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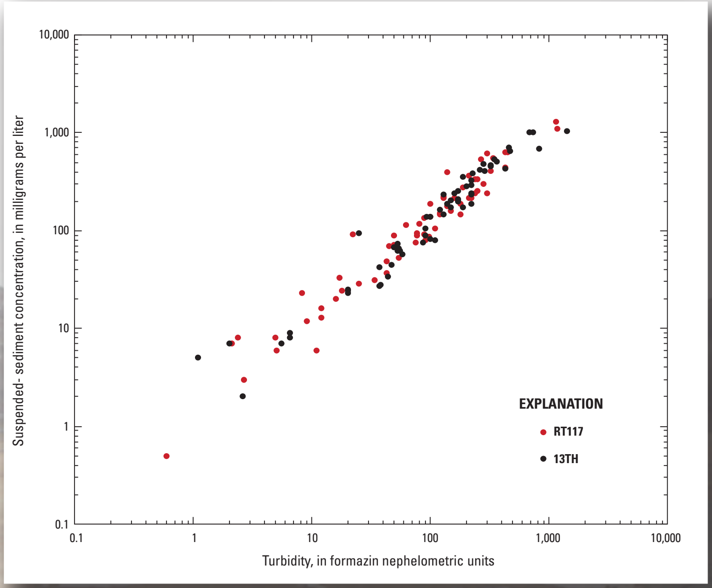

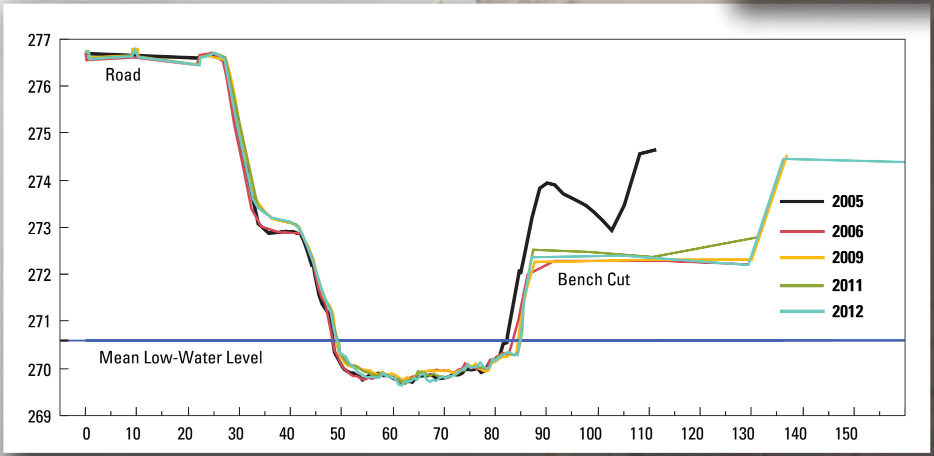

Scientific Investigations Report 2015–5111

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Cover images. *Left:* Line graph showing channel topography at site 15. *Right:* Plot showing turbidity and suspended-sediment concentration data for samples collected at two monitoring stations, Roanoke River, Virginia, 2005–2012 (see figure 19, p. 42). *Background:* Photograph of Roanoke River, looking upstream from 13th Street Bridge, Roanoke, Virginia, December 27, 2006.

Fluvial Geomorphology and Suspended-Sediment Transport During Construction of the Roanoke River Flood Reduction Project in Roanoke, Virginia, 2005–2012

By John D. Jastram, Jennifer L. Krstolic, Douglas L. Moyer, and Kenneth E. Hyer

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second per square mile [(ft^3/s)/mi^2]	0.01093	cubic meter per second per square kilometer [(m^3/s)/km^2]
	Mass	
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per day per square mile [(ton/d)/mi^2]	0.3503	megagram per day per square kilometer [(Mg/d)/km^2]
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year

SI to Inch/Pound

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foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
square foot (ft^2)	929.0	square centimeter (cm^2)

Supplemental Information

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

°F=(1.8×°C)+32

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C). Concentrations of chemical constituents in water are in milligrams per liter (mg/L)

Datums

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

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

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Field assistance was provided by an extensive team of technicians; in particular, the efforts of Carlos Rodriguez, Brent Banks, Amy Jensen, Amanda Hodges, Brian Hasty, and Cathy Wright were vital to the data collection components of this study.

Fluvial Geomorphology and Suspended-Sediment Transport During Construction of the Roanoke River Flood Reduction Project in Roanoke, Virginia, 2005–2012

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Abstract

Beginning in 2005, after decades of planning, the U.S. Army Corps of Engineers (USACE) undertook a major construction effort to reduce the effects of flooding on the city of Roanoke, Virginia—the Roanoke River Flood Reduction Project (RRFRP). Prompted by concerns about the potential for RRFRP construction-induced geomorphological instability and sediment liberation and the detrimental effects these responses could have on the endangered Roanoke logperch (*Percina rex*), the U.S. Geological Survey (USGS) partnered with the USACE to provide a real-time warning network and a long-term monitoring program to evaluate geomorphological change and sediment transport in the affected river reach. Geomorphological change and suspended-sediment transport are highly interdependent and cumulatively provide a detailed understanding of the sedimentary response, or lack thereof, of the Roanoke River to construction of the RRFRP.

Bed-sediment composition was usually finer in post-construction than pre-construction measurements, yet the annual changes in composition were not significantly different; thus, there was minimal evidence that RRFRP construction practices alone induced fining of bed materials. Cross-sectional surveys revealed variability in bankfull and base-flow channel geometry metrics, but no significant differences in this variability were detected between pre- and post-construction measurements, excluding designed alterations in channel geometry. A lack of channel-forming streamflow events, however, limited the ability to fully characterize the stability of the constructed channel and floodplain features, as bankfull flow events occurred only 2 of the 8 years of study. Therefore, additional channel surveys may be needed in the future, once sufficient channel-forming events have occurred, to fully assess stability. Relations between turbidity and suspended sediment were statistically indistinguishable between the upstream and downstream limits of the RRFRP construction reach. These relations did not change over time, indicating no significant changes in suspended-sediment composition or source in the construction reach during the period of study.

Results of the geomorphological and suspended-sediment monitoring components were largely in agreement and consistent with those of a related effort that monitored the logperch population before and during construction. These findings suggest that construction and sediment-control practices sufficiently protected in-stream habitat and the organisms that inhabit those locations, namely the Roanoke logperch, during the period monitored.

Introduction

The city of Roanoke, Virginia (hereinafter referred to as the city), has suffered substantial flood damages over the course of its history, particularly throughout the 20th century as floodplain areas along the Roanoke River have been increasingly urbanized. For example, the flood of November 4, 1985, which had a 0.01 annual exceedance probability (100-year recurrence interval; Carpenter, 1990; Austin and others, 2011), took the lives of 10 people and caused an estimated $440 million in damage in the Roanoke area (Carpenter, 1990). With more than $1 billion worth of property at risk from potential flood damage (U.S. Fish and Wildlife Service, 2005), the City of Roanoke partnered with the U.S. Army Corps of Engineers (USACE) to construct the Roanoke River Flood Reduction Project (RRFRP) in an effort to reduce flooding impacts within the city. Construction of the RRFRP was complicated, however, by concerns about potential effects on the habitat of the Roanoke logperch (*Percina rex*), an endangered fish species endemic to the Roanoke River Basin in Virginia and North Carolina.

Description of Study Area

The city of Roanoke is located in southwest Virginia, along the headwaters of the Roanoke River and within the Blue Ridge and Valley and Ridge Physiographic Provinces (fig. 1). The Roanoke River begins at the confluence of the

North and South Forks of the Roanoke River, approximately 17 river miles upstream of the city limits. Downstream from the confluence, the river flows through rural portions of Montgomery County, into the urbanized and industrialized areas of the cities of Salem and Roanoke. The focus of this study was on the approximately 10-mile section of the river flowing through Roanoke.

Land cover in the watershed at the start of the study in 2006 was dominated by three major land-cover categories–forest, developed land, and agriculture–which cover 70, 19.5, and 9.5 percent of the watershed area, respectively (Fry and others, 2011). Water, wetland, herbaceous, bare, and other land-cover categories together make up less than 1 percent of the watershed. The surficial geology of the watershed comprises 66 percent siliciclastic rocks, 20 percent carbonate rocks, and 14 percent metamorphic rocks. Soils in the watershed are dominated by well-drained silt loams on surfaces that range from flat to very steeply sloping (Soil Survey Staff, 2015). Impervious surface in the watershed was 6.0 percent in 2006 and did not change substantially during the study.

The Flood Reduction Approach

The RRFRP sought to reduce effects of flooding in the city of Roanoke through the use of multiple types of floodplain modifications aimed at containing floodwaters within the floodplain, reducing flood elevations, and removing vulnerable assets from flood-prone areas. The effort primarily relied upon the excavation of “bench cuts,” or reductions in the floodplain elevation, along approximately 6.2 miles of the 10 miles of river within the city limits (U.S. Army Corps of Engineers, 2014). The intent of these bench cuts was to increase the volume of floodwater contained within the floodplain, thereby reducing the elevation of flood levels. While excavating the bench cuts, “snagging” was performed to remove debris and vegetation that could potentially be transported downstream and create jams or blockages that could constrict flow and increase water levels during flood events. Initially, all vegetation along the river bank was removed in the snagging process, but this practice was changed after concerns were raised about the stability and ecological effects of removing shade trees with well-established root systems from the banks of the river. Snagging in the later phases of the project utilized selective removal of vegetation to achieve a balance between flood risk reduction and ecological needs. An example of bench cut excavation and the early approach of snagging all vegetation is shown in figure 2.

In areas where flood risks remained after bench cut excavation, “training walls” were constructed to locally contain flood flows within the desired river channel and floodplain. These training walls, of which approximately 6,300 linear feet were constructed, were composed of earthen berms, driven steel sheet pile walls, or a combination of earthen berms and steel sheet pile walls.

Construction of the flood reduction measures required the relocation or removal of utilities, roads, and structures within the floodplain and river channel. Upon completion of the flood reduction measures, recreational and river-access features, such as parks and trails, were constructed within the newly created “greenway.”

Potential Ecological Effects of the Flood Reduction Project

The potential for social and economic benefits from the RRFRP were apparent, as reduction of flood effects throughout the city could decrease the loss of life and costs of recovering from such flood events on a recurring basis. Ecological effects, however, were a concern because the Roanoke River is home to the Roanoke logperch (*Percina rex*), a federally listed endangered fish species (U.S. Fish and Wildlife Service, 2005).

The Roanoke logperch (hereinafter called logperch) is a large darter in the Percidae family, typically 3–5 inches long with a cylindrical body and conical snout (fig. 3; Jenkins and Burkhead, 1994). The logperch is endemic to Virginia and North Carolina, specifically to the Roanoke and Chowan River Basins (U.S. Fish and Wildlife Service, 2005). In the Roanoke River, adult logperch inhabit reaches with deep, fast flow over gravel and cobble substrates, where they use their conical snouts to flip gravel and feed on exposed invertebrates (Rosenberger and Angermeier, 2003). Spawning occurs in areas with high water velocity and gravel or pebble substrate (Ensign and others, 1997), where the adhesive eggs are buried in the substrate and left without further parental care (Mattingly and others, 2003). Upon hatching, larvae are believed to drift to areas with slower velocities (Burkhead, 1983), with young typically inhabiting slower runs and pools with sandy substrate (Rosenberger and Angermeier, 2003).

The U.S. Fish and Wildlife Service (USFWS) concluded that the status of the logperch is stable to declining, and survival of the species is dependent upon survival of the Roanoke River population (U.S. Fish and Wildlife Service, 2005). The USFWS identified the main causes of logperch population decline as nonpoint source pollution, siltation, chemical spills and pollution, channelization, impoundments, and cold-water releases from dams (U.S. Fish and Wildlife Service, 1992), with siltation identified as the most widespread threat (U.S. Fish and Wildlife Service, 2005).

The extensive excavation and associated activities for the RRFRP posed a potential threat to the logperch because these activities could lead to increased sediment transport into the river which could subsequently settle on the river bottom and affect the logperch habitat. The USFWS issued a biological opinion to the USACE, in accordance with the Endangered Species Act of 1973, stating that the RRFRP “will directly affect the logperch and its habitat though the increase in sedimentation and turbidity” and that “direct impacts to the logperch include the potential to kill and/or injure individuals”

Base from Virginia Department of Conservation and Recreation, 2004, Virginia Jurisdiction Boundaries; USGS, 2012, National Hydrography Dataset, 1:24,000; Adapted physiography from Fenneman and Johnson (1946), 1:7,000,000 and Virginia Geologic Map, Dicken and others. (2005), 1:500,000

Figure 1. Monitoring station locations on the Roanoke River in Roanoke and Salem, Virginia. Geomorphology monitoring site numbers defined in table 1. Suspended-sediment monitoring stations and short names defined in table 9.

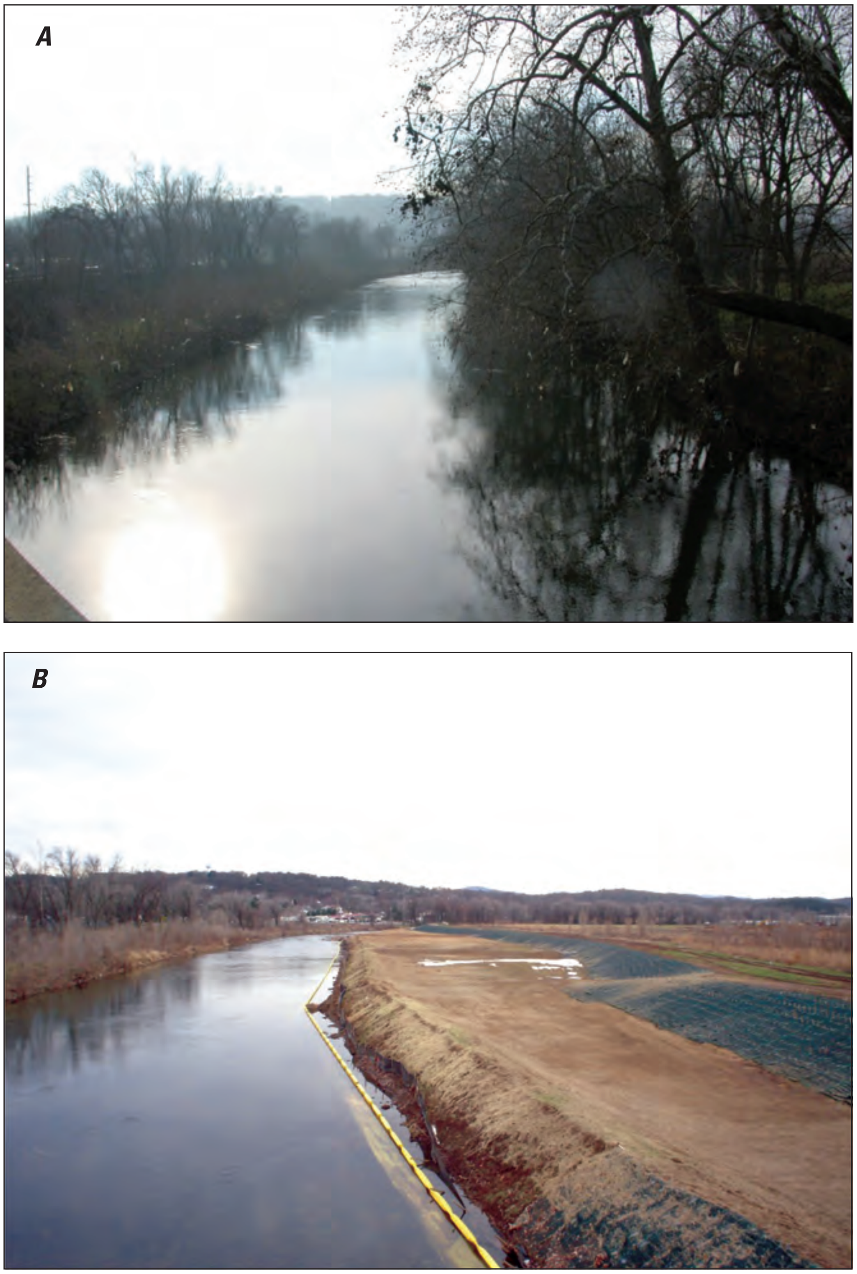


Figure 2. Photos of *A*, pre- and *B*, post-construction channel upstream of 13th Street, Roanoke, Virginia, 2005 and 2006, respectively.

Figure 3. Photograph of the Roanoke logperch (*Percina rex*; photograph by Noel Burkhead, U.S. Geological Survey).

(U.S. Fish and Wildlife Service, 2005). The USFWS found that though the RRFRP would likely affect the logperch, the effects were not likely to jeopardize the survival of the species, and the project was permitted to proceed under an incidental “take” permit –a permit required when approved activities may result in the harm or killing of an endangered species–with numerous conditions (U.S. Fish and Wildlife Service, 2005). These conditions included such measures as prohibiting construction activities during the logperch spawning season, limiting active construction to 4,000 linear feet of the river at any time, observing strict controls on the location and duration of specific activities to reduce the likelihood of sediment or other pollutants (for example, fuel and pesticides) entering the river, and completing a comprehensive monitoring program to evaluate logperch population and habitat quality, suspended-sediment transport and turbidity, bed-sediment composition, and river channel geomorphology. In addition to excavation activities, a dam removal was permitted during the RRFRP to increase potential connectivity of logperch populations. The dam removal was monitored and assessed in conjunction with geomorphological analyses.

Logperch population and habitat-quality monitoring was conducted by the U.S. Geological Survey (USGS) Virginia Cooperative Fish and Wildlife Research Unit at Virginia Polytechnic and State University as a continuation of the monitoring program that was initiated during the planning phases of the RRFRP (Roberts and others, 2013). Bed-sediment composition, river geomorphology, suspended-sediment transport, and turbidity, which were monitored by the USGS Virginia Water Science Center, are the focus of this report.

The overall objective of the study was to monitor sediment dynamics through the construction reach to document the effects, if any, of the RRFRP on logperch habitat. This was accomplished by using a bilateral approach with one study component focused on bed-sediment and river geomorphology and the second study component focused on suspended-sediment transport. The specific objectives of the geomorphological monitoring component and the suspended-sediment component are described in detail in the respective sections of this report.

Purpose and Scope

The purpose of this report is to document data collected in support of the previously described study and to present analyses and interpretation of those data conducted to satisfy the study objectives. The data presented and analyzed include precipitation, streamflow, annual geomorphic surveys, annual river substrate size distributions, continuously and discretely measured turbidity, and discretely measured suspended sediment. The data presented span the 8 years of the study period—water years (WYs) 2005–2012, where a WY is defined as October 1 through September 30 for the year in which the period ends (for example, WY 2007 is October 1, 2006–September 30, 2007).

Hydrologic Conditions

Geomorphic change and transport of suspended sediment are largely dependent upon runoff events, typically from rainfall or snowmelt, of sufficient magnitude to erode or otherwise entrain sediment from the landscape and transport it to stream channels, and (or) to entrain sediments already present in stream channels. These dependencies on hydrologic conditions are important factors when considering the level of risk for habitat-damaging effects during construction of the RRFRP. Precipitation and hydrologic conditions during the study period were evaluated for comparison with the observed patterns in geomorphic change and suspended-sediment transport.

Precipitation

Total monthly precipitation data for 2004–2012 and mean monthly precipitation data (computed for the climate period 1980–2010) were downloaded from the National Oceanic and Atmospheric Administration's Climate Data Online database (http://www.ncdc.noaa.gov/cdo-web/; National Oceanic and Atmospheric Administration, 2013) for the meteorological station at Roanoke Regional Airport (Station GHCND:USW00013741). Monthly total precipitation values were summed over WY periods to determine total annual precipitation during the WY, and monthly mean precipitation values were summed to determined mean annual precipitation.

Annual precipitation throughout the study period of WYs 2005–2012 was generally below average, with two WYs (2009 and 2012) having approximately average total precipitation and one WY (2010) having greater than average precipitation (fig. 4*A*). Most WYs were characterized by below-average total annual precipitation, though some months within those WYs had monthly precipitation much greater than average, notably June 2006 and September 2011 (fig. 4*B*). Precipitation in June 2006 totaled 8.5 inches, more than twice the mean monthly precipitation of 3.9 inches, with the majority of the rain falling over 3 days (June 25–27). Precipitation in September 2011, which totaled 7.4 inches, also was more than twice the mean monthly precipitation of 2.9 inches, with the majority of the rain falling over 2 days (September 5–6) as the remnants of Tropical Storm Lee passed through the area.

Above-average precipitation was received in WY 2010, when nearly 13.5 inches more than the average annual precipitation of about 41 inches fell on the area (fig. 4*A*). Though the annual total precipitation was well above average, February, April, and June received only 30–50 percent of the respective monthly precipitation amounts (fig. 4*B*). Those deficits were offset by 3 months (November, December, and September) of precipitation more than twice the monthly means, with the remaining months receiving at least average precipitation amounts (fig. 4*B*).

Streamflow

Streamflow conditions throughout the study period were characterized by using data from the USGS Roanoke River at Roanoke, Virginia, streamgage (USGS station 02055000), located within the construction reach (fig. 1). Streamflow metrics evaluated include the cumulative daily streamflow volume, downloaded from the USGS WaterWatch Web site (http://waterwatch.usgs.gov/?id=flood_cumflow), and annual peak streamflow, downloaded from the USGS National Water Information System Web Interface (NWISWeb; http://nwis.waterdata.usgs.gov). Evaluation of cumulative daily streamflow volume by water year permits comparison of the overall hydrologic conditions throughout the study period, with dry periods (gentle slopes) and large-magnitude stormflow events (steep, short-duration slopes) clearly depicted (fig. 5*A*). Evaluation of the non-exceedance probability of annual peak streamflow, which is the probability that the annual peak streamflow will be less than the specified value, computed from 114 years (WYs 1899–2013) of record at the Roanoke River at Roanoke streamgage, provides historical perspective of the commonality or rarity of peak streamflows observed during the study period (fig. 5*B*).

The driest year of the study, as measured at the streamgage (USGS station 02055000), was WY 2008 (fig. 5*A*), which had a total annual streamflow volume less than half of the next driest year in the study period (WY 2006). The low streamflow volumes observed in WY 2008 were a result of below-average precipitation throughout much of WY 2007 and the first half of WY 2008 (fig. 4*B*).

