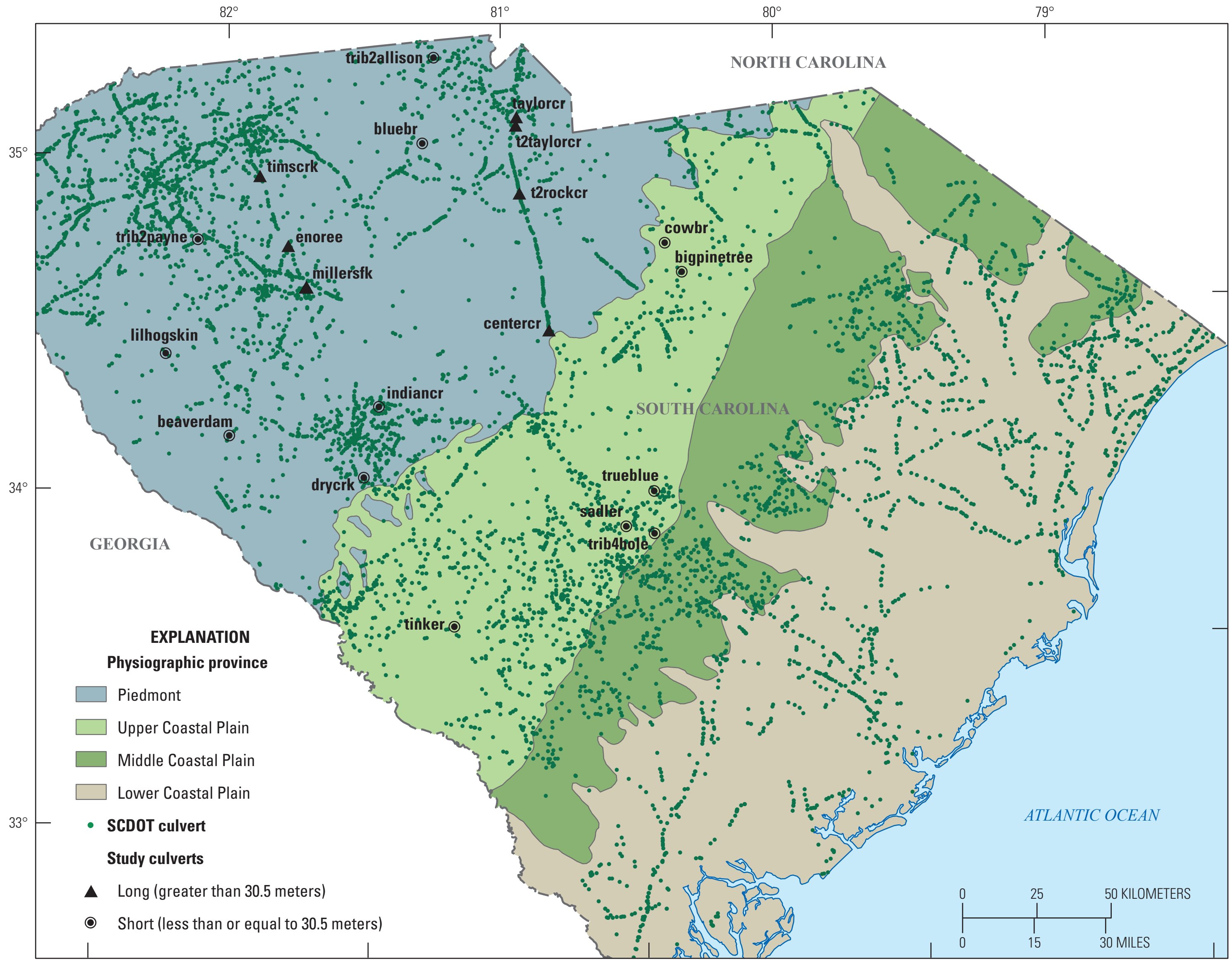
The South Carolina Department of Health and Environmental Control (SCDHEC) requires that the South Carolina Department of Transportation (SCDOT) evaluate the potential effects of culvert installations on streams by using the U.S. Army Corps of Engineers (USACE) guidelines for compensatory mitigation (U.S. Army Corps of Engineers, 2010). These guidelines set numerical ratings for assessing potential effects related to culvert construction and installation. One of the factors considered is the culvert length class: (1) less than or equal to 30.5 meters (m) or (2) greater than 30.5 m, with culverts longer than 30.5 m (referred to as “pipes”) assigned a higher rating, suggesting greater effects on streams. These ratings do not consider additional factors such as culvert size, culvert type, or site-specific monitoring data. If a stream is affected by culvert installation, then compensatory mitigation requires some form of restoration or enhancement action that may include stream channel restoration, bank stabilization, in-stream habitat recovery, or structure removal. Restoration activities are designed to improve ecological conditions, including habitat quality, water quality, and biological and morphological integrity. The USACE assessments, however, provide limited data to quantify the actual effects of culverts on the ecological conditions of streams and the degree of restoration that would be necessary to achieve targeted conditions. Prior to selection of restoration strategies, additional assessments would be required to understand (1) the changes in geomorphology and habitat of the natural streams associated with the construction of culverts at highways and roads and (2) the effects of those changes, if any, on the biological community within the streams.

Purpose and Scope

The U.S. Geological Survey (USGS), in cooperation with the SCDOT, investigated the effects of box culverts on stream ecosystems in the Piedmont and Upper Coastal Plain of South Carolina from 2016 to 2018. This report describes the results of the investigation to provide the SCDOT with scientific information to help guide future culvert design and mitigation. The objective of this study was to evaluate whether culverts alter stream morphology, habitat, and biotic communities. Furthermore, the study sought to examine how culvert effects, if any, varied by physiographic province and culvert length category (as defined by the USACE guidelines for compensatory mitigation assessments; U.S. Army Corps of Engineers, 2010). Thus, a primary intent of this investigation was to evaluate sites by culvert length. We hypothesized that long culverts (greater than 30.5 m) may have more adverse effects on stream ecology than short culverts (less than or equal to 30.5 m) because they disrupt a longer segment of the natural stream (U.S. Army Corps of Engineers, 2010). The assessment was based on characterization of stream channel geomorphology, habitat, and community structure of fish and benthic macroinvertebrates collected at 20 culvert sites in the Piedmont and Upper Coastal Plain of South Carolina (fig. 1, table 1). To assess potential culvert effects, data were collected in reaches above and below each culvert. The reach upstream from the culvert was considered free of culvert influence, whereas the downstream reach was potentially affected by the culvert. We examined differences in selected variables between upstream and downstream reaches to infer possible culvert effects. Because biological data are known to display a high degree of spatial and temporal variability (Schlosser, 1982; Downes and others, 1993), it was necessary to collect replicate samples. Given the study duration, it was not possible to collect data over multiple seasons or years at individual sites. Instead, spatial replicates were collected and used to evaluate culvert effects for each category of culvert length and physiographic province.

Description of Study Area

This study focused on the Piedmont and Upper Coastal Plain physiographic provinces (which correspond to the Piedmont and Southeastern Plains Level III ecoregions, respectively; U.S. Environmental Protection Agency, 2013) of South Carolina (fig. 1). The Piedmont covers approximately 38 percent of the State, and the Upper Coastal Plain covers about 18 percent. These two provinces differ in their topographic, geologic, and biotic characteristics. The Piedmont is hilly and dominated by loamy to clayey Ultisol soils underlain by metamorphic and, to a lesser degree, igneous bedrock. In contrast, the Upper Coastal Plain has more subtle topography and sandy to clayey Entisol or Ultisol soils underlain by massive, semiconsolidated sand deposits of aeolian and marine origin (Swezey and others, 2016). Streams in the Piedmont generally have coarse-grained bed material and are commonly incised and disconnected from their floodplains. Streams in the Upper Coastal Plain are generally low gradient with relatively low banks and have less confined channels that often are well connected to wide floodplains. These streams are dominated by sandy bed material and greater amounts of organic debris. These differences in landscape and stream characteristics could moderate or exacerbate the potential effects of culverts on stream habitat and biotic communities.



Base modified from U.S. Geological Survey digital data, 1:2,000,000 scale, 1972

Figure 1. Map showing locations of selected South Carolina Department of Transportation (SCDOT) culverts and physiographic provinces in South Carolina.

Table 1. Selected culvert sites in South Carolina that were assessed for morphological and ecological effects, 2016–18.

[Culvert length classes: short, less than or equal to 30.5 meters; long, greater than 30.5 meters. USGS, U.S. Geological Survey; km^2, square kilometer; US, United States; SC, South Carolina; I, Interstate]

USGS station number	USGS station name	Site identification	Physiographic province	Culvert length class	Drainage area (km^2)
340427082131900	Beaverdam Branch on US 221, near Bradley, SC	beaverdam	Piedmont	Short	13.36
345132081212000	Blue Branch on SC 322, near York, SC	bluebr	Piedmont	Short	5.46
335324081452100	Dry Creek on SC 193, near Saluda, SC	drycrk	Piedmont	Short	12.28
340537081394100	Indian Creek on SC 194, near Saluda, SC	indiancr	Piedmont	Short	18.23
342050082243600	Little Hogskin Creek on SC 20, near Due West, SC	lilhogskin	Piedmont	Short	4.20
350632081155500	Tributary to Allison Creek on SC 236, near Clover, SC	trib2allison	Piedmont	Short	2.85
344024082135600	Tributary to Payne Branch on SC 418, near Fountain Inn, SC	trib2payne	Piedmont	Short	2.38
341438080596000	Center Creek on I-77, near Ridgeway, SC	centercr	Piedmont	Long	11.60
343654081541500	Enoree Creek on SC 49, near Cross Anchor, SC	enoree	Piedmont	Long	4.56
342916081513800	Millers Fork Creek on SC 72, near Clinton, SC	millersfk	Piedmont	Long	2.15
345347080592900	Taylor Creek on I-77, near Rock Hill, SC	taylorcr	Piedmont	Long	8.00
345009081581300	Tims Creek on I-26, near Moore, SC	timscrk	Piedmont	Long	4.77
343953081014400	Tributary to Rock Creek on I-77 near Richberg, SC	t2rockcr	Piedmont	Long	2.12
345207081001200	Tributary to Taylor Creek on I-77, near Rock Hill, SC	t2taylorcr	Piedmont	Long	3.39
342115080285500	Big Pine Tree Creek on US 1, near Cassatt, SC	bigpinetree	Upper Coastal Plain	Short	14.17
342652080313400	Cow Branch on Lockhart Road, near Westville, SC	cowbr	Upper Coastal Plain	Short	10.83
333722080495800	Sadler Swamp on SC 122, near St. Matthews, SC	sadler	Upper Coastal Plain	Short	8.75
332418081304100	Tinker Creek on SC 781, near White Pond, SC	tinker	Upper Coastal Plain	Short	11.06
333521080440800	Tributary to Four-Hole Swamp on US 176, near Cameron, SC	trib4hole	Upper Coastal Plain	Short	3.83
334250080423900	True Blue Creek on True Blue Road, near Singleton, SC	trueblue	Upper Coastal Plain	Short	6.27

Previous Investigations

It is difficult to extrapolate findings from other studies of culvert effects on stream ecosystems to the present study because of past land-use disturbances. Researchers in other States (for example, Ohio [Tumeo and Pavlick, 2011], Texas [Cleveland and others, 2013], and Minnesota [Zytkovicz and Murtada, 2017]) have investigated different approaches to culvert design and the possible implications to stream systems, but the physical landscape settings are different from the present study area. Historical agricultural practices over much of the southern Piedmont led to greatly altered stream systems, many of which have deeply incised channels that are filled in with fine sediment (Trimble 1974; Jackson and others, 2005; Voli and others, 2013). Such incised channels have greater volumetric capacity and experience fewer overbank flows than unaltered streams; therefore, high-flow conditions disturb stream channels more frequently because the hydraulic energy is constrained within the channel. These factors make the current study an important contribution to better understand how, if at all, box culverts may affect channel stability, habitat, and biotic communities in these previously altered systems.

The influence of culverts on benthic macroinvertebrates and nongame fish species has received relatively little scientific study. A consistent finding from two studies was that disturbance to the macroinvertebrate community tended to be localized and was likely driven by altered habitat adjacent to the culvert (Khan and Colbo, 2008; Peterson, 2010). It is important to note that these two studies focused on streams that have coarse-grained bed sediments and disturbance led to relatively small changes in bed-material size. In streams of the southeastern United States, disturbance often results in copious amounts of sand and silt becoming the dominant bed material; this substrate is not suitable for many sensitive taxa. We are unaware of any studies on southeastern Piedmont streams that have investigated how macroinvertebrate communities may differ in relation to culvert proximity. The negative effects of fine sediment on macroinvertebrate communities, however, have been documented in many studies (Waters, 1995; Wood and Armitage, 1997; Kaller and Hartman, 2004; Jones and others, 2012; Gieswein and others, 2019).

In contrast to benthic macroinvertebrates, fish generally are more mobile and better able to avoid disturbances associated with localized habitat alterations from culvert-induced scour. A concern with fish is their ability to move through culverts to allow for colonization, dispersal, and gene flow (Anderson and others, 2012). Research in this regard has focused mainly on the swimming abilities of adult salmonids and, in limited cases, native or protected species (Benton and others, 2008; Norman and others, 2009; Bouska and Paukert, 2010). In Great Plains streams, physical factors that influenced the passage of small fish through culverts were water velocity; suitable depth; culvert slope, length, width; and perch height that limited migration of target species (Bouska and Paukert, 2010). Perch height, or "perching" refers to a situation where the bottom of the culvert is above (at a higher elevation) the bed of the stream. This can lead to a sharp step in the longitudinal profile that may be a barrier for fish and other aquatic species. Most studies of culvert effects on fish have focused on the requirements of specific groups or species and have rarely considered entire community assemblages. However, ensuring no net loss of ecosystem function (U.S. Army Corps of Engineers, 2010) resulting from in-stream engineering activities requires an understanding of potential effects to the biotic community composition to effectively characterize and mitigate impairments.

Approach and Methods

We compared geomorphology, habitat characteristics, and community assemblages from the upstream reach to those from the downstream reach at each site to infer possible effects of culverts. This approach assumed that upstream reaches were relatively free from the influence of culverts and were suitable as controls to compare to downstream reaches; however, some culverts may also alter upstream habitat conditions.

An ideal approach for assessing the effects of a given activity is to collect pre- and post-disturbance data from disturbed and control sites that can then be evaluated in a before-after-control-impact analysis framework (Smokorowski and Randall, 2017). This approach often is not attainable because ecological impairment frequently is studied long after a structure or process was put in place, which is the case for the current study. Therefore, we collected spatial replicates of "control-impact," where the difference in geomorphic and biotic conditions between upstream and downstream reaches could be evaluated to infer the possible effects of culvert presence and whether there is variation by culvert category (physiographic province or culvert length). Thus, we examined metrics intended to detect differences between upstream and downstream geomorphic and biotic community characteristics.

Site Selection

Culvert locations were provided by the SCDOT, and additional locations were identified by intersecting the USGS high-resolution National Hydrography Dataset (U.S. Geological Survey, 2016) with a South Carolina roads digital data layer (http://info2.scdot.org/sites/GIS/SitePages/default.aspx; accessed July 7, 2017) by using ArcGIS 10.3 software. The drainage area above each culvert was determined by using the USGS National Elevation Dataset (U.S. Geological Survey, 2017) 1-arc-second digital elevation data and ArcGIS 10.3 software. Sites were considered for further evaluation if the drainage area was less than 25.9 square kilometers and landcover was minimally disturbed (50–100 percent forest, 0–25 percent agriculture, and 0–10 percent urban), based on the 2011 National Land Cover Dataset (U.S. Geological Survey, 2014). The initial intent of the study was to select five long and five short culverts from both the Upper Coastal Plain and Piedmont physiographic provinces (*n*=20) to achieve a balanced design for data collection. This design would allow for an assessment of differences in ecological and geomorphic conditions on the basis of culvert length and physiographic province. The initial criteria, however, limited the number of potential sites to 20 (out of more than 9,000). During field reconnaissance, we found that several of these sites were immediately downstream from impoundments or were located on swamps. Furthermore, of these 20 culverts, only 3 were longer than 30.5 m. After removing all constraints except culvert type (box culvert), five long culverts suitable for study still could not be found in the Upper Coastal Plain. Therefore, the design was altered to focus on short culverts in the Upper Coastal Plain and Piedmont, allowing for a regional comparison of short culverts, and to focus on long culverts in the Piedmont to evaluate the role of culvert length on biotic communities and stream geomorphology in the Piedmont physiographic province only.

After an initial geographic information system (GIS)-based screening, field reconnaissance was completed to evaluate local-scale conditions. The primary focus was to identify site-specific conditions that may limit or confound the ability to isolate culvert effects. For example, some streams in the Upper Coastal Plain are characterized as swamp-like and have multiple channels. When a berm is built across the floodplain for a road bed and a culvert is installed, the once multichannel stream is constrained into a single-channel passage under the road that continues on the downstream side. Although constraining the stream in this manner is related to the culvert, it is not caused by the interaction of stream flow and culvert design but rather by confining the once broad floodplain. An alternative explanation could be that the transition from multiple channels to a single channel represents a natural change in channel form due to local valley constrictions or other natural factors, and engineers exploit this location to reduce design and construction costs associated with crossing multiple channels. Regardless of cause, this difference in channel form makes it difficult to effectively compare conditions upstream, where there are multiple channels and substantial areas for overbank flow and energy dissipation, to conditions downstream from the culvert, where there is often a single channel. Therefore, only sites that had a single confined channel above and below the culvert were included in the study.

Reach Layout

Field assessments were completed at two scales, by reach and by zone. Fish community, habitat, and geomorphic characterizations were assessed at the reach scale: one reach above and one reach below the culvert. Reaches were 100 m long, except at the site centercr, where reach length was 120 m. Habitat and geomorphic characteristics were assessed along transects crossing the channels. Transects were numbered from downstream (transect 1) to upstream (transect 22). In general, data were evaluated by comparing upstream (assumed to be free of culvert influence) to downstream (potentially affected by culvert) to assess whether box culverts may lead to changes in stream channel morphology, aquatic habitat, or community structure.

Benthic macroinvertebrates and particle-size distributions were sampled in four discrete zones that varied by proximity to the culvert (fig. 2). Zones were 20 m long and were situated adjacent to both ends of the culvert and at both ends of the reach. Zone 1 was at the top of the reach (transects 20–22) and was designated the “background zone.” This zone was assumed to be free of culvert influence. Zone 2 was adjacent to the upstream side of the culvert (transects 12–14) and was called the “upstream impact zone.” This zone was used to evaluate any localized effects upstream from the culvert. Next was zone 3, the “downstream impact zone,” which was adjacent to the downstream side of the culvert (transects 9–11) and used to evaluate any localized effects downstream from the culvert. Zone 4 was the “recovery zone,” which was at the most downstream end of the reach (transects 1–3) and was used to evaluate whether any culvert effects were localized or persistent. Macroinvertebrate and particle-size data were compared among the zones, with primary interest in how the zones adjacent to the culvert compared to those farther away. Possible differences were examined by culvert length class and physiographic province.

Habitat and Geomorphic Assessments

Habitat and geomorphic features were assessed to characterize aquatic habitat, including morphology of the stream channel, channel-bed sediment-size distributions, canopy closure, in-stream habitat features, large woody debris (LWD), macrobedforms (geomorphic channel units [GCUs]), and streambed slope (table 2). The general reach layout and assessment procedures are described in Fitzpatrick and others (1998) and McDonald and others (2018). Modifications of the referenced methods primarily relate to reach layout and are indicated in table 2.

In addition to characterizing habitat and stream channel morphology, detailed culvert measurements were made to evaluate the size of the culvert in relation to the stream channel, which could affect local hydraulics and aquatic habitat. Culvert slopes were also measured and compared to streambed slopes to evaluate possible deviations that could alter local velocity, associated stream power, and scour (Abt and others, 1985).

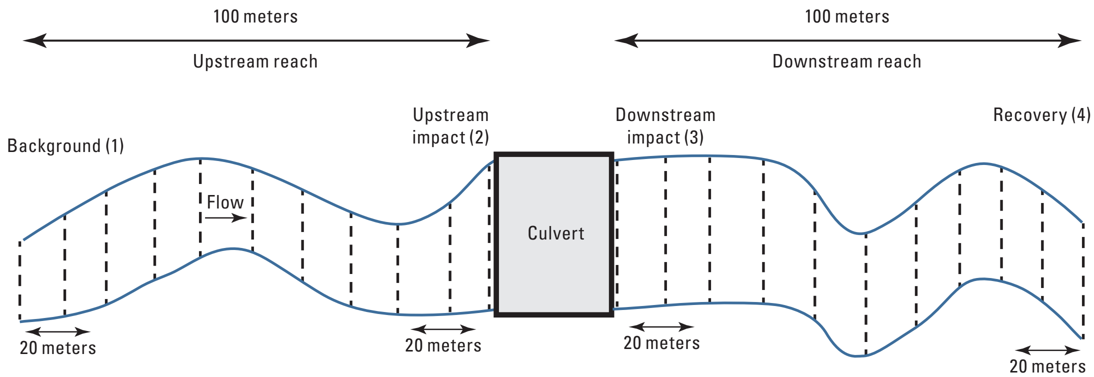


Figure 2. Diagram of reaches, transects, and zones sampled in streams at selected culvert sites in South Carolina, 2016–18. Dashed lines represent transects where habitat and geomorphic characteristics were assessed. Transects were numbered from downstream (transect 1) to upstream (transect 22). Macroinvertebrates were collected and bed sediment was characterized in four 20-meter zones. Zone 1 is the background zone, assumed to be relatively free from culvert effects. Zone 2 is the upstream impact zone, immediately upstream from the culvert. Zone 3 is the downstream impact zone, immediately downstream from the culvert. Zone 4 is the recovery zone, at the downstream end of the reach.

Table 2. Habitat and geomorphic features measured in streams at selected culvert sites in South Carolina, 2016–18; associated method references; and any deviations from the cited methods.

[NA, not applicable; GCU, geomorphic channel unit]

Habitat/geomorphic variable	Method reference	Description or modification to referenced methods
Bankfull depth	Fitzpatrick and others (1998)	NA
Bankfull width	Fitzpatrick and others (1998)	NA
Bankfull cross-sectional area	NA	Product of mean bankfull depth and bankfull width
Canopy closure	Fitzpatrick and others (1998)	Only facing upstream and downstream at each transect
Channel-full depth	McDonald and others (2018)	NA
Channel-full width	McDonald and others (2018)	NA
Channel-full cross-sectional area	NA	Product of mean channel-full depth and channel-full width
Flow velocity	Fitzpatrick and others (1998)	Thalweg velocity only
GCU count and length	Fitzpatrick and others (1998)	NA
Large woody debris volume	McDonald and others (2018)	Product of total length and mean diameter
Bed-sediment particle size	Wolman (1954); Fitzpatrick and others (1998); McDonald and others (2018)	Particles measured from the active channel only
Thalweg slope	Fitzpatrick and others (1998)	NA
Wetted depth	Fitzpatrick and others (1998)	NA
Wetted width	Fitzpatrick and others (1998)	NA
Wetted cross-sectional area	NA	Product of mean wetted depth and wetted width

Channel morphology was assessed at three elevations: wetted, bankfull, and channel-full (incised channel top) levels (fig. 3). Wetted channel dimensions were based on water levels measured during site visits when habitat variables were measured. Bankfull dimensions were based on morphological indicators, where present, and extrapolated where indicators were inadequately defined (Wolman and Leopold, 1957; Harman, 2000). Bankfull dimensions had the greatest uncertainty because indicators were deficient or nonexistent at some sites, especially in many incised channels. Lastly, channel-full dimensions were measured at the top of the first surface above the bankfull elevation (terrace), where water would begin to spill out of a defined channel. In channels that were not incised and had an intact floodplain, bankfull and channel-full elevation were the same.

Bed sediments were sampled by using the pebble count approach originally described by Wolman (1954), with deviations presented in table 2. Particle-size data were used to evaluate the distribution of grain sizes in the zones where macroinvertebrates were collected, and data were summarized to the reach and zone level. Selected particle-size percentiles were calculated for comparison between reaches and across strata (Kondolf and Wolman, 1993). The median diameter (D_{50}) describes the central tendency; the 16th-percentile diameter (D_{16}) describes the fine tail (lower portion) of the distribution, and the 84th-percentile diameter (D_{84}) describes the coarse tail (upper portion) of the distribution. The subscript represents the percentage of particles with diameter finer than the given value. For example, if D_{16} is equal to12 millimeters (mm), then 16 percent of the sampled particles had diameter less than or equal to 12 mm. Percentiles were calculated after removing observations of bedrock, which does not have a defined diameter. Instead, the number of bedrock encounters was recorded for each zone.

Large woody debris (Gregory and others, 2003; Wohl, 2017) was measured and classified following the techniques described in McDonald and others (2018). This method uses a census approach where all LWD greater than 1 m in length and greater than or equal to 0.10 m in diameter was included in the assessment. These data were converted to volume, assuming each piece of wood could be approximated as a cylinder. The values were then aggregated to the reach and zone levels to allow for comparison among reaches, within and between sites.

Fish Community Assessments

Fish communities were assessed in two 100-m reaches at each site, one reach downstream from the culvert and one reach upstream from the culvert (fig. 2). Sampling methods generally followed South Carolina Department of Natural Resources standard operating procedures (Scott and others, 2009). Block nets were placed at the upper limits of each reach. A Smith-Root LR–20B battery-powered backpack electrofishing unit was used to make a single upstream pass through each sampling reach. Collected fish were identified to species, and total length (in millimeters) was measured for up to 30 individuals of each species. Vouchered specimens were fixed in 10 percent formalin, transferred to ethanol for preservation, and cataloged in the Florida Museum of Natural History fish collection. Fish data were stored in the USGS BioData Retrieval System and are publicly accessible (U.S. Geological Survey, 2019).

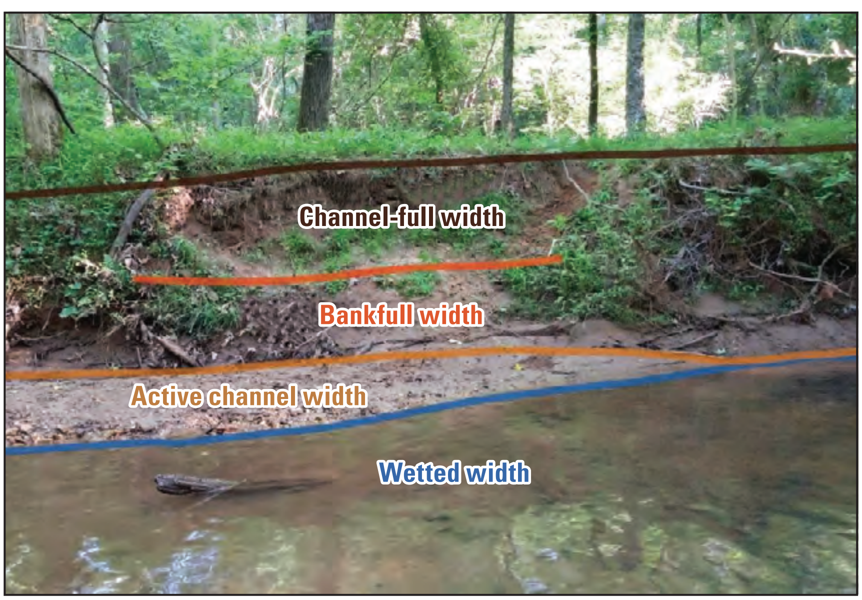


Figure 3. Annotated photograph showing the channel levels, or elevations, where channel morphology measurements were made. Figure modified from McDonald and others (2018).

Macroinvertebrate Community Assessments

Benthic macroinvertebrate samples were collected in the four 20-m sampling zones at each site (fig. 2). The composited sample compromised 10 subsamples collected from all available habitats within a zone. Each habitat type was sampled in proportion to its occurrence for a timed duration of 30 seconds per subsample. This collection procedure approximates the Timed-Qualitative Multiple Habitat Sampling Protocol of the South Carolina Department of Health and Environmental Control (South Carolina Department of Health and Environmental Control, 2017). A D-frame dip net (500-micrometer [µm] mesh) was used to sample undercut banks, leaf packs, and streambeds. For woody snags and large cobbles (128–256 mm), the material was lightly brushed and visually inspected. The samples were sieved through a 500-µm sieve, and large organic and inorganic material was visually inspected and removed. The remaining material was transferred to a 1-liter bottle and preserved with 10 percent buffered formalin. Samples were shipped to Pennington & Associates, Inc., in Cookeville, Tennessee, where macroinvertebrates were identified to the lowest practicable taxonomic level (Pennington, 2016). Macroinvertebrate data were stored in the USGS BioData Retrieval System and are publicly accessible (U.S. Geological Survey, 2019).

Data Analysis

Initially, all habitat and biological data were screened by using summary statistics, simple correlations, bivariate plots, and boxplots to compare data within sites and within and among culvert categories. This preliminary data analysis allowed for the examination of distributions, detection of outliers, and identification of possible associations between variables. Further statistical tests used two approaches: (1) comparisons of reach-level and culvert-category-level summaries (averages) with the use of nonparametric statistical tests and (2) comparisons of community compositions with the use of multivariate permutation tests. Pairwise comparison tests were used for all habitat and geomorphic data and the fish community metrics (for example, the Shannon-Wiener diversity index). For pairwise comparisons, the reach or zone averages of variables of interest were used to test for statistical significance. Because of the small sample size and large variability of measured habitat features, statistical tests used a significance level (α) of 0.10. This significance threshold was used because the chance of Type II error can increase substantially when sample size is small (Kish, 1959; Kim, 2015). Furthermore, given the low within-group sample sizes, nonparametric tests were used to avoid the assumptions of normality that are difficult to verify with small samples. To examine differences within sites (that is, differences between upstream and downstream reaches) a paired-sample Wilcoxon signed-rank test was used to test the null hypothesis that the distribution of paired differences is symmetrical around zero (Ott and Longnecker, 2001). When comparing between the different categories (for example, short Upper Coastal Plain culverts versus short Piedmont culverts), a Wilcoxon rank-sum test was used to test for a shift in distribution of ranks between two samples. Before running statistical tests, the morphological data were converted to z-scores (Ott and Longnecker, 2001) to determine how individual transect measurements deviated from the site-level average. This rescaling approach reduces the effect of absolute magnitude on statistical analysis because all observations represent the number of standard deviations from the respective site-level average. All pairwise statistical analyses were conducted using the software R (R Core Team, 2017), and the Wilcoxon signed-rank tests used implementations in the coin package (Hothorn and others, 2008). To test for longitudinal differences in channel constriction or widening (ratio of channel width to culvert width) that may be related to culvert proximity, a Kruskal-Wallis test was used. This analysis tested the null hypothesis that data from each transect are from the same distribution.

For fish community data, the catch per unit effort (*C/f*) was calculated for sample comparison (Hubert and Fabrizio, 2007). For macroinvertebrate community data, species that occurred in less than 2 percent of the samples were eliminated. Ambiguities in the taxonomic assemblage were resolved by distributing the abundance of ambiguous individuals among those identified to lower taxonomic levels according to the relative abundance of those identified to the lowest level by using the Invertebrate Data Analysis System (Cuffney and Brightbill, 2011). This approach maximizes taxa abundance without affecting the taxa richness and is one of the methods suggested by Cuffney and others (2007).

For both fish and macroinvertebrates, the assemblage data were square-root transformed and a Bray-Curtis similarity matrix was calculated by using Plymouth Routines in Multivariate Ecological Research (PRIMER) software (PRIMER v7; Clarke and Gorley, 2015). A square-root transformation is a mild adjustment of quantitative data to reduce the influence or dominance of very abundant species. Several routines in the PRIMER software were used to evaluate the biological community data. A one-way analysis of similarities (ANOSIM) test was performed to assess statistical differences between zones within each category. Nonmetric multidimensional scaling (nMDS) plots produced an ordination based on resemblance matrices in two-dimensional (2D) and three-dimensional (3D) space; samples that plot near each other are more similar than samples that plot far away. In conjunction with nMDS, hierarchical cluster analysis (CLUSTER) with similarity profile analysis (SIMPROF; with 999 permutations) tests identified statistically significant groupings of samples with similar biological community composition. Whereas nMDS plots provide a qualitative view of how samples plot relative to each other, CLUSTER with SIMPROF provides statistically significant groupings of samples.

Associations between biological community structure and abiotic and biotic variables were explored by using the Bio-Env + Stepwise (BEST) routine in PRIMER. The BEST routine determines which variable or combination of variables explains the variation in the biological community. Draftsman plots were examined to eliminate correlated abiotic (habitat) variables. Then, the agreement between the biological community was compared with the variable matrix (Euclidean matrix for habitat variables or Bray-Curtis matrix for macroinvertebrate metrics) by using a Spearman rank correlation coefficient.

The Shannon-Wiener diversity index, Simpson's diversity index, and Pielou's evenness are metrics commonly calculated for biological communities. These diversity indices provide more information about community composition than taxonomic richness alone. The Shannon-Wiener index is the ratio of the number of species to their importance values in the community. Simpson's diversity index is a measure of both taxonomic richness and the relative abundance of each species and is therefore an indicator of dominance. Pielou's evenness is a measure of how evenly species are distributed in the community.

Habitat and Geomorphic Characterization

Overall, geomorphic and habitat characteristics were highly variable regardless of culvert length or physiographic province, possibly due to the influence of site-specific factors masking or overriding potential culvert effects. The following sections focus on a subset of the geomorphic and habitat characteristics to evaluate changes to broad-scale habitat, channel morphology, LWD, and bed-sediment texture. Where differences were observed, statistical tests were performed to evaluate the strength of the relation. The habitat and geomorphic data used in this report are available at https://doi.org/10.5066/P9VD9AYY (Riley and Walsh, 2019).

Geomorphic Channel Units

Across all sites, runs were the most prevalent GCU, accounting for an average of 75 percent of the reach length, followed by riffles (15 percent), and pools (10 percent). A greater prevalence of riffles was observed in the Piedmont (mean = 20 percent of reach length) than in the Upper Coastal Plain (mean = 2 percent of reach length). Upper Coastal Plain riffles were formed by woody debris, and their temporal persistence likely is shorter than that of the rock-dominated riffles in the Piedmont. Although there were differences in the proportions of GCUs between physiographic provinces, as expected, no substantial or significant differences were observed between the long or short culverts within the Piedmont.

The number of GCUs encountered within a reach served as an indicator of habitat complexity. In five of the six Upper Coastal Plain sites, habitat complexity was greater downstream from the culvert, as indicated by a greater number of GCUs in downstream reaches (fig. 4). A paired-sample Wilcoxon signed-rank test indicated a significant difference in channel complexity between upstream and downstream reaches in the Upper Coastal Plain (table 3); however, this pattern was not observed for Piedmont sites of either culvert length class. Comparing the difference in the number of GCUs from upstream to downstream reaches between regions, for short culverts only, indicated that Upper Coastal Plain sites generally had a greater difference in habitat complexity between upstream and downstream (fig. 4). On average, the Upper Coastal Plain sites had four more GCUs in the downstream reach than in the upstream reach, whereas the Piedmont sites (short culverts) had, on average, one fewer GCU in the downstream reach. The results from a Wilcoxon rank-sum test indicated a significant difference in distributions between regions. The estimated median difference (or shift parameter) of 3.00 does not necessarily have an ecologically meaningful interpretation. Rather, the positive estimate simply indicates that Piedmont sites collectively did not show the degree of channel complexity increase from upstream to downstream that was observed at the Upper Coastal Plain sites. A comparison between short and long culverts in the Piedmont indicated no significant differences between upstream and downstream channel complexity.

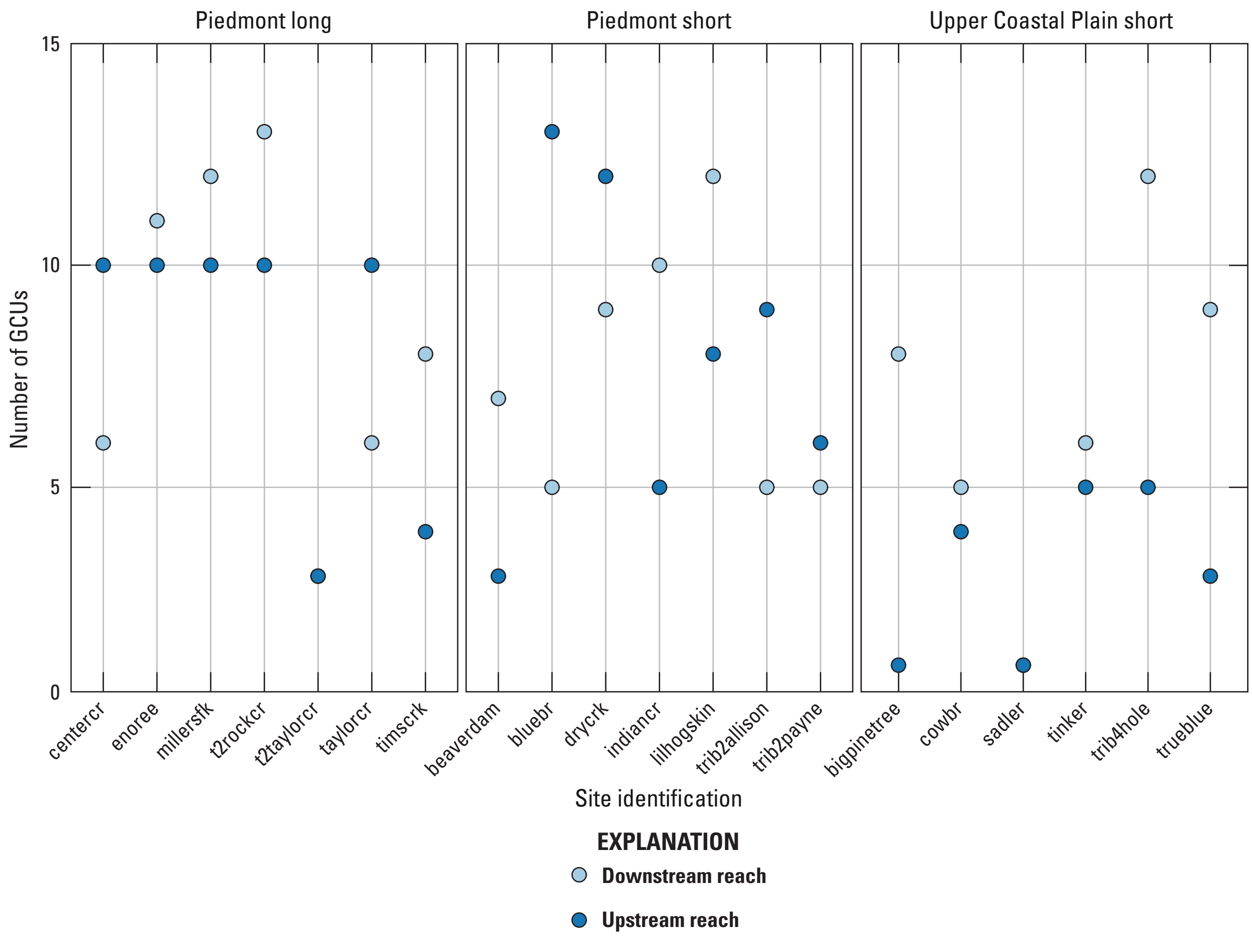


Figure 4. Graph showing habitat complexity, as defined by the number of geomorphic channel units (GCUs) per reach, at selected culvert sites in South Carolina. Each panel represents a combination of physiographic province and culvert length class: Piedmont long culverts, Piedmont short culverts, and Upper Coastal Plain short culverts.

Table 3. Results of nonparametric tests on habitat complexity measured in upstream (US) and downstream (DS) reaches at selected culvert sites in South Carolina, 2016–18.

[Habitat complexity is defined as the number of geomorphic channel units per reach. CI, confidence interval]

Comparison	Number of observations[1]	Upper 90% CI	Lower 90% CI	*p*-value	Pseudo-median/difference in location[2]
Wilcoxon signed-rank test					
DS versus US complexity—Upper Coastal Plain short culverts	6/6	7.00	1.00	[3]0.06	4.00
DS versus US complexity—Piedmont short culverts	7/7	4.00	−4.50	1	1.86e−05
DS versus US complexity—Piedmont long culverts	7/7	2.99	−1.50	1	2.49e−05
Wilcoxon rank-sum test					
Difference in DS and US reach complexity—Upper Coastal Plain short culverts versus Piedmont short culverts	6/7	8.99	0.99	[3]0.09	3.00
Difference in DS and US reach complexity—Piedmont long culverts versus short culverts	7/7	4.99	−3.00	0.95	−4.94e−05

[1]Number of observations in each group in the comparison.

[2]Pseudo-median for the Wilcoxon signed-rank test and difference in location for Wilcoxon rank-sum test. These values represent the approximate median of the differences between groups.

[3]Significant at the 90-percent confidence level.

Channel Morphology

Channel morphology was assessed at three elevations: wetted, bankfull, and channel-full levels (fig. 3). The assessment of culvert effects, however, focused only on channel-full characteristics because the variability in water level between sites affected wetted dimensions and because of the uncertainty associated with delineation of bankfull dimensions in many of the incised streams. To evaluate differences in gross channel morphology (width, depth, cross-sectional area), data were normalized as previously described. Transect data were then summarized to the reach scale to evaluate differences in average channel characteristics between upstream and downstream reaches. Cross-sectional area was the primary metric for evaluating changes in channel morphology. This variable represents gross changes in morphology without considering the dimension (lateral or vertical) of adjustments, which may change over time in response to a reoccurring perturbation (in the sense of channel evolution models; Simon, 1989). In general, channel-full area was variable at the Piedmont sites, and there was no consistent trend between upstream and downstream reaches for long or short culverts (fig. 5). At five of the six Upper Coastal Plain sites, mean channel-full area increased downstream from the culvert (mean difference of 2.16 square meters [m^2]), which differed significantly from the short culvert sites in the Piedmont (mean difference of 0.10 m^2) (table 4). The Wilcoxon rank-sum test indicated that the distribution in the Upper Coastal Plain was shifted 0.98 unit (approximately one standard deviation) compared to Piedmont sites. Like the analysis of GCUs, the positive value (shifted to the right of zero) indicates that the difference between upstream and downstream channel-full area is greater at Upper Coastal Plain sites than at Piedmont sites.

Field observations, particularly at the Upper Coastal Plain sites, as well as exploratory plots, indicated that channel-full depths were often greater downstream from the culverts (fig. 6). The results of a Wilcoxon signed-rank test showed a significant difference in the average depth between upstream and downstream reaches in the Upper Coastal Plain (table 5); however, no significant differences between upstream and downstream reaches were observed for Piedmont sites of either culvert length class (table 5). The difference in average depth between upstream and downstream reaches was significantly different across physiographic provinces (short culverts only), with the Upper Coastal Plain shifted to the right, indicating a greater difference in depth between the upstream and downstream reaches than in the Piedmont. Although differences were significant, they were not of substantial magnitude, with an average increase in depth of 0.17 m in Upper Coastal Plain downstream reaches and −0.12 m in Piedmont downstream reaches. The negative value indicates that, on average, the Piedmont downstream reaches were shallower than upstream reaches. No significant differences were observed between the culvert length classes for the Piedmont sites.