The wettest years of the study period, as measured at the streamgage (USGS station 02055000), were WYs 2005 and 2010 (fig. 5*A*), with total annual streamflow in 2010 (15,800 million cubic feet) more than 60 percent greater than the average annual total streamflow for the study period (9,600 million cubic feet). As with most other WYs, the majority of the streamflow volume in WYs 2005 and 2010 occurred during the first half of the WY, with relatively low flow accumulation during the latter half of the WY. All other WYs (2006, 2007, 2009, 2011, and 2012) had near-average total annual streamflow volumes, though rates of

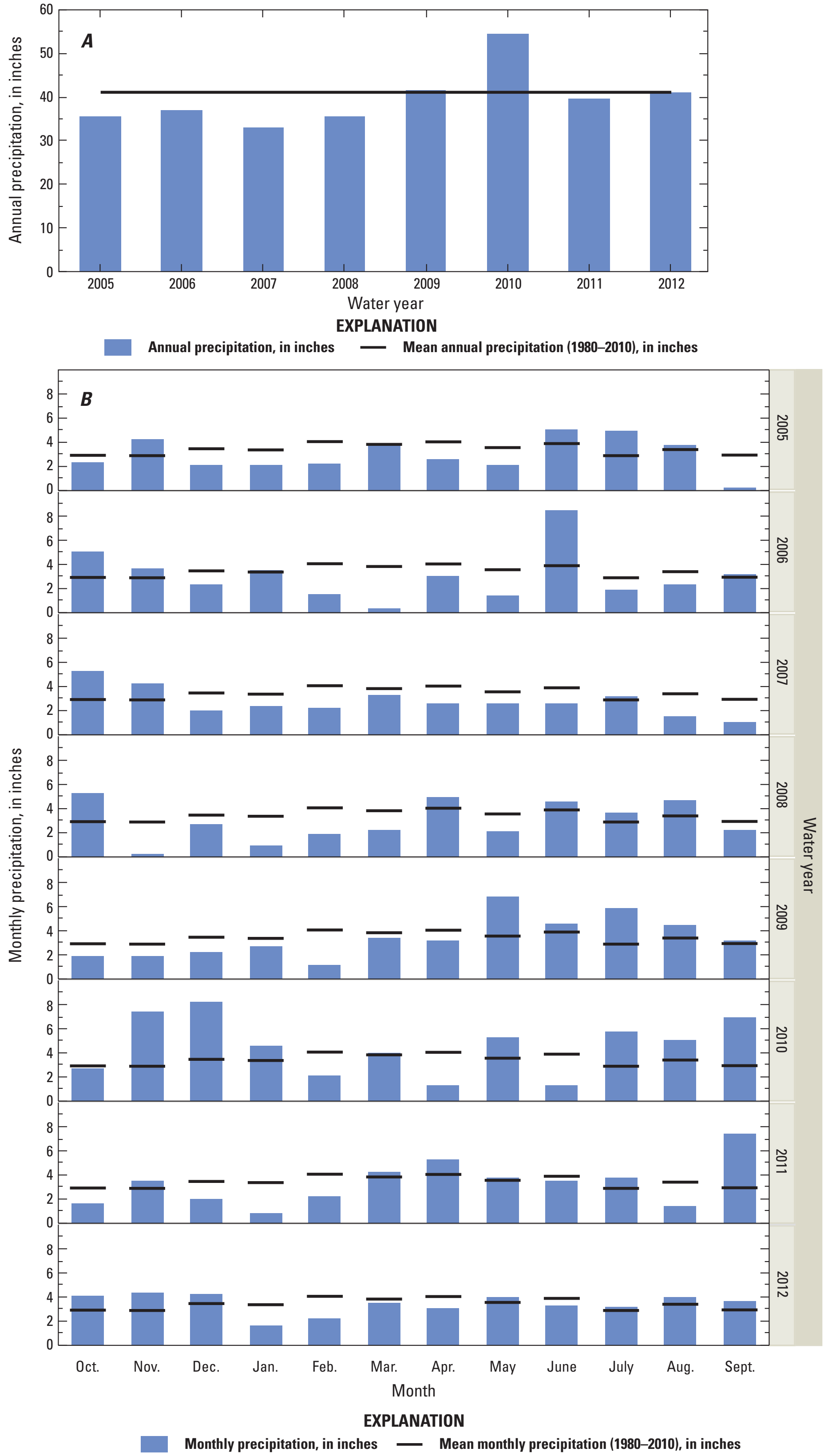


Figure 4. Annual and monthly precipitation for water years 2005–2012 and mean precipitation for 1980–2010, from the National Weather Service station at Roanoke Regional Airport (NWS ID GHCND:USW00013741).

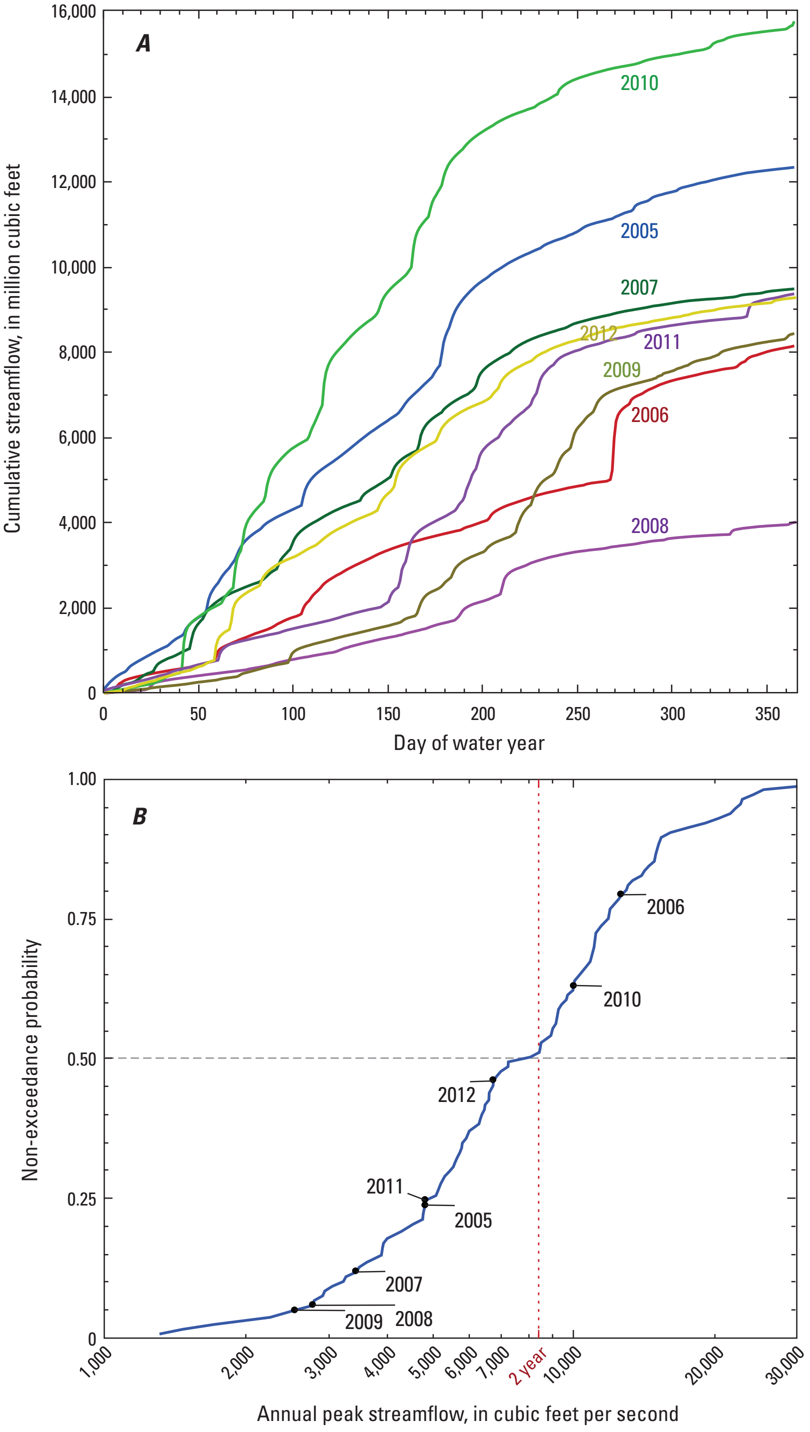


Figure 5. Plots of *A*, cumulative daily streamflow volume per water year and *B*, non-exceedance probabilities of annual peak streamflows from 1899 to 2013 with annual peaks for water years 2005–2012 labeled, for Roanoke River at Roanoke, Virginia (USGS station 02055000; see fig. 1 for location).

accumulation during the WY varied (fig. 5*A*). WYs 2009 and 2011 had low streamflows, and therefore little flow accumulation, early in each WY, with rapid accumulation during the middle of each WY, as a result of greater precipitation during that period. Dry conditions and low streamflows also occurred during much of WY 2006, which was the second driest (lowest cumulative annual flow) WY during the study (fig. 5*A*). Heavy rains during a 3-day period in June, however, resulted in the highest streamflows observed during the study period and increased the cumulative streamflow for WY 2006 to near-average conditions (fig. 5*A*).

Annual peak streamflows were relatively low during much of the study period, with two exceptions: WYs 2006 and 2010 (fig. 5*b*). The annual peak streamflows of 12,600 and 9,950 cubic feet per second (ft^3/s) in WYs 2006 and 2010, respectively, were greater than about 80 percent and 63 percent, respectively, of the annual peaks observed from 1899 to 2013. Austin and others (2011) computed the 2-year recurrence interval (0.5 annual exceedance probability), also considered the "channel-forming event" (Wolman and Miller, 1960), as 8,400 ft^3/s; six of the eight WYs of the study period had annual peak streamflows less than the 2-year recurrence interval.

Geomorphological Responses

Geomorphological monitoring was conducted to ascertain whether impacts to Roanoke logperch habitat, such as aggradation or degradation in the active channel, were detectable in greater magnitude in association with the RRFRP construction than in upstream monitoring sites unaffected by the RRFRP. The specific objectives of the geomorphological monitoring component were to utilize annual surveys of river channel cross sections and substrate size distributions to

- Determine effects on habitat resulting from RRFRP construction activities;
- Assess long-term changes in bed-material characteristics; and
- Assess the long-term stability of the RRFRP in selected areas.

A potential effect of any construction activity within a river floodplain is excess sedimentation. Lisle and Eads (1991) noted that addition of fine sediment deposits on the channel bed can penetrate through gravel and cobble substrates and reduce intergravel flow, and organic matter in the fine sediment may consume dissolved oxygen and thus inhibit respiration of eggs. Logperch prefer loose, unembedded, and unsilted substrates (Rosenberger and Angermeier, 2003) and silt-free gravel and cobble in riffles and runs (Burkhead, 1983). Lahey and Angermeier (2007) assert that favorable habitat conditions for logperch occur where substrates contain less than 25-percent silt/clay content. Thresholds of concern for fine sediment for other species commonly fall in this range as well (Lisle and Eads, 1991); however, Lisle and Eads point out that studies often consider fine material to be 2 millimeters (mm) in size or less. For this investigation, silt/clay particles (represented by less than 0.063 mm) and sands (from 0.063 mm up to and including 2 mm) were examined to evaluate any changes that may be occurring. Long-term changes in bed-material characteristics were represented by shifts in percentages of silt/clay, sand, gravel, cobble, boulder, or bedrock measured from pebble counts before, during, and after RRFRP construction. Determinations of annual variation in percentages of bed-material size-class distributions upstream of construction were used to help identify impacts attributable to RRFRP activities, if any, and serve as a reference to variation typical for each year of the study and throughout the entire study period.

Surveys of geomorphic cross sections also were used to examine potential effects on habitat such as aggradation from deposition or degradation from scour, or loss of stability from widening and bank erosion. Bank stability is important because unstable banks are often significant sediment sources in rivers and do not offer the structural or functional services that stable, vegetated banks provide to instream organisms (Flotemersch and others, 2006). Stability was inferred by examining geomorphological variables for discernible changes to base-flow or bankfull width, mean depth, or cross-sectional area, as well as consistent water-surface slopes and floodplain elevations. Surveys of cross sections can provide high precision and accuracy in bed elevations over time but do not represent the maximum of scour (Lisle and Eads, 1991); rather, such surveys represent an integration of scour and fill since the previous survey year. Long-term changes in geomorphological variables may indicate effects attributable to the RRFRP. As with bed material, comparisons of the annual percentage changes in geomorphological variables between construction-affected sites and sites upstream where no construction occurred should help identify impacts attributable to RRFRP activities, if any, and serve as a reference to geomorphic variation typical for each year of the study and throughout the entire study period.

The goal of the RRFRP was to have no net effect or "take" of logperch from the river through adequate sediment-control measures and minimal impact to the active-channel geomorphology outside of designed changes. For this to be the case, subsequent to bench cut, trail, or training wall construction, construction monitoring sites would experience relatively little change in channel geomorphology or shifts in composition of bed material, relative to the control sites upstream of the RRFRP.

Geomorphology Study Design

Geomorphology monitoring sites were selected at 15 locations representing riffle or pool habitat along the Roanoke River in Salem and Roanoke, Virginia (fig. 1; table 1). Geomorphology monitoring sites were located where construction activities would physically alter the floodplain while also maximizing co-location with existing Roanoke logperch biological-monitoring sites (Roberts and others, 2013). A mix of riffles and pools were selected throughout the study area to represent habitats used by logperch. Sites were designated as "control" or "construction" to discern between sites upstream of the RRFRP, and therefore unaffected by construction activities, and sites within the construction reach. Six pools were monitored (three control and three construction), and nine riffles were monitored (three control and six construction). Monitoring included substrate data collection and cross-section topographic surveys conducted annually from 2005 to 2012 at each site.

Construction began near 13th Street in October 2005 and proceeded sequentially in an upstream direction until September 2011; therefore, many of the sites were not affected by construction until late in the RRFRP (table 2). Sites within the construction reach were either physically altered at the geomorphic survey cross section (for example, a bench cut changed the grade of the bank or the floodplain directly within the vicinity of a cross section) or sites were located downstream of construction activity, but were not locations of physical construction. For sites where channel characteristics were intentionally altered to a new geomorphic condition by the RRFRP, long-term stability measures were evaluated from the period of time after local construction was completed until the end of the study (2012). For those sites simply located downstream of construction activity, year-to-year comparisons were made from pre-construction and post-construction monitoring data to detect any changes greater in magnitude than those observed during the same year in the control reach.

Though sites were designated as "control" or "construction" based on location inside or outside of the RRFRP reach, data analysis was conducted by using classifications of "pre-construction" and "post-construction." Data for each site–year combination were classified as pre-construction (grouping control-site data and unaltered construction-site data) or post-construction to indicate conditions after construction occurred adjacent to or upstream of the cross section (table 2); thus, the sample size for each class changed annually. For example, site 8 was classified pre-construction for 2005–2007, but was re-classified as post-construction for 2008–2012 because

Table 1. Roanoke River Flood Reduction Project geomorphic monitoring stations, Roanoke and Salem, Virginia.

[USGS, U.S. Geological Survey; mi^2, square miles; NAD 83, North American Datum of 1983; na, not applicable, no logperch monitoring at the site; RR, reference reach and site number; p, pool; CR, construction reach and site number]

USGS station identifier	Site number (see fig. 1)	Description	Drainage area (mi^2)	Decimal latitude (NAD 83)	Decimal longitude (NAD 83)	Habitat type	Site type	Logperch monitoring site code[1]
0205458550	1	Roanoke River near Front Street at Salem, VA	310	37.284028	–80.062722	Pool	Control	RR4p
0205458560	2	Roanoke River above Eddy St Bridge at Salem, VA	310	37.282944	–80.059972	Riffle	Control	RR4
0205459510	3	Roanoke River along Riverside Drive at Salem, VA	316	37.273278	–80.039139	Riffle	Control	na
0205459530	4	Roanoke River above Apperson Dr Bridge at Salem, VA	316	37.272222	–80.038972	Pool	Control	na
0205459890	5	Roanoke River above Mason Creek at Salem, VA	317	37.265639	–80.027722	Pool	Control	na
0205474910	6	Roanoke River below Barnhardt Cr at Roanoke, VA	351	37.270583	–80.012194	Riffle	Control	CR6
0205491520	7	Roanoke River above Bridge St Bridge at Roanoke, VA	371	37.274694	–79.981528	Riffle	Construction	CR5
0205493075	8	Roanoke River along Wiley Dr below dam at Roanoke, VA	374	37.267806	–79.963083	Riffle	Construction at bench cut	CR4
0205493515	9	Roanoke River above Main St Bridge at Roanoke, VA	375	37.268083	–79.958444	Pool	Construction at bench cut	na
0205494810	10	Roanoke River at Smith Park at Roanoke, VA	375	37.261389	–79.956639	Riffle	Construction	CR3
0205494950	11	Roanoke River above Walnut St Bridge at Roanoke, VA	384	37.257583	–79.939472	Pool	Construction at bench cut	na
0205500550	12	Roanoke River at Whitman Street at Roanoke, VA	384	37.257361	–79.931278	Riffle	Construction at bench cut	na
0205504515	13	Roanoke River below Garnand Branch at Roanoke, VA	388	37.252889	–79.916472	Riffle	Construction	na
0205506875	14	Roanoke River at Riverdale Road at Roanoke, VA	390	37.259222	–79.913028	Riffle	Construction	CR1
0205507720	15	Roanoke River at Carlisle Avenue at Roanoke, VA	390	37.261944	–79.913972	Pool	Construction at bench cut	na

[1] From Roberts and others (2013).

Table 2. Timing of construction activity at each geomorphology study site on the Roanoke River, Roanoke and Salem, Virginia.

[water year, October of the previous year to September 30 of the year listed. Surveys and pebble counts were conducted during the months of June–September. See table 1 for station information]

Water year	Pre-construction	Post-construction
	Monitoring sites unaffected by construction (located upstream of bench cuts or other construction activities)	Monitoring sites under construction or located downstream of bench cuts or other construction activities
2005	1–15 (all sites)	(Pre-construction monitoring)
2006	1–12	[1]13–15
2007	1–11	[2]12–15
2008	1–7	[3]8, 9–15
2009	1–7	8–15
2010	1–7	8–15
2011	1–6 (only control sites)	7–15
2012	1–6 (only control sites)	7–15 (Post-construction monitoring)

[1] For change analysis of site 15 where the bench cut changed the bank morphology, 2006 represents survey of construction measurements and 2007 represents the first year post-construction.

[2] For change analysis of site 12 where the rock wall for the trail changed bank morphology, 2007 represents survey of construction measurements and 2008 represents the first year post-construction.

[3] For change analysis of site 8 where the bench cut changed the bank morphology, 2008 represents survey of construction measurement and 2009 represents the first year post-construction. For change analysis of site 9 where the bench cut changed the bank morphology, 2008 represents survey of construction measurements and 2009 represents the first year post-construction.

construction occurred at or near the site after geomorphology monitoring was completed for 2007. In addition to supporting the evaluation of construction-related changes, application of this classification scheme supported isolation of variability induced by rainfall or flow conditions from construction activities.

Methods Used to Determine Bed-Material Sizes

Pebble counts, which are often conducted to analyze stream habitat or evaluate the success of mitigation efforts (Bunte and Abt, 2001), were conducted annually to determine the distribution of bed-material sizes. Substrate surveys were conducted using systematic sampling at evenly-spaced increments along a tape because the traditionally used Wolman (1954) pebble count, which uses heel-to-toe walk methodology, has a higher probability of operator bias against fines, cobbles, and boulders (Bunte and Abt, 2001), as well as higher variability between samples and operators (Bunte and Abt, 2001).

Pebble-count methods varied slightly for pools and riffles, with some portions of the procedures remaining constant across both site types. At all sites, measurement of bed-material size was conducted at approximately 100 evenly spaced increments of at least 1 ft across three different cross sections, for a total of 300 bed-material measurements. One tag line was strung across the river at the location of the bed-topography cross section, bed-material measurements were made along that transect, and two subsequent transects were established a distance at least 3 feet (ft) upstream and downstream of the initial topography cross section. Sampling was conducted within the bankfull channel width, which includes banks outside the active-channel wetted perimeter, because this area contains a local supply of sand, silt, or clay fine sediments and experiences channel-forming flows on a regular basis. Measurements during 2006–2012 were annotated to specify whether they represented bank or active-channel substrate. Samples in 2005 were not annotated to denote bank or active-channel substrate, and therefore represent the entire bankfull channel.

In riffles, at each sampling increment along the tag line, bed material was collected and measured using a Gravelometer size template (Federal Interagency Sediment Project US SAH–97 Gravelometer), measuring tape, ruler, or Sand-gauge© (W.F. McCullough, 1984). The size template was used for all particles between 8 and 128 mm because templates are comparable to using a square sieve and provide higher accuracy with reduced variability between operators when compared to rulers (Bunte and Abt, 2001). Particles smaller than 1 mm (including silt/clay) were visually determined by comparison with a sand gauge, and particles between 2 and 8 mm or larger than 128 mm were measured with a ruler or tape across the b-axis, which is the intermediate-length axis of a particle, to determine the appropriate sieve size class. Bed-material measurements representing bedrock were counted for accurate representation of the complete size distribution. Bed-material measurements in riffles were grouped into sieve size classes based upon the Wentworth scale (Wentworth, 1922) with half-size classes included (Bunte and Abt, 2001; table 3), and the percent composition of silt/clay, sand, gravel, cobble, boulder, and bedrock classes was computed.

Table 3. Size classes and recorded representative diameter for categorization of pebble-count data in the Roanoke River, Virginia.

[Size classes originally developed by Wentworth (1922), and half-size classes specified by Bunte and Abt (2001); Bedrock diameter of 10,000 arbitrarily set to designate bedrock]

Material	Recorded representative diameter	Diameter greater than (mm)	Diameter less than (mm)
Silt	0	0	0.062
Sand	0.062	0.062	0.13
	0.13	0.13	0.25
	0.25	0.25	0.5
	0.5	0.5	1
	1	1	2
Gravel	2	2	4
	4	4	6
	6	6	8
	8	8	11
	11	11	16
	16	16	23
	23	23	32
	32	32	45
	45	45	64
Cobble	64	64	90
	90	90	128
	128	128	180
	180	180	256
Boulder	256	256	362
	362	362	512
	512	512	1,024
	1,024	1,024	2,048
Bedrock	10,000	10,000	10,000

Pools presented a measurement challenge because they were too deep to wade and often included a large percentage of bedrock and boulders, thus precluding the use of a dredge for sampling. To overcome this challenge, the bed-material size class was estimated by probing the substrate with a rod to differentiate between the major particle types. This technique was a modification of the U.S. Environmental Protection Agency's non-wadeable stream methodologies for sampling substrate (Lazorchak and others, 2000) where the "feel" of the bottom substrate was determined by dragging a survey rod to differentiate between bedrock, boulder, cobble, gravel, sand, or fine (silt/clay) substrates. Descriptors such as "gritty," "not gritty," "gritty up to ladybug size," and "tennis ball up to basketball" were included to guide substrate assessments (Lazorchak and others, 2000). In the modified method applied in the Roanoke River study, bed-material size class was determined by stringing a tag line along the bed-topography cross section and probing the substrate with a 1-inch by 1-inch wooden rod from a canoe. The canoe operator held the tag line and moved the canoe across the section in 1-ft increments as the observer probed, using the feel, sound, and when possible, appearance of the bed material to estimate the major particle type. Only silt/clay, sand, gravel, cobble, boulder, and bedrock classes were recorded for pools, consistent with Lazorchak and others (2000).