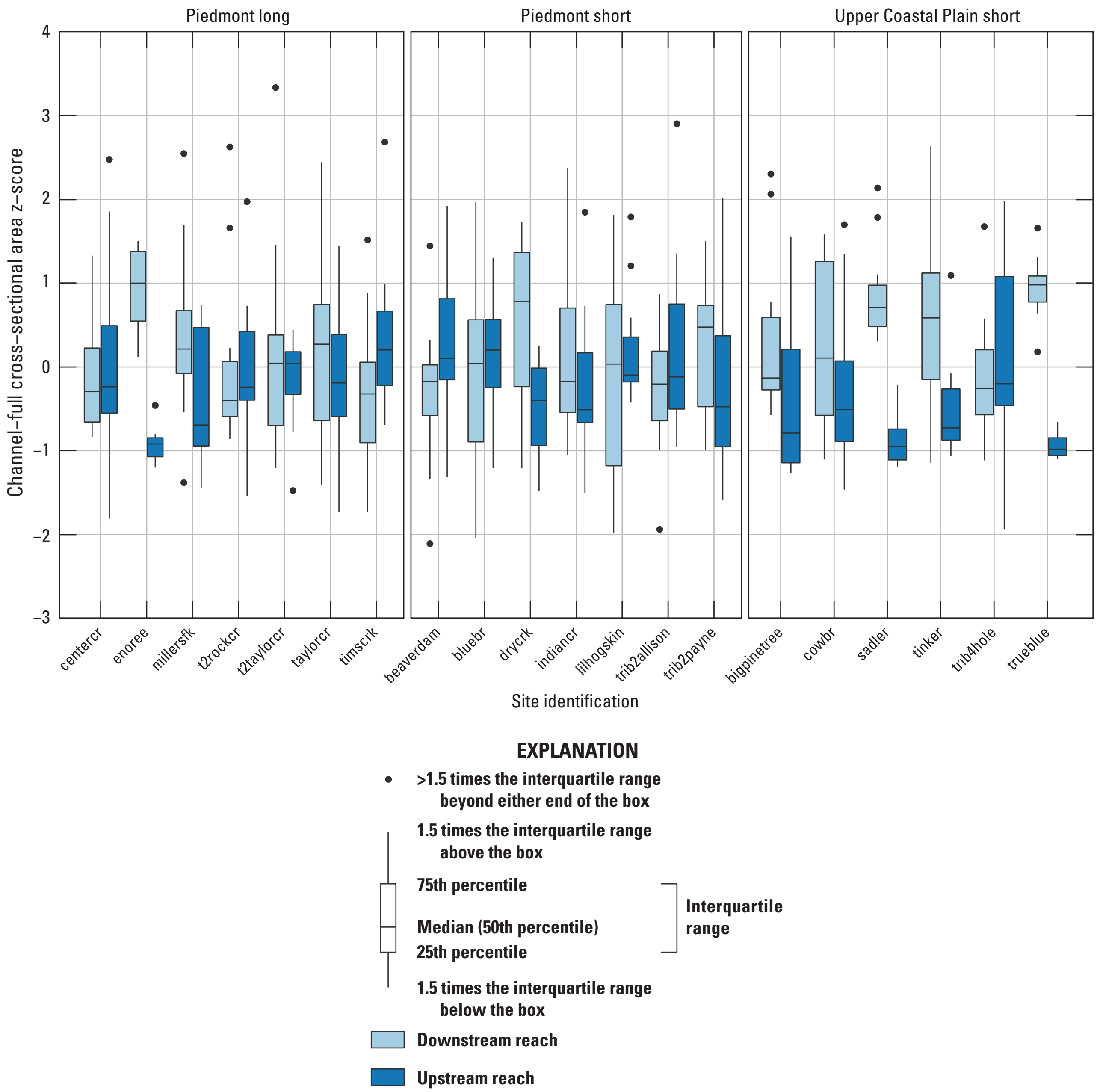


Figure 5. Boxplots showing the distribution of channel-full cross-sectional area z-scores for upstream and downstream reaches at selected culvert sites in South Carolina, 2016–18. Each panel represents a combination of physiographic province and culvert length class: Piedmont long culverts, Piedmont short culverts, and Upper Coastal Plain short culverts.

Table 4. Results of nonparametric tests on mean channel-full cross-sectional area z-scores for upstream (US) and downstream (DS) reaches at selected culvert sites in South Carolina, 2016–18.

[CI, confidence interval]

Comparison	Number of observations[1]	Upper 90% CI	Lower 90% CI	*p*-value	Pseudo-median/difference in location[2]
Wilcoxon signed-rank test					
DS versus US mean channel-full cross-sectional area z-score—Upper Coastal Plain short culverts	6/6	1.73	0.23	[3]0.06	0.82
DS versus US mean channel-full cross-sectional area z-score—Piedmont short culverts	7/7	0.45	−0.49	0.81	−0.01
DS versus US mean channel-full cross-sectional area z-score—Piedmont long culverts	7/7	1.07	−0.17	0.29	0.32
Wilcoxon rank-sum test					
Difference in DS and US mean channel-full cross-sectional area z-score—Upper Coastal Plain short culverts versus Piedmont short culverts	6/7	1.42	0.22	[3]0.03	0.98
Difference in DS and US mean cross-sectional area channel-full z-score—Piedmont long culverts versus short culverts	7/7	0.96	−0.36	0.56	0.35

[1]Number of observations in each group in the comparison.

[2]Pseudo-median for the Wilcoxon signed-rank test and difference in location for the Wilcoxon rank-sum test. These values represent the approximate median of the differences between groups.

[3]Significant at the 90-percent confidence level.

The width-to-depth ratio was also evaluated as an indicator of changes in channel shape between upstream and downstream reaches (fig. 7). This variable can indicate which dimension may be dominating the change in cross-sectional area. Large values indicate a relatively wide and shallow channel, whereas small values indicate a relatively narrow and deep channel. Upper Coastal Plain sites had a reduced mean channel-full width-to-depth ratio downstream from the culvert, indicating a deeper and (or) narrower channel shape, at five of the six sites. The Piedmont sites were highly variable; at five of the seven short culverts, channels were deeper and (or) narrower downstream, but the opposite effect was observed at the long culverts (channels were wider and [or] shallower downstream at five of the seven sites). Wilcoxon rank tests, however, showed no significant differences in width-to-depth ratios within or among any of the strata. This result was unexpected given the differences in cross-sectional area and depth in the Upper Coastal Plain and indicates that any channel enlargement was not consistent in one dimension and included both lateral and vertical adjustments.

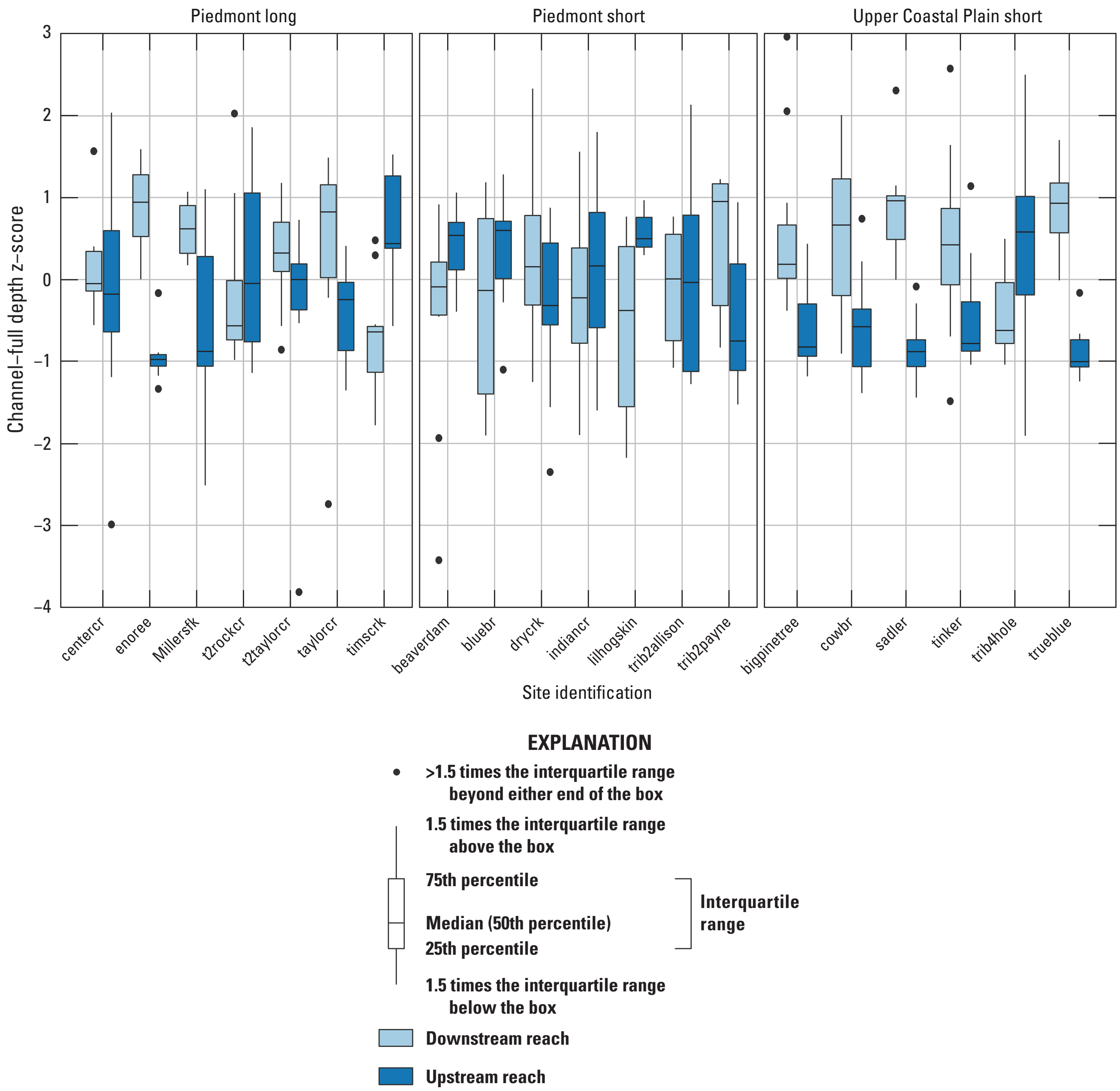


Figure 6. Boxplots showing the distribution of channel-full depth z-scores for upstream and downstream reaches at selected culvert sites in South Carolina, 2016–18. Each panel represents a combination of physiographic province and culvert length class: Piedmont long culverts, Piedmont short culverts, and Upper Coastal Plain short culverts.

Table 5. Results of nonparametric tests on mean channel-full depth z-scores for upstream (US) and downstream (DS) reaches at selected culvert sites in South Carolina, 2016–18.

[CI, confidence interval]

Comparison	Number of observations[1]	Upper 90% CI	Lower 90% CI	*p*-value	Pseudo-median/difference in location[2]
Wilcoxon signed-rank test					
DS versus US mean channel-full depth z-score—Upper Coastal Plain short culverts	6/6	1.70	0.16	[3]0.06	1.15
DS versus US mean channel-full depth z-score—Piedmont short culverts	7/7	0.39	−0.80	0.47	−0.28
DS versus US mean channel-full depth z-score—Piedmont long culverts	7/7	1.21	−0.41	0.38	0.50
Wilcoxon rank-sum test					
Difference in DS and US mean channel-full depth z-score—Upper Coastal Plain short culverts versus Piedmont short culverts	6/7	2.07	0.37	[3]0.05	1.40
Difference in DS and US mean channel-full depth z-score—Piedmont long culverts versus short culverts	7/7	0.96	−0.36	0.56	0.35

[1]Number of observations in each group in the comparison.

[2]Pseudo-median for the Wilcoxon signed-rank test and difference in location for the Wilcoxon rank-sum test. These values represent the approximate median of the differences between groups.

[3]Significant at the 90-percent confidence level.

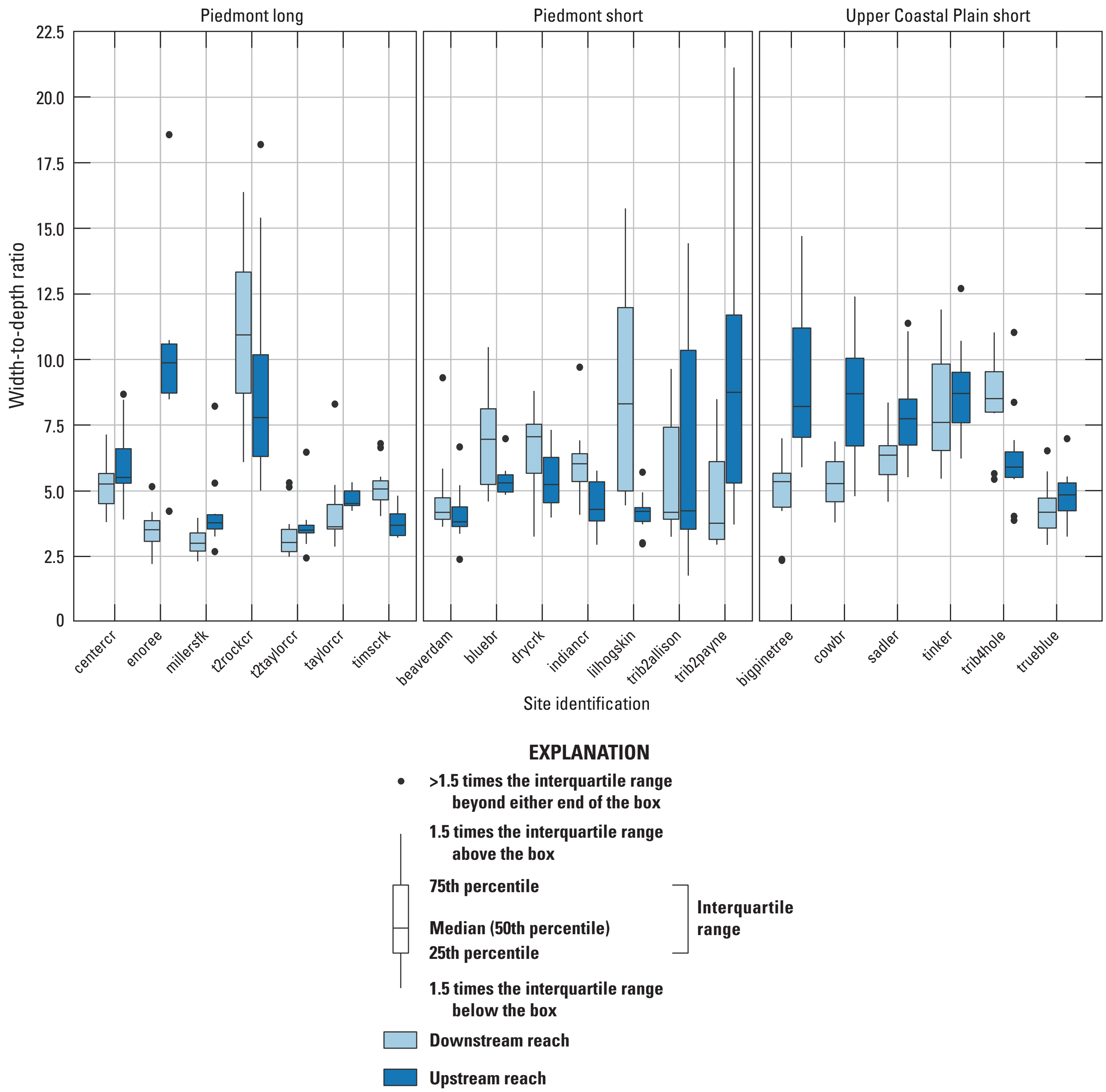


Figure 7. Boxplots showing the distribution of channel-full width-to-depth ratio for upstream and downstream reaches at selected culvert sites in South Carolina, 2016–18. Each panel represents a combination of physiographic province and culvert length class: Piedmont long culverts, Piedmont short culverts, and Upper Coastal Plain short culverts.

Bed-Sediment Characteristics and Large Woody Debris

Pebble counts were conducted in the four sampling zones (fig. 2) at each Piedmont site to determine the distributional characteristics of the bed sediment in the areas where macroinvertebrates were collected. Bed-sediment particle sizes in the Upper Coastal Plain were not analyzed because of the dominance of sand and finer bed material. Median particle size (D_{50}) from the 14 Piedmont sites ranged from 1 mm (the value assigned to sand and finer material), which was observed at multiple sites and zones, to 50.5 mm in the background zone at the site taylorcr. There were no clear trends between zones (that is, proximity to the culvert) and median particle size at any of the sites, regardless of culvert length (fig. 8). The prevalence of bedrock encountered during pebble counts was also evaluated. The greatest prevalence of bedrock was observed in the background zone at the site millersfk, which was 48 percent bedrock. Bedrock was not encountered at several sites. There were no observed patterns in bedrock prevalence related to zone or culvert length. Large woody debris also varied across reaches and sites and did not show any distinct trends between upstream or downstream reaches, by physiographic province or culvert length class (fig. 9).

Culvert Slope

Only 4 of the 20 sites had culvert slopes greater than 2 percent, and they were distributed equally among long and short culverts, with only 1 site in the Upper Coastal Plain (fig. 10). Of these four sites (t2rockcr, millersfk, bigpinetree, trib2payne), t2rockcr had the greatest slope and perch height, as well as the greatest apparent effects downstream from the culvert. A consistent observation among these sites was that the culverts retained little to no sediment. Other sites that had culvert slopes less than 1 percent, however, also did not retain sediment, indicating that culvert slope is not the sole determinant of sediment retention. Furthermore, culvert slope was not a good indicator of culvert perching. Perching was observed at the culverts with the steepest slopes, as well as at culverts with slopes less than the streambed slope (for example, the site enoree). The observation of perching at culverts with low slopes could be the result of headward migration of a knickpoint (a part of a channel where there is a sharp change in slope) that was halted by the erosion-resistant culvert.

Ratio of Culvert Width to Bankfull Width

The ratio of culvert width to bankfull width at each transect was assessed to evaluate if constriction (or over widening) resulted in systematic changes in channel morphology. The ratio of culvert width to bankfull width at each transect was inconsistent at most sites. Across all sites, Kruskal-Wallis tests suggested no significant differences based on transect distance from the culvert. There were exceptions, such as the site t2rockcr, where the channel was three to five times wider than the culvert at transects 10 and 11, just downstream from the culvert. There were other differences that were substantial but not necessarily related to water flowing through the culvert. For example, at the sites bluebr and trib2payne, the bankfull width just upstream from the culvert (transect 12) was much wider than the culvert opening. Presumably, the widening was related to an acute approach angle, where the culvert was installed in a slight bend that led to bank erosion adjacent to the culvert wing wall on the cut bank side and subsequent channel enlargement. The culverts were narrower than the bankfull width at 11 sites and wider at 9 sites. The greatest deviations were at site indiancr, where the culvert was 1.68 times wider than the mean bankfull width, and site trib2payne, where the culvert constricted flows to about one-half (0.47 percent) of the mean bankfull width. At several sites where multiple culvert boxes were present, sediment had accumulated in the secondary box to a level above the bankfull elevation, concentrating the flow to a single box for that flow level and below. This concentration of flow could lead to greater erosion during a small range of events, whereas lower frequency but high-magnitude events would contribute flow to the area in the second box above the sediment surface. Although the above results indicate a slightly greater prevalence of culvert opening widths that are narrower than bankfull widths, the morphological data characterizing the reach transects do not suggest that contemporaneous contraction scour is a widespread issue at the study sites.

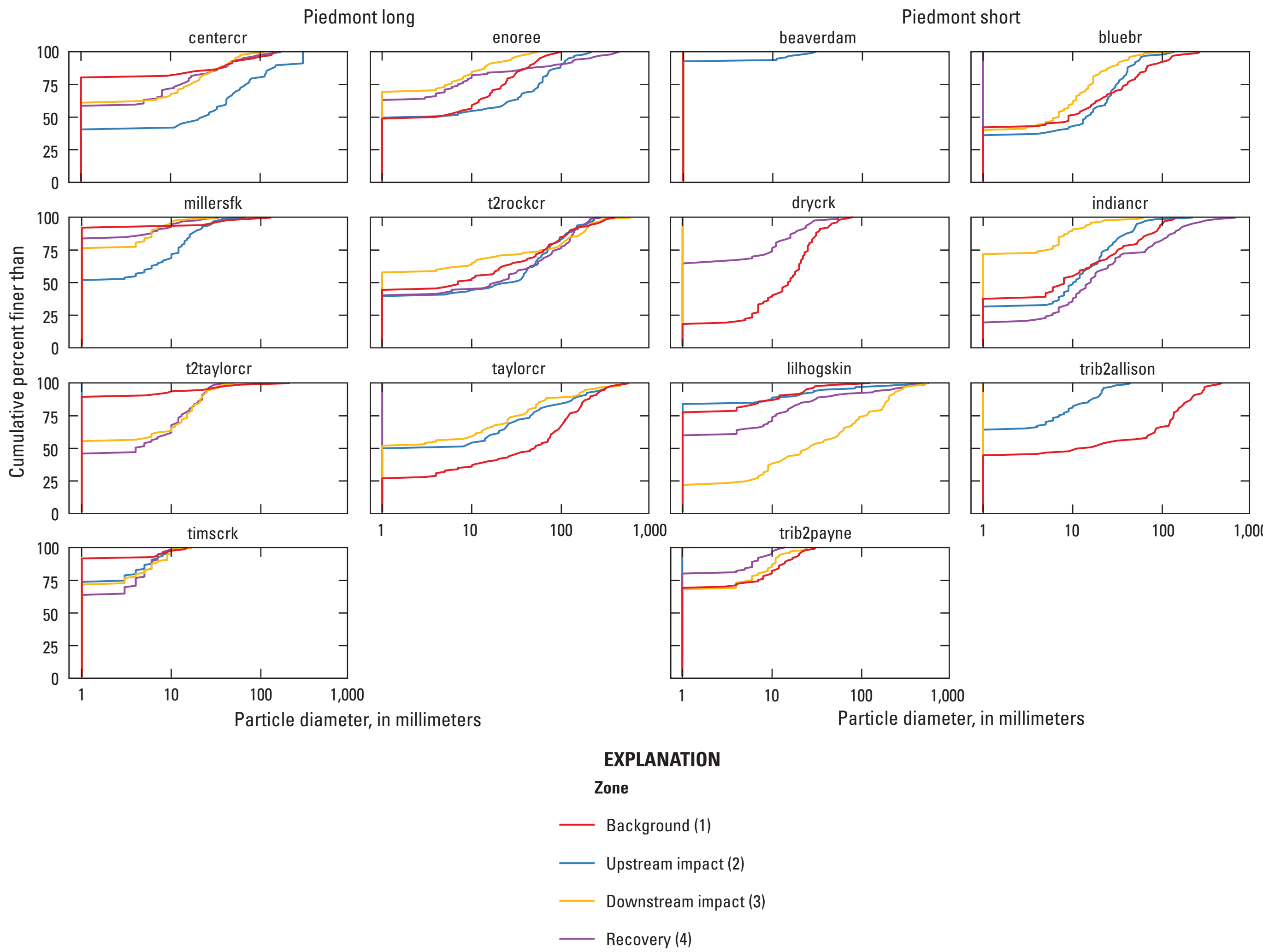


Figure 8. Graphs showing particle-size cumulative frequency distributions within each zone for the 14 Piedmont study sites. Zone 1 is the background zone (at the upstream end of the reach, assumed to be relatively free from culvert effects). Zone 2 is the upstream impact zone (immediately upstream from the culvert). Zone 3 is the downstream impact zone (immediately downstream from the culvert). Zone 4 is the recovery zone (at the downstream end of the reach). Vertical lines at the 1-millimeter mark indicate that all bed particles in that zone were sand or finer material; some lines are obscured where all particles were sand or finer in more than one zone.