To ensure repeatability of the method, all observers made training measurements in shallow, wadeable parts of pools where the rod method results could be verified. Duplicate pebble counts were conducted at one pool and one riffle each year from 2006 to 2012. These quality-control data provide information about the variability attributable to the sampling techniques.

Bed-Sediment Statistical Evaluations

Evaluation of long-term changes in substrate characteristics required assessment of the variability in the initial year of data (2006), annually, and over the entire study period for pre- and post-construction conditions. For this analysis, three questions were of interest. First, did the post-construction increase in the percentages of silt/clay, sand, or fines (silt/clay plus sand) in the construction reach exceed the increase observed during pre-construction? Second, if an increase in silt/clay, sand, or fines occurred, was the magnitude sufficient to affect logperch habitat? Third, were the changes localized or evident throughout the construction reach? Logperch prefer habitat with less than 25 percent silt/clay (Lahey and Angermeier, 2007); therefore, a 25-percent silt/clay threshold was set as the indicator of detrimental impact to logperch habitat.

The variability of the 2006 active-channel bed-material data (banks were omitted) was assessed by using a 2-sided F-test (Helsel and Hirsch, 2002), comparing construction riffles with control riffles, or construction pools with control pools. A Wilcoxon rank-sum test (Helsel and Hirsch, 2002) was used to compare means of these two groups as a cursory indication of differences existing at the start of the study.

The at-site year-to-year differences for each size class were calculated by subtracting the previous year's percent size class from that of the current year, as follows:

$$\Delta M_{s,y} = M_{s,y} - M_{s,y-1} \ , \qquad (1)$$

where

$\Delta M_{s,y}$ is the change in the measurement of interest for site *s* during year *y*;

$M_{s,y}$ is the measurement of interest for site *s* during year *y*; and

$M_{s,y-1}$ is the measurement of interest for site *s* during the previous year *y-1*.

These year-to-year differences are provided in percentage units because the original units are percentages, but do not represent percentage of change. For example, an annual change from 15 percent sand to 20 percent sand would have a year-to-year difference of 5 percent. Year-to-year differences were plotted to illustrate the variability and direction of change (fining or coarsening) of bed-material size distributions at each site. Annual differences in silt/clay, sand, or fines between pre-construction and post-construction periods were tested using a Wilcoxon rank-sum test. The mean difference and the range were used to illustrate the variability at pre-construction and post-construction measurements each year.

Analysis of variance (ANOVA) and Student's t-test, or Welsh test (Helsel and Hirsch, 2002) were conducted to test for differences in period of study (2006–2012) mean percentage of each bed-material size class and the year-to-year differences between pre- and post-construction. Welsh test is appropriate and was used if variances were considered not equal; otherwise, standard ANOVA was used. These tests were performed separately for pools and riffles with alpha = 0.05.

Results and Summary of Bed-Sediment Data

Pebble-count data were aggregated for each site–year combination, recorded as percent-finer-than size-class values, and stored in the USGS National Water Information System (NWIS) database. Percent-finer-than values represent the percent composition for a particular sediment size class from a cumulative distribution curve for the entire pebble count (Bunte and Abt, 2001). The diameters of the particles composing the 50th percentile (median; D_{50}), 16th percentile (D_{16}), and 84th percentile (D_{84}) were used to summarize the distribution of particle sizes for each riffle sample—D_{16} and D_{84} are commonly used summary statistics for particle size distributions because they represent one standard deviation from the mean in a normal distribution (Bunte and Abt, 2001).

Control-site D_{16} values were fairly consistent throughout the study, while some construction-site D_{16} values indicated fining over time (fig. 6). Sites 2, 3, and 6 in the control section started with medium to coarse gravel-sized D_{16} values and fluctuated between sand and coarse gravel during the study period, but the samples collected in 2012 were almost identical to those collected in 2006, with D_{16} sizes within one Wentworth half-size class of the D_{16} recorded in 2006 (fig. 6). During 2011 and 2012, D_{16} values in control riffles remained of similar magnitude and did not demonstrate changes similar to those observed at sites 7 and 8. Sites 7 and 8 in the construction reach showed variability in D_{16} values similar to that of the control sites during 2006–2010, yet the D_{16} size shifted from gravel-sized material to sand, and the percentage of sand increased during 2011 and 2012 (fig. 6). D_{16} values in the construction riffle at site 7 decreased during the first year of construction, and D_{16} values at site 8 decreased following extensive construction in the vicinity of site 8 after a high-flow year (2010), which may have mobilized sand and silt from the recent construction. Site 14 had D_{16} values of medium or fine gravel in 2006–2007, but shifted to silt/clay or sand for the rest of the study (fig. 6). Sites 10, 12, and 13 had D_{16} values equal to sand in 2006 (fig. 6) and fluctuated between medium to fine gravel, sand, and silt/clay through the study. The D_{50} and D_{84} at all riffle sites remained relatively constant throughout the study period, indicating that any fining of bed material during the study was limited to the fine tail of the distribution.

For each pool and riffle site, the percentage of each major particle size class of each bed-sediment sample was summarized for silt/clay, sand, gravel, cobble, boulder, and bedrock classes. The percent distributions for gravel-sized and larger particles were fairly consistent from year to year at all sites (fig. 7). For example, particle size distributions each year at site 6 (fig. 7*A*) were consistent, as indicated by similar heights of beige-colored bars representing gravel and brown portions of the stacked bars representing silt/clay or sand. The greatest changes in bed-sediment composition were represented by changes in the silt/clay or sand percentages, so further summarization and analysis were done only for silt/clay and sands.

Duplicate measurements were made at two sites each year to assess reproducibility of the pebble-count data. Comparisons of these duplicate measurements with the associated environmental sample demonstrate good reproducibility with relatively little variability (fig. 8).

Bed-sediment samples were composed of less than 6 percent silt/clay in all riffles during 2006 and 2007 (fig. 7*A*), which were low-flow and below-average precipitation years. During the rest of the study, bed-sediment samples from riffles in the control reach had less than 10 percent silt/clay. In the construction reach, bed-sediment samples from sites 7, 8, 10, and 13 also were less than 10 percent silt/clay during the rest of the study. Bed-sediment samples from site

14 were composed of less than 15 percent silt/clay, though the sample from site 12 was as much as 24 percent silt/clay during 2007–2012.

Bed-sediment samples in control and construction pools during 2006 were composed of less than 10 percent silt/clay except for the sample from site 11 which was 12 percent silt/clay (fig. 7*B*). During 2007–2012, the percentage of silt/clay in control pools ranged from 5 percent to 21 percent (but was usually less than 16 percent), and in construction pools, silt/clay composition ranged from 4 percent to almost 25 percent.

In 2006, bed-sediment samples from riffles were equal to or less than 10 percent sand in the control reach and at sites 7, 8, and 14 in the construction reach (fig. 7*A*). Generally, bed-sediment composition in riffles was less than 15 percent sand at all sites throughout the rest of thestudy. The percentage of sand in pools during 2006 ranged from 10.6 percent to 27 percent in the control reach and from 22 to 28 percent in the construction reach (fig. 7*B*). Sand in pools in the control reach was between 15 and 27 percent during the rest of the study except for during 2010 which was the highest flow year, where samples from all control pools were less than 13 percent sand. In the construction reach, samples from site 11 in 2009 and site 9 in 2010 were less than 6 percent sand. Throughout the rest of the study, samples from all other construction pools ranged from 20 to 53 percent sand.

In pools, fines—the sum of silt/clay and sand—usually exceeded the 25-percent silt/clay threshold that was evaluated as an indicator of detrimental impact to logperch habitat. Only two riffle sites, site 12 and site 8, equaled or exceeded this threshold (fig. 7*A*).

Analysis of Temporal Changes in Bed-Sediment Composition

A Wilcoxon rank-sum test showed no significant difference in means or variance in the percentage of silt/clay between control and construction riffles for 2006, though a significant difference was detected in pools. This indicates that the percentage of silt/clay in construction pools was higher than that in control pools at the start of the study; however, the small sample size for both tests provides only a cursory indication of differences.

The annual difference $(\Delta M_{s,y})$ in percentages of silt/clay was less than 5 at the majority of sites during 2007, 2009, and 2012, but ranged from 0.1 to 17 during 2008, 2010, and 2011 (fig. 9). On average, the silt/clay annual differences between pre- and post-construction measurements for a given year were not statistically significant, with the exception of 2012 (table 4). In 2012, percentages of silt/clay from pre-construction measurements (only sites in the control reach) all decreased slightly from the previous year, while post-construction measurement differences ranged from –4.1 to 12.6 (fig. 9; table 4). No construction activities occurred during 2012, although construction sites may have remained a silt/clay source during high-precipitation events.

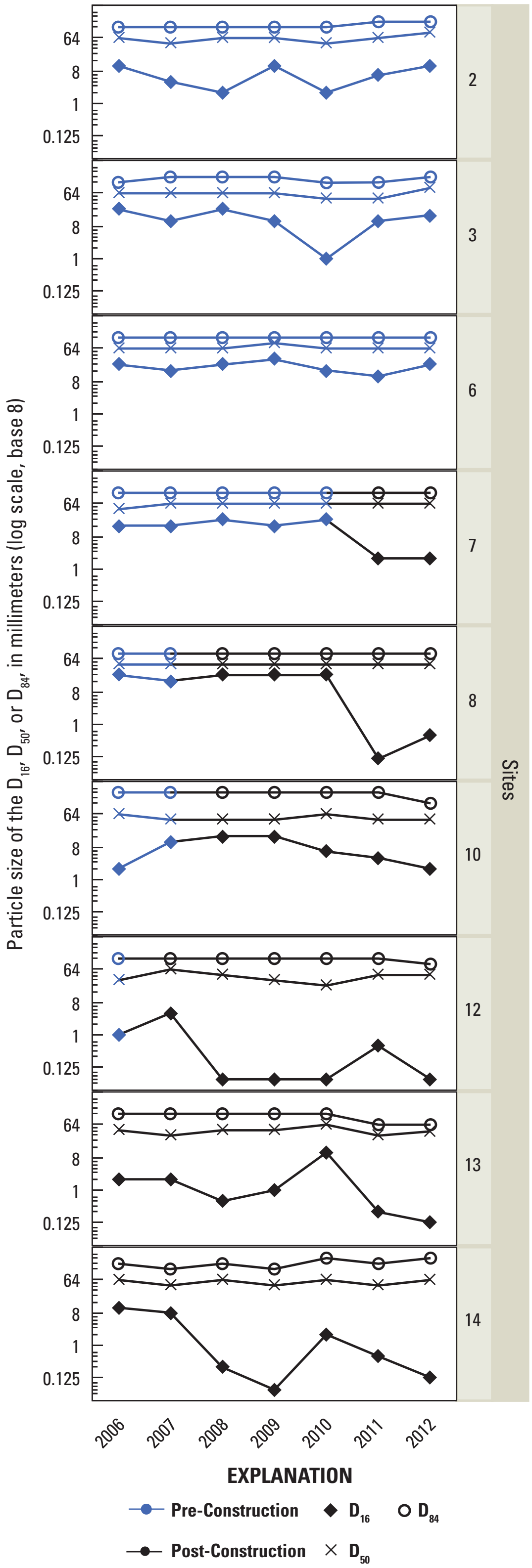


Figure 6. Particle size diameters representing the 16th (D16), 50th (D50), and 84th (D84) cumulative percentiles for each riffle pebble-count measurement at geomorphology monitoring sites, 2006–2012, Roanoke River, Virginia. [See table 1 for site information.]

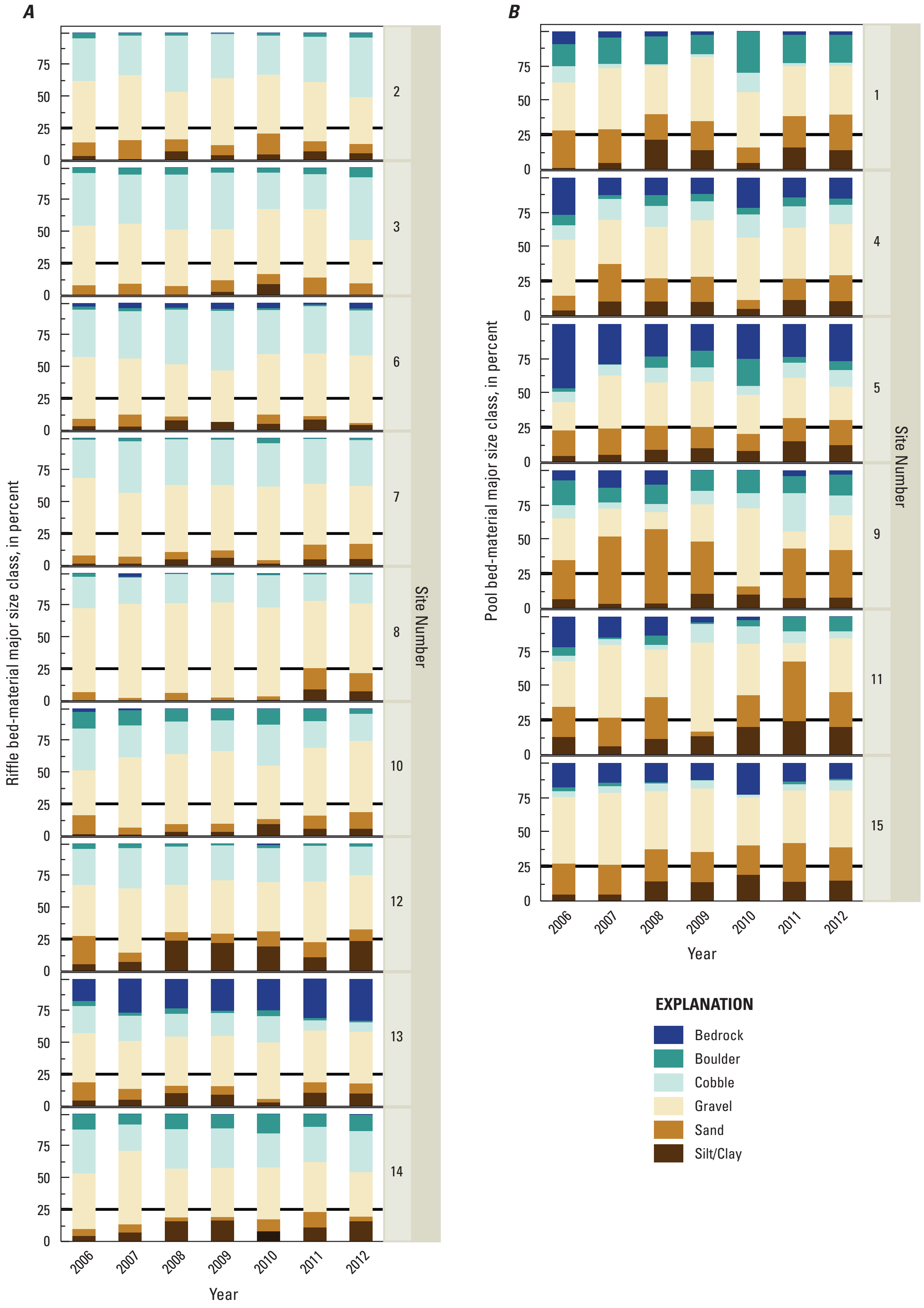


Figure 7. Bed-sediment distribution in *A*, riffles, and *B*, pools, Roanoke River, Virginia, 2006–2012. [See table 1 for site information. Line at 25 percent indicates favorable habitat conditions for logperch when substrates contain less than 25-percent silt/clay content (Lahey and Angermeier, 2007)]

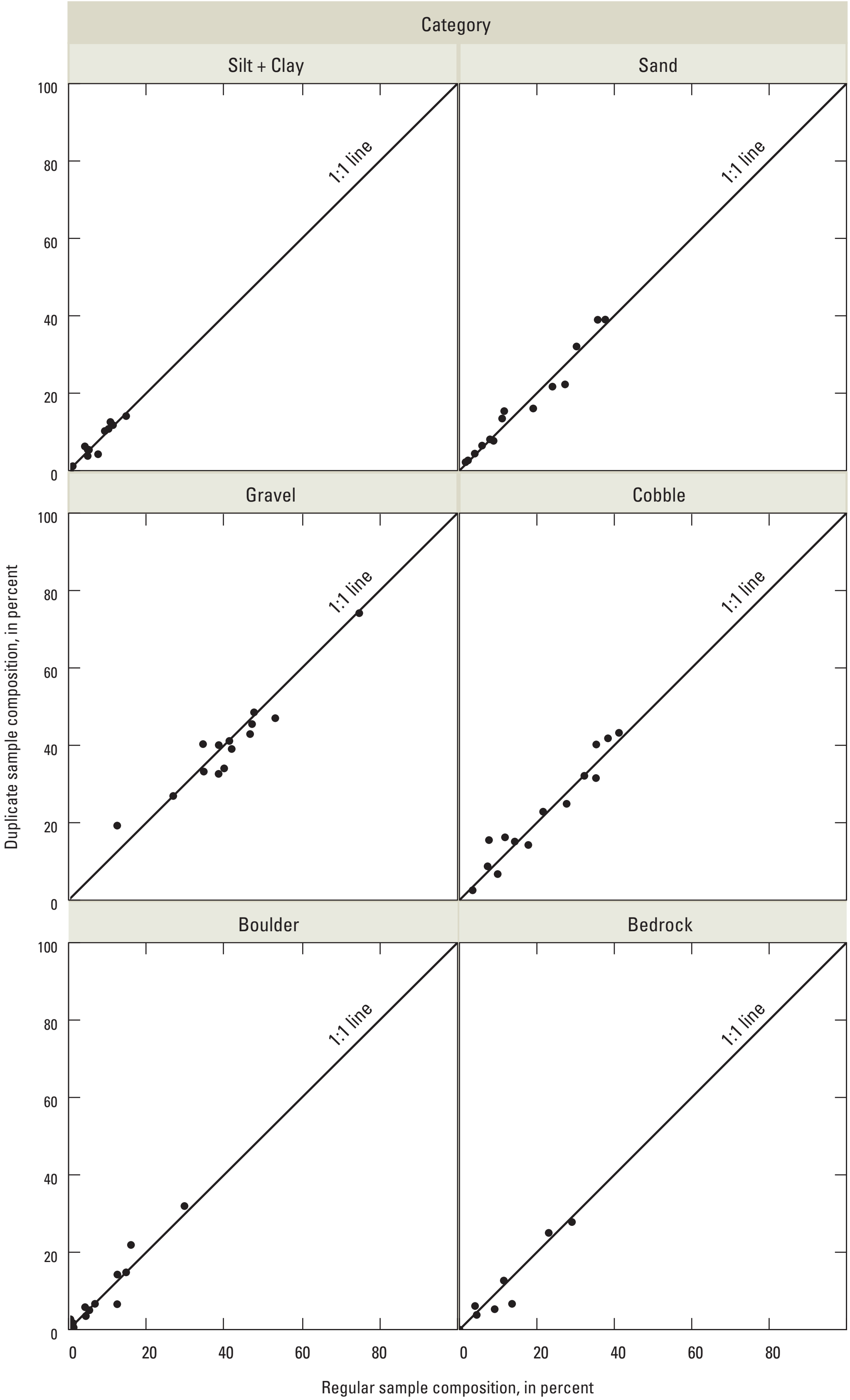


Figure 8. Regular sample percent composition and duplicate sample percent composition of pebble count data for pools and riffles in the Roanoke River, Virginia, 2006–2012.

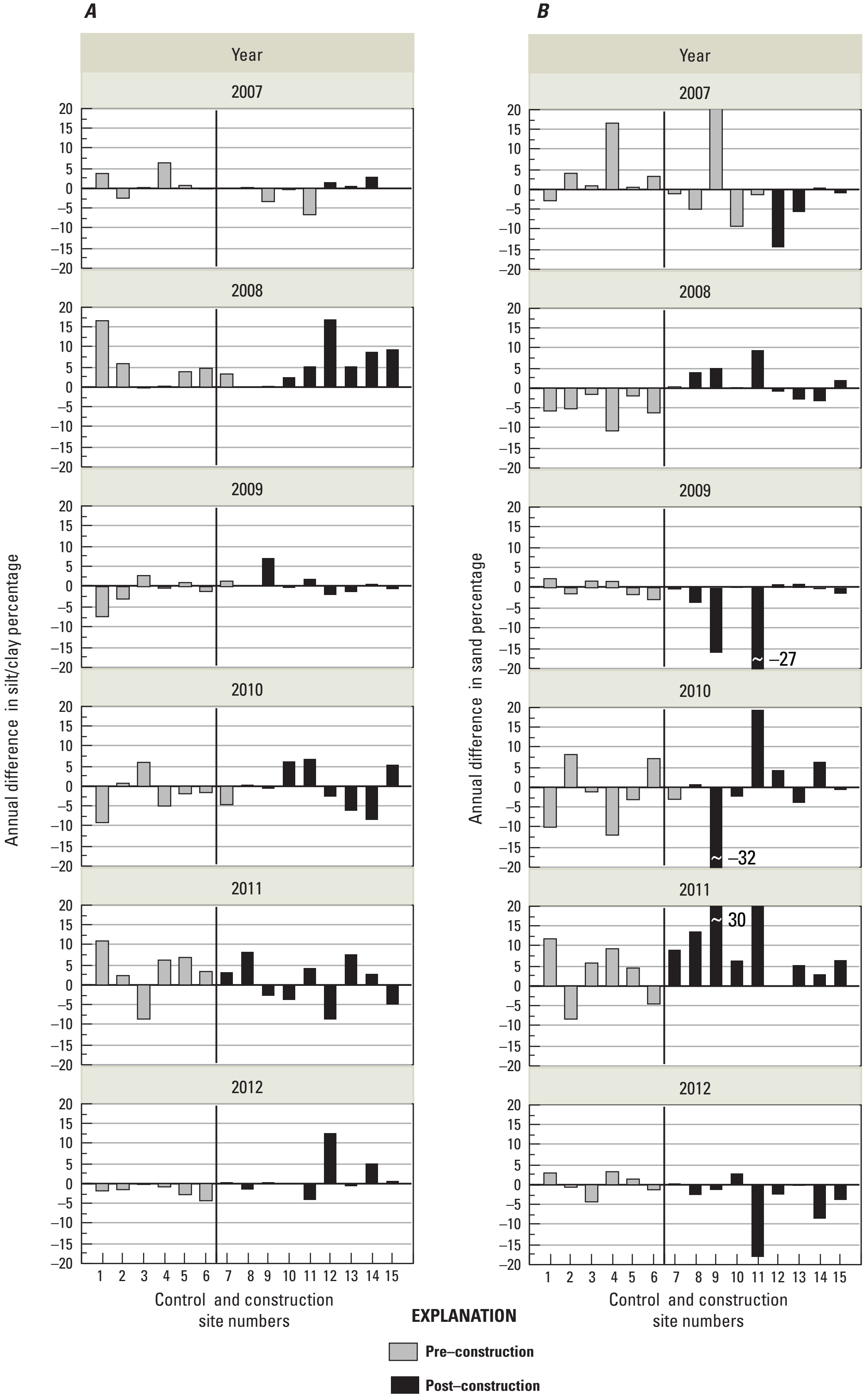


Figure 9. Annual difference in *A*, percent silt/clay or *B*, percent sand for each monitoring site on the Roanoke River, Virginia, 2006–2012. [See table 1 for site information. Vertical line designates boundary between control sites 1–6 and construction sites 7–15. Pools located at sites 1, 4, 5, 9, 11, and 15.]