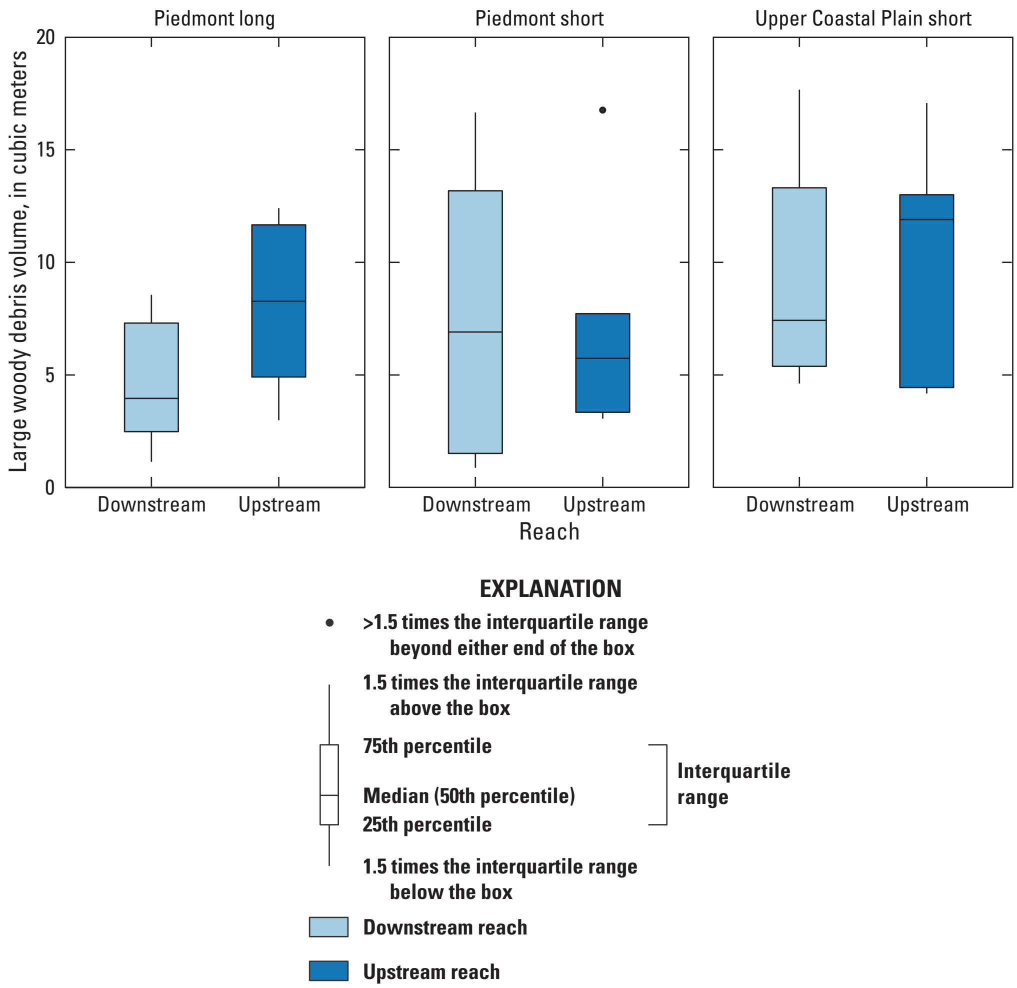


Figure 9. Boxplots showing the distribution of large woody debris volume, aggregated to the reach level, at selected culvert locations in South Carolina, 2016–18. Each panel represents a combination of physiographic province and culvert length class: Piedmont long culverts, Piedmont short culverts, and Upper Coastal Plain short culverts.

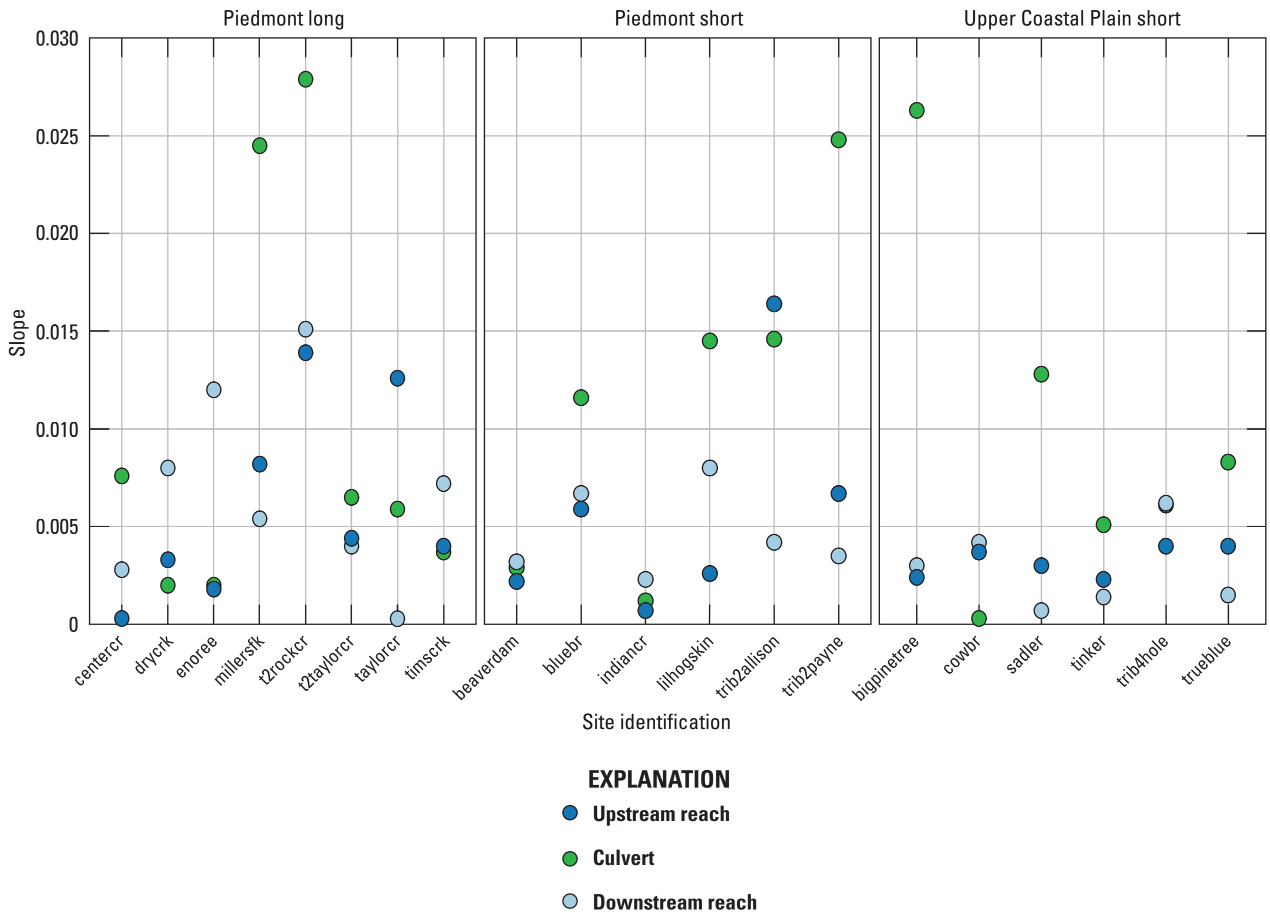


Figure 10. Graph showing the slope of culvert bottom and stream thalweg in upstream and downstream reaches at selected culvert sites in South Carolina, 2016–18. Each panel represents a combination of physiographic province and culvert length class: Piedmont long culverts, Piedmont short culverts, and Upper Coastal Plain short culverts.

Fish Community Characterization

A total of 3,968 fish specimens were collected, representing 44 species in 21 genera and 10 families (table 6). Of the total individuals caught, 82.2 percent were represented by 10 species: 5 species of minnows (family Cyprinidae), 3 species of sunfishes (family Centrarchidae), and 1 species each of suckers (family Catostomidae) and mosquitofish (family Poeciliidae). The remaining 34 species ranged from 0.03 to 1.66 percent of the total sample (number of individuals of each species ranging from 1 to 66). Because more sites were sampled in the Piedmont (14) than in the Upper Coastal Plain (6), more fish specimens were captured in the Piedmont than in the Upper Coastal Plain (3,142 and 826 fish specimens, respectively).

A prominent geographic separation was apparent for 26 of the species, with 15 captured only at sites in the Piedmont physiographic province and 11 captured only at sites in the Upper Coastal Plain; 18 species were common to both the Piedmont and the Upper Coastal Plain (table 6). Of the 10 most abundant fish species, 5 were collected in only one physiographic province; 4 of these species were confined to the Piedmont (the percent composition of total number of fish caught from both physiographic provinces is in parentheses): *Nocomis leptocephalus* (15.93 percent), *Notropis lutipinnis* (5.92 percent), *Lepomis cyanellus* (5.65 percent), and *Notropis chlorocephalus* (3.05 percent). The sixth most common species, *Pteronotropis stonei* (5.80 percent) was found only in the Upper Coastal Plain. The second to fourth most abundant species were collected in both physiographic provinces: *Lepomis auritus* (15.47 percent), *Semotilus atromaculatus* (14.79 percent), and *Lepomis macrochirus* (7.69 percent)—all were collected in greater numbers in the Piedmont, partly because more sites were sampled and that province presumably had greater habitat suitability than the Upper Coastal Plain. The other 2 species represented among the 10 most abundant were also collected in both physiographic provinces: *Gambusia holbrooki* (5.22 percent) and *Erimyzon oblongus* (2.67 percent)—more individuals of both species were collected in the Piedmont because they were present in many stream reaches and were found at a few reaches in especially high abundance.

Table 6. Fish species collected at selected culvert sites in South Carolina, 2016–18, physiographic province, number of sites, number of reaches where each species was collected, number of specimens, and percent composition of total sample.

[Shading indicates the 10 most abundant species, which represent 82.2 percent of all fish captured. x, species captured in that physiographic province; —, not applicable or species not captured in that physiographic province]

Species	Common name	Upper Coastal Plain	Piedmont	No. of sites	No. of reaches	No. of specimens	Percent composition
			Family Anguillidae				
Anguilla rostrata	American eel	x	—	1	2	19	0.48
			Family Cyprinidae				
Clinostomus funduloides	Rosyside dace	—	x	2	3	51	1.29
Hybognathus regius	Eastern silvery minnow	—	x	1	2	5	0.13
Hybopsis hypsinotus	Highback chub	—	x	3	5	59	1.49
Hybopsis rubrifrons	Rosyface chub	—	x	2	3	12	0.30
Nocomis leptocephalus	Bluehead chub	—	x	11	20	632	15.93
Notemigonus crysoleucas	Golden shiner	x	x	5	6	30	0.76
Notropis chlorocephalus	Greenhead shiner	—	x	4	8	121	3.05
Notropis cummingsae	Dusky shiner	—	x	2	2	4	0.10
Notropis hudsonius	Spottail shiner	—	x	2	2	6	0.15
Notropis lutipinnis	Yellowfin shiner	—	x	2	4	235	5.92
Notropis petersoni	Coastal shiner	x	x	3	3	19	0.48
Notropis procne	Swallowtail shiner	—	x	1	1	3	0.08
Pteronotropis stonei	Lowland shiner	x	—	4	7	230	5.80
Semotilus atromaculatus	Creek chub	x	x	11	20	587	14.79
			Family Catostomidae				
Erimyzon oblongus	Creek chubsucker	x	x	10	15	106	2.67
Erimyzon sucetta	Lake chubsucker	x	—	1	1	1	0.03
			Family Ictaluridae				
Ameiurus brunneus	Snail bullhead	x	x	4	5	8	0.20
Ameiurus natalis	Yellow bullhead	x	x	13	16	37	0.93
Ameiurus nebulosus	Brown bullhead	x	x	3	5	10	0.25
Noturus gyrinus	Tadpole madtom	x	—	1	1	2	0.05
Noturus insignis	Margined madtom	x	x	5	9	39	0.98
			Family Esocidae				
Esox americanus	Grass pickerel	x	x	7	13	63	1.59
Esox niger	Chain pickerel	x	—	1	2	11	0.28
			Family Aphredoderidae				
Aphredoderus sayanus	Pirate perch	x	x	7	10	36	0.91
			Family Fundulidae				
Fundulus lineolatus	Lined topminnow	x	—	1	2	10	0.25
			Family Poeciliidae				
Gambusia holbrooki	Eastern mosquitofish	x	x	9	15	207	5.22
			Family Centrarchidae				
Acantharchus pomotis	Mud sunfish	x	—	1	1	1	0.03
Enneacanthus chaetodon	Blackbanded sunfish	x	—	1	1	6	0.15
Enneacanthus gloriosus	Bluespotted sunfish	x	—	2	2	8	0.20
Lepomis auritus	Redbreast sunfish	x	x	18	33	614	15.47

Table 6. Fish species collected at selected culvert sites in South Carolina, 2016–18, physiographic province, number of sites, number of reaches where each species was collected, number of specimens, and percent composition of total sample.—Continued

[Shading indicates the 10 most abundant species, which represent 82.2 percent of all fish captured. x, species captured in that physiographic province; —, not applicable or species not captured in that physiographic province]

Species	Common name	Upper Coastal Plain	Piedmont	No. of sites	No. of reaches	No. of specimens	Percent composition
Family Centrarchidae—Continued							
Lepomis cyanellus	Green sunfish	—	x	6	10	224	5.65
Lepomis gibbosus	Pumpkinseed	—	x	2	3	33	0.83
Lepomis gulosus	Warmouth	x	x	7	11	66	1.66
Lepomis macrochirus	Bluegill	x	x	13	20	305	7.69
Lepomis marginatus	Dollar sunfish	x	—	3	6	16	0.40
Lepomis microlophus	Redear sunfish	x	x	3	3	11	0.28
Lepomis punctatus	Spotted sunfish	x	—	3	5	31	0.78
Micropterus salmoides	Largemouth bass	x	x	10	14	31	0.78
Family Percidae							
Etheostoma collis	Carolina darter	—	x	5	7	18	0.45
Etheostoma fusiforme	Swamp darter	x	x	2	2	2	0.05
Etheostoma hopkinsi	Christmas darter	—	x	2	4	23	0.58
Etheostoma olmstedi	Tessellated darter	x	x	5	6	34	0.86
Etheostoma thalassinum	Seagreen darter	—	x	1	2	2	0.05
Total	—	**28**	**32**	**—**	**—**	**3,968**	**100**

The occurrence of fish species among sites and reaches was highly variable. The number of sites where a species was collected ranged from 1 to 18 and averaged 4.5 (table 6). Ten species were found at a single site; half of those were collected in both upstream and downstream reaches, and the other half were collected in only one reach. Of the total 44 species collected, 32 were found at no more than five sites and 9 species were found at only one or two sites. Each species was collected in at least 1 reach and at most 33 reaches; 28 species were found in 6 reaches or fewer.

The values of the Shannon-Wiener diversity index (S–W, $\log_{10}$) for fish per reach ranged from 0.16 to 1.04 among all sites, excluding the downstream reach at site drycrk, which had only one species (fig. 11). At 4 of the 6 Upper Coastal Plain sites and 8 of the 14 Piedmont sites, the downstream reach S–W value was higher than that of the upstream reach (fig. 11). Despite this possible trend, there were no significant differences between upstream and downstream S–W values across culvert categories, nor were there differences in the other diversity metrics examined for fish, Pielou's evenness and Simpson's diversity (dominance) index, based on Wilcoxon signed-rank tests.

A resemblance matrix of fish *C/f* (catch per unit effort; Hubert and Fabrizio, 2007) data was input into PRIMER for further analysis. The results of a global ANOSIM analysis of this resemblance matrix revealed a significant difference among groups (test statistic [R]=0.273; p=0.01). Individual pairwise comparisons of the ANOSIM test statistic showed significant differences between eight strata (R ranging from 0.472 to 0.765), but each of these pairwise differences was between a reach and culvert length combination of separate Upper Coastal Plain and Piedmont sites. A SIMPROF test in PRIMER indicated general separation of sites largely by physiographic province (fig. 12; test statistic [π]=3.46, p=0.01). There was complete separation of Piedmont and Upper Coastal Plain sites in the nonmetric multidimensional scaling (nMDS) plot with a moderate 2D stress level of 0.15 (fig. 13); however, there was no organized grouping of the fish assemblages among sites within either physiographic province. On the basis of the hierarchical cluster analysis, the sites beaverdam and drycrk grouped together and were separated from all other sites in the Piedmont. Both sites centercr and indiancr grouped with Upper Coastal Plain sites. Among all Piedmont sites, centercr and indiancr are closest to the boundary between the physiographic provinces and thus have more fish species in common with the Upper Coastal Plain sites.

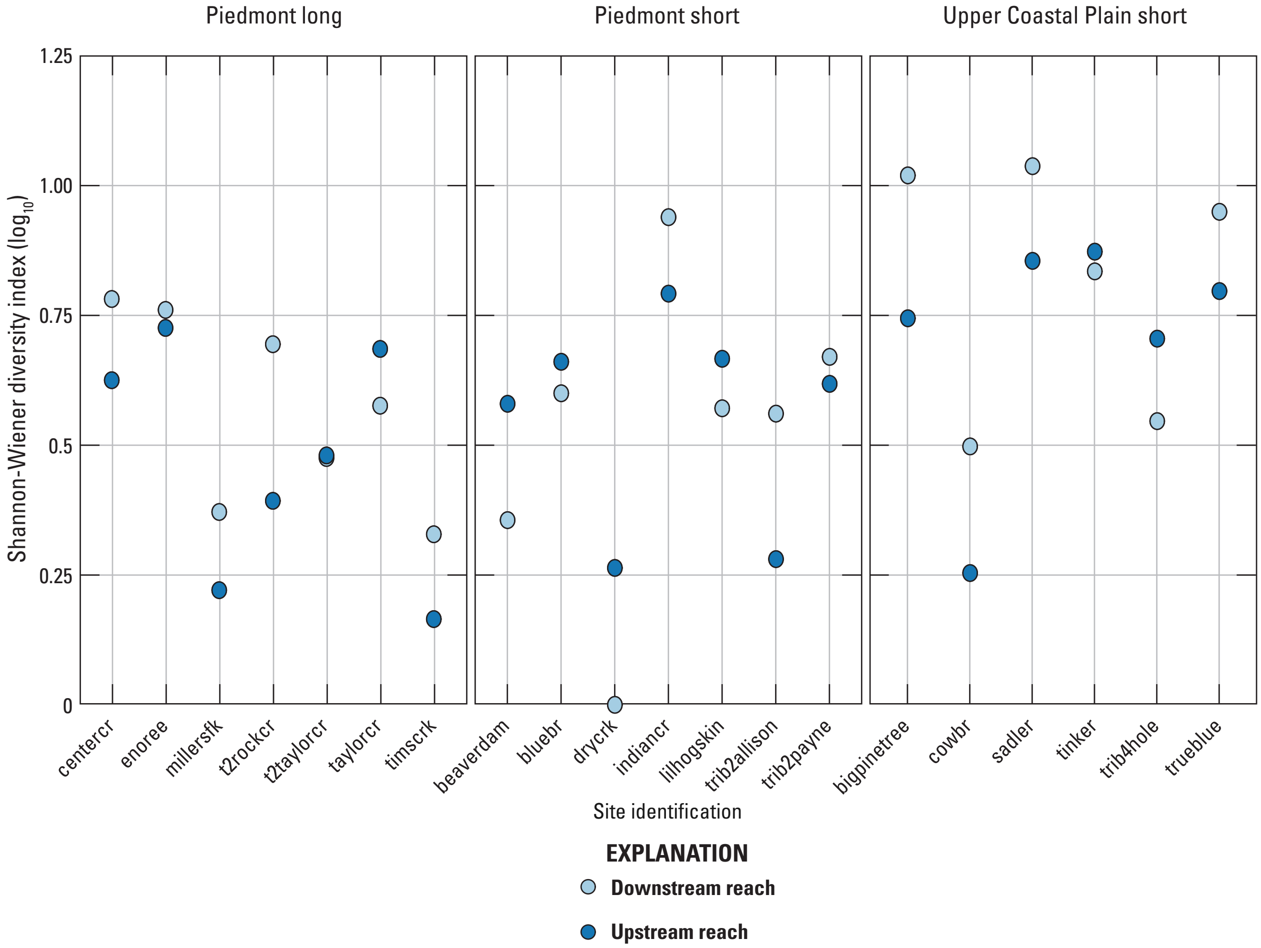


Figure 11. Graph showing Shannon-Wiener diversity index values for fish communities sampled at selected culvert sites in South Carolina, 2016–18.

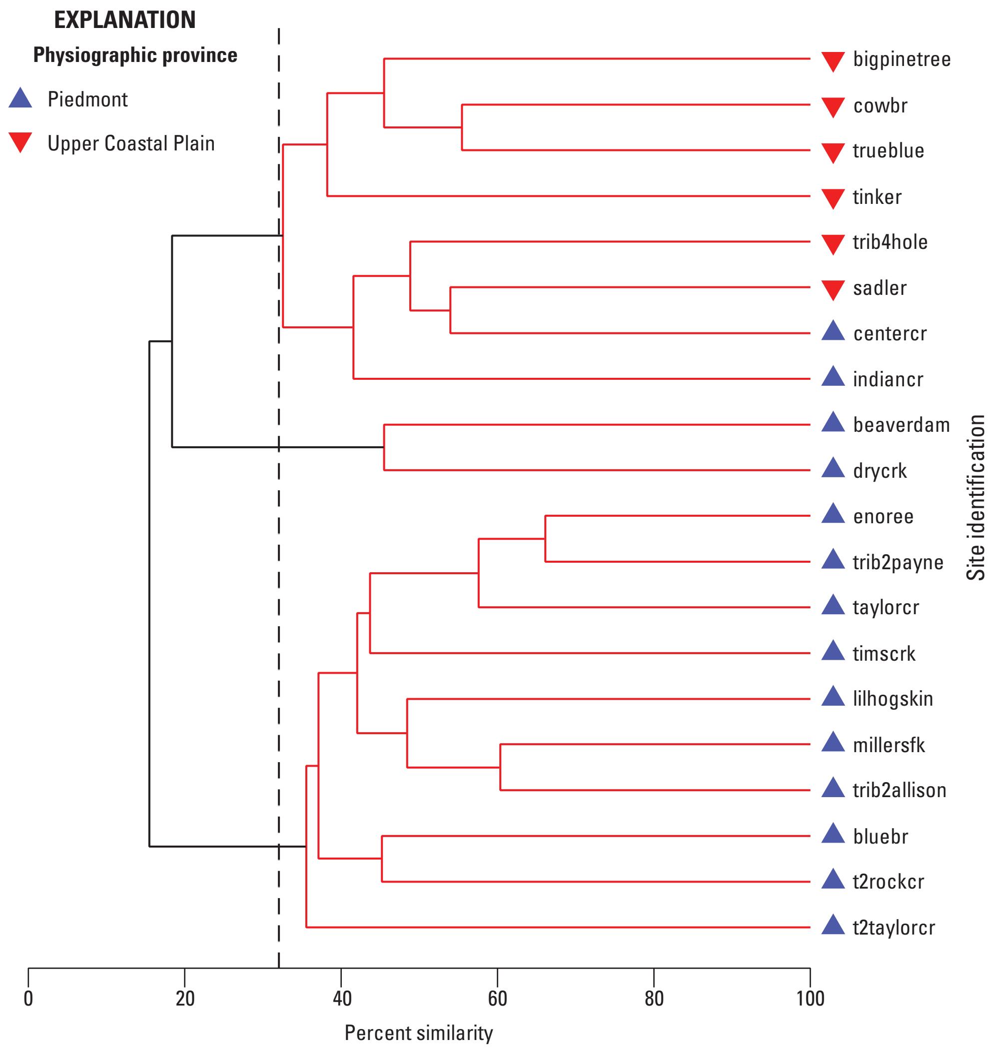


Figure 12. Hierarchical clustering dendrogram of selected culvert sites in South Carolina, with upstream and downstream reaches combined, created by using group-averaging Bray-Curtis similarities calculated from square-root transformed catch per unit effort data for fish samples. The vertical dashed line indicates 32-percent resemblance. Black horizontal lines indicate significant multivariate structure; there is no evidence from the Plymouth Routines in Multivariate Ecological Research (PRIMER) similarity profile (SIMPROF) test to support the detailed clustering structure shown by red lines.

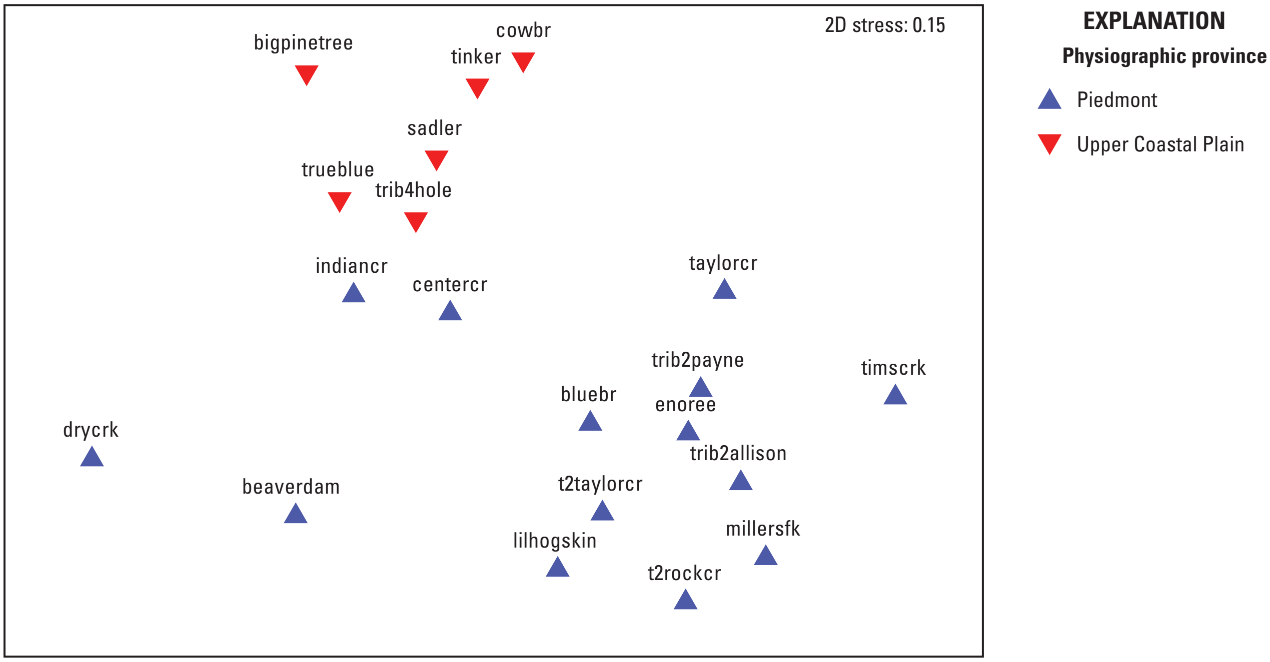


Figure 13. Two-dimensional (2D) nonmetric multidimensional scaling (nMDS) plot of fish catch per unit effort data for selected culvert sites in South Carolina factored by physiographic province; upstream and downstream reaches are combined for each site. Ordination is based on a square-root transformed Bray-Curtis similarity matrix.

Fish species richness at each site (downstream and upstream reaches combined) ranged from 4 to 17 and averaged 10. The most fish species were captured at the sites bigpinetree and sadler, 17 species each, and the fewest were captured at sites drycrk and millersfk, 4 species each (fig. 14). At 12 sites, more species were captured in the downstream reach than the upstream reach. At five sites, more species were captured upstream from the culvert than downstream, and at three sites, an equal number of species was caught in both reaches. The largest difference between reaches at a single site was observed at site bigpinetree, where 16 fish species were caught downstream from the culvert but only 7 were caught upstream. The fewest species found in a single reach was at the site drycrk, where one species, *Gambusia holbrooki*, was captured in the downstream reach. At all other sites, the difference in the number of species between upstream and downstream reaches was less than or equal to 3. There was a possible trend of more species captured at downstream reaches than upstream reaches within both physiographic provinces. For the Upper Coastal Plain, four sites had two to nine more species downstream from the culvert than upstream, one site had an equal number, and one site had one more species upstream than downstream. For the Piedmont, 8 of the 14 sites had one to three more species downstream than upstream from the culvert, 2 sites had an equal number, and 4 sites had two to three more species in the upstream reach than downstream. To test for possible differences in fish species richness between downstream and upstream reaches while factoring in culvert length and physiographic province, a series of nonparametric comparisons was made by using the difference in number of species between test categories (table 7); no significant differences were found across all culvert categories.

A SIMPROF test of all fish *C/f* data in PRIMER with downstream and upstream reaches separated revealed general clustering similar to that found by the analysis with reaches combined for each site (fig. 15; π=3.73, p=0.01). Three groups were distinguished at a 26-percent resemblance level (see solid horizontal lines bisected by a vertical dashed line in fig. 15): (1) sites beaverdam and drycrk; (2) most of the Piedmont sites, and; (3) all Upper Coastal Plain sites plus sites centercr and indiancr, the two Piedmont sites geographically closest to the physiographic province boundary (fig. 1). The sites beaverdam and drycrk were distinct from each other and all other sites. Eight fish species were collected at site beaverdam but only four at site drycrk, and these two sites had only a single species in common, *Gambusia holbrooki*. At these two sites, *G. holbrooki* was much more abundant than other species and was more abundant than *G. holbrooki* at all other sites, accounting for why the two sites clustered together. There was no support for multivariate structuring among sites in the Piedmont, but there was additional structuring within the Upper Coastal Plain cluster. At a 30-percent resemblance level, the sites bigpinetree, cowbr, trueblue, and tinker formed a group separate from a group consisting of sites sadler, trib4hole, centercr, and indiancr. Additionally, site sadler was distinct from the cluster of sites trib4hole and centercr, and site indiancr was distinct from these three sites. The nMDS ordination of all reaches and sites allows visualization of the seven clusters for which the SIMPROF test demonstrated statistical support (fig. 16); however, the nMDS ordination had moderately high 2D stress (0.17).

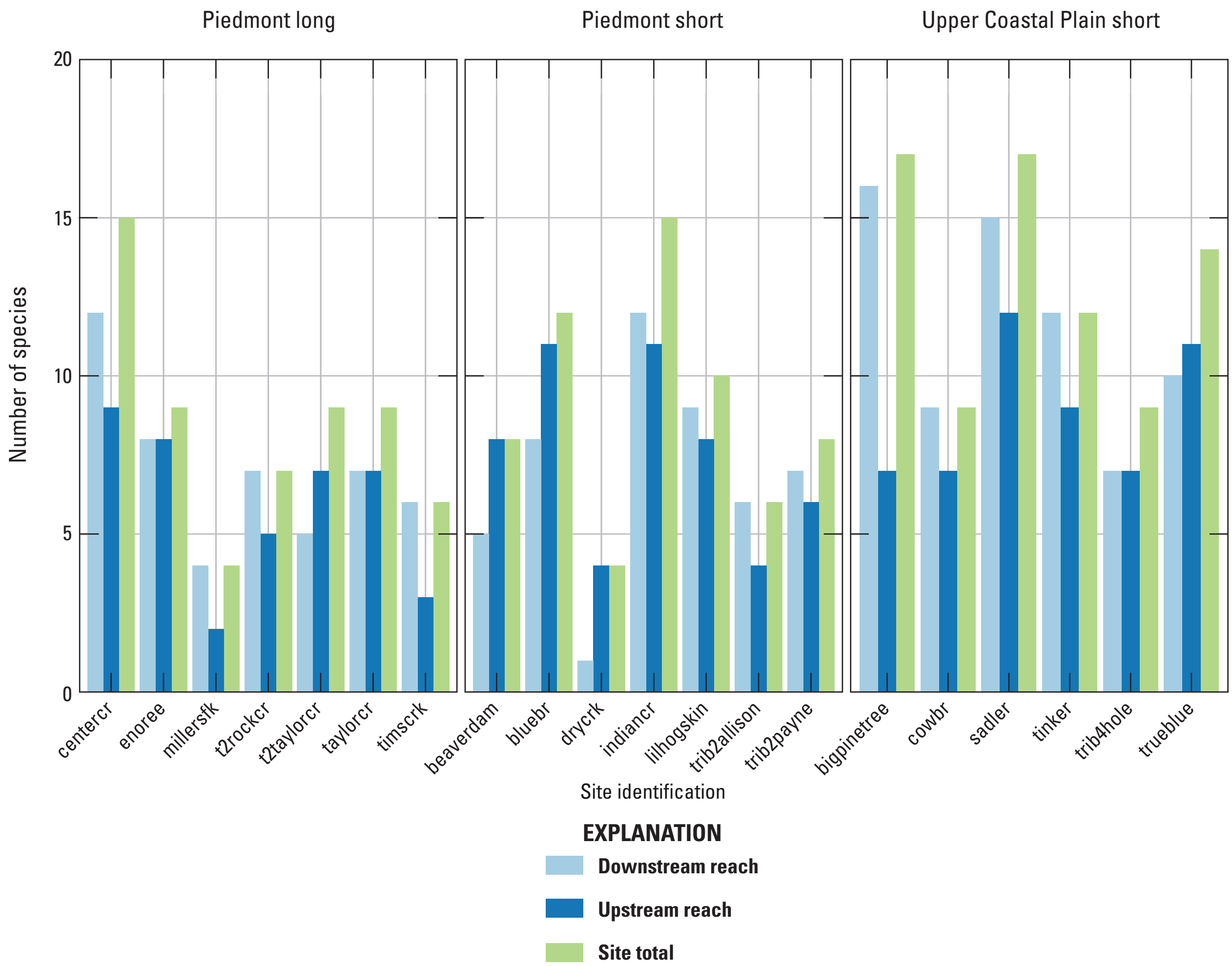


Figure 14. Bar graph showing the taxonomic richness of fish species collected at selected culvert sites in South Carolina.

A set of 15 habitat variables was used to evaluate possible linkages between abiotic factors and the fish assemblage groupings identified by the SIMPROF procedure by using the constrained (two-way) BEST routine with the Spearman rank correlations method in PRIMER. Draftsman plots were examined to confirm that the selected habitat variables were not correlated with others, and variables were normalized prior to ordination. The results of the global BEST analysis indicated a general relation between fish communities and habitat variables (Spearman rank correlation coefficient [ρ]=0.38; p=0.01). Six habitat variables provided the best combined correlations to account for the major groupings of fish assemblages by site (fig. 12): mean wetted depth, mean canopy closure, mean velocity, percentage of riffle habitat, percentage of pool habitat, and LWD volume.

To further explore for possible relations between fish *C/f* and habitat variables among sites and reaches, additional BEST routines were run for Upper Coastal Plain sites and reaches and independently for Piedmont long and short culvert sites and reaches. The results of these tests provided no statistical support for relating habitat variables to biotic assemblages (table 8). The habitat variables that provided the best correlations varied considerably among the combinations of physiographic province, culvert length, and upstream or downstream reach. In terms of accounting for the greatest correlation between habitat variables and fish communities, mean reach wetted width was the only habitat variable common to all combinations of physiographic province, culvert length, and reach. Other abiotic parameters common to two or more combinations of strata included mean reach wetted depth, percent of reach that was either run or pool, mean reach velocity, total reach volume of LWD, and culvert slope.

Table 7. Results of nonparametric tests of fish species richness between downstream and upstream reaches by physiographic province.

Comparison	Number of observations	*p*-value
Wilcoxon signed-rank test with continuity correction		
Upper Coastal Plain short culverts: downstream versus upstream	6/6	0.104
Piedmont short culverts: downstream versus upstream	7/7	0.730
Piedmont long culverts: downstream versus upstream	7/7	0.272
Wilcoxon rank-sum test with continuity correction		
Difference in upstream and downstream reaches: Upper Coastal Plain short culverts versus Piedmont short culverts	6/7	0.128
Difference in upstream and downstream reaches: Piedmont long culverts versus short culverts	7/7	0.475

The restriction of over one-half of the fish species to sites within a single physiographic province and the results of the SIMPROF and BEST tests confounded multivariate analyses to explore trends in the fish community data. In general, upstream and downstream reaches for nearly all sites clustered together, indicating that reaches at the same site were more closely related to each other than to reaches at other sites. The sites bigpinetree and trueblue were exceptions. At bigpinetree, this result was primarily attributable to the collection of a suite of lowland species that were concentrated near the culvert in an open-canopy area of the downstream reach where there was a thick bed of aquatic macrophytes. The culvert slope at bigpinetree was high, potentially limiting movement from downstream to upstream. Like bigpinetree, the occurrence and abundance of several fish species were notably different between the downstream and upstream reaches at site trueblue. The site trueblue also had a high culvert slope, shallow water depth in the culvert, and a large riprap cascade downstream from the culvert, which possibly limited fish movement from downstream to upstream.

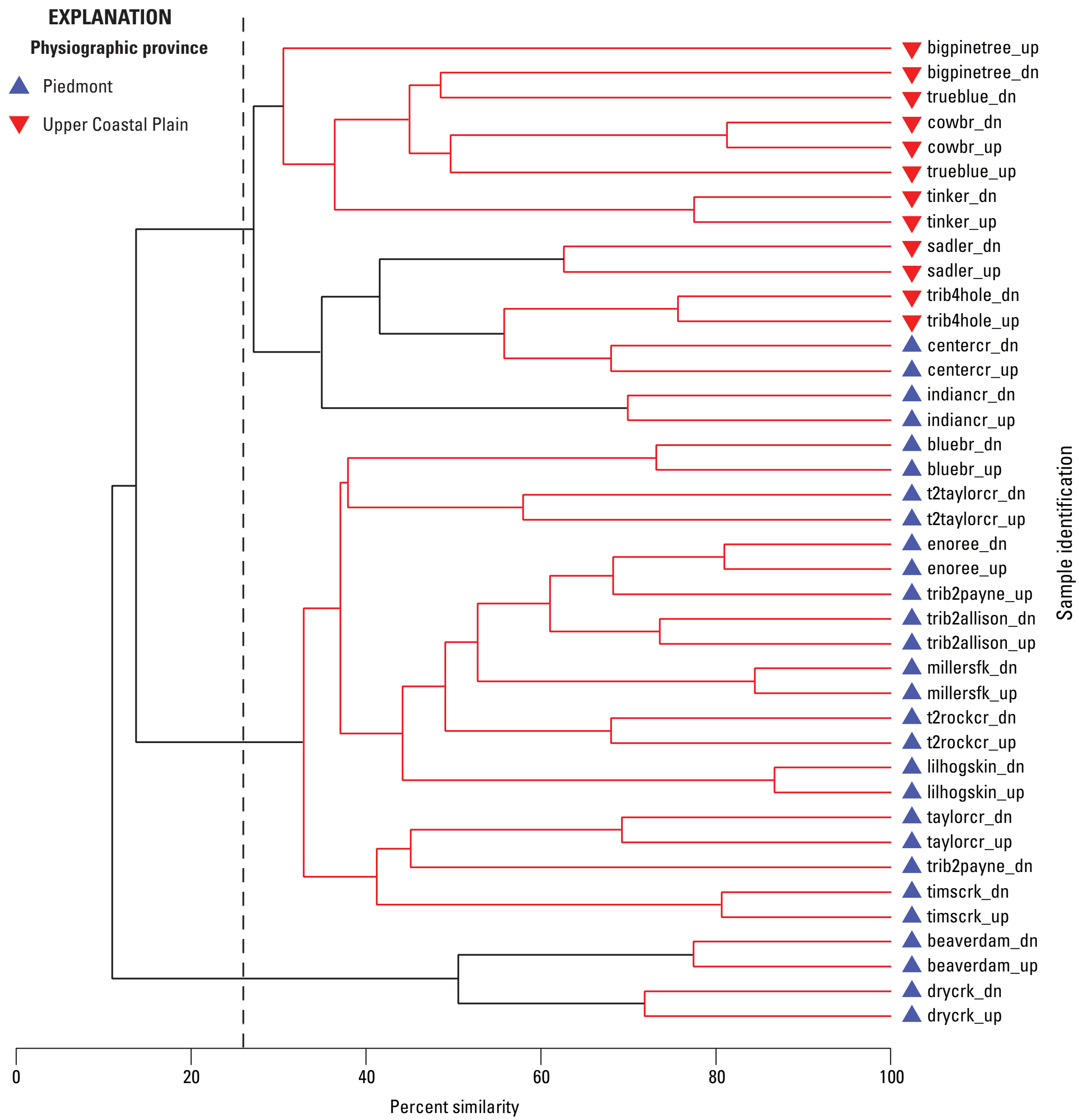


Figure 15. Hierarchical clustering dendrogram of downstream (dn) and upstream (up) reaches at selected culvert sites in South Carolina, created by using group-averaging Bray-Curtis similarities calculated from square-root transformed catch per unit effort data for fish samples. The vertical dashed line indicates 26-percent resemblance. Black horizontal lines indicate significant multivariate structure; there is no evidence from the Plymouth Routines in Multivariate Ecological Research (PRIMER) similarity profile (SIMPROF) test to support the detailed clustering structure shown by red lines.

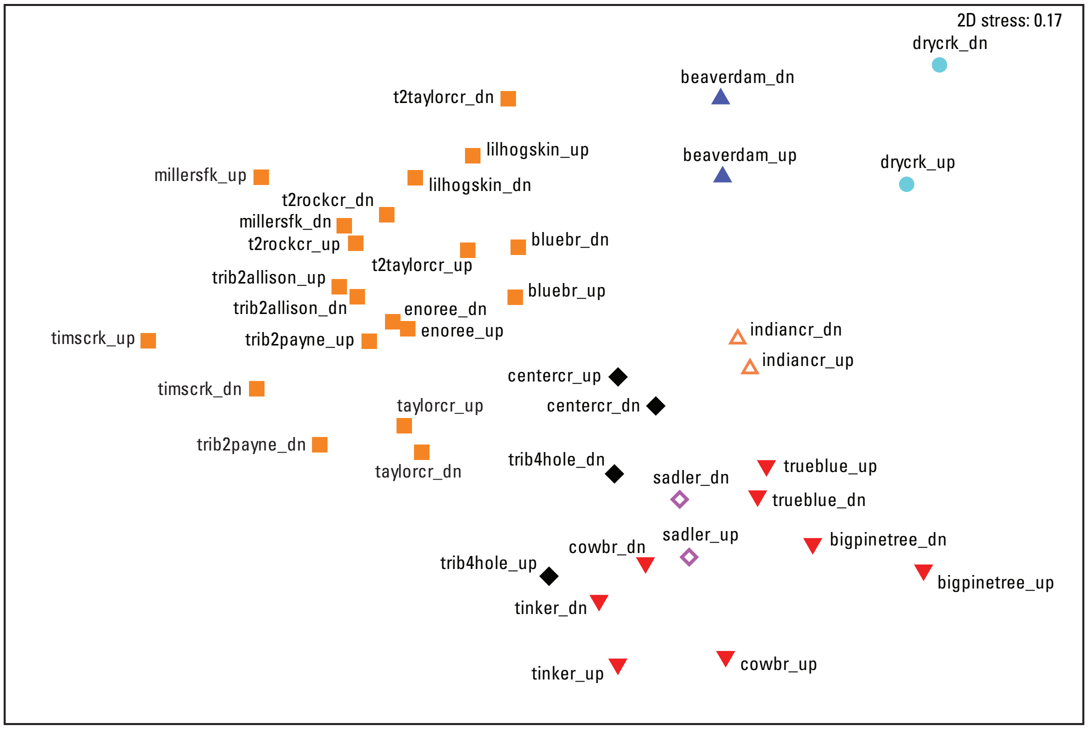


Figure 16. Two-dimensional (2D) nonmetric multidimensional scaling (nMDS) plot of downstream (dn) and upstream (up) reaches for selected culvert sites in South Carolina. Ordination is based on group-averaging Bray-Curtis similarities calculated from square-root transformed fish catch per unit effort data. The different symbols represent the groups for which the Plymouth Routines in Multivariate Ecological Research (PRIMER) similarity profile (SIMPROF) test demonstrated statistical support (see fig. 15).