Table 4. Results from Wilcoxon rank-sum tests of year-to-year differences from 2006 to 2012 in silt/clay or sand percentage from pre-construction and post-construction measurements, Roanoke River, Virginia.

[Bold p-values indicate significant differences]

Year	Pre- or Post-Construction	Number of measurements	Percent Silt/Clay				Percent Sand			
			Mean difference from previous year	Minimum difference from previous year	Maximum difference from previous year	Wilcoxon p-value	Mean difference from previous year	Minimum difference from previous year	Maximum difference from previous year	Wilcoxon p-value
2007	Post	4	1.3	0.1	2.9	0.215	–5.2	–14.5	0.5	0.170
2007	Pre	11	–0.1	–6.6	6.4		2.4	–9.2	20.4	
2008	Post	8	6.0	0.0	16.9	0.524	1.7	–3.2	9.5	**0.024**
2008	Pre	7	4.9	–0.2	16.6		–4.4	–10.7	0.3	
2009	Post	8	0.7	–2.1	7.0	0.685	–5.7	–26.7	1.0	0.272
2009	Pre	7	–1.0	–7.4	2.7		–0.1	–2.9	2.3	
2010	Post	8	0.2	–8.4	6.8	0.444	–1.0	–32.0	19.4	0.603
2010	Pre	7	–2.2	–9.1	6.0		–2.0	–12.0	8.2	
2011	Post	9	0.7	–8.6	8.3	0.444	10.4	0.0	30.0	0.263
2011	Pre	6	3.6	–8.5	11.0		3.1	–8.3	11.8	
2012	Post	9	1.4	–4.1	12.6	**0.029**	–3.8	–18.1	2.8	0.141
2012	Pre	6	–1.9	–4.3	–0.2		0.2	–4.3	3.3	

[1] Data for 2007 represent differences in silt/clay or sand from 2006 measurements.

The only year with statistically significant mean annual difference in percentages of sand between the pre-construction and post-construction measurements was 2008 (table 4). Pre-construction annual differences of sand slightly increased at one site and decreased at the rest by a maximum of –10.7, while post-construction annual differences ranged from –3.2 to 9.5 with no consistent pattern of increase or decrease during 2008 (fig. 9).

Very few significant differences between pre- and post-construction annual change measurements were found with Wilcoxon rank-sum tests (table 4); therefore, significant differences over the entire study period were not expected. The ANOVA comparing annual differences $(\Delta M_{s,y})$ in percentages of silt/clay or percentages of sand at each site during 2006–2012 showed no significant difference for pre- and post-construction measurements (table 5). These results indicate that throughout the study period, the mean amount of change in silt/clay or sand detected with pre-construction measurements was not different from post-construction measurements.

Notably, the variability of sand in pools and silt/clay in riffles was greater in post-construction measurements than in pre-construction measurements (fig. 10). A two-sided F-test indicated that differences in variance were statistically significant in post-construction measurements of sand in pools ($p = 0.0008$) and silt/clay in riffles ($p = 0.0015$). The greatest variability of sand in pools is derived from annual change measurements at sites 9 and 11 (fig. 10) during 2009, 2010, and 2011, from subsequent years of scour and deposition after construction and high-flow events. Geomorphological field data collection indicated that sediment in the pools at sites 9 and 11 accumulated throughout much of the channel cross section but developed bar formations on one bank opposite of the thalweg. These bar formations were under flowing water at mean low water, which may reflect the predominance of sand deposits. The greatest variability in riffles was derived from annual change measurements at sites 12, 13, and 14 (fig. 10) and appeared to result from re-working of gravel bars and roughness from vegetation as side-channels developed after construction. Typically the areas with silt deposits had standing water or were dry during mean low water and likely frequently experienced wet and dry periods. Silt deposition may have occurred as high flows receded when the channel margin roughness from a gravel bar, boulder, large bedrock outcrop, or vegetation would reduce water velocity and promote silt deposition.

In the case of sand in pools and silt/clay in riffles it appears that somewhat greater change occurred post-construction; however, variation of this magnitude does not appear to be detrimental to the Roanoke logperch habitat. The ANOVA for means of measured percent silt/clay or percent sand from 2006 through 2012 indicated that post-construction measurements had significantly higher means than pre-construction measurements (table 5), but did not exceed the 25-percent threshold for logperch habitat health in riffles. In riffles, the pre- and post-construction means of silt/clay in bed-material samples were 3.5 percent and 9.2 percent, respectively. In pools, pre- and post-construction means of silt/clay in bed-material samples were 9.3 percent and 12.7 percent,

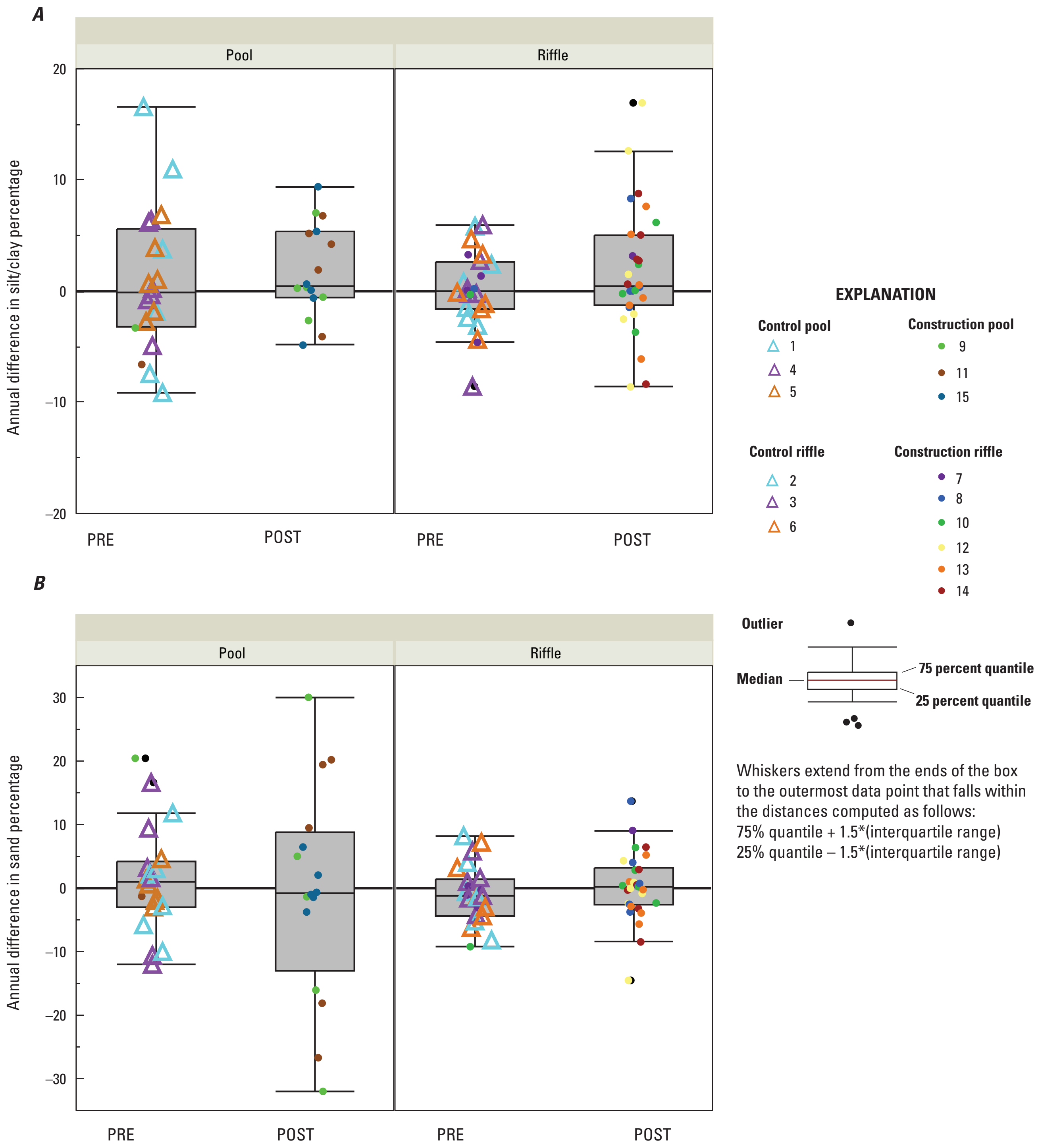


Figure 10. Range and distribution of annual differences in *A*, silt/clay or *B*, sand percentages in riffles and pools in the Roanoke River, Virginia, 2006–2012. [See table 1 for site information. Points represent measurements for a given year of the study for each site.]

Table 5. Pre- and post-construction means and standard deviations of silt/clay or sand measurement data and year-to-year differences from 2006 to 2012 in the Roanoke River, Virginia, and probability values for ANOVA and Welsh tests.

[ANOVA, analysis of variance; percent composition, population of measurements of percent silt/clay or percent sand from each year's bed-sediment pebble counts for each site; year-to-year difference, population of measurements calculated by subtracting the previous year's percent size class from the current year for each site. Bold values indicate statistically significant differences between pre- and post-construction samples]

Category	Pool or riffle	Pre- or post-Construction	Number of values	Percent composition		ANOVA or Welsh[1] test	Year-to-year difference[2]		ANOVA
				Mean	Standard deviation	p-value	Mean	Standard deviation	p-value
Silt/Clay	Pool	Post	17	12.7	5.9	**0.0484**	1.7	1.2	0.5480
		Pre	25	9.3	4.8		0.7	1.0	
Silt/Clay	Riffle	Post	32	9.2	6.5	**[1]0.00005**	1.6	0.8	0.1834
		Pre	31	3.5	2.8		0.1	0.8	
Sand	Pool	Post	17	26.7	12.2	**0.0394**	–0.5	2.9	0.6844
		Pre	25	20.1	8.1		1.0	2.4	
Sand	Riffle	Post	32	8.0	3.9	0.9241	0.3	0.8	0.3756
		Pre	31	7.9	4.7		–0.8	0.8	

[1] Welsh test is appropriate and was used if variances were considered not equal; otherwise, standard ANOVA was used.

[2] Year-to-year differences are not equivalent to percent differences, and because sediment data are presented in percent units to begin with, an example may be useful. An annual change from 15 percent sand to 20 percent sand would have a year-to-year difference equal to 5, as does annual change from 20 percent sand to 25 percent sand. However, the percent difference in each case would be 33 and 25 percent, respectively.

respectively, though when combined with sand, all pools exceeded the 25-percent fines threshold for logperch habitat quality at some point during the study. While this observation has statistical validity and may indicate a slight increase in the fines at construction sites, ultimately the question remains as to whether any increases may have been detrimental to logperch habitat. Total fines percentages greater than 25 percent throughout pools in the study area may negatively affect young-of-year, or age-0 fish. Other research has noted that the higher fine-sediment composition in the Roanoke River reduces the viability of pools as logperch habitat relative to pools in other rivers throughout the logperch geographic range (Lahey and Angermeier, 2007). In considering the total effect that the RRFRP may have had on logperch habitat, temporal analysis of annual change in silt/clay or sand showed pre- and post-construction measurements remaining fairly consistent, with minimal difference in the magnitude of change observed (table 5; fig. 10).

Cross-Section Survey Methods

Geomorphology monitoring sites were designed to facilitate repeated measurements at the same cross section over time. Local benchmarks were installed at each monitoring site to provide horizontal and vertical control. At a minimum, each site had two benchmarks (BM) and two transect control marks (TC) that were usually pipe or steel t-shaped property markers. TCs were situated along the cross section on each bank of the river to ensure consistent alignment of cross sections each year, whereas BMs used to geo reference the cross section may or may not be located in line with the cross section. It was critical that benchmarks have open sky view without obstructions because in January 2006 survey-grade Global Positioning System (GPS) static surveys of all benchmarks were conducted to establish control to the nearest centimeter. An elevation control network was established using both National Geodetic Survey (NGS) benchmarks and City of Roanoke survey markers (Lumsden Associates, P.C., 1992). Baselines from each of the NGS and City of Roanoke survey control marks were surveyed with a GPS and the network adjusted for maximum accuracy and comparability across sites. Subsequent GPS surveys used two positions from the control network to provide correction factors for determining location and elevation at one BM at each geomorphology monitoring site. Each BM and TC was located and maintained annually, and if lost or destroyed, was re-established based on existing BMs or TCs onsite. The BMs and TCs still in place at the close of the 2012 field season are listed in appendix 1.

Cross-section surveys were conducted annually during summer low-flow periods at the 15 geomorphology monitoring sites. The total station horizontal angle of the transect was verified, and a tag line was strung across the river between two TCs to guide the rod person during the survey. Floodplains, banks, channels, and water-surface elevations were surveyed, with each survey beginning on the floodplain a minimum of 50 ft from the active channel. Floodplain features were surveyed on 5–10-ft intervals. At major breaks in slope, channel banks were surveyed on 1–5-ft intervals, and the active channel was surveyed on 1–2-ft intervals to document channel changes with greater resolution. Most sites had one bank that was steeper and more vegetated than the other, which occasionally prevented complete surveying of the banks. Pools were surveyed from a canoe when depths prohibited wading. Water-surface slope within 30 ft upstream and downstream of the cross section was surveyed each year for evaluation of changes in gradient. Water-surface slope was also calculated between geomorphological monitoring riffles—from site 2 to 3, site 6 to 7, site 7 to 8, site 12 to 13, and site 13 to 14—to determine the consistency of slopes throughout the entire reach. Surveys were plotted to display cross-section elevation profiles and mapped to ensure horizontal angle alignment across years (appendix 2). Cross-section surveys and slopes were used to classify sites into geomorphological categories (Rosgen, 1994) for general interpretation and regional context.

Site-specific mean water-surface level (WSL) was calculated for one bank at each site with data from 2005 to 2012 to provide a reference for depth calculations from mean low WSL at each site. The intersection of the mean low WSL and channel elevations on both banks was used as a reference point to calculate width for each year, making it possible to calculate base-flow cross-sectional area as well. These standardized depth, width, and area measurements were then used to evaluate changes resulting from aggradation or degradation of the bed or widening or narrowing of the channel.

Channel topographic surveys also were evaluated in the context of bankfull cross-sectional area, width, and mean depth. The 2-year flood recurrence interval (0.5 exceedance probability) has been regarded as the dominant discharge which determines cross-sectional capacity (Wolman and Leopold, 1957) or that performs the most work in terms of sediment transport (Wolman and Miller, 1960). Knighton (1998) summarized the dominant discharge concept as the condition in which river channels are adjusted to a flow which just fills the available bankfull cross section, so that it is generally regarded as the channel-forming flow. Bankfull channel dimensions were calculated by using the survey data and streamflow statistics from the Roanoke River at Roanoke, Virginia, streamgage, which is just downstream of geomorphology monitoring site 11 (fig. 1). The 2-year (0.5 exceedance probability) flood at that streamgage is 8,406 ft^3/s (Austin and others, 2011), which occurs at a stage of 9.17 ft. During the survey conducted on August 18, 2005, at site 11, the surveyed WSL was 908.10 ft above NAVD 88, coincidentally equal to the mean low WSL surveyed across all years of the study, and the stage was 0.84 ft above mean low WSL. Using the difference between the observed stage of 0.84 ft at mean low WSL and the bankfull stage of 9.17 ft, it was determined that the bankfull elevation occurred at approximately 8.3 ft above mean low WSL at site 11.

This bankfull elevation factor of 8.3 ft was added to the mean low WSL for each site to estimate bankfull elevation. Resulting elevations were graphically evaluated with cross-section survey data to determine if the bankfull elevations reflected actual topographic indicators of bankfull stage. Minor adjustments were made at a few sites, but the estimated bankfull elevations generally were supported by topographic data. From the estimated bankfull elevations, bankfull cross-sectional area (CSA), bankfull width, and bankfull mean depth were calculated for analysis and comparison with regional curve geometry representations of streams in the non-urban Valley and Ridge Physiographic Province (Keaton and others, 2005).

No obvious bankfull features were present at site 9 prior to construction, and the estimated bankfull elevation was 9 ft below the top of the bank. It did not seem appropriate to use the top of the bank to indicate bankfull, even though functionally that was the best indicator prior to construction. To remain consistent with the other sites in the study, the estimated bankfull elevation (8.3 ft above mean low WSL) was held constant at site 9 throughout the study. After bench cuts were constructed, the new bankfull elevation approximated the WSL associated with the 2-year flood.

In cooperation with the USACE, USFWS, and the City of Roanoke, the USGS conducted additional cross-section monitoring in conjunction with the removal of a dam in Wasena Park (fig. 1). The dam removal was an additional special project taken on by the aforementioned parties, but accomplished at the same time RRFRP construction activities took place. The dam and reservoir, which had been located 650 ft upstream of site 8, were surveyed prior to removal by the USACE in April 2009. During the winter of 2008, three cross-sectional surveys were conducted, along with a thalweg and WSL profile upstream of the dam spanning 4,590 ft to the MEMORIAL monitoring station using differential GPS (fig. 1). One cross section 130 ft downstream from the dam was surveyed by using a total station.

Cross-Section Survey Data Statistical Analysis

Cross-section elevation survey data were analyzed to assess aggradation or degradation in the active channel at each cross section. Geomorphological variables, including base-flow and bankfull width, mean depth, and CSA, also were examined for discernible changes. Channel geometry metrics were evaluated in terms of inter-annual (year-to-year) percent change to normalize scales and permit comparison across sites with differing magnitudes for the metrics of interest. Sites where bench cut, training wall, or trail construction occurred were excluded from analysis for the initial year following construction because the bank and floodplain changes were intentional and of such great magnitude that unintended changes in subsequent years could be obscured by these intentional changes; therefore, subsequent years represent a percent change from the newly established cross-section profile and indicate whether increased rates of change occurred subsequent to construction. Four monitoring sites (Sites 8, 9, 12, and 15) experienced such construction, thus requiring the initial year of construction for each site to be removed from the statistical analysis (table 2).

ANOVA and Student's t-test were conducted to test for differences (alpha = 0.05) in study period (2005–2012) means of percent change in bankfull and base-flow average depth, CSA, and width between pre- and post-construction periods.

Inter-annual percent change in channel geometry metrics was calculated for each site in a similar manner as bed-sediment annual change (eq. 1). Annual differences in bankfull and base-flow width, mean depth, and CSA between pre-construction and post-construction periods were tested by using a Wilcoxon rank-sum test. The mean difference and 95-percent confidence interval range were computed to determine if there was a greater range of variability post-construction than was observed in pre-construction measurements representing natural hydrologic variability.

A more in-depth examination of percent change for sites 8, 9, 12, and 15 with RRFRP-designed changes in bankfull channel dimensions was conducted to ascertain if further alteration of the cross section resulted after construction was complete. Bankfull width was intentionally increased when bench cuts were installed, bankfull elevation (top of the bank) was lowered, or banks were re-graded and stabilized. The annual percent changes in base-flow width at the mean low WSLs at sites 8, 9, 12, and 15 were examined before, during, and after construction to determine if base-flow widths increased or decreased at a magnitude greater than those of sites that did not have intentional re-shaping of the cross section. The before, during, and after construction base-flow mean depths calculated from the mean low WSL were evaluated to determine if any temporal patterns in aggradation or degradation were apparent.

Results from Geomorphic Cross-Section Surveys

The classification of sites from the control and construction reaches using typical geomorphological classification schemes verifies the similarity of channel form throughout the study area and lays the groundwork for comparisons of bankfull channel dimensions within the RRFRP. Water-surface slopes measured at each monitoring cross section were consistent throughout the study. Water-surface slope was a consistent ratio of 0.002, or 0.2 percent, from one geomorphological monitoring riffle to the next downstream monitoring riffle. Width-to-depth ratios ranged from 17.6 to 43.3. Sites that appeared least affected by urbanization had naturally forming gravel bars along the banks or established floodplains and greater width-to-depth ratios. Surveys of flood-prone widths (width of the cross section at the elevation equal to 2 times the maximum depth) did not always extend far enough on the land surface because of localized anthropogenic alterations to the floodplain such as buildings or railroad beds with extensive armoring. Flood-prone widths were estimated to be between 100 ft and 150 ft and would result in entrenchment ratios between 1.4 and 2.5 depending on the bankfull width of the cross section. The range of possible entrenchment ratios, describing the extent of vertical containment of the channel, presents a challenge to using the Rosgen (1994) classification system for this urban river, as it could be classified as a "B" or "C" channel based on various measurements. Given slopes of 0.002, width-to-depth ratios of 17.6 to 43.3, and the potential for entrenchment ratios greater than 2.2, along with gravel, cobble, and boulder substrates, this reach of the Roanoke River is best classified as a "C2" to a "C4"channel (Rosgen, 1994). Streams classified as C4 are slightly entrenched, meandering, gravel-dominated, riffle/pool channels with a well-developed floodplain (Rosgen, 1996), and C2 streams include boulder substrates. The Roanoke River in the study area fits the C4 description, but has a substantial amount of cobble, boulders, and bedrock in addition to the gravel, and relatively low sinuosity. Banks in this reach are often composed of sands and fine material among gravel and stabilized by vegetation, or by rip-rap and concrete when artificially enhanced.