Table 8. Combinations of mean reach habitat variables that best match the fish community structure as measured by Spearman rank correlation test using the Bio-Env + Stepwise (BEST) routine in Plymouth Routines in Multivariate Ecological Research (PRIMER).

Physiographic province, culvert length, and reach	No. of variables	Habitat variables	Sample statistic (ρ)	*p*-value
Piedmont, long, upstream	5	Wetted width, wetted depth, percent of reach that was run, percent of reach that was pool, total reach volume of LWD	0.579	0.283
Piedmont, long, downstream	3	Wetted width, velocity, number of GCUs per reach	0.596	0.524
Piedmont, short, upstream	5	Wetted width, canopy closure, channel-full area, culvert length, culvert slope	0.702	0.110
Piedmont, short, downstream	5	Wetted width, wetted depth, culvert length, culvert slope, total reach volume of LWD	0.755	0.100
Upper Coastal Plain, short, upstream	4	Wetted width, percent of reach that was pool, perch height of downstream culvert bottom, culvert slope	0.614	0.680
Upper Coastal Plain, short, downstream	5	Wetted width, canopy closure, velocity, percent of reach that was run, percent of reach that was riffle	0.804	0.084

Macroinvertebrate Community Characterization

A total of 178 macroinvertebrate taxa were identified: 121 common to both the Piedmont and Upper Coastal Plain physiographic provinces, 47 unique to the Piedmont, and 10 unique to the Upper Coastal Plain. Data were subset into three categories: Piedmont long, Piedmont short, and Upper Coastal Plain short. A one-way analysis of similarities (ANOSIM) test was run to assess possible differences between the four sampling zones within each category. For all three categories, there were no significant differences (*p* less than 0.05) between zones. The nMDS ordinations for each category (fig. 17*A*–*C*) had moderate stress values in 2D space (Piedmont long, 0.2; Piedmont short, 0.21; Upper Coastal Plain short, 0.23), and these stress values improved in 3D space (Piedmont long, 0.16; Piedmont short, 0.16; Upper Coastal Plain short, 0.15).

Because there was no apparent difference between zones within each category, a SIMPROF test was used to evaluate macroinvertebrate community similarities among all samples and samples within each category. When all macroinvertebrate samples were combined, there was no clear separation based on physiographic province; therefore, further discussion focuses on the three categories. A similarity threshold of 65 percent was selected because it resulted in three distinct groups within each stratum and allowed for consistency in discussing patterns within and among categories. The three groups within a category are designated “A,” “B,” and “C” (from top to bottom, fig. 18*A*–*C*).

In the Piedmont long category, there were 10 samples in group A, 11 samples in group B, and 7 samples in group C. At three sites, three of the four samples were within one group and the least similar sample (similarity less than 65 percent) was collected adjacent to the culvert (upstream impact zone for sites enoree and t2taylorcr; downstream impact zone for site millersfk). In the Piedmont short category, there were 11 samples in group A, 14 samples in group B, and 3 samples in group C. At four sites, three of the four samples were within one group and the least similar sample (similarity less than 65 percent) was collected adjacent to the culvert (upstream impact zone for site trib2payne; downstream impact zone for sites beaverdam, bluebr, and lilhogskin). In the Piedmont short category, there were 18 samples in group A, 4 samples in group B, and 2 samples in group C. At two sites, three of the four samples were within one group and the least similar sample (similarity less than 65 percent) was collected adjacent to the culvert (downstream impact zone for sites bigpinetree and tinker).

For all three categories, most samples were in groups A and B (Piedmont long, 75 percent of samples; Piedmont short, 89 percent; and Upper Coastal Plain short, 92 percent). For the Piedmont long and Piedmont short categories, the samples in groups A and B were essentially evenly distributed. In the Upper Coastal Plain category, 75 percent of the samples were in group A, indicating that 75 percent of the macroinvertebrate community assemblages in the Upper Coastal Plain were, at minimum, 65 percent similar. These results indicate that the overall macroinvertebrate community structure for samples within a category were more variable, or dissimilar, in the Piedmont (both long and short culverts) than in the Upper Coastal Plain. Each category had at least two sites where three of four samples grouped together (Piedmont long, three sites; Piedmont short, four sites; and Upper Coastal Plain short, two sites) and the least similar sample (similarity less than 65 percent) was collected adjacent to the culvert. These results suggest that some of the macroinvertebrate communities may indeed be affected by culverts. Our study design, however, was not optimized to assess site-level differences, so additional samples collected over time would be needed to substantiate the significance of these relations.

The metrics used for this study were determined by assessing culvert-related studies on macroinvertebrate communities, comparable to existing biomonitoring programs in the southeastern United States. Metric values were based on percent abundances, unless otherwise indicated (appendix 1, table 1.1). The metrics were used to evaluate the macroinvertebrate communities by running the BEST procedure in PRIMER, resulting in a metric or combination of metrics that had the highest similarity to the macroinvertebrate community structure. Results are listed by all samples within a category and by each sampling zone within a category (table 9). When all samples within a category were combined, each category had a combination of metrics that were considered highly significant (*p* less than 0.001). Each metric was then individually evaluated by using the Wilcoxon rank-sum test to determine if the metric was significantly different among the four sampling zones: background (zone 1), upstream impact (zone 2), downstream impact (zone 3), and recovery (zone 4). Statistical tests failed to reject the null hypothesis of any significant difference (α=0.10) in distributions between pairs of samples. Among the four zones within each category (*n*=12), variability in the macroinvertebrate community structure was explained by a combination of metrics in only three zones: five metrics in Piedmont long background zone, four metrics in Piedmont long upstream impact zone, and six metrics in Upper Coastal Plain short recovery zone.

A. **Piedmont long**

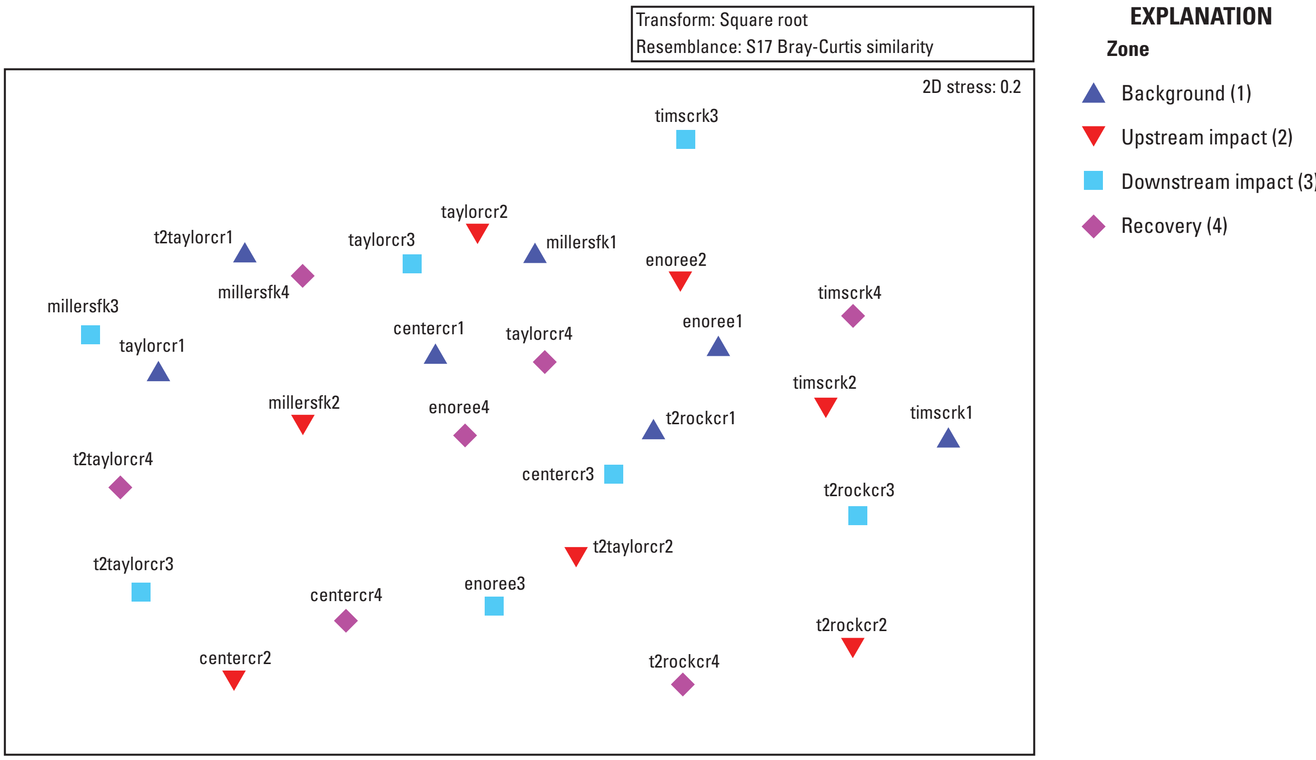
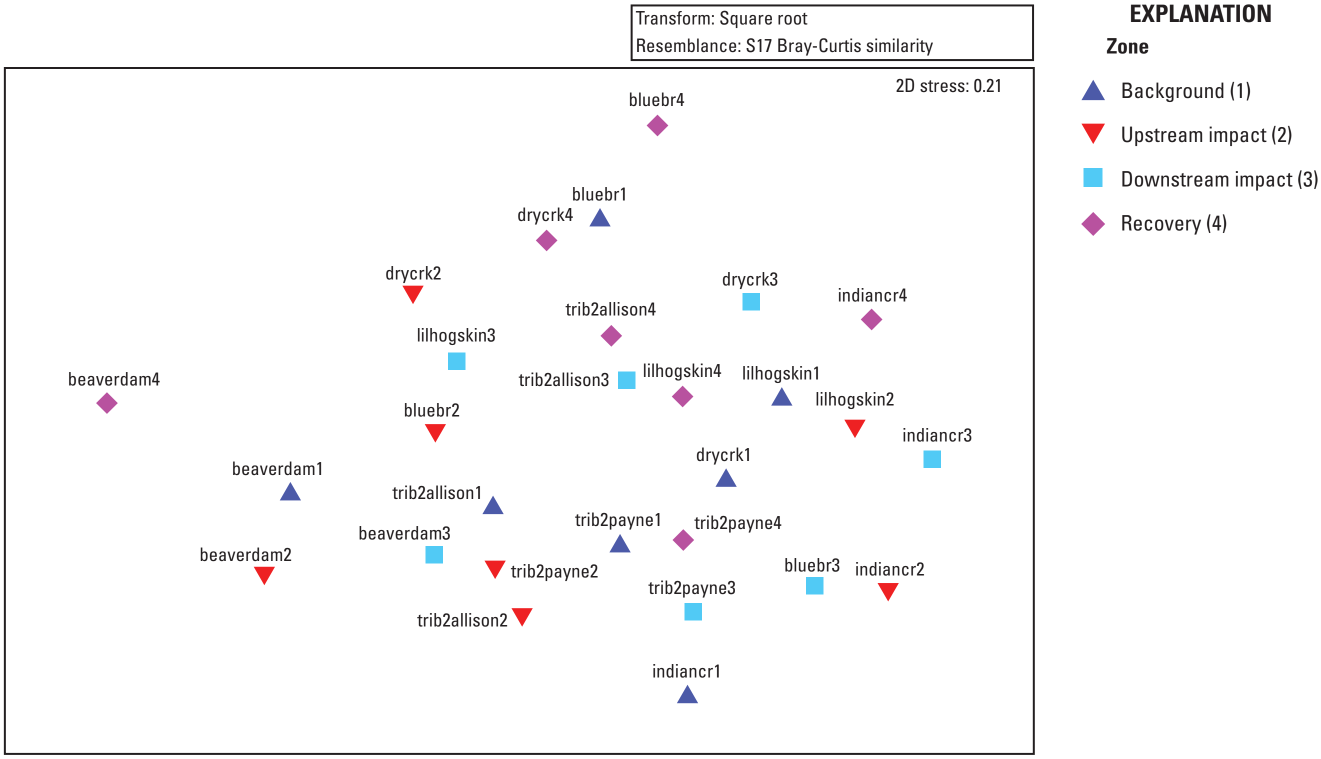


Figure 17. Two-dimensional (2D) nonmetric multidimensional scaling (nMDS) plots of macroinvertebrate assemblage data for samples collected in four zones at selected culvert sites in South Carolina. Ordination is based on a square-root transformed Bray-Curtis similarity matrix. *A*, Piedmont long culverts. *B*, Piedmont short culverts. *C,* Upper Coastal Plain short culverts.

***B.* Piedmont short**



***C.* Upper Coastal Plain short**

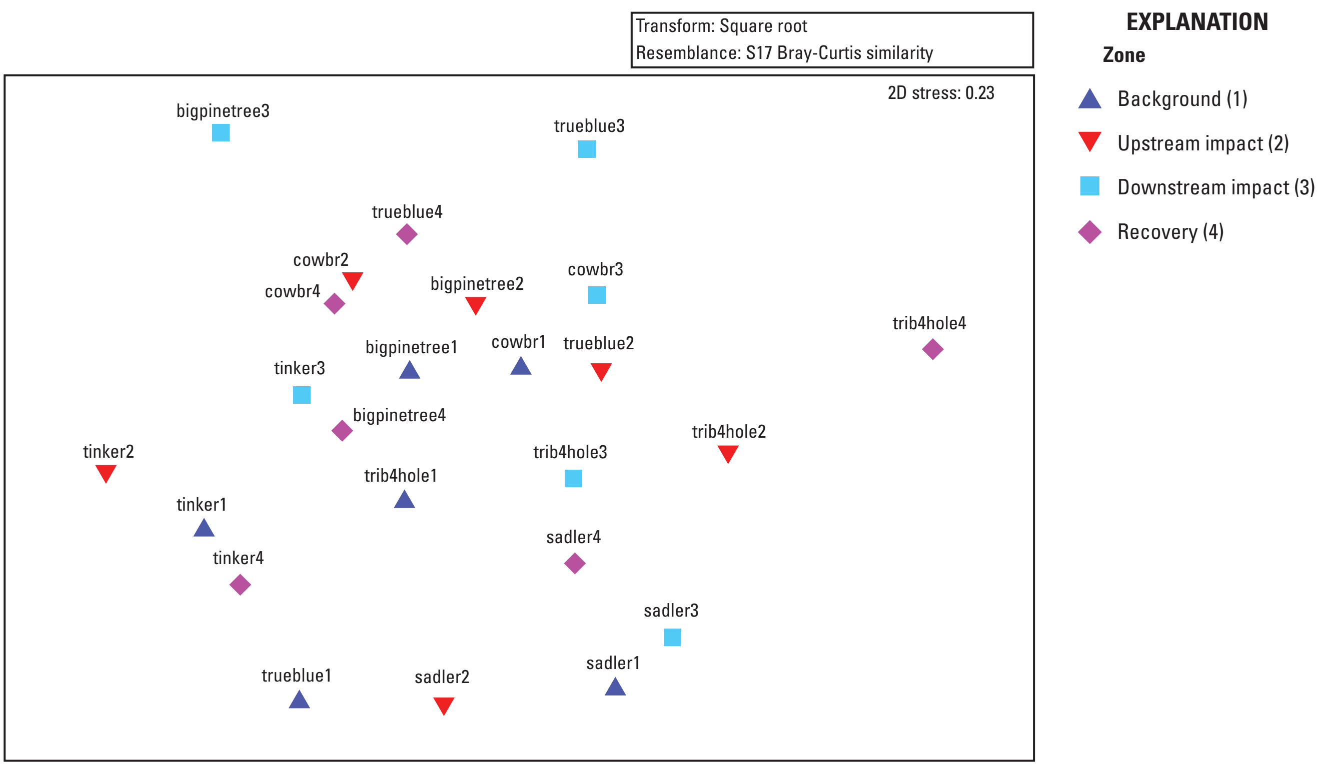


Figure 17. —Continued

A. **Piedmont long**

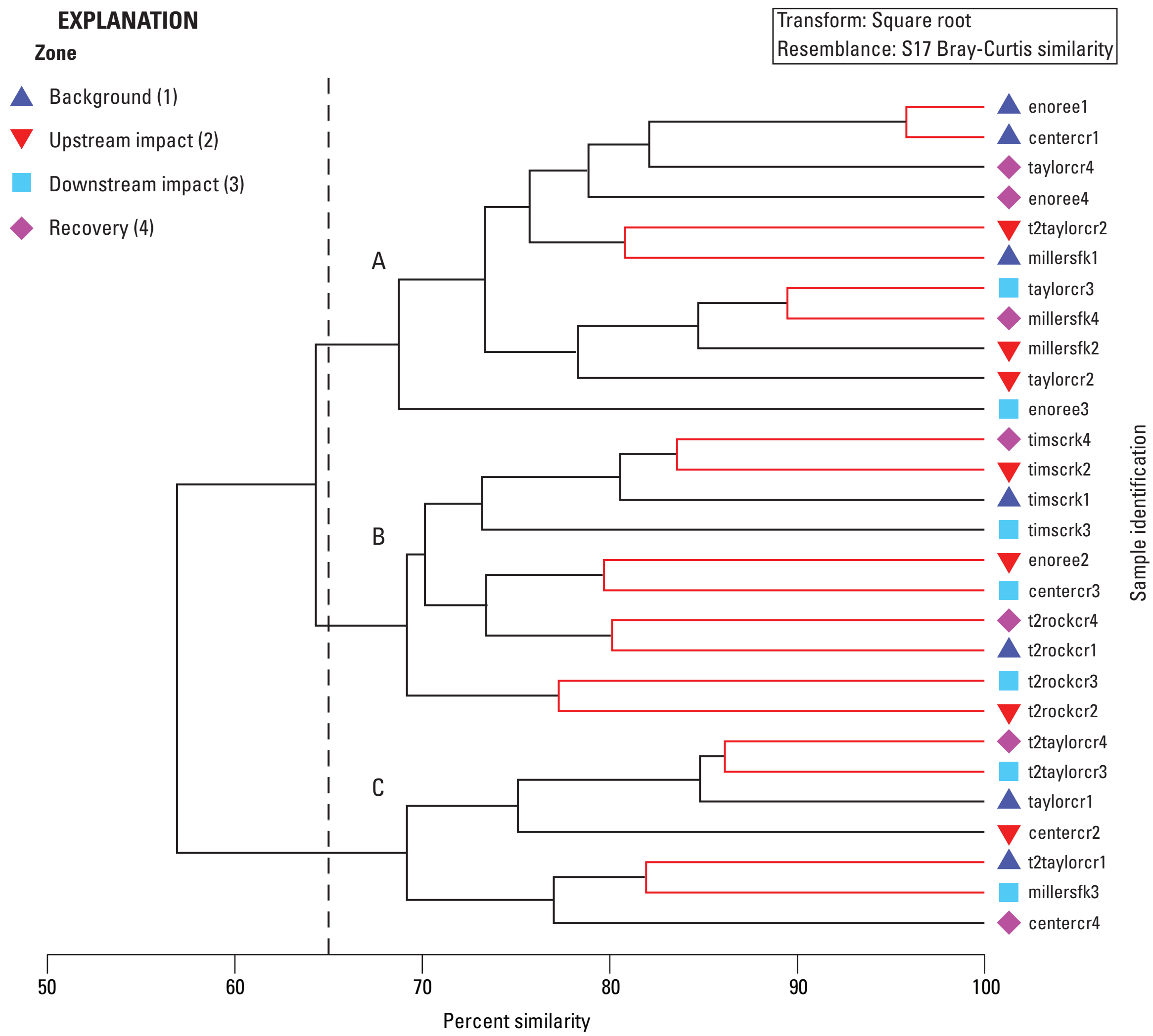


Figure 18. Hierarchical clustering dendrograms of samples collected in four zones at selected culvert sites in South Carolina, created by using group-averaging Bray-Curtis similarities calculated from square-root transformed macroinvertebrate abundance data. The vertical dashed lines indicate 65-percent resemblance. Black horizontal lines indicate significant (*p* less than 0.05) groups; red lines indicate a lack of significant groups. *A*, Piedmont long culverts. *B*, Piedmont short culverts. *C*, Upper Coastal Plain short culverts.