At the start of the study in 2005, sites within the control and construction reaches had similar median values for base-flow CSA (table 6), yet ranges of base-flow CSA were wider in the construction reach than in the control reach in pools and riffles (fig. 11). Ranges of bankfull CSA were greater in the construction reach than in the control reach in riffles and pools in 2005, but the ranges of bankfull CSA remained fairly constant throughout the rest of the study.

Percent change in channel dimensions from the previous year provides a context by which to ascertain if a particular construction site experienced a greater amount of change than pre-construction sites (table 6; fig. 12). The percent change observed in bankfull CSA and width in the control reach (sites 1 through 6) was within ±5 percent, except for at site 1 in 2012, and ±10 percent for mean bankfull depth for each site. Percent change in the construction reach (sites 7 through 15) was also ±5 percent for bankfull CSA and width and ±10 percent for bankfull depth except for a few sites during a few years. During the first year of construction at sites 15 and 9, bankfull CSA increased by 30.1 percent and 4.5 percent, respectively. During the first year of construction at sites 15, 12, and 9, bankfull width increased by 88.3, 13.0, and 68.9 percent, respectively. For the same years, sites 15, 12, and 9 bankfull mean depth decreased by 31.8, 13.6, and 37.5 percent, respectively. After 2008, percent change in bankfull dimensions in control and construction sites were consistently ±5 percent for the rest of the study, with few exceptions. The annual percent change plots demonstrate variability of channel dimensions that may be due to natural hydrologic conditions, direct physical changes resulting from bench cut construction, or indirect physical changes resulting from nearby construction. The natural variability for each year represented by control sites helps establish or describe acceptable variability and identify changes in construction sites that may be of greater magnitude than would be expected for the natural hydrologic variability.

Aggradation and degradation were more apparent in the active-channel base-flow measurements than in bankfull

Table 6. Annual base-flow and bankfull channel dimensions and percent change for each geomorphic monitoring site in the Roanoke River, Roanoke and Salem, Virginia.

[Bold text indicates year of initial construction. CSA, cross sectional area; ft², square feet; ft, feet; mi², square miles; NAVD 88, North American Vertical Datum of 1988]

Site (see table 1 and fig. 1)	Year	Base-flow CSA (ft²)	Base-flow width (ft)	Base-flow mean depth (ft)	Annual percent change[1] base-flow CSA	Annual percent change[1] base-flow width	Annual percent change[1] base-flow mean depth	Bankfull elevation (ft, NAVD 88)	Bankfull CSA (ft²)	Bankfull width (ft)	Mean bankfull depth (ft)	Annual percent change[1] bankfull CSA	Annual percent change[1] bankfull width	Annual percent change[1] bankfull mean depth	Drainage area (mi²)
								Control sites							
1	2005	276.6	85.6	3.3	0	0	0	1,001.0	768.5	110.2	6.9	0	0	0	310
1	2006	301.4	84.3	3.6	8.9	–1.5	10	1,001.0	793.3	107.3	7.6	3.2	–2.7	9.5	310
1	2007	294.9	85.3	3.6	–2.1	1.2	0	1,001.0	783.6	105.0	7.6	–1.2	–2.1	0	310
1	2008	288.5	85.0	3.3	–2.2	–0.4	–9.1	1,001.0	775.0	105.3	7.2	–1.1	0.3	–4.3	310
1	2009	275.6	80.4	3.3	–4.5	–5.4	0	1,001.0	764.2	106.6	7.2	–1.4	1.2	0	310
1	2010	285.2	84.6	3.3	3.5	5.3	0	1,001.0	773.9	107.3	7.2	1.3	0.6	0	310
1	2011	275.6	84.3	3.3	–3.4	–0.4	0	1,001.0	765.3	109.6	6.9	–1.1	2.1	–4.5	310
1	2012	271.3	83.7	3.3	–1.6	–0.8	0	1,001.0	759.9	119.8	6.2	–0.7	9.3	–9.5	310
2	2005	117.3	97.4	1.3	0	0	0	1,001.6	783.6	174.5	4.6	0	0	0	310
2	2006	125.9	95.8	1.3	7.3	–1.7	0	1,001.6	781.5	182.1	4.3	–0.3	4.3	–7.1	310
2	2007	123.8	95.1	1.3	–1.7	–0.7	0	1,001.6	781.5	183.7	4.3	0	0.9	0	310
2	2008	116.3	94.2	1.3	–6.1	–1	0	1,001.6	756.7	182.4	4.3	–3.2	–0.7	0	310
2	2009	116.3	94.2	1.3	0	0	0	1,001.6	768.5	183.4	4.3	1.6	0.5	0	310
2	2010	120.6	94.2	1.3	3.7	0	0	1,001.6	767.5	181.1	4.3	–0.1	–1.3	0	310
2	2011	125.9	94.5	1.3	4.5	0.3	0	1,001.6	778.2	177.8	4.3	1.4	–1.8	0	310
2	2012	115.2	94.5	1.3	–8.5	0	0	1,001.6	765.3	171.3	4.6	–1.7	–3.7	7.7	310
3	2005	81.8	87.3	1.0	0	0	0	983.9	876.2	199.1	4.3	0	0	0	316
3	2006	92.6	90.6	1.0	13.2	3.8	0	983.9	897.7	198.2	4.6	2.5	–0.5	7.7	316
3	2007	84.0	90.6	1.0	–9.3	0	0	983.9	887.0	201.4	4.3	–1.2	1.7	–7.1	316
3	2008	81.8	90.2	1.0	–2.6	–0.4	0	983.9	884.8	201.4	4.3	–0.2	0	0	316
3	2009	84.0	89.2	1.0	2.6	–1.1	0	983.9	862.2	190.9	4.6	–2.6	–5.2	7.7	316
3	2010	90.4	90.2	1.0	7.7	1.1	0	983.9	865.4	195.2	4.6	0.4	2.2	0	316
3	2011	93.7	91.2	1.0	3.6	1.1	0	983.9	867.6	194.9	4.6	0.2	–0.2	0	316
3	2012	95.8	89.9	1.0	2.3	–1.4	0	983.9	869.7	194.2	4.6	0.2	–0.3	0	316
4	2005	287.4	99.4	3.0	0	0	0	983.9	1,300.3	150.6	8.5	0	0	0	316

Table 6. Annual base-flow and bankfull channel dimensions and percent change for each geomorphic monitoring site in the Roanoke River, Roanoke and Salem, Virginia.—Continued

[Bold text indicates year of initial construction. CSA, cross sectional area; ft^2, square feet; ft, feet; mi^2, square miles; NAVD 88, North American Vertical Datum of 1988]

Site (see table 1 and fig. 1)	Year	Base-flow CSA (ft^2)	Base-flow width (ft)	Base-flow mean depth (ft)	Annual percent change[1] base-flow CSA	Annual percent change[1] base-flow width	Annual percent change[1] base-flow mean depth	Bankfull elevation (ft, NAVD 88)	Bankfull CSA (ft^2)	Bankfull width (ft)	Mean bankfull depth (ft)	Annual percent change[1] bankfull CSA	Annual percent change[1] bankfull width	Annual percent change[1] bankfull mean depth	Drainage area (mi^2)
								Control sites—Continued							
4	2006	231.4	100.7	2.3	–19.5	1.3	–22.2	983.9	1,234.6	147.0	8.5	–5	–2.4	0	316
4	2007	221.7	98.4	2.3	–4.2	–2.3	0	983.9	1,220.6	150.9	8.2	–1.1	2.7	–3.8	316
4	2008	218.5	98.4	2.3	–1.5	0	0	983.9	1,213.1	149.3	8.2	–0.6	–1.1	0	316
4	2009	213.1	97.8	2.3	–2.5	–0.7	0	983.9	1,220.6	150.6	8.2	0.6	0.9	0	316
4	2010	256.2	98.8	2.6	20.2	1	14.3	983.9	1,246.5	145.7	8.5	2.1	–3.3	4	316
4	2011	253.0	98.8	2.6	–1.3	0	0	983.9	1,257.2	150.6	8.2	0.9	3.4	–3.8	316
4	2012	266.9	94.2	3.0	5.5	–4.7	12.5	983.9	1,233.5	147.3	8.5	–1.9	–2.2	4	316
5	2005	186.2	70.5	2.6	0	0	0	975.7	861.1	97.1	8.9	0	0	0	317
5	2006	186.2	67.3	2.6	0	–4.7	0	975.7	856.8	97.8	8.9	–0.5	0.7	0	317
5	2007	167.9	69.6	2.3	–9.8	3.4	–12.5	975.7	836.4	96.1	8.9	–2.4	–1.7	0	317
5	2008	160.4	69.6	2.3	–4.5	0	0	975.7	831.0	97.8	8.5	–0.6	1.7	–3.7	317
5	2009	160.4	68.6	2.3	0	–1.4	0	975.7	831.0	96.5	8.5	0	–1.3	0	317
5	2010	183.0	69.9	2.6	14.1	1.9	14.3	975.7	857.9	97.4	8.9	3.2	1	3.8	317
5	2011	184.1	70.5	2.6	0.6	0.9	0	975.7	859.0	96.1	8.9	0.1	–1.3	0	317
5	2012	187.3	70.5	2.6	1.8	0	0	975.7	862.2	95.8	8.9	0.4	–0.3	0	317
6	2005	150.7	100.1	1.6	0	0	0	964.6	965.5	127.6	7.6	0	0	0	351
6	2006	135.6	100.4	1.3	–10	0.3	–20	964.6	949.4	126.0	7.6	–1.7	–1.3	0	351
6	2007	131.3	98.4	1.3	–3.2	–2	0	964.6	940.8	124.7	7.6	–0.9	–1	0	351
6	2008	122.7	94.2	1.3	–6.6	–4.3	0	964.6	900.9	127.6	6.9	–4.2	2.4	–8.7	351
6	2009	134.6	98.8	1.3	9.6	4.9	0	964.6	942.9	131.2	7.2	4.7	2.8	4.8	351
6	2010	138.9	98.1	1.3	3.2	–0.7	0	964.6	950.5	129.6	7.2	0.8	–1.3	0	351
6	2011	125.9	93.2	1.3	–9.3	–5	0	964.6	907.4	126.3	7.2	–4.5	–2.5	0	351
6	2012	130.2	97.1	1.3	3.4	4.2	0	964.6	941.8	128.9	7.2	3.8	2.1	0	351

Table 6. Annual base-flow and bankfull channel dimensions and percent change for each geomorphic monitoring site in the Roanoke River, Roanoke and Salem, Virginia.—Continued

[Bold text indicates year of initial construction. CSA, cross sectional area; ft^2, square feet; ft, feet; mi^2, square miles; NAVD 88, North American Vertical Datum of 1988]

Site (see table 1 and fig. 1)	Year	Base-flow CSA (ft^2)	Base-flow width (ft)	Base-flow mean depth (ft)	Annual percent change[1] base-flow CSA	Annual percent change[1] base-flow width	Annual percent change[1] base-flow mean depth	Bankfull elevation (ft, NAVD 88)	Bankfull CSA (ft^2)	Bankfull width (ft)	Mean bankfull depth (ft)	Annual percent change[1] bankfull CSA	Annual percent change[1] bankfull width	Annual percent change[1] bankfull mean depth	Drainage area (mi^2)
Construction sites															
7	2005	106.6	75.1	1.3	0	0	0	944.9	1,181.9	167.3	7.2	0	0	0	371
7	2006	99.0	70.9	1.3	–7.1	–5.7	0	944.9	1,153.9	162.4	7.2	–2.4	–2.9	0	371
7	2007	95.8	71.5	1.3	–3.3	0.9	0	944.9	1,150.7	163.1	7.2	–0.3	0.4	0	371
7	2008	93.7	70.5	1.3	–2.2	–1.4	0	944.9	1,146.4	157.5	7.2	–0.4	–3.4	0	371
7	2009	93.7	70.2	1.3	0	–0.5	0	944.9	1,150.7	166.0	6.9	0.4	5.4	–4.5	371
7	2010	107.6	74.5	1.3	14.9	6.1	0	944.9	1,163.6	162.7	7.2	1.1	–2	4.8	371
7	2011	109.8	71.5	1.6	2	–4	25	944.9	1,155.0	153.2	7.6	–0.7	–5.8	4.5	371
7	2012	108.7	73.8	1.3	–1	3.2	–20	944.9	1,167.9	162.7	7.2	1.1	6.2	–4.3	371
8	2005	71.0	75.1	1.0	0	0	0	932.4	988.1	145.0	6.9	0	0	0	374
8	2006	64.6	73.8	1.0	–9.1	–1.7	0	932.4	977.4	148.3	6.6	–1.1	2.3	–4.8	374
8	2007	88.3	88.3	1.0	36.7	19.6	0	932.4	1,063.5	165.0	6.6	8.8	11.3	0	374
8	2008	59.2	78.1	0.7	–32.9	–11.5	–33.3	932.4	1,017.2	165.4	6.2	–4.4	0.2	–5	374
8	2009	61.4	82.0	0.7	3.6	5	0	932.4	1,029.0	164.4	6.2	1.2	–0.6	0	374
8	2010	88.3	88.3	1.0	43.9	7.6	50	932.4	1,063.5	165.0	6.6	3.3	0.4	5.3	374
8	2011	84.0	87.6	1.0	–4.9	–0.7	0	932.4	1,044.1	161.1	6.6	–1.8	–2.4	0	374
8	2012	85.0	89.9	1.0	1.3	2.6	0	932.4	1,055.9	164.7	6.6	1.1	2.2	0	374
9	2005	88.3	57.1	1.6	0	0	0	928.9	925.9	95.3	9.7	0	0	0	375
9	2006	77.5	50.2	1.6	–12.2	–12.1	0	928.9	902.4	95.3	9.5	–2.5	0	–2.5	375
9	2007	110.9	59.4	2.0	43.1	18.3	20	928.9	954.6	95.7	10.0	5.8	0.5	5.3	375
9	2008	71.0	48.9	1.3	–35.9	–17.7	–33.3	928.9	997.8	161.7	6.2	4.5	68.9	–37.5	375
9	2009	63.5	48.6	1.3	–10.6	–0.7	0	928.9	984.9	160.4	6.2	–1.3	–0.8	0	375
9	2010	42.0	37.7	1.0	–33.9	–22.3	–25	928.9	942.9	162.1	5.9	–4.3	1	–5.3	375
9	2011	40.9	39.7	1.0	–2.6	5.2	0	928.9	951.5	158.8	5.9	0.9	–2	0	375
9	2012	45.2	42.0	1.0	10.5	5.8	0	928.9	958.0	159.8	5.9	0.7	0.6	0	375
10	2005	66.7	66.3	1.0	0	0	0	925.2	827.7	109.3	7.6	0	0	0	375

Table 6. Annual base-flow and bankfull channel dimensions and percent change for each geomorphic monitoring site in the Roanoke River, Roanoke and Salem, Virginia.—Continued

[Bold text indicates year of initial construction. CSA, cross sectional area; ft^2, square feet; ft, feet; mi^2, square miles; NAVD 88, North American Vertical Datum of 1988]

Site (see table 1 and fig. 1)	Year	Base-flow CSA (ft^2)	Base-flow width (ft)	Base-flow mean depth (ft)	Annual percent change[1] base-flow CSA	Annual percent change[1] base-flow width	Annual percent change[1] base-flow mean depth	Bankfull elevation (ft, NAVD 88)	Bankfull CSA (ft^2)	Bankfull width (ft)	Mean bankfull depth (ft)	Annual percent change[1] bankfull CSA	Annual percent change[1] bankfull width	Annual percent change[1] bankfull mean depth	Drainage area (mi^2)
								Construction sites—Continued							
10	2006	74.3	65.0	1.3	11.3	–2	33.3	925.2	833.1	109.3	7.6	0.7	0	0	375
10	2007	72.1	65.0	1.0	–2.9	0	–25	925.2	829.9	109.6	7.6	–0.4	0.3	0	375
10	2008	67.8	63.7	1.0	–6	–2	0	925.2	825.6	109.6	7.6	–0.5	0	0	375
10	2009	70.0	64.0	1.0	3.2	0.5	0	925.2	826.7	110.9	7.6	0.1	1.2	0	375
10	2010	72.1	63.7	1.0	3.1	–0.5	0	925.2	831.0	109.6	7.6	0.5	–1.2	0	375
10	2011	71.0	65.6	1.0	–1.5	3.1	0	925.2	812.7	104.0	7.9	–2.2	–5.1	4.3	375
10	2012	65.7	64.6	1.0	–7.6	–1.5	0	925.2	823.4	108.6	7.6	1.3	4.4	–4.2	375
11	2005	390.7	108.6	3.6	0	0	0	916.0	1,358.4	144.4	9.5	0	0	0	384
11	2006	414.4	109.3	3.9	6.1	0.6	9.1	916.0	1,381.0	143.0	9.5	1.7	–0.9	0	384
11	2007	373.5	109.3	3.3	–9.9	0	–16.7	916.0	1,339.0	142.4	9.5	–3	–0.5	0	384
11	2008	353.1	108.9	3.3	–5.5	–0.3	0	916.0	1,377.8	156.2	8.9	2.9	9.7	–6.9	384
11	2009	350.9	108.6	3.3	–0.6	–0.3	0	916.0	1,377.8	156.8	8.9	0	0.4	0	384
11	2010	401.5	108.9	3.6	14.4	0.3	10	916.0	1,428.4	156.2	9.2	3.7	–0.4	3.7	384
11	2011	398.3	108.9	3.6	–0.8	0	0	916.0	1,423.0	156.8	9.2	–0.4	0.4	0	384
11	2012	400.4	108.6	3.6	0.5	–0.3	0	916.0	1,423.0	155.8	9.2	0	–0.6	0	384
12	2005	181.9	111.6	1.6	0	0	0	909.8	1,752.4	250.7	6.9	0	0	0	384
12	2006	183.0	109.6	1.6	0.6	–1.8	0	909.8	1,694.2	238.8	7.2	–3.3	–4.7	4.8	384
12	2007	173.3	109.3	1.6	–5.3	–0.3	0	909.8	1,720.1	270.0	6.2	1.5	13	–13.6	384
12	2008	179.8	107.0	1.6	3.7	–2.1	0	909.8	1,709.3	252.0	6.9	–0.6	–6.7	10.5	384
12	2009	174.4	107.0	1.6	–3	0	0	909.8	1,717.9	253.0	6.9	0.5	0.4	0	384
12	2010	174.4	107.6	1.6	0	0.6	0	909.8	1,714.7	252.3	6.9	–0.2	–0.3	0	384
12	2011	171.2	102.7	1.6	–1.9	–4.6	0	909.8	1,684.6	249.7	6.9	–1.8	–1	0	384
12	2012	173.3	97.1	1.6	1.3	–5.4	0	909.8	1,702.9	253.0	6.9	1.1	1.3	0	384
13	2005	191.6	118.1	1.6	0	0	0	903.2	1,367.0	181.8	7.6	0	0	0	388
13	2006	208.8	116.8	1.6	9	–1.1	0	903.2	1,379.9	182.1	7.6	0.9	0.2	0	388

Table 6. Annual base-flow and bankfull channel dimensions and percent change for each geomorphic monitoring site in the Roanoke River, Roanoke and Salem, Virginia.—Continued

[Bold text indicates year of initial construction. CSA, cross sectional area; ft^2, square feet; ft, feet; mi^2, square miles; NAVD 88, North American Vertical Datum of 1988]

Site (see table 1 and fig. 1)	Year	Base-flow CSA (ft^2)	Base-flow width (ft)	Base-flow mean depth (ft)	Annual percent change[1] base-flow CSA	Annual percent change[1] base-flow width	Annual percent change[1] base-flow mean depth	Bankfull elevation (ft, NAVD 88)	Bankfull CSA (ft^2)	Bankfull width (ft)	Mean bankfull depth (ft)	Annual percent change[1] bankfull CSA	Annual percent change[1] bankfull width	Annual percent change[1] bankfull mean depth	Drainage area (mi^2)
Construction sites—Continued															
13	**2007**	203.4	117.1	1.6	–2.6	0.3	0	903.2	1,363.8	173.9	7.9	–1.2	–4.5	4.3	388
13	2008	198.1	116.8	1.6	–2.6	–0.3	0	903.2	1,357.3	174.2	7.9	–0.5	0.2	0	388
13	2009	193.8	115.8	1.6	–2.2	–0.8	0	903.2	1,347.6	173.6	7.9	–0.7	–0.4	0	388
13	2010	199.1	116.5	1.6	2.8	0.6	0	903.2	1,357.3	173.9	7.9	0.7	0.2	0	388
13	2011	195.9	117.1	1.6	–1.6	0.6	0	903.2	1,356.3	172.9	7.9	–0.1	–0.6	0	388
13	2012	199.1	117.1	1.6	1.6	0	0	903.2	1,362.7	174.2	7.9	0.5	0.8	0	388
14	2005	179.8	123.0	1.3	0	0	0	898.6	1,411.2	179.8	7.9	0	0	0	390
14	**2006**	189.4	122.1	1.6	5.4	–0.8	25	898.6	1,409.0	179.8	7.9	–0.2	0	0	390
14	**2007**	198.1	123.0	1.6	4.5	0.8	0	898.6	1,343.3	179.5	7.6	–4.7	–0.2	–4.2	390
14	2008	177.6	122.4	1.3	–10.3	–0.5	–20	898.6	1,324.0	179.5	7.6	–1.4	0	0	390
14	2009	185.1	122.7	1.6	4.2	0.3	25	898.6	1,335.8	179.1	7.6	0.9	–0.2	0	390
14	2010	184.1	123.0	1.6	–0.6	0.3	0	898.6	1,330.4	180.1	7.6	–0.4	0.5	0	390
14	2011	187.3	122.7	1.6	1.8	–0.3	0	898.6	1,335.8	180.8	7.6	0.4	0.4	0	390
14	2012	187.3	122.1	1.6	0	–0.5	0	898.6	1,330.4	180.8	7.2	–0.4	0	–4.3	390
15	2005	247.6	111.6	2.3	0	0	0	895.7	1,268.0	174.2	7.2	0	0	0	390
15	**2006**	237.9	115.5	2.0	–3.9	3.5	–14.3	895.7	1,649.0	328.1	4.9	30.1	88.3	–31.8	390
15	**2007**	232.5	116.5	2.0	–2.3	0.9	0	895.7	1,609.2	296.6	5.6	–2.4	–9.6	13.3	390
15	2008	229.3	116.5	2.0	–1.4	0	0	895.7	1,597.4	295.3	5.3	–0.7	–0.4	–5.9	390
15	2009	228.2	116.8	2.0	–0.5	0.3	0	895.7	1,602.7	296.6	5.3	0.3	0.4	0	390
15	2010	235.7	116.8	2.0	3.3	0	0	895.7	1,589.8	295.6	5.3	–0.8	–0.3	0	390
15	2011	235.7	117.1	2.0	0	0.3	0	895.7	1,509.1	296.3	5.3	–5.1	0.2	0	390
15	2012	245.4	117.5	2.0	4.1	0.3	0	895.7	1,603.8	296.3	5.6	6.3	0	6.2	390