***B*. Piedmont short**

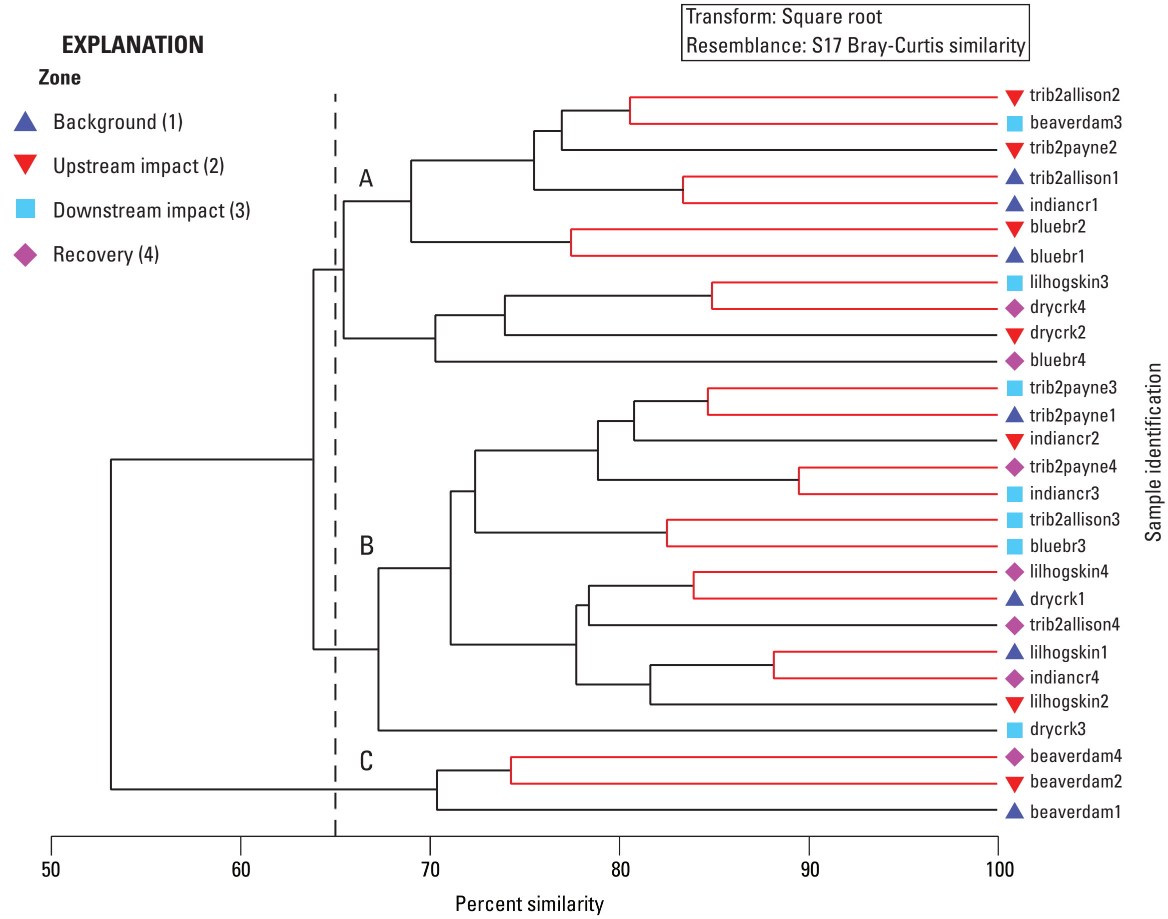


Figure 18. —Continued

C. **Upper Coastal Plain short**

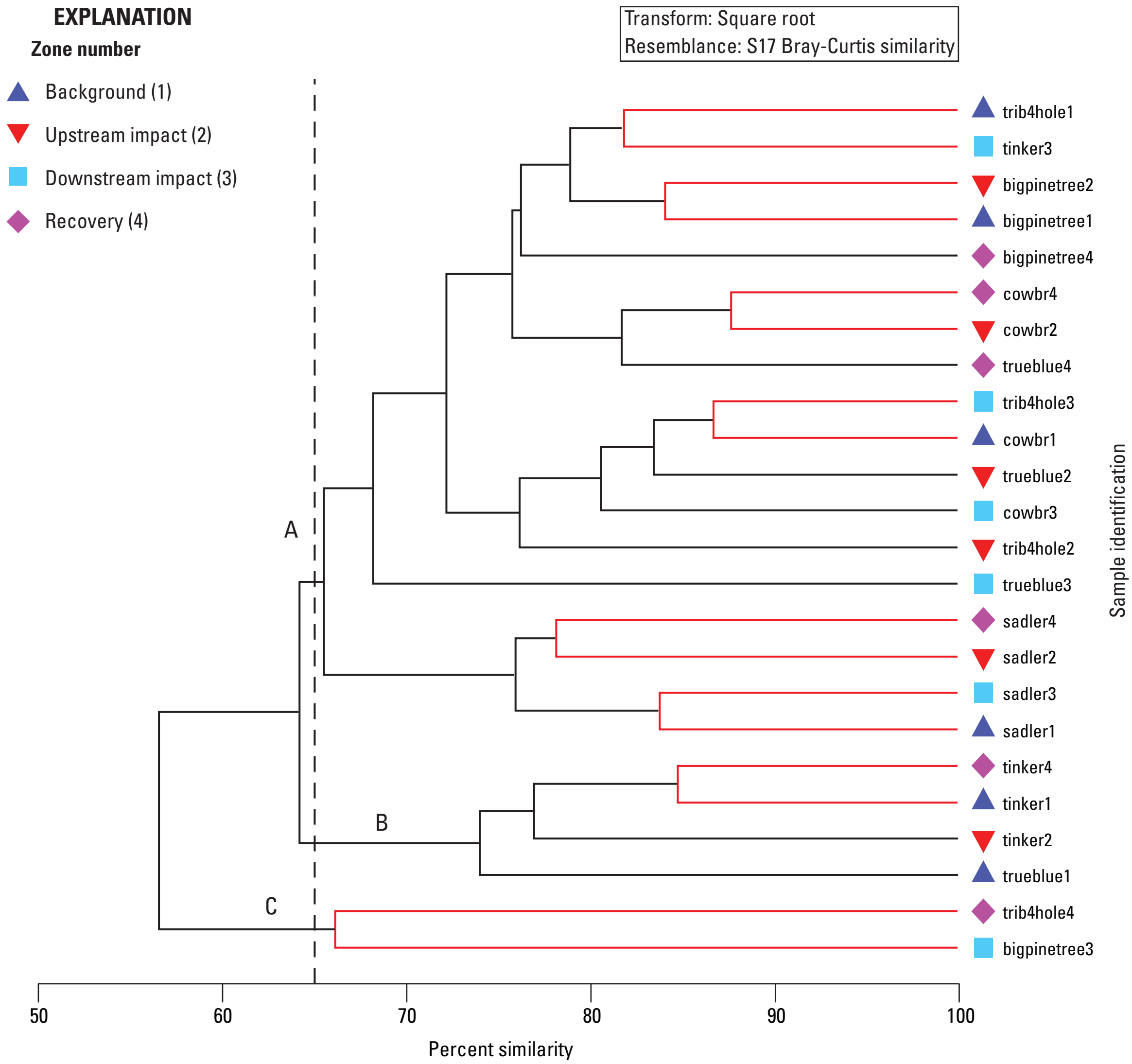


Figure 18. —Continued

The AbundTOL metric is the abundance-weighted U.S. Environmental Protection Agency tolerance value calculated for each sample (appendix 1, table 1.2). Lenat (1993) created classification criteria for the Piedmont and Coastal Plain ecoregions and established five classes for AbundTOL values as follows: (1) less than or equal to 5.24, excellent; (2) 5.25–5.95, good; (3) 5.96–6.67, good-fair; (4) 6.68–7.70, fair; and (5) greater than or equal to 7.71, poor. In the Piedmont long category, six of the seven sites had all samples in one class or in two consecutive classes; the exception was site trib2taylorcr, which had samples in three classes. Samples within sites were generally classified similarly; however, this was not the case among sites. For example, three samples at site enoree were classified as excellent, whereas three samples at site millersfk were fair. Of all the samples in the Piedmont long category, two were classified as poor: one sample

Table 9. Combinations of macroinvertebrate metrics that best match the macroinvertebrate community structure as measured by Spearman rank correlation test using the Bio-Env + Stepwise (BEST) routine in Plymouth Routines in Multivariate Ecological Research (PRIMER).

[Zone numbers: 1, background; 2, upstream impact; 3, downstream impact; 4, recovery]

Physiographic province, culvert length, and zone	No. of variables	Metrics	Sample statistic (ρ)	*p*-value
Piedmont, long, all	2	Abund, Margalef	0.611	0.001
Piedmont, long, 1	5	Abund, Pielou's evenness, Simpson, Dom1, CHp	0.813	0.026
Piedmont, long, 2	4	Abund, Margalef, pOM_abund, CHp	0.804	0.023
Piedmont, long, 3	6	Rich, Margalef, Simpson, pPR_abund, pOM_abund, pSH_abund	0.662	0.077
Piedmont, long, 4	2	Rich, pSC_abund	0.651	0.139
Piedmont, short, all	5	AbundTOL, Abund, Margalef, pSH_abund, EPT_CHp	0.454	0.001
Piedmont, short, 1	1	pSH_abund	0.477	0.75
Piedmont, short, 2	1	Abund	0.744	0.21
Piedmont, short, 3	1	EPTR	0.564	0.269
Piedmont, short, 4	3	ShannonDiv, EPTR, EPT_CHp	0.847	0.293
Upper Coastal Plain, short, all	2	Abund, CHp	0.531	0.001
Upper Coastal Plain, short, 1	1	pOM_abund	0.639	0.648
Upper Coastal Plain, short, 2	1	EPT_CHp	0.693	0.423
Upper Coastal Plain, short, 3	3	Abund, pOM_abund, CHp	0.65	0.231
Upper Coastal Plain, short, 4	6	Abund, Rich, SimpsonDiv, pSC_abund, pSH_abund, EPT_CHp	0.868	0.028

collected at the top of a sampling reach (site millersfk1) and one just above a culvert (site t2taylorcr2). In the Piedmont short category, three sites had samples in two classes and four sites had samples in three classes. Unlike the Piedmont long category, two sites (drycrk and trib2payne) had samples in nonconsecutive classes without an intermediate classification. Piedmont short sites had sample classifications ranging from excellent to fair; no samples were classified as poor. The Upper Coastal Plain samples and sites scored differently than the Piedmont samples and sites. Three Upper Coastal Plain sites had all samples in the same class (cowbr, sadler, trueblue), and two sites had samples in two consecutive classes (bigpinetree and tinker). The only site with samples in three classes was trib4hole, which was also the only site that had samples classified as fair or good-fair. All other samples in the Upper Coastal Plain were either excellent or good.

Habitat variables at the zone level were examined, and correlated variables were eliminated after evaluating scatter plots. Eight habitat variables were selected to assess the macroinvertebrate communities by running the BEST procedure in PRIMER, resulting in a habitat variable or combination of variables that had the highest similarity to the macroinvertebrate community structure. Table 10 lists the results by sampling zone in each category. In the Piedmont physiographic province, there was only one significant relation (p less than 0.001) between habitat variables and the macroinvertebrate community. For Piedmont short samples collected in the upstream impact zone, the combination of canopy closure, channel-full area, mean velocity, and presence of bedrock best explained the community structure of those samples. In the Upper Coastal Plain short category, there also was only one significant relation (p less than 0.03), which was for samples collected in the recovery zone and was based solely on mean wetted width.

Table 10. Combinations of mean zone habitat variables that best match the macroinvertebrate community structure as measured by Spearman rank correlation test using the Bio-Env + Stepwise (BEST) routine in Plymouth Routines in Multivariate Ecological Research (PRIMER).

[Zone numbers: 1, background; 2, upstream impact; 3, downstream impact; 4, recovery]

Physiographic province, culvert length, and zone	No. of variables	Habitat variables	Sample statistic (ρ)	*p*-value
Piedmont, long, 1	5	Wetted width, canopy closure, velocity, particle size of the 84th percentile, bedrock	0.073	0.924
Piedmont, long, 2	2	Wetted width, canopy closure	0.403	0.358
Piedmont, long, 3	3	Wetted depth, velocity, bedrock	0.536	0.107
Piedmont, long, 4	4	Wetted width, velocity, particle size of the 84th percentile, bedrock	0.425	0.533
Piedmont, short, 1	1	Velocity	0.07	0.884
Piedmont, short, 2	4	Canopy closure, channel-full area, velocity, bedrock	0.926	0.001
Piedmont, short, 3	3	Channel-full area, velocity, bedrock	0.556	0.112
Piedmont, short, 4	3	Canopy closure, channel-full area, velocity	0.508	0.61
Upper Coastal Plain, short, 1	2	Wetted depth, channel-full area	0.368	0.719
Upper Coastal Plain, short, 2	1	Velocity	0.054	0.985
Upper Coastal Plain, short, 3	3	Wetted depth, canopy closure, channel-full area	0.55	0.191
Upper Coastal Plain, short, 4	1	Wetted width	0.786	0.03

Role of Culverts in Shaping Channel Morphology, Aquatic Habitat, and Biotic Community Structure

The results of the geomorphic and in-stream habitat assessments indicate a high degree of variation within most sites, regardless of whether the reach was upstream or downstream from the culvert. This result was not entirely unexpected. When evaluating a rather short reach of stream, many stochastic processes, operating over different spatial and temporal scales, combine to make up the observed channel form at a particular location and time. If a consistent response was driven by culverts, the effect should have been detected in the upstream versus downstream analyses. An initial hypothesis was that any differences in channel form were more likely to be observed in the Piedmont, owing to the hilly topography, steeper slopes, and more clay-rich banks that may be prone to mass wasting (Simon and Rinaldi, 2006), than in the lower gradient and sandy Upper Coastal Plain streams. The opposite result, however, was observed. Although the Upper Coastal Plain has streams with lower gradients and generally greater access to overbank areas to dissipate flow energy, the placement of a berm across a once expansive floodplain forces naturally occurring low-velocity sheet flow into a narrower channel, which contributed to incision downstream from the culvert at five of the six sites. It is unknown how these findings may apply to pipes or other types of culverts. In a study focused on the North Carolina Piedmont, the greatest alteration to cross-sectional area was adjacent to pipe and arch culverts and sites with box culverts were the least altered (Merrill and Gregory, 2004; Merrill, 2005). In the current study, the lack of observed changes in the Piedmont could be partly due to a singular focus on box culverts but could also be somewhat attributed to past land disturbances that caused channels to be much larger than would be expected on the basis of drainage area and climate (Trimble, 1974; Dunne and Leopold, 1978; Doll and others, 2002).

Placing Current Geomorphic Settings in Perspective

Historical agricultural activities associated with initial European settlement have been implicated in dramatic changes to landscapes and aquatic systems across the Piedmont (Trimble, 1974; Walter and Merritts, 2008). Trimble (1974) estimated that the entire southern Piedmont lost approximately 19 centimeters of topsoil from 1700 to 1970 and that many stream channels were filled with sediment as deep as 3 m. When these stream channels filled in, the reduced capacity to transport water resulted in flooded valley bottoms until the streams could cut through the alluvium, once again forming a channel. Similarly, Jackson and others (2005) found a nearly uniform sediment deposit, 1.65 m thick, overlying a buried A horizon (top layer of mineral soil) in the Murder Creek watershed (Altamaha River Basin) in the Piedmont of Georgia. The absence of detectable culvert effects on physical habitat and channel morphology at the current South

Carolina Piedmont study sites (long and short culverts) could be because many culverts were installed after substantial channel enlargement had already occurred; therefore, only the highest magnitude discharge events place enough stress on banks and beds to lead to further morphological changes. Incipient floodplain formation, the accumulation of sediments and debris that begin to collect and stabilize within the channel above the low-flow level, was observed at many of the Piedmont sites. On the basis of the channel evolution models of Schumm and others (1984) and Simon (1989), this observation would indicate that streams are in an aggregational phase, leading to an eventual morphology that represents a "channel within a channel" and high banks that represent terraces.

The South Carolina Piedmont sites can be placed in a broader context by comparing observed conditions with those derived from empirical relations based on drainage area. Bankfull elevation represents the point at which water is just contained within the defined channel, and bankfull discharge occurs, on average, once every 1.5 years (Dunne and Leopold, 1978). Harman and others (1999) found that in rural North Carolina Piedmont streams, the bankfull recurrence interval (RI) was 1.09–1.8 years. In incised streams, however, a channel-filling discharge event does not necessarily correspond to this range of RI and may be far less common. By using the RI or exceedance probability from streamflow records, it is possible to apply hydraulic geometry relations to streams in a similar setting to approximate a historical bankfull discharge and associated morphology on the basis of drainage area (for example, Doll and others, 2002). Assuming that hydraulic geometry relations developed for similar regions in North Carolina (Harman and others, 1999; Doll and others, 2002, 2003) are a fair approximation for the present study area, channel cross-sectional area at the South Carolina Piedmont sampling sites was, on average, 193 percent greater than would be expected for undisturbed streams with the same drainage area, thus highlighting the enlargement of channels at the Piedmont sites in this study.

Channel enlargement can directly affect stream habitat stability and biotic communities. High-energy conditions will be more frequent when flows cannot spill out of the channel onto the floodplain. This condition can be examined more explicitly by computing the maximum potential shear stress that would have been placed on the streambed and associated habitat and benthic communities during a bankfull flow event, assuming undisturbed conditions approximated by hydraulic geometry relations (Harman and others, 1999; Doll and others, 2002). Shear stress based on the present channel-full morphology was, on average, 150 percent greater than what would be expected in undisturbed channels where the bankfull level represents the top of the channel, demonstrating the importance of floodplain connectivity for overbank flow and energy dissipation. The large increase in channel cross-sectional area, which results in increased energy and shear stress for moderate- to low-frequency flow events, could explain why no culvert effects were observed in the Piedmont. Alternatively, if culverts are adequately sized to allow passage of moderate flood discharges, are properly installed with a slope similar to that of the streambed, and have buried inverts (bottom edge of culvert), then under normal conditions, culverts should not affect the continuity of water and sediment and, therefore, should not lead to persistent geomorphic or habitat alterations.

An additional concern, especially in the Piedmont, is that even if a culvert effect was observed, there was some uncertainty regarding the disturbance propagation. Were changes in morphology downstream from the culvert induced by scour because of an undersized or over-sloped culvert, or were differences driven by larger-scale adjustment processes, such as upstream knickpoint migration? With the present data, it is not possible to isolate a sole disturbance, but on the basis of culvert characteristics and overall site-level conditions, it seems likely that a combination of factors are involved. Many of the Piedmont culverts are wider than the stream channels, and perching, although not widespread, was observed across the range of culvert slopes. These characteristics suggest that broad-scale adjustments may be the dominant factor, where streams channels are still adjusting to past disturbances and stream morphology has yet to reestablish equilibrium (Trimble, 1977; Simon, 1989).

Effects of Box Culverts on Habitat and Biotic Communities

Although past studies have found that bridges and culverts can impede LWD transport (Lassettre and Kondolf, 2012), we did not find that to be the case in the current study. Owing to the headwater nature of most streams in the current study, the variability in LWD volume and density may simply reflect recruitment variation and have less to do with transport mechanisms. Although there were a few sites where the culvert obviously interrupted the transport of LWD (sites millersfk, indiancr, and centercr), the infrequent flow magnitude needed to move LWD in these small headwater channels likely has a larger role than the culvert acting as a constriction or barrier.

Several studies that evaluated bed-sediment size distributions in relation to culverts have reported increased fine sediment either immediately below or above the culvert compared to adjacent stream reaches (Wellman and others, 2000; Khan and Colbo, 2008; Peterson, 2010; MacPherson and others, 2012). This effect was not observed at the Piedmont sites, and the response was highly variable with no consistent trend. This result likely reflects the controls of local geology and disturbance history, which may influence the retention or flushing of fine sediment. Both LWD and bed-sediment size are important habitat elements for fish and macroinvertebrates, but they showed little correlation in the current study.

A large body of evidence corroborates the myriad effects of culverts on fish species and communities (Hotchkiss and Frei, 2007; Cocchiglia and others, 2012). At the species or population level, much of the focus has been on how culverts affect fish movement or disrupt passage, specifically how these structures impede dispersal or create unfavorable conditions through alteration of habitats, hydrology, and fluvial connectivity. Mark-recapture methods are commonly applied to assess bidirectional movement of fish through culverts (Warren and Pardew, 1998; Huser, 2009; Norman and others, 2009; Bouska and Paukert, 2010; Briggs and Galarowicz, 2013). Additionally, as in our study, most investigations of barriers to fish movement associated with roadways involve sampling fish upstream and downstream from culverts or other structures. In many studies, the focus has been on comparing different types of structures—for example, box culverts, bottomless box culverts, pipe culverts, bridges, and so on—in terms of how they affect fish movement or alter habitat. These studies often include physical habitat measurements to ascertain which conditions affect fish passage or community composition (Gibson and others, 2005; Bouska and others, 2010; MacPherson and others, 2012; Briggs and Galarowicz, 2013; Favaro and others, 2014). Other studies examined swimming performance or behavior of fish in simulated streams (Kemp and Williams, 2008; Johnson and others, 2019) or used modeling approaches to evaluate the probability of movement or passability (Cote and others, 2009; Norman and others, 2009; Anderson and others, 2012). Despite prevailing evidence in the literature of direct and indirect effects of culverts on fish communities, few studies have addressed the effects of culvert length, in contrast to culvert type or other physical attributes (for example, perched or hanging culvert). Using an information-theoretic approach based on fish movement in both natural and experimental streams, Bouska and Paukert (2010) found that the best model to account for the greatest proportion of two species of Great Plains cyprinids (*Cyprinella lutrensis* and *Notropis topeka*) that moved upstream from culverts included decreased culvert slope and length, perching, and increased culvert width. Using a similar logistic regression approach, Briggs and Galarowicz (2013) found that of several variables examined, culvert length had the greatest effect on the proportion of the cyprinid *Semotilus atromaculatus* found upstream from culverts in an agricultural setting in Michigan.

Like our study, Wellman and others (2000) were unable to detect any differences in fish diversity, abundance, or richness between streams with culverts and those with bridges. Nor could they detect differences between upstream and downstream reaches. It is possible that our sample sizes were too small and that samples were collected over too short of a duration to detect any meaningful differences, or the culverts in our study simply might not affect the fish communities. Moreover, the dominance of relatively few common, widespread species and the low abundance of many fish species that were found at a few sites did not allow for sufficient numbers to discriminate between sites or reaches, with the only notable difference being that communities were closely associated with physiographic province.

Unlike fish, some localized effects to the macroinvertebrate communities were evident adjacent to the culverts, but results were inconsistent and often confounding. As demonstrated by the preceding results, there was considerable variability. No consistent patterns were observed in macroinvertebrate community composition in relation to proximity to the culvert, among or between any of the categories (fig. 18*A*–*C*).

Many studies have assessed how land-use changes affect stream biota (Cuffney and others, 2010; Brown and others, 2012; Waite and others, 2014). Booth and Jackson (1997), Coles and others (2004), and Gregory and Calhoun (2007) reported that stream biota responded to low levels of development. For the current study, the land-cover criteria were initially constrained to minimize natural variation among study sites. Under these conditions, suitable study sites were unavailable; therefore, land-cover criteria were relaxed to meet the study design goal of 20 sites. As a result, responses of the macroinvertebrate community to culvert effects may have been masked by differences in the amount of watershed development between study sites (Booth and Jackson, 1997).

Other culvert studies that were in smaller geographic areas with fewer sites that had similar geomorphic and habitat (including substrate) conditions reported that culverts affected macroinvertebrate communities (Khan and Colbo; 2008; Peterson, 2010; Lawrence and others, 2014). In contrast, our study focused on collecting spatial replicates of “control-impact” sites over a large geographic area that spanned two physiographic provinces. Although the results were inconsistent and confounding, changes in the macroinvertebrate communities were detected near the culvert at a few sites in the Piedmont (both short and long culverts). Additional sampling and site-specific analysis could provide further information as to the abiotic variables contributing to the observed differences in macroinvertebrate community assemblage, yet such a site-specific analysis was beyond the scope of this investigation. Nonetheless, this study does provide foundational information that could be used to design future culvert studies in South Carolina.

Historical land-use practices and the channel alteration (straightening) that was prevalent with past culvert construction make drawing straightforward conclusions difficult. At many sites, we noted potentially confounding factors such as evidence of historical channel straightening, remnants of mill dams, or past beaver activity. The ability to link changes in channel morphology and habitat with culvert effects alone is confounded by these additional factors that likely led to some of the observed variability within and among sites. Nonetheless, the data indicate that sites in the Upper Coastal Plain showed a consistent geomorphologic response of channel incision downstream from culverts at five of the six sites; however, this geomorphic alteration was not necessarily associated with degraded biological conditions. At several sites, it was associated with more diverse habitat conditions (fig. 4) and a more diverse fish community (fig. 14).