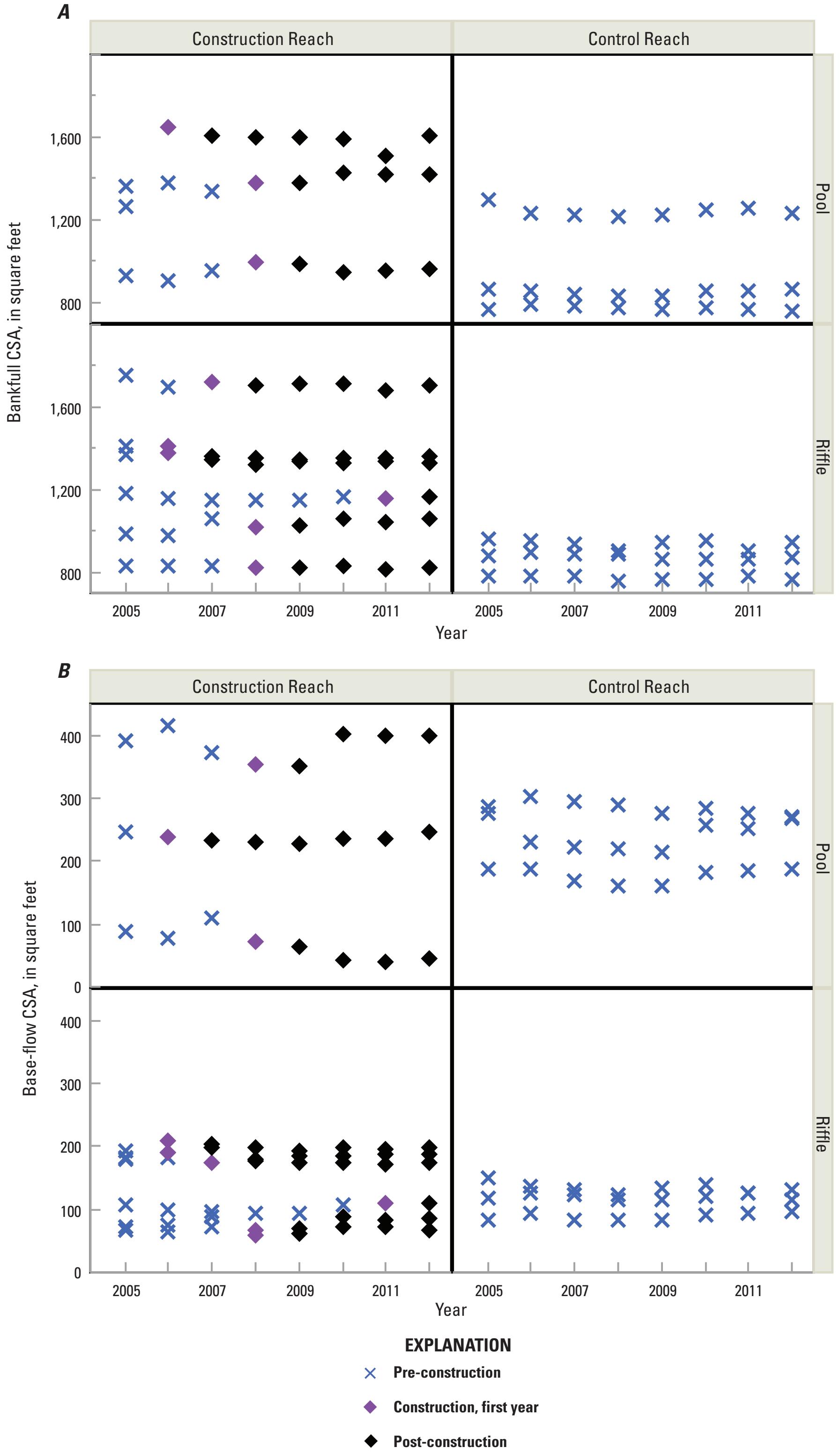


Figure 11. Annual measurements of *A*, bankfull cross-sectional area (CSA) and *B*, base-flow (CSA) in control and construction reaches in the Roanoke River, Virginia, 2005–2012. [Riffles in the construction reach are sites 7, 8, 12, 13, and 14. Riffles in the control reach are sites 2, 3, and 6. Pools in the construction reach are sites 9, 11, and 15. Pools in the control reach are sites 1, 4, and 5.]

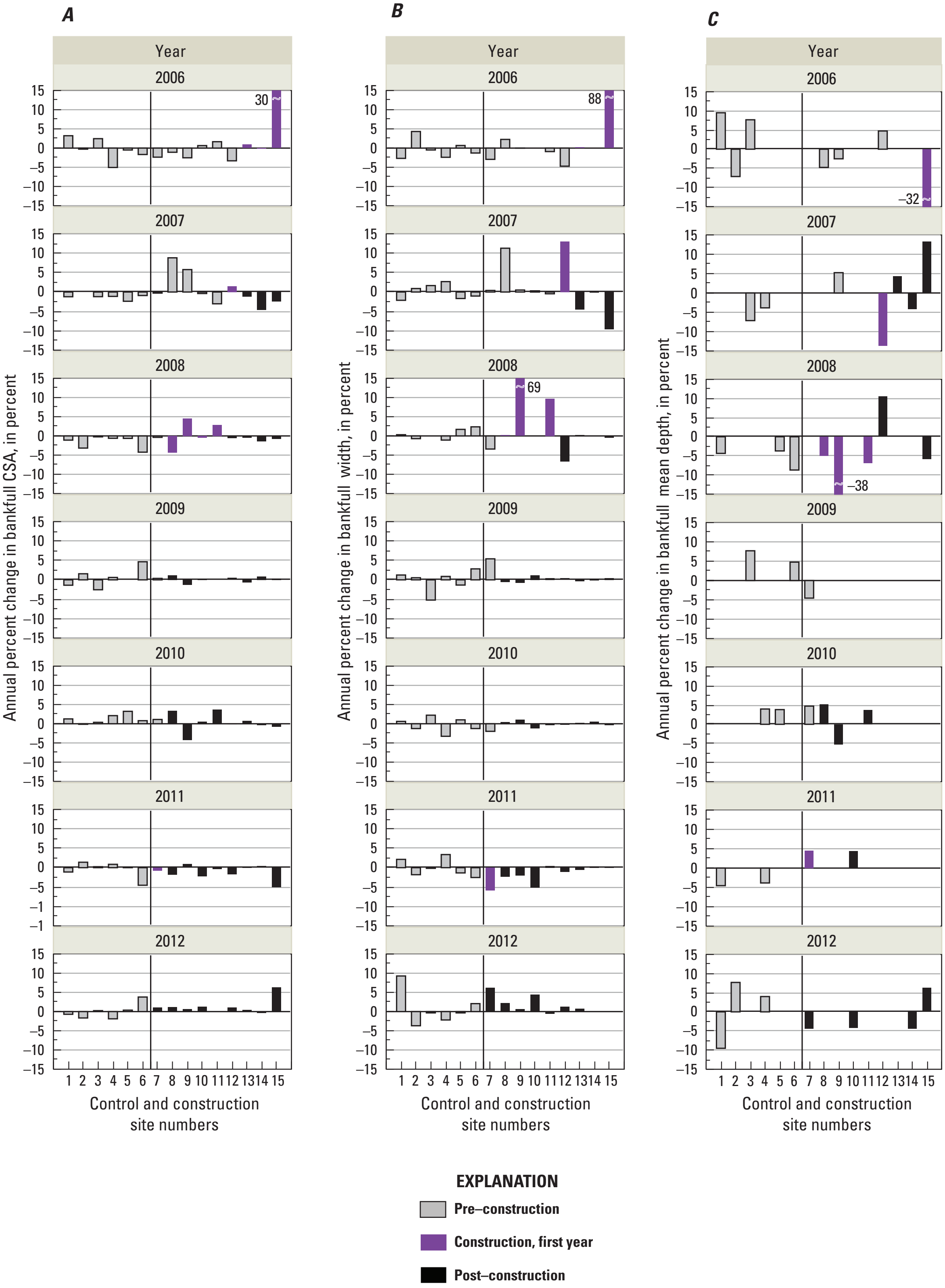


Figure 12. Annual percent change in *A*, bankfull cross-sectional area (CSA), *B*, bankfull width, and (*C*) bankfull mean depth for each site in the Roanoke River, Virginia, 2005–2012. [See table 1 for site information. Vertical line designates boundary between control sites 1–6 and construction sites 7–15. Pools located at sites 1, 4, 5, 9, 11, and 15.]

channel dimension measurements (fig. 13). Base-flow CSA followed similar patterns as bankfull CSA for most sites and years, but high-flow years 2006 and 2010 had higher percent change observed across control and construction sites. Most sites had base-flow CSA within ±10 percent from that of the previous year, with the exception of sites 8 and 9, which had base-flow CSA change greater than 30 percent in 2007, 2008, and 2010. Base-flow width was within ±10 percent at all sites except at sites 8 and 9 throughout the study (fig. 13). Base-flow mean depth percent change appears to have some of the greatest changes (fig. 13); however, these larger percentages are the result of small numbers changing relatively little (for example, a mean depth change from 1.6 to 2.0 ft equates to a 20-percent increase). Sites 8 and 9 had greater magnitudes of percent change in all base-flow dimensions (fig. 13) than did control or construction sites in 2007, 2008, and 2010. These changes are further discussed in the Changes in Channel Dimension and the Wasena Dam Removal section of this report.

Analysis of Temporal Changes in Channel Geometry

No statistically significant differences in annual variability were found for percent change in bankfull CSA, bankfull width, or bankfull mean depth for any year between pre- and post-construction values when each year was analyzed separately with the Wilcoxon rank-sum test (table 7). The initial construction years were removed from these evaluations because intentional or designed change to the cross section occurred, but the subsequent years show little evidence of long-term effect on the overall geometry of sites. A few cases were examined more closely to ascertain the effects (if any) resulting from construction activities where greater than 10-percent change was observed.

The percent changes observed (2005–2012) for bankfull mean depth, bankfull CSA, and bankfull width were of similar magnitude for pre- and post-construction channel dimensions (fig. 14). The initial year of construction reflected large changes in channel dimension and was displayed separately to distinguish between designed changes and subsequent variability. With pool and riffle habitats combined, the Student's t-test of pre- and post-construction percent-change (omitting the first year of construction for sites 8, 9, 12, and 15) indicates no significant difference in bankfull channel geometry. For each comparison of pre-construction and post-construction means for bankfull CSA, width, or depth, the Least Significant Difference (LSD) values were all negative, indicating no significant difference between groups. ANOVA results indicate no significant difference for bankfull CSA, width, or depth (table 8). Base-flow channel dimensions also show a consistent pattern to bankfull channel dimensions, and ANOVA results indicate no significant difference in pre- and post-construction base-flow CSA, width, and depth (table 8).

Change Associated with Local Bench Cuts and Dam Removal

Bench cuts were designed to increase floodplain volume through removal of material, widening of the floodplain, and lowering of the bankfull elevation. Changes in the bankfull or base-flow characteristics from bench cuts and re-shaping of banks for training walls at sites 8, 9, 12, and 15 ranged from 13.0 percent to 88.3 percent and were much greater than changes at other monitoring sites (table 6 and fig. 12). Subsequent to these intended changes, annual changes at these sites returned to magnitudes similar to those at other construction or control sites.

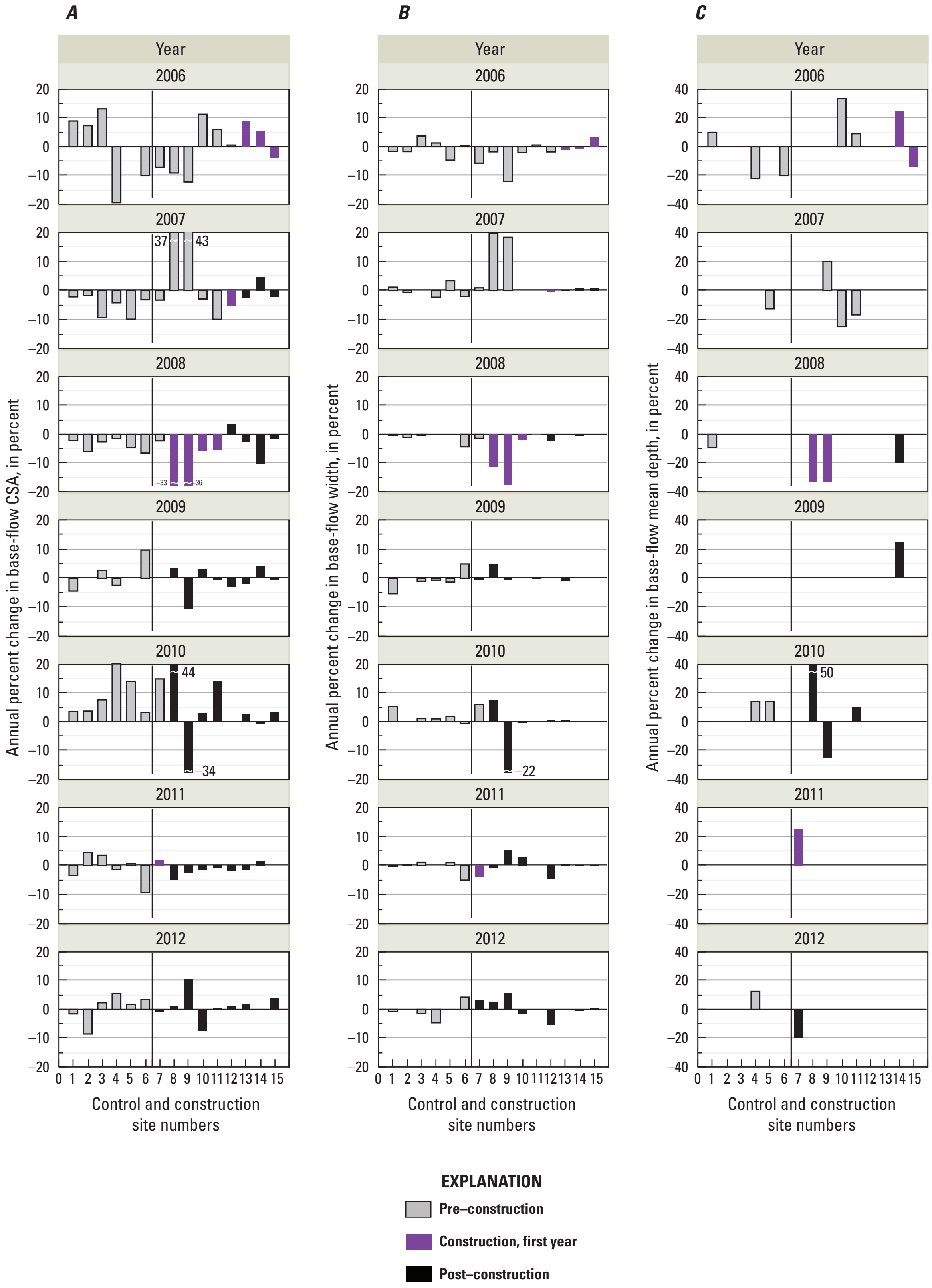


Figure 13. Annual percent change in *A*, base-flow cross-sectional area (CSA), *B*, base-flow width and *C*, base-flow mean depth for each site in the Roanoke River, Virginia, 2006–2012. [See table 1 for site information. Vertical line designates boundary between control sites 1–6 and construction sites 7–15. Pools located at sites 1, 4, 5, 9, 11, and 15.]

Table 7. Results from Wilcoxon rank-sum tests of percent change in bankfull cross-sectional area, bankfull mean depth, or bankfull width compared between pre- and post-construction measurements to assess annual variability, Roanoke River, Virginia.

[CSA, cross-sectional area; na, not applicable]

			Bankfull CSA				Bankfull mean depth				Bankfull width			
Year	Pre- or post-construction	Number of values	Mean percent change in bankfull CSA	Minimum percent change	Maximum percent change	p-value	Mean percent change bankfull depth	Minimum percent change	Maximum percent change	p-value	Mean percent change bankfull width	Minimum percent change	Maximum percent change	p-value
[1]2006[a]	Pre	12	–0.7	–5.1	3.2	na	0.6	–7.1	9.5	na	–0.7	–4.7	4.3	na
2007	Post	3	–2.3	–4.7	–1.2	0.087	4.5	–4.2	13.3	0.343	–4.8	–9.6	–0.2	0.062
2007	Pre	11	0.4	–3.0	8.8		–0.5	–7.1	5.3		1.1	–2.1	11.3	
2008	Post	4	–0.8	–1.4	–0.5	1.000	1.2	–5.9	10.5	0.471	–1.7	–6.7	0.2	0.570
2008	Pre	7	–1.5	–4.2	–0.2		–2.4	–8.7	0.0		–0.1	–3.4	2.4	
2009	Post	8	0.1	–1.3	1.2	0.908	0.0	0.0	0.0	0.563	0.1	–0.8	1.2	0.272
2009	Pre	7	0.5	–2.6	4.7		1.1	–4.6	7.7		0.6	–5.2	5.4	
2010	Post	8	0.3	–4.3	3.7	0.272	0.5	–5.3	5.3	0.396	0.0	–1.2	1.0	0.603
2010	Pre	7	1.3	–0.1	3.2		1.8	0.0	4.8		–0.6	–3.3	2.2	
2011	Post	8	–1.3	–5.1	0.9	0.333	0.5	0.0	4.4	0.088	–1.3	–5.1	0.4	0.651
2011	Pre	6	–0.5	–4.5	1.4		–1.4	–4.6	0.0		–0.1	–2.5	3.4	
2012	Post	9	1.3	–0.4	6.3	0.088	–0.7	–4.4	6.3	0.443	1.7	–0.6	6.2	0.263
2012	Pre	6	0.0	–1.9	3.8		0.4	–9.5	7.7		0.8	–3.7	9.3	

[1] 2006 was the first year of construction; therefore, three sites were under construction and were omitted from the analysis, and no sites met the "post-construction" classification during 2006.

Table 8. Results from analysis of variance (ANOVA) of percent change in bankfull or base-flow channel dimensions for pre- and post-construction measurements of the Roanoke River, Virginia, 2005–2012.

[Statistical comparisons omit year-1 of construction for four sites where construction of bench cuts significantly altered the channel geometry. CSA, cross-sectional area]

Channel dimension parameter	Pre- or post-construction	Number of values	Mean percent change	Lower 95 percent	Upper 95 percent	p-value
		Bankfull				
Annual percent change bankfull CSA	Post	45	–0.1	–0.8	0.6	0.962
	Pre	56	–0.1	–0.7	0.5	
Annual percent change bankfull width	Post	45	–0.3	–1.1	0.6	0.485
	Pre	56	0.2	–0.6	0.9	
Annual percent change bankfull depth	Post	45	0.4	–0.7	1.5	0.603
	Pre	56	0.0	0.0	0.9	
		Base flow				
Annual percent change base-flow mean depth	Post	45	1.6	–1.4	4.5	0.486
	Pre	56	0.1	–2.5	2.5	
Annual percent change base-flow CSA	Post	45	0.5	–2.3	3.2	0.783
	Pre	56	1.0	–1.3	3.2	
Annual percent change base-flow width	Post	45	–0.2	–1.5	1.1	0.630
	Pre	56	0.2	–1.0	1.4	

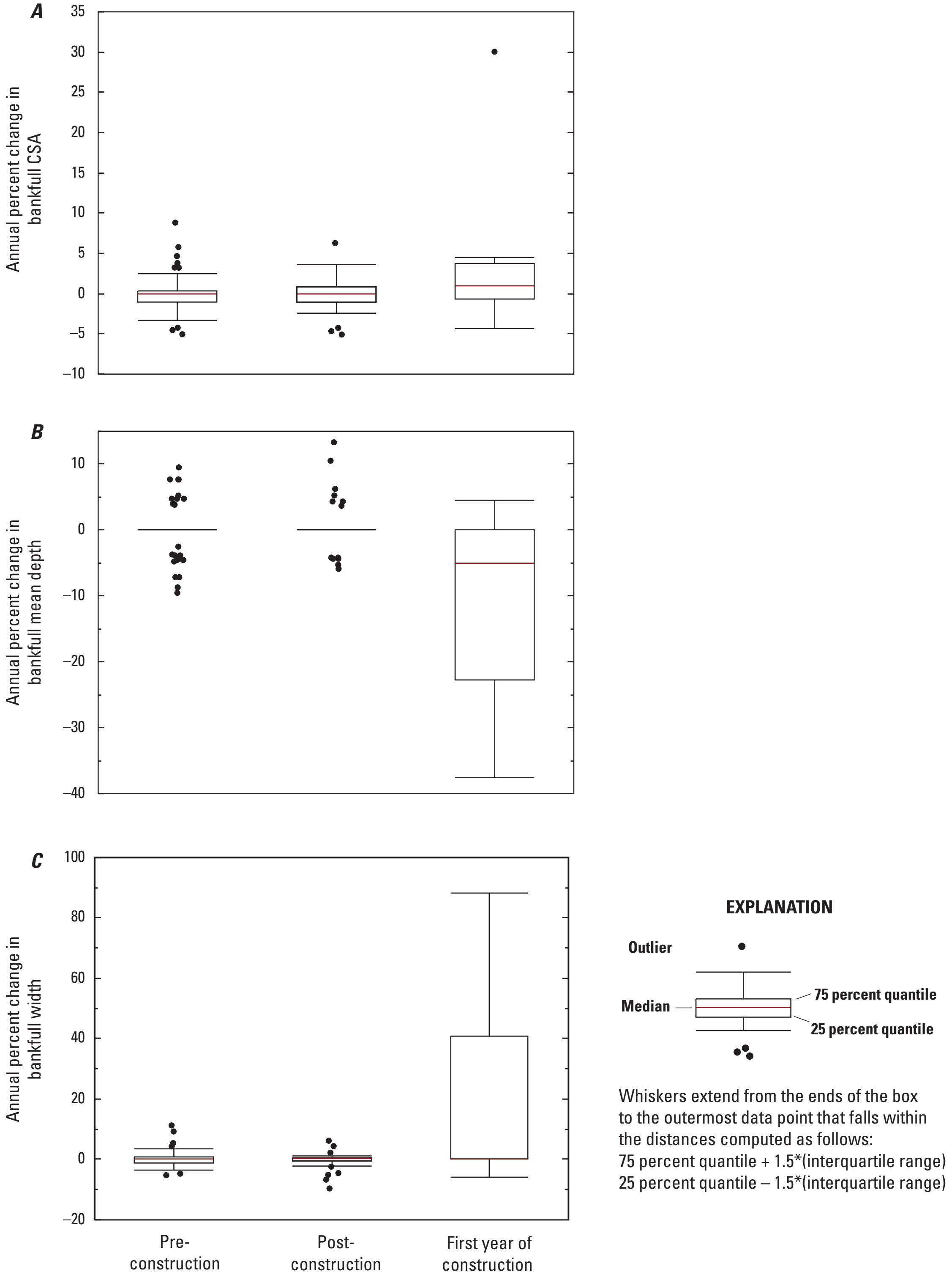


Figure 14. Annual percent changes in *A*, bankfull cross-sectional area (CSA), *B*, bankfull mean depth, and *C*, bankfull width during pre-construction, post-construction, and the first year of construction in the Roanoke River, Virginia, 2005–2012. [Bankfull mean depth percent change was zero for most records.]