Implications for Future Culvert Design and Mitigation

Although results from the present study are specific to box culverts and are based on a small sample size, several findings are consistent with previous research and are worth highlighting as considerations for future culvert design and mitigation. Streams in relatively undisturbed Piedmont and Upper Coastal Plain settings often have intact floodplains that allow frequent high flows (1- to 2-year RI) to exit the channel and spread out, thereby reducing energy and stresses applied to the streambed and banks. Flood attenuation is a critical function of stream ecosystems to maintain the balance of erosion and deposition, which influences the stability and productivity of aquatic habitats. In this regard, some States (for example, Minnesota and Texas) have studied and demonstrated the benefits of floodplain culverts in reducing flooding, channel erosion, sedimentation, and maintenance costs (Zytkovicz and Murtada, 2017). Analogous to the floodplain culvert is the staggered culvert design that has been researched in Texas (Cleveland and others, 2013). The staggered culvert approach uses a master culvert that handles bankfull and low flows in the main channel and additional culverts with inverts (culvert lip) at a higher elevation that only receive water when flow exits the main channel. This design reportedly helps reduce maintenance costs by reducing sediment accumulation and allowing a more natural sediment transport regime. Another approach that has been implemented in Ohio is the use of bankfull embedded culvert design (Tumeo and Pavlick, 2011). The rationale is similar to that of floodplain culverts in that the first step in design is to evaluate the size and characteristics of the natural channel and design a culvert that will accommodate similar flow. The primary focus is to prevent perching that leads to disconnected stream systems and to maintain consistent benthic habitat and ecological integrity. The use of floodplain culverts or staggered culverts may alleviate, or even reverse, incision downstream from culverts, as was observed in the Upper Coastal Plain in the present study. It is generally accepted that incision occurs when high-flow events are funneled through the culvert opening in a deeper, faster, more concentrated stream rather than the broad, shallow sheet flow that would have occurred prior to berm construction. Although these approaches may improve potential issues related to morphological adjustments, there is uncertainty regarding the biological response that may result from these alternate designs because no significant differences in community structure were observed in the current study.

Conclusions

The South Carolina Department of Transportation is required by the South Carolina Department of Health and Environmental Control and the U.S. Army Corps of Engineers to mitigate any perceived effects of culvert installation or replacement. A key factor in the level of mitigation is the length of the culvert. A long culvert would disrupt a longer section of natural stream but, if properly sized and installed, could have less overall effect on the stream channel stability and ecological integrity than a short culvert. In this analysis, geomorphic and biotic community structure were evaluated at sites with box culverts that varied by length. Although our sample size was small, the results did not suggest that culvert length influenced geomorphic conditions or community structure of fish or macroinvertebrates in the Piedmont region of South Carolina. Differences were noted in geomorphic conditions in the Upper Coastal Plain in the form of channel enlargement, primarily deepening, downstream from the culvert at five of the six sites. The prevalence of channel enlargement and the possible interaction with culvert length and type warrant further study. If this result is found to be common across culvert types (pipes, boxes, arches), other culvert design methods could be explored that may alleviate or reduce the effects.

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Appendix 1. Macroinvertebrate Metrics and Sample Classifications

This appendix contains two tables related to the macroinvertebrate sample results. Specifically, table 1.1 defines metrics that were calculated and evaluated for use in data analysis for the report. Table 1.2 contains the values for each metric described in table 1.1, for each sample.

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Table 1.1. Macroinvertebrate metric descriptions.

[EPA, U.S. Environmental Protection Agency; EPT, Ephemeroptera, Plecoptera, Tricoptera (mayflies, stoneflies, caddisflies)]

Metric	Description
Abund	Total number of organisms in the sample
Rich	Total richness (number of nonambiguous taxa)
AbundTOL	Abundance-weighted EPA tolerance value for sample
EPTR	Richness composed of EPT
EPTp	Percent of total abundance composed of EPT
EPT_CHp	Ratio of EPT to Chironomidae midge abundance
CHp	Percent of total abundance composed of Chironomidae midges
pPR_abund	Percent of total abundance composed of predators
pOM_abund	Percent of total abundance composed of omnivores
pCG_abund	Percent of total abundance composed of collector gatherers
pFC_abund	Percent of total abundance composed of filtering collectors
pSC_abund	Percent of total abundance composed of scrapers
pSH_abund	Percent of total abundance composed of shredders
Dom1	Percentage of total abundance represented by the most abundant taxa
Margalef	Margalef’s Diversity
Pielou’s evenness	Pielou’s evenness
ShannonDiv	Shannon’s diversity
SimpsonDiv	Simpson’s diversity

Table 1.2. Macroinvertebrate metrics for samples collected at selected culvert sites in South Carolina, 2016–18.

[Metric descriptions are provided in table 1.1. Classes were defined by Lenat (1993) and are based on AbundTOL values]

Sample identification	Abund	Rich	Abund-TOL	Class	EPTR	EPTp	EPT_CHp	CHp	pPR_abund	pOM_abund	pCG_abund	pFC_abund	pSC_abund	pSH_abund	Dom1	Margalef	Pielou's evenness	Shannon Div	Simpson Div
Piedmont long culverts																			
centercr1	3,881	18	7.35	Fair	0	0	0	20.87	4.77	1.56	46.02	11.17	31.72	4.77	35.74	2.06	0.66	1.90	0.77
centercr2	5,760	24	6.98	Fair	1	0.56	0.0002	61.11	11.39	5.06	34.81	22.78	24.68	1.27	21.11	2.66	0.78	2.48	0.88
centercr3	1,103	35	7.05	Fair	2	4.35	0.0070	56.21	15.82	7.96	25.25	17.49	27.11	6.39	18.68	4.85	0.82	2.92	0.92
centercr4	3,837	27	6.86	Fair	2	1.67	0.0009	49.44	16.08	2.07	30.09	37.07	14.70	0	18.35	3.15	0.80	2.64	0.90
enoree1	1,722	39	3.36	Excellent	13	62.02	0.2061	17.48	13.29	0.80	67.93	7.74	6.28	3.94	25.38	5.10	0.81	2.96	0.90
enoree2	834	41	5.34	Good	10	26.86	0.0574	56.12	32.10	2.05	35.17	9.59	7.42	13.68	9.59	5.95	0.89	3.32	0.95
enoree3	4,205	38	4.06	Excellent	8	48.11	0.0354	32.37	13.04	2.75	54.77	19.16	2.06	8.23	33.48	4.43	0.78	2.82	0.87
enoree4	1,210	30	4.72	Excellent	8	20.66	0.0249	68.60	46.67	2.86	20.95	11.43	3.81	14.29	15.70	4.09	0.89	3.01	0.93
millersfk1	1,720	19	8.29	Poor	0	0	0	25.29	11.79	8.23	64.52	4.78	0	10.68	29.36	2.42	0.78	2.30	0.85
millersfk2	2,893	18	7.53	Fair	0	0	0	23.92	12.87	8.47	55.23	4.24	0	19.19	23.89	2.13	0.84	2.44	0.88
millersfk3	10,859	18	7.73	Fair	0	0	0	17.40	11.37	2.28	63.63	2.28	0	20.44	54.33	1.83	0.62	1.79	0.68
millersfk4	3,040	24	6.76	Fair	1	0.66	0.0005	42.11	7.23	0	42.17	3.61	0	46.99	25.00	2.87	0.73	2.31	0.85
t2rockcr1	1,496	42	6.05	Good-fair	7	21.39	0.0270	52.94	20.77	3.80	20.72	33.94	0	20.77	11.76	5.61	0.88	3.28	0.95
t2rockcr2	668	39	6.02	Good-fair	7	11.38	0.0327	52.10	7.25	15.94	17.39	30.43	0	28.99	13.17	5.84	0.86	3.15	0.94
t2rockcr3	796	39	6.16	Good-fair	6	29.65	0.0720	51.76	6.98	5.67	36.76	16.86	0	33.73	23.62	5.69	0.80	2.94	0.91
t2rockcr4	1,608	40	6.18	Good-fair	8	7.96	0.0070	71.14	10.62	10.62	19.80	19.94	4.59	34.43	17.91	5.28	0.83	3.05	0.93
t2taylorcr1	3,104	22	6.16	Good-fair	3	3.61	0.0035	33.51	15.67	10.07	43.28	19.40	0	11.57	49.48	2.61	0.60	1.84	0.71
t2taylorcr2	1,515	20	7.87	Poor	0	0	0	49.24	12.17	3.37	50.19	27.34	0	6.93	28.84	2.59	0.78	2.32	0.85
t2taylorcr3	5,344	18	6.68	Fair	2	4.79	0.0028	31.74	12.75	0.67	41.61	26.85	0.67	17.45	59.88	1.98	0.55	1.60	0.62
t2taylorcr4	6,440	14	6.73	Fair	1	1.24	0.0010	19.25	21.11	2.13	49.47	15.78	0	11.51	73.91	1.48	0.45	1.18	0.45
taylorcr1	7,383	22	5.94	Good	3	2.32	0.0016	20.24	22.94	17.43	16.51	25.69	14.68	2.75	33.52	2.36	0.63	1.96	0.76
taylorcr2	2,736	24	5.88	Good	3	7.02	0.0084	30.41	12.75	8.28	25.64	16.28	34.33	2.71	51.46	2.91	0.60	1.90	0.71
taylorcr3	1,879	24	6.04	Good-fair	5	3.99	0.0059	35.82	22.13	5.74	40.98	20.49	9.02	1.64	37.47	3.05	0.66	2.11	0.79
taylorcr4	1,022	30	6.32	Good-fair	3	4.11	0.0073	55.19	15.32	12.90	32.26	25.81	8.87	4.84	22.41	4.18	0.79	2.68	0.88

Table 1.2. Macroinvertebrate metrics for samples collected at selected culvert sites in South Carolina, 2016–18.—Continued

[Metric descriptions are provided in table 1.1. Classes were defined by Lenat (1993) and are based on AbundTOL values]

Sample identification	Abund	Rich	Abund-TOL	Class	EPTR	EPTp	EPT_CHp	CHp	pPR_abund	pOM_abund	pCG_abund	pFC_abund	pSC_abund	pSH_abund	Dom1	Margalef	Pielou's evenness	Shannon Div	Simpson Div
Piedmont long culverts—Continued																			
timscrk1	308	33	5.53	Good	4	4.22	0.0227	60.39	13.29	1.27	39.87	12.03	0.63	32.91	12.01	5.58	0.88	3.08	0.94
timscrk2	606	33	5.37	Good	2	2.48	0.0073	56.27	7.26	2.89	33.83	7.26	0.74	48.02	21.78	4.99	0.81	2.84	0.90
timscrk3	1,288	35	5.37	Good	4	3.11	0.0038	63.98	14.79	6.34	48.59	23.94	2.82	3.52	22.98	4.75	0.77	2.75	0.89
timscrk4	578	40	5.39	Good	2	2.77	0.0093	51.38	15.52	2.59	52.59	16.38	0.86	12.07	9.34	6.13	0.88	3.26	0.95
Piedmont short culverts																			
beaverdam1	542	31	5.79	Good	4	2.95	0.0063	86.53	8.74	2.14	34.17	15.92	1.17	37.86	33.95	4.77	0.73	2.49	0.84
beaverdam2	330	44	6.40	Good-fair	5	10.91	0.0718	46.06	21.33	13.33	38.00	22.67	0	4.67	10.91	7.41	0.88	3.33	0.95
beaverdam3	870	34	6.11	Good-fair	4	12.64	0.0269	54.02	11.54	14.10	42.31	14.74	4.49	12.82	13.22	4.88	0.86	3.02	0.93
beaverdam4	210	38	6.80	Fair	4	6.67	0.0623	50.95	10.66	19.29	29.95	19.29	1.02	19.80	16.67	6.92	0.85	3.10	0.93
bluebr1	1,900	30	6.36	Good-fair	3	12.63	0.0100	66.32	8.88	15.38	7.69	60.95	5.33	1.78	49.47	3.84	0.63	2.16	0.73
bluebr2	1,240	39	6.20	Good-fair	4	18.06	0.0443	32.90	21.11	11.11	32.22	24.44	8.89	2.22	26.45	5.33	0.81	2.96	0.90
bluebr3	6,208	23	5.91	Good	4	3.61	0.0019	31.44	5.71	8.57	31.43	50.00	2.86	1.43	60.31	2.52	0.54	1.68	0.62
bluebr4	1,940	27	7.47	Fair	2	9.79	0.0090	56.19	17.61	10.23	37.50	19.89	6.25	8.52	30.93	3.43	0.77	2.54	0.87
drycrk1	2,541	37	5.90	Good	5	21.25	0.0202	41.36	13.76	2.31	39.66	16.67	14.37	13.23	13.42	4.59	0.86	3.09	0.94
drycrk2	712	22	6.70	Fair	1	1.12	0.0088	17.98	20.51	0	25.64	12.82	38.46	2.56	21.35	3.20	0.82	2.55	0.88
drycrk3	2,826	26	6.96	Fair	1	3.26	0.0059	19.64	23.49	1.58	17.23	9.35	42.09	1.58	26.04	3.15	0.78	2.54	0.86
drycrk4	900	28	6.90	Fair	3	4.44	0.0143	34.44	15.87	0	23.81	30.16	28.57	1.59	12.22	3.97	0.91	3.04	0.94
indiancr1	5,417	25	6.33	Good-fair	3	3.93	0.0010	71.42	9.00	2.12	5.83	72.46	8.47	2.12	64.98	2.79	0.51	1.64	0.57
indiancr2	7,246	27	6.82	Fair	1	1.09	0.0006	24.43	4.34	1.45	39.11	25.38	26.09	3.63	20.66	2.93	0.77	2.53	0.88
indiancr3	4,321	19	7.13	Fair	1	3.70	0.0029	29.62	1.60	6.44	43.54	17.75	30.66	0	17.29	2.15	0.88	2.60	0.91
indiancr4	4,455	23	6.32	Good-fair	4	7.79	0.0044	39.51	3.12	4.35	41.58	35.44	3.73	11.78	23.34	2.62	0.81	2.54	0.88
lilhogskin1	2,658	32	6.36	Good-fair	2	3.20	0.0015	79.23	10.30	0.64	41.29	23.28	10.30	14.20	12.87	3.93	0.86	2.98	0.93

Table 1.2. Macroinvertebrate metrics for samples collected at selected culvert sites in South Carolina, 2016–18.—Continued

[Metric descriptions are provided in table 1.1. Classes were defined by Lenat (1993) and are based on AbundTOL values]

Sample identification	Abund	Rich	Abund-TOL	Class	EPTR	EPTp	EPT_CHp	CHp	pPR_abund	pOM_abund	pCG_abund	pFC_abund	pSC_abund	pSH_abund	Dom1	Margalef	Pielou's evenness	Shannon Div	Simpson Div
Piedmont short culverts—Continued																			
lilhog-skin2	3,504	31	6.64	Good-fair	3	1.83	0.0007	76.71	10.31	1.55	25.77	24.74	21.13	15.46	15.07	3.68	0.83	2.86	0.92
lilhog-skin3	1,005	28	5.06	Good	5	4.18	0.0053	77.91	5.50	0.57	24.40	27.49	0.57	41.47	19.10	3.91	0.77	2.57	0.89
lilhog-skin4	1,760	39	6.14	Good-fair	5	4.55	0.0036	72.73	15.97	1.39	27.08	30.56	7.64	17.36	12.50	5.08	0.87	3.18	0.94
trib2allison1	1,416	33	3.76	Excellent	6	11.86	0.0141	59.32	22.67	4.00	41.35	11.99	3.31	16.68	23.73	4.41	0.77	2.69	0.88
trib2allison2	1,637	38	4.03	Excellent	10	16.43	0.0156	64.57	32.23	4.13	45.45	4.13	2.48	11.57	38.42	5.00	0.74	2.69	0.83
trib2allison3	1,630	41	6.00	Good-fair	3	4.91	0.0040	74.85	15.20	0	60.00	14.40	0	10.40	20.86	5.41	0.83	3.07	0.92
trib2allison4	1,280	38	5.44	Good	4	6.25	0.0063	78.13	8.84	2.76	65.75	6.08	2.21	14.36	21.25	5.17	0.82	2.98	0.91
trib-2payne1	1,740	43	5.03	Excellent	9	20.34	0.0239	49.02	12.66	28.48	35.44	21.52	1.27	0.63	7.99	5.63	0.91	3.42	0.96
trib-2payne2	1,224	37	6.24	Good-fair	4	3.27	0.0035	76.47	7.14	18.75	38.39	25.00	1.79	8.93	16.34	5.06	0.85	3.08	0.93
trib-2payne3	2,272	33	5.21	Excellent	4	23.94	0.0238	44.37	5.59	35.20	34.08	23.46	0.56	1.12	17.61	4.14	0.89	3.11	0.94
trib-2payne4	1,980	39	6.42	Good-fair	8	16.16	0.0207	39.39	12.64	25.82	24.18	31.32	1.10	4.95	30.81	5.01	0.75	2.75	0.87
Upper Coastal Plain short culverts																			
bigpinetree1	1,863	30	5.69	Good	5	20.77	0.0230	48.58	25.89	0.87	33.94	37.49	0	1.81	12.88	3.85	0.86	2.92	0.93
bigpinetree2	1,540	40	5.61	Good	7	11.04	0.0107	66.88	31.71	5.69	22.76	37.40	0.81	1.63	16.23	5.31	0.82	3.01	0.92
bigpinetree3	2,849	24	5.25	Good	3	4.39	0.0070	21.94	11.97	0	5.36	76.72	2.64	3.31	66.76	2.89	0.49	1.57	0.55
bigpinetree4	2,157	34	4.78	Excellent	4	20.40	0.0149	63.56	31.49	1.39	39.97	21.46	0.70	4.99	12.98	4.30	0.88	3.11	0.94
cowbr1	2,416	37	5.10	Excellent	6	9.27	0.0055	70.20	25.44	3.51	32.46	29.82	7.02	1.75	19.87	4.62	0.81	2.94	0.91
cowbr2	1,910	33	5.03	Excellent	7	15.71	0.0143	57.59	22.58	10.32	23.87	27.10	14.19	1.94	17.28	4.24	0.84	2.93	0.93

Table 1.2. Macroinvertebrate metrics for samples collected at selected culvert sites in South Carolina, 2016–18.—Continued

[Metric descriptions are provided in table 1.1. Classes were defined by Lenat (1993) and are based on AbundTOL values]

Sample identification	Abund	Rich	AbundTOL	Class	EPTR	EPTp	EPT_CHp	CHp	pPR_abund	pOM_abund	pCG_abund	pFC_abund	pSC_abund	pSH_abund	Dom1	Margalef	Pielou's evenness	Shannon Div	Simpson Div
Upper Coastal Plain short culverts—Continued																			
cowbr3	3,380	29	4.59	Excellent	4	7.69	0.0029	78.11	31.54	4.62	32.31	23.85	4.62	2.31	16.57	3.45	0.78	2.63	0.90
cowbr4	1,392	30	4.85	Excellent	5	11.49	0.0138	59.77	17.29	6.77	33.08	33.83	8.27	0.75	22.41	4.01	0.79	2.70	0.90
sadler1	4,484	31	4.55	Excellent	5	6.53	0.0018	80.95	4.60	7.78	31.18	16.22	1.29	38.92	35.68	3.57	0.75	2.56	0.84
sadler2	2,101	26	5.06	Excellent	4	9.14	0.0063	69.54	1.38	7.49	27.93	25.12	7.49	30.59	26.18	3.27	0.80	2.62	0.88
sadler3	5,150	35	5.12	Excellent	4	4.66	0.0011	81.32	3.81	8.12	27.55	25.91	6.50	28.10	26.93	3.98	0.78	2.77	0.89
sadler4	3,460	41	5.18	Excellent	6	8.09	0.0037	63.01	7.97	13.77	16.67	34.78	7.25	18.84	13.87	4.91	0.85	3.17	0.94
tinker1	1,264	37	5.09	Excellent	7	29.11	0.0758	30.38	5.43	3.26	71.20	17.39	2.17	0.54	10.13	5.04	0.88	3.17	0.95
tinker2	1,124	41	5.29	Good	10	14.23	0.0262	48.31	8.97	2.97	59.48	16.08	12.5	0	22.51	5.69	0.80	2.97	0.90
tinker3	1,820	43	5.50	Good	8	37.91	0.0665	31.32	8.42	5.26	50.53	27.37	4.21	4.21	13.19	5.60	0.88	3.30	0.95
tinker4	1,144	45	5.40	Good	6	13.29	0.0198	58.74	8.20	2.98	20.88	54.49	13.44	0	8.39	6.25	0.92	3.50	0.96
trib4hole1	1,990	24	6.67	Good-fair	1	2.51	0.0015	82.41	4.82	1.20	37.35	9.64	0	46.99	60.80	3.03	0.56	1.78	0.62
trib4hole2	4,586	21	7.21	Fair	0	0	0	79.28	5.02	1.04	48.48	16.19	21.21	8.05	45.20	2.37	0.70	2.13	0.77
trib4hole3	1,980	23	6.80	Fair	0	0	0	82.83	3.28	1.64	59.02	29.51	1.64	3.28	43.94	2.90	0.69	2.18	0.78
trib4hole4	10,023	25	5.76	Good	3	2.13	0.0003	67.55	0	0	45.95	37.84	0	16.22	25.01	2.61	0.76	2.44	0.87
trueblue1	640	28	5.65	Good	4	3.75	0.0105	55.63	7.80	14.18	25.53	41.13	9.93	0.71	23.75	4.18	0.82	2.74	0.90
trueblue2	3,820	30	5.82	Good	1	1.05	0.0003	80.10	14.69	16.95	12.43	46.33	8.47	1.13	33.51	3.52	0.75	2.54	0.85
trueblue3	3,480	18	5.87	Good	0	0	0	86.21	8.82	17.65	28.24	44.71	0.59	0	29.89	2.08	0.75	2.18	0.84
trueblue4	1,800	25	5.48	Good	2	1.67	0.0015	60	6.06	6.67	15.15	56.97	13.94	1.21	36.11	3.20	0.70	2.24	0.82

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