At monitoring sites with riffles or pools where the RRFRP created bench cuts, the 2012 bankfull CSAs were plotted along with the previously published values for the bankfull regional curves developed by Keaton and others (2005; fig. 15). For Roanoke River drainage areas ranging from 310 mi^2 to 390 mi^2, bankfull CSAs predicted for riffles by using the regional curve regression equation range from 791.9 to 935.0 square feet (ft^2). At the end of the study in 2012, measured bankfull CSAs for all sites, regardless of riffle or pool habitat type, ranged from 759.9 to 1,702.9 ft^2 (table 6). The drainage areas of monitoring sites are slightly larger than the sites included in Keaton and others (2005), but the Roanoke data are within the 95-percent prediction interval of the regional curves (fig. 15).

Bankfull mean depth and width also were within the 95-percent prediction interval for regional curves, but a closer look was given to sites 9, 12, and 15 before and after bench cut construction. At site 12, in association with trail construction and bank grading, bankfull width increased by 13.1 percent from 2006 to 2007 (table 6). After 2008, changes in bankfull width, depth, and CSA remained within 1.8 percent. Sites 9 and 15 are pools which were slightly entrenched at the start of the study. The top of the bank elevation at site 9 was the only topographic bankfull indicator, but was located 9 ft higher than the estimated bankfull WSL. The floodplain was narrow and almost non-existent at the estimated bankfull elevation for site 15. Regardless of entrenchment, the estimated bankfull WSL was used for calculation of bankfull dimensions pre- and post-construction. As a result of bench cut construction at site 9, the floodplain elevation was lowered by approximately 9 ft, and bankfull CSA increased 4.5 percent mostly due to the bankfull width increase of 68.9 percent (table 6). The new bankfull CSA for site 9 remained similar to the CSAs of previous years, but the channel form changed from tall, mostly vertical banks to an expansive floodplain on the right bank in Wasena Park. In much the same way, channel dimension changes associated with bench cut construction from 2005 to 2006 at site 15 increased bankfull CSA by 30.1 percent as bankfull width increased by 88.3 percent (table 6). Although the resulting bankfull CSA of 1,649.0 ft^2 is much larger than the predicted bankfull CSA of 935.4 ft^2, it is within the 95-percent prediction interval. In comparison with two extremely stable upstream riffles at sites 13 and 14 with bankfull CSA ranging from 1,362.7 ft^2 to 1,330.4 ft^2, the new bankfull CSA for site 15 is reasonable. Overall, for sites 9, 12, and 15, the range of bankfull CSA values is wide, but within the 95-percent prediction intervals for the Valley and Ridge regional curves (fig. 15; Keaton and others, 2005), and is therefore a reasonable design to maximize flood conveyance within the bounds of observed conditions in natural channels in the region.

Base-flow channel dimensions for sites 12 and 15 also were examined, yet they changed only slightly from 2005 to 2012. The base-flow width at site 15 increased by 3.9 ft during construction from 2005 to 2006, then an additional 2.0 ft by 2012, indicating some bank erosion. Base-flow mean depth also decreased from 2.3 ft in 2005 to 2.0 ft for the rest of the study period. Aggradation of silt/clay or sand steadily over time may be attributed to the decrease in mean base-flow depth at site 15, but appears to be of a similar amount as control pools. Similar to other riffles in the study area, site 12 maintained a constant base-flow mean depth throughout the study period. Inter-annually, site 12 had silt/clay percentages that were greater in magnitude than other riffles monitored during the study, but this does not appear to be related to

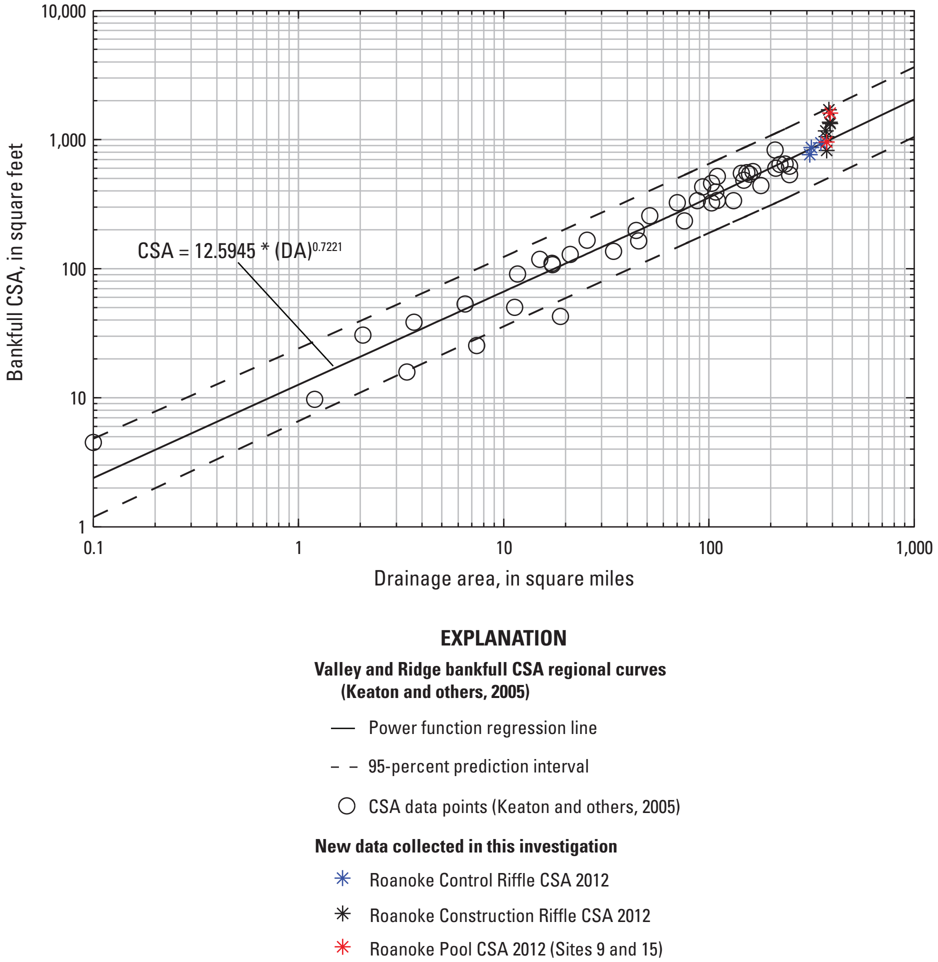


Figure 15. Bankfull cross-sectional area (CSA) in 2012 for Roanoke River riffles and pools at sites 9 and 15 including Valley and Ridge regional curve data and power curve developed in Keaton and others (2005).

RRFRP construction activities. The cross section is located across a heavily vegetated island or gravel bar on the right bank of the river and crosses another island near the left bank of the river. The local channel morphology suggests that the increased percent silt/clay is a result of the increased roughness from trees and emergent vegetation in this section which potentially traps sediment during higher flows.

Changes in Channel Dimension and the Wasena Dam Removal

Channel topography near sites 8 and 9 was potentially altered in association with the Wasena Dam removal upstream of site 8 (fig. 16). The 2008 differential GPS and total station surveys indicated the dam elevation prior to removal was 928.2 ft, with a WSL decrease of 2.7 ft on the downstream side of the dam. Over a distance of 164 ft upstream of the dam, the thalweg depth shallowed by almost 3 ft from an elevation of 922.6 to 924.9 ft and continued to an elevation of 925.5 ft at the downstream base of the dam, indicating a gradual deposition similar to that of a glide habitat at the downstream end of the pool. From the dam base to 130 ft downstream of the dam, the elevation decrease was 3.61 ft. The active-channel width of the pool and channel in the vicinity of the dam ranged from 108.9 to 147.6 ft, yet the active-channel width at site 8 was only 78.1 ft wide in 2008. These discrepancies in thalweg elevation and active-channel width in the vicinity of the Wasena Dam indicated potential for erosion and re-working of the channel bed material with the removal of the dam.

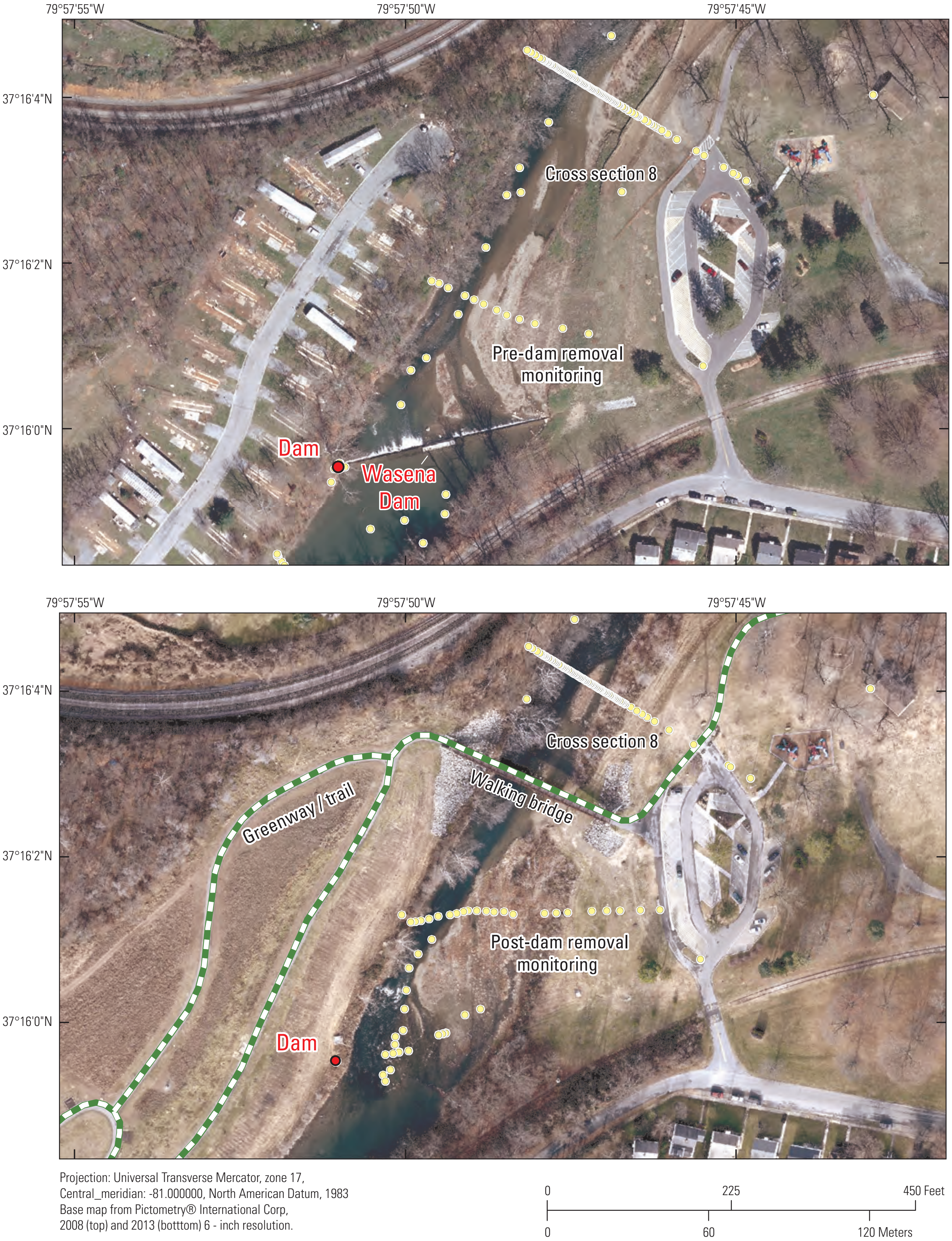
Within the reach immediately downstream of the Wasena Dam, base-flow mean depth, width, and CSA changes suggest that widening at site 8 and aggradation at site 9 followed bench cut construction and dam removal activity (fig. 17). Prior to 2009, base-flow CSA increased or decreased in accordance with natural variation in hydrology for both sites. However, after some RRFRP bench cut construction occurred in 2008 and the Wasena Dam was removed by April 2009 (table 2), a 3.3-percent increase in base-flow CSA at site 8 and a 10.6-percent decrease at site 9 was observed (fig. 17). High flows during 2010 seemed to rework the channel, resulting in an increase in width at site 8, contributing to the 44-percent increase in base-flow CSA. The change in CSA was of similar magnitude as observed during pre-construction measurements in 2007 (fig. 13). However, base-flow dimensions measured for site 9 in 2010 changed in a manner opposite those observed in 2007. Sediment deposition appears to have contributed to decreases in depth and width, resulting in a 34-percent decrease in base flow CSA at site 9 (fig. 17).

Cumulatively, in the vicinity of sites 8 and 9, there were bench cuts on both banks, removal of the Wasena dam, construction of a walking bridge over the river, and construction of a trail along the river in Wasena Park, making the amount of potential impact at sites 8 and 9 more extensive than at other areas in the RRFRP. Slight elevation variations in the dam concentrated flow from the reservoir into a channel closer to the left bank during moderate and low-flow events. Removal of the Wasena Dam allowed the river to adjust and meander throughout the downstream channel in a much more natural way than it had while the dam was present. With the dam no longer concentrating the flow to a narrow portion of the channel, remaining sediment deposits upstream or downstream of the dam and a gravel bar on the right bank of site 8 were more likely to be mobilized during floods. Following the dam removal and the high-flow year of 2010, channel adjustment resulted in widening of the riffle at site 8 and aggradation in the pool at site 9 as indicated by decreased base-flow mean depth and a greater percentage of gravel (fig. 17). While the percent change in channel dimension at site 9 indicates a departure from response to the natural variation in hydrology, it does not appear that the RRFRP bench cut activity could be cited as the sole cause of the changes observed because of the effects of dam removal.

Discussion of Geomorphology Survey Results

Comparisons of 2005–2012 pre- and post-construction bankfull or base-flow CSA, width, and mean depth indicated no significant differences when as-designed alterations in channel geometry were removed from the analysis. Roanoke River bankfull CSAs were within the range of previously published data for Valley and Ridge bankfull regional curves developed by Keaton and others (2005).

Changes to the base-flow channel dimensions, or active channel, were explored at a few sites where designed bench cuts resulted in decreased depths and increased widths. Observations for sites 8 and 9 indicated greater changes than for most other sites; however, extensive RRFRP construction and the removal of an upstream dam confound the analysis. Some readjustment and widening in the channel at site 8 has occurred, and possibly a new sediment storage location has developed in the pool at site 9. These are localized changes, although the percent fines at site 8 increased to greater than 25 percent during 2011. Site 12 had high percentages of fines most years as a result of sediment trapping by extensive vegetation along the channel edge. Site 15 appears to have adjusted to a new base-flow width and depth after construction and has accumulated more fines with time than were measured during pre-construction; however, bankfull channel dimensions at site 15 are within published ranges for regional curves and similar to nearby upstream sites.



Projection: Universal Transverse Mercator, zone 17,
Central_meridian: -81.000000, North American Datum, 1983
Base map from Pictometry® International Corp,
2008 (top) and 2013 (botttom) 6 - inch resolution.

Figure 16. Wasena Dam and downstream river channel before removal in 2008 and after removal of the dam in 2013, Roanoke, Virginia.

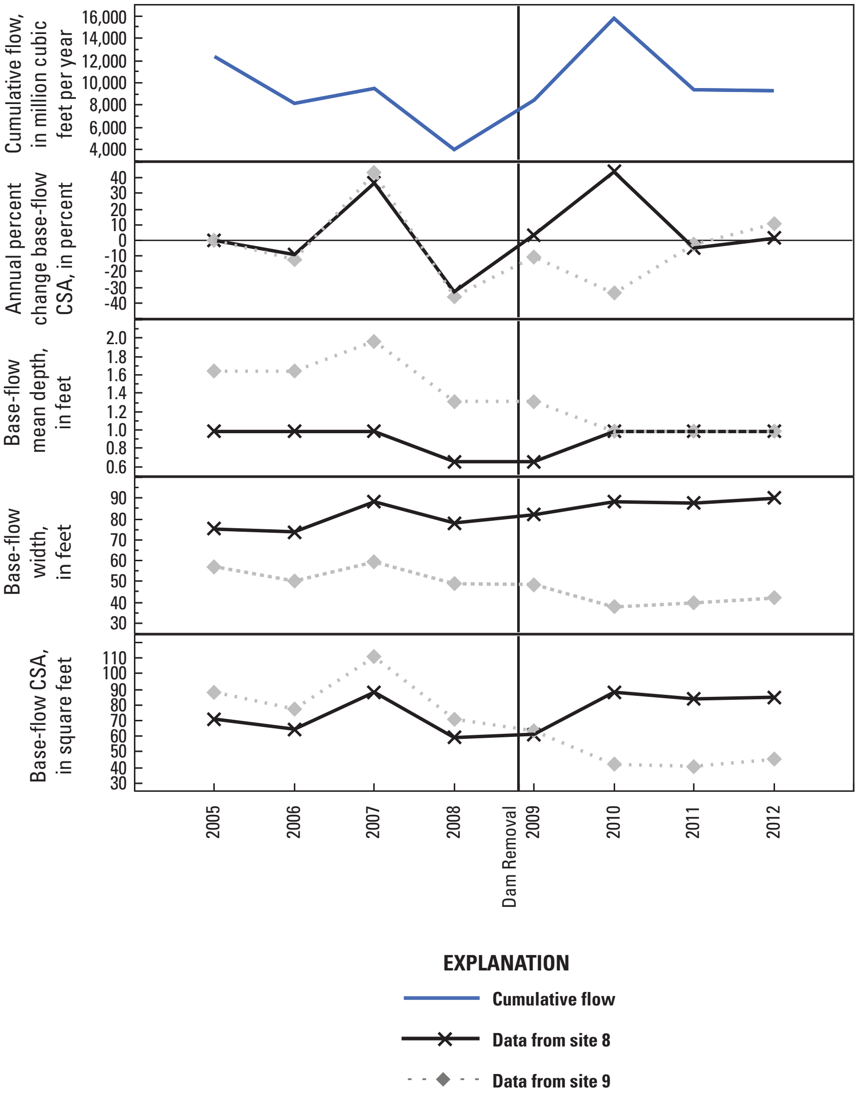


Figure 17. Base-flow channel geometry changes for sites 8 and 9 and annual total streamflow, Roanoke River, Virginia, 2005–2012. [CSA, cross-sectional area]

Suspended-Sediment Transport

The overall goals of the suspended-sediment transport component of this study were to determine what effects, if any, the RRFRP had on suspended-sediment transport through the construction reach and to provide a mechanism to rapidly detect potential increases in sediment transport resulting from construction activities. Specifically, the objectives of the suspended-sediment component were to operate a monitoring program designed to generate the requisite data to

1. Detect short-term changes in suspended-sediment transport during construction of the RRFRP in near real time and
2. Assess spatial and temporal trends in suspended-sediment transport in the affected section of the Roanoke River.

Suspended-Sediment Transport Study Design and Methods

In general, the approach used to satisfy the objectives of the suspended-sediment transport component of the study involved continuous water-quality monitoring instruments equipped with turbidity sensors to monitor the turbidity of water flowing into and out of the river reach affected by the RRFRP. In addition, manual suspended-sediment sampling of the river at these locations was conducted to generate the requisite data to determine the relation between turbidity and suspended-sediment concentration (SSC).

Turbidity is a measure of the optical clarity of water that is largely controlled by light-scattering suspended particles within the volume of water (Davies-Colley and Smith, 2001), and is therefore generally well correlated with SSC (Davies-Colley and Smith, 2001). High-frequency measurements of turbidity are feasible because instruments capable of measuring turbidity in-situ do not require physical collection of a sample for analysis. The use of turbidity as a surrogate for SSC has increased over the last two decades as advances in instrumentation have enabled the unattended deployment of turbidity sensors (Lewis, 1996; Christensen and others, 2000; Lee and others, 2008; Rasmussen and others, 2008; Jastram and others, 2009, 2010; Baldwin and others, 2012; Chanat and others, 2013; Miller and others, 2013). Further support for the increased use of turbidity as a surrogate for SSC comes from the widespread findings that the turbidity approach yields results superior to traditional methods reliant upon streamflow as a surrogate for SSC (Lewis, 1996; Christensen and others, 2000; Jastram and others, 2009; Rasmussen and others, 2009).

Data Collection Methods

Continuous water-quality monitors, configured to measure water temperature, specific conductance, pH, and turbidity, were deployed at multiple locations along the construction reach for various time periods (table 9). These deployments were located, spatially and temporally, such that active construction reaches were closely bracketed with a monitor near the upstream and downstream extents of active construction to monitor flow into and out of the active construction reach. Continuous water-quality monitors also were deployed at the upstream and downstream extent of the RRFRP, the RT117 and 13TH, for the entire duration of the RRFRP (fig. 1).

The conditions set forth in the Biological Opinion (U.S. Fish and Wildlife Service, 2005) required that construction of the RRFRP proceed upstream, beginning at the downstream extent of the project, and that construction activities progress in increments of 4,000 linear feet, with a new increment not beginning until the previous one had been completed. The turbidity monitoring program maintained two “benchmark” monitoring stations at the upstream and downstream extents of the RRFRP for the duration of the project, with additional monitoring stations directly bracketing the zone of active construction for the period of time that the particular zone was active. Occasionally, pre-monitoring was conducted prior to activation of a construction zone, though pre-monitoring periods were typically short. The construction and suspended-sediment monitoring phases and the spatial extent of the monitoring zones are provided in table 10.

Continuous water-quality monitors were operated at bridge crossings where they were suspended from a bridge using a braided steel support cable such that the sensors were located in the upper portion of the water column near the center of the primary flow path. This deployment approach allowed the monitor to be positioned appropriately in the stream to provide measurements representative of the cross section, while also providing a mechanism to allow the monitors to shed potentially damaging debris. Large debris, primarily trees or tree branches, were commonly transported by the river during storm flow. When such debris encountered the water-quality monitors, it would typically cause the monitor to rise up in the water column and slide over the debris, then fall back into place.

Instruments used for continuous water-quality monitoring were YSI, Inc., Model 6920 Multiparameter Sondes equipped with sensors for making standard measurements of water temperature (in degrees Celsius; °C), pH (in standard units), and specific conductance (in microsiemens per centimeter at 25 °C; µS/cm). Additionally, sondes were equipped with turbidity sensors; however, turbidity measurement is not standardized—measures are highly dependent on sensor configuration, and measurements from different sensor configurations are not directly comparable (Anderson, 2005). YSI, Inc., Model 6136 turbidity sensors were used for this study. These sensors use near-infrared wavelengths with 90-degree detector geometry calibrated using formazin-based standards; therefore, data are expressed in formazin nephelometric units (FNUs; Anderson, 2005).

The water-quality monitors were configured to measure the suite of water-quality parameters every 15 minutes. These data were stored on a datalogger mounted to the bridge rail, and the data were transmitted to USGS facilities via cellular modem or satellite transmitter every 1–3 hours. These “real-time” data were then displayed on NWISWeb soon after being transmitted from the site.

Table 9. Monitoring station locations and period of operation for real-time turbidity monitoring, Roanoke River, Roanoke, Virginia.

[USGS, U.S. Geological Survey]

USGS station identifier	Station name	Station abbreviation	Begin date	End date
02055080	Roanoke River at Thirteenth Street Bridge at Roanoke, VA	13TH	4/13/2005	4/16/2012
02055010	Roanoke River at Ninth Street Bridge at Roanoke, VA	9TH	4/28/2005	11/1/2007
0205494935	Roanoke River at Jefferson Street Bridge at Roanoke, VA	JEFF	11/8/2006	11/12/2009
0205492550	Roanoke River at Memorial Avenue Bridge at Roanoke, VA	MEMORIAL	11/2/2007	10/2/2008
0205491522	Roanoke River at Bridge Street Bridge at Roanoke, VA	BRIDGE	10/3/2008	10/4/2011
02054750	Roanoke River at Route 117 at Roanoke, VA	RT117	4/13/2005	4/16/2012

Table 10. Construction and monitoring zones and period of monitoring activity for turbidity monitoring, Roanoke River, Roanoke, Virginia.

[Monitoring station abbreviations defined in table 9]

Phase	Begin date	End date	Monitoring stations bracketing reach (see fig. 1)
Pre-construction	04/28/2005	09/05/2005	RT117, 9TH, 13TH
First construction	09/06/2005	10/31/2006	9TH, 13TH
Second construction	12/18/2006	10/23/2007	JEFF, 9TH
Third construction	11/02/2007	10/01/2008	MEMORIAL, JEFF
Pre-fourth construction	10/03/2008	01/13/2009	BRIDGE, JEFF
Fourth construction	01/14/2009	09/22/2009	BRIDGE, JEFF
Pre-fifth construction	09/23/2009	05/31/2010	RT117, BRIDGE
Fifth construction	06/01/2010	09/29/2011	RT117, BRIDGE
Post-construction	09/30/2011	09/30/2012	RT117, 13TH

Water-quality monitors were operated in accordance with standard USGS protocols detailed in Wagner and others (2006) and the U.S. Geological Survey National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). In general, this required conducting site visits to clean the sensors of any fouling and to document the effect of fouling on the measurements made since the previous site visit, checking the calibration of the sensors, re-calibrating sensors if warranted, and documenting the effect of calibration drift on the measurements made since the previous site visit. Site visits were conducted on an approximately monthly basis, and the documented effects of fouling and calibration drift were used to adjust measurements made over the period to account for the documented deviations.

Samples for analysis of SSC and sand/fine split, or percent of material finer than 0.0625 mm, were collected periodically at the two benchmark stations, RT117 and 13TH, throughout the study period. These samples were collected using methods and sampling devices designed to collect samples representative of the complete river cross section at the sampling location so that any variability in the measured constituents across the depth of the water column and across the width of the cross section is appropriately represented in the sample analyzed (U.S. Geological Survey, variously dated). Once collected, samples were prepared in accordance with USGS protocols (U.S. Geological Survey, variously dated) and shipped to the USGS Eastern Region Sediment Laboratory in Louisville, Kentucky. Analyses of SSC and sand/fine split were performed according to Guy (1969) and Shreve and Downs (2005).

Data Analysis Methods

Data analysis included real-time assessments of continuous turbidity data and annual unpublished assessments of continuous turbidity and discrete-sampling data to identify potential sediment-related issues during construction of the RRFRP. The final data analysis, which is presented within this report, is a complete analysis of all turbidity and suspended-sediment data collected before, during, and after construction of the RRFRP.

Evaluation of Turbidity Patterns

During the study, and particularly during active construction phases, continuous turbidity data were visually inspected daily to identify potential inputs of sediment from construction activities. With instruments monitoring the water flowing into and out of active construction reaches, an input potentially attributed to the RRFRP was expected to generate an increased turbidity response at the outflow location as compared to turbidity at the inflow location. In the event of such a pattern, further data exploration utilizing the other measured parameters was conducted, and, if warranted, a site visit was performed to rule out instrument fouling or other malfunction as the cause of the observed pattern.

Evaluation of Turbidity—Suspended-Sediment Relations

The final analysis of data collected for the suspended-sediment transport component of the study included evaluations of the turbidity data and relations between turbidity and SSC. Distributions of turbidity at the respective monitoring stations during the various RRFRP phases were evaluated to determine if locations downstream of construction activities had appreciably lower or higher turbidity than the locations upstream of those activities. Evaluations of the relation between turbidity and SSC were conducted to define the relation and determine whether the relation changed over time and (or) space during the study. Evaluations of suspended-sediment loads and yields at the respective monitoring stations during the various RRFRP phases were conducted to determine if construction activities affected downstream loading of suspended sediment.

Exceedance probabilities were computed for all turbidity measurements by station and RRFRP phase. These probabilities were plotted as cumulative distribution function (CDF) plots by RRFRP phase for comparison of turbidity distributions for each station active during the phase.

The relation between turbidity and SSC was determined, and potential changes in this relation over time and (or) space were explored by using linear regression. Turbidity (the explanatory variable) and SSC (the response variable) were transformed with a natural logarithm (ln) transformation to meet the assumption of normality in linear regression analysis (Helsel and Hirsch, 2002). Site-specific simple linear regression (SLR) models of the general form

$$ln\text{SSC} = \beta_0 + \beta_1 ln\text{Turbidity} + \varepsilon \,, \qquad (2)$$

where

ln	is the natural logarithm;
SSC	is suspended-sediment concentration;
β_0	is the intercept;
β_1	is a model coefficient; and
ε	is the model error

were developed using SSC and corresponding turbidity measurements from the discrete-sampling activities at the two benchmark stations, RT117 and 13TH. Determination of change in the turbidity-SSC relation over time was accomplished by adding a time term to the turbidity-SSC model and evaluating the significance of time in the model. These models took the general form of

$$ln\text{SSC} = \beta_0 + \beta_1 ln\text{Turbidity} + \beta_2\text{DecTime} + \varepsilon \,, \qquad (3)$$

where

β_2	is a model coefficient; and
DecTime	is decimal time.

Evaluation of whether the turbidity-SSC relation varied between RT117 and 13TH was accomplished using analysis of covariance (ANCOVA; Helsel and Hirsch, 2002). The ANCOVA was performed by adding terms to the turbidity-SSC SLR to determine significance of location within a pooled model calibrated using data from both stations. The form of the ANCOVA model was

$$\begin{aligned} ln\text{SSC} = {} & \beta_0 + \beta_1\text{Turbidity} + \beta_2\text{STA} + \\ & \beta_3\left(\text{Turbidity} \times STA\right) + \varepsilon, \end{aligned} \qquad (4)$$

where

ln	is the natural logarithm;
STA	is an indicator variable (0 or 1) identifying the sampling location;
β_0	is the intercept;
β_{1-3}	are model coefficients; and
ε	is the model error.

Significant differences in the turbidity-SSC relation between the two sites would be identified by significance ($\alpha = 0.05$) of the β_2 and β_3 terms. The indicator variable, *STA*, was assigned a value of 0 for samples collected at RT117, which canceled the β_2 and β_3 terms, simplifying the model to the form of the SLR (eq. 1). For samples collected at 13TH, *STA* was assigned a value of 1, which resulted in a simplified model with the intercept and slope changed to reflect the relation at 13TH:

$$ln\text{SSC} = \left(\beta_0 + \beta_2\right) + \left(\beta_1 + \beta_3\right)\text{Turbidity} + \varepsilon \,. \qquad (5)$$

Evaluation of Suspended-Sediment Loads and Yields

Suspended-sediment loads—the total mass of sediment transported over a specified time period—were estimated by station and RRFRP phase. Loads were estimated at a daily time step using daily mean streamflow from the Roanoke River at Roanoke, Virginia, streamgage and daily mean turbidity measured at the site of interest as input variables. Daily mean SSC was estimated using the pooled-station turbidity-based SSC model. Daily load was computed by multiplying the daily flow by the daily mean sediment concentration.

Watershed-area scaling was applied to adjust the streamflow data to better represent streamflow at the turbidity monitoring locations because streamflow was not measured at those locations. Scaled streamflow values were computed by multiplying the daily mean streamflow from the streamgage by the percentage of the watershed area represented by the continuous water-quality monitoring station (table 11).

Daily mean turbidity was computed for each station from the continuous turbidity data measured at that location. In the event of missing or otherwise insufficient continuous data for computation of a daily mean, the mean of the mean daily turbidity for all other stations operational that day was used to fill in the missing periods.

Daily mean SSC was then computed using the SLR model (eq. 1) calibrated from the pooled dataset, as was determined acceptable through the ANCOVA procedure. Consistency in the turbidity-SSC relation between the furthest upstream (RT117) and downstream (13TH) stations supports the assumption that this single model is applicable at all

Table 11. Relation of watershed areas of continuous water-quality monitoring stations with the watershed area of the Roanoke River at Roanoke, Virginia, streamgage.

[Station abbreviations defined in table 2]

Station	Watershed area, in square miles	Percent of gaged watershed area
RT117	352	91.7
BRIDGE	371	96.6
MEMORIAL	374	97.4
JEFF	384	100.0
Roanoke River at Roanoke, Virginia	384	100.0
9TH	385	100.3
13TH	390	101.6

stations between the two calibration stations, though samples were not collected at the intermediate stations to verify this.

Daily mean suspended-sediment loads were then computed as the product of daily mean streamflow and daily mean SSC. Daily loads were summed, by station, over the RRFRP phases and plotted as cumulative loads for comparison and determination of potential loading from construction activities. Loads also were adjusted for watershed area and expressed as yields, or load per unit area, to provide better comparability.

Summary of Data Collected

Continuous water-quality monitors measured water temperature, pH, specific conductance, and turbidity on 15-minute intervals at six stations during various time periods (table 9). In the absence of sensor fouling, malfunction, or other issues, continuous monitoring resulted in 96 measurements of each of these parameters per day of operation. Of the parameters measured, only turbidity data are summarized and used in the analyses presented herein; however, all other data are available online at http://waterdata.usgs.gov/nwis.

Turbidity at the continuous monitoring stations was low during non-stormflow conditions, as indicated by the minimums at or near 0 FNU (table 12). Median turbidity values were low as well, ranging from 3.5 to 6.5 FNU, as a result of the relative lack of stormflow conditions during much of the study period (figs. 4 and 5). During stormflow events, however, turbidity was substantially elevated, with most stations recording maximum turbidity near 2,000 FNU (table 12). Maximum values greater than 1,000 FNU exceed the operational and calibrated limits of the turbidity sensor; however, such high values were recorded infrequently and were not persistent over multiple 15-minute measurements, so these values were not adjusted. Exceptions to the high maximum values generally occurred at stations with shorter periods of operation because they were not operational during the few stormflow events that generated the high turbidity values elsewhere.

Discrete suspended-sediment samples were collected throughout the study period at the two benchmark stations—RT117 and 13TH. The sampling approach focused on periods when sediment transport was occurring and turbidity was elevated, though samples were occasionally collected at low turbidity to inform the low-end of the models (fig. 18). Totals of 62 and 66 samples were collected at 13TH and RT117, respectively, at an average rate of 9 samples per year, excluding the year in which the program ended (2012; fig. 18). In WY2006, the number of samples collected was greater than average, 19 and 18 at 13TH and RT117, respectively, as a result of complementary research that was conducted at the monitoring stations that year (Jastram and others, 2010).

Suspended-sediment concentrations of discrete samples ranged from <0.5 to 1,310 milligrams per liter (mg/L) and from 2 to 1,050 mg/L at RT117 and 13TH, respectively (fig. 19). Corresponding turbidity values for the samples ranged from 0.6 to 1,180 FNU and from 1.1 to 1,430 FNU, respectively. The relation between turbidity and SSC was linear in log-log space.

Table 12. Minimum, median, mean, and maximum turbidity, and years of operation, for six continuous water-quality monitoring stations, Roanoke River, Roanoke, Virginia.

[FNU, formazin nephelometric units]

Station	Minimum turbidity, in FNU	Median turbidity, in FNU	Mean turbidity, in FNU	Maximum turbidity, in FNU	Years of operation
13TH	0.0	5.0	13	1,930	7.0
9TH	0.0	6.5	16	2,030	2.5
JEFF	0.0	4.8	13	1,200	3.0
MEMORIAL	0.0	3.7	8	510	0.9
BRIDGE	0.1	4.5	14	1,710	3.0
RT117	0.0	3.5	11	1,960	7.0

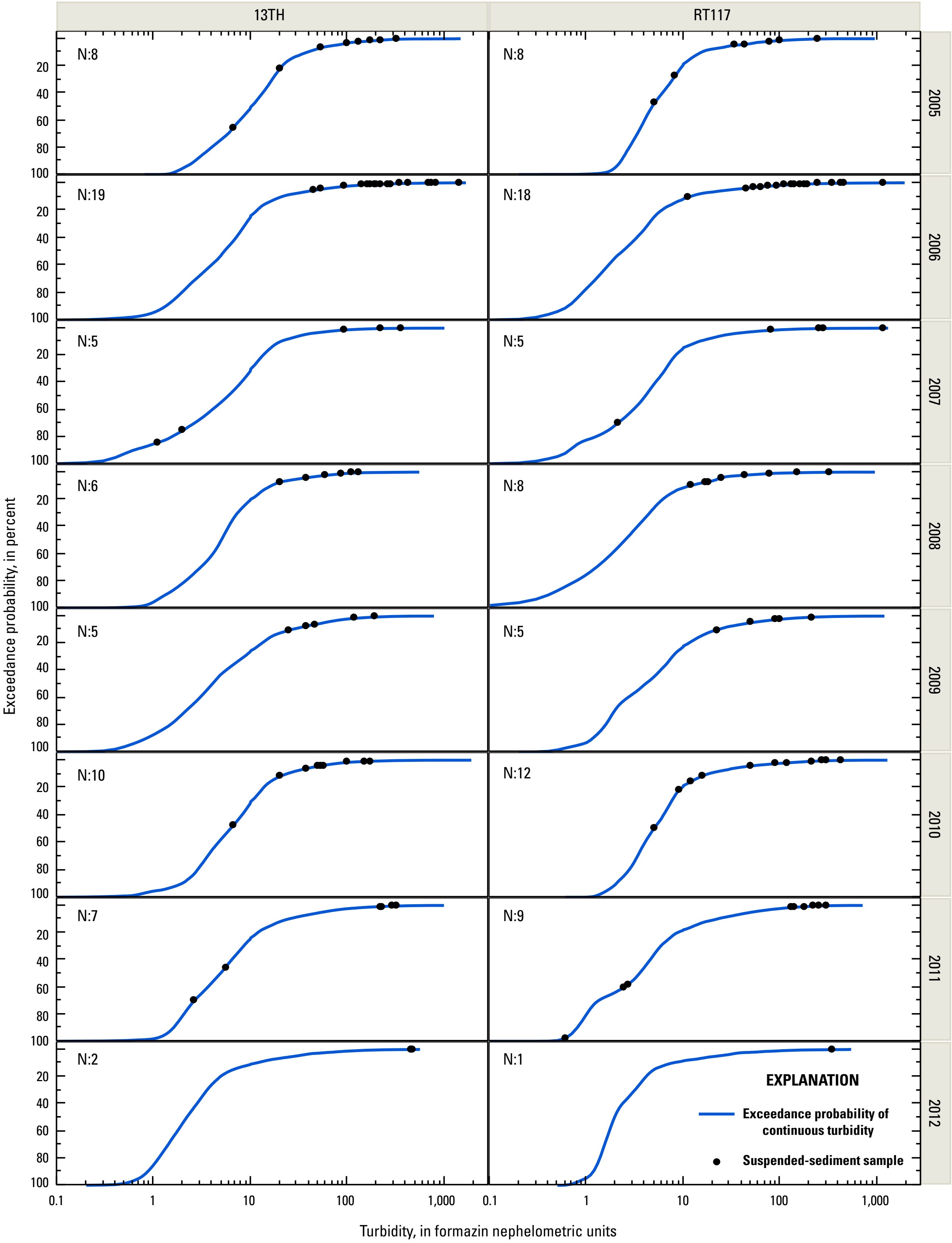


Figure 18. Turbidity of suspended-sediment samples collected plotted on exceedance probability plots of continuous turbidity, by monitoring station and water year, for two monitoring stations, Roanoke, Virginia, 2005–2012.

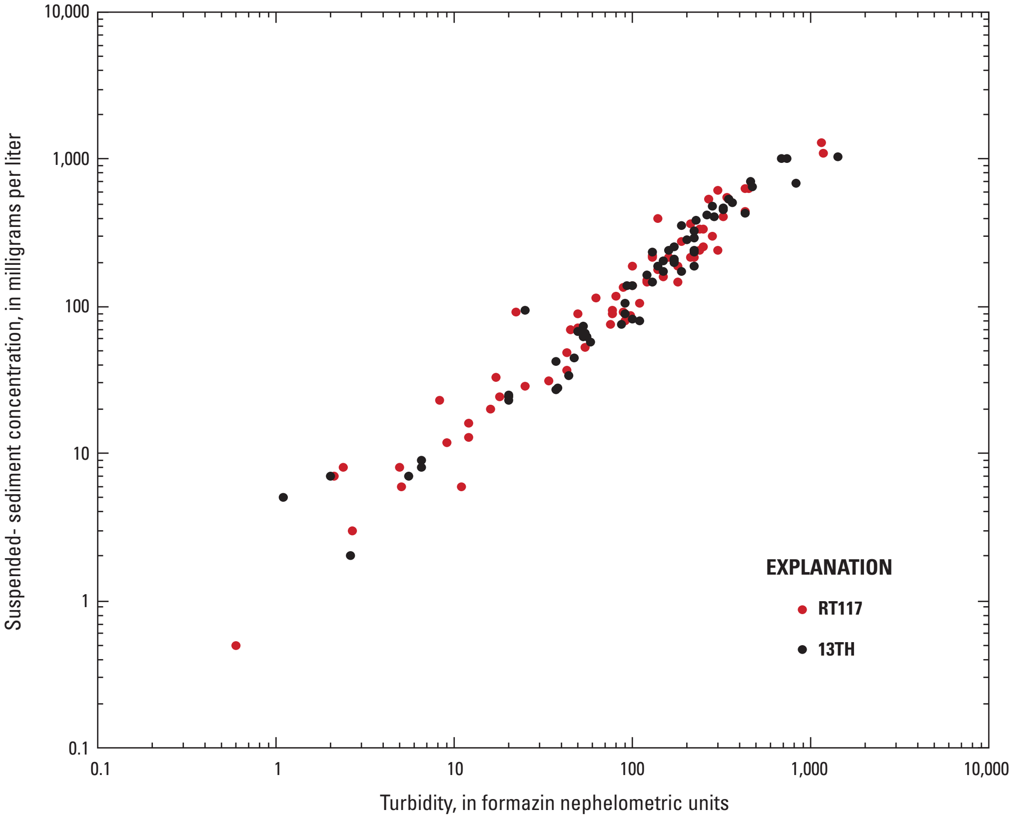


Figure 19. Turbidity and suspended-sediment concentration data for samples collected at two monitoring stations, Roanoke River, Virginia, 2005–2012. [See table 9 for station information.]

Results of Data Analysis

Analysis of suspended-sediment transport data is composed of three major analysis foci: (1) patterns in continuous turbidity data, (2) relations between turbidity and suspended sediment, and (3) comparison of suspended-sediment loads and yields entering and leaving construction reaches. Collectively, these three groups of analysis provide a body of evidence from which the potential effects of the RRFRP can be ascertained.

Patterns in Continuous Turbidity Data

Cumulative distribution frequency plots of continuous turbidity measurements, grouped by RRFRP phases, generally indicate increasing turbidity in the downstream direction regardless of construction activities (fig. 20). This background pattern of increasing turbidity is attributed to the increasing proportion of watershed area disturbed by urbanization, particularly near the river, as the river progresses downstream through the city of Roanoke.

Turbidity data prior to initiation of the RRFRP construction activities are limited in duration, representing only a 5-month period. During this period, turbidity was generally low, with median values of 15 FNU or less at the three sites monitored (fig. 20). The two sites closely bracketing the first construction reach, 9TH and 13TH, were similar, particularly for elevated turbidity levels, indicating no likely existing source of sediment input in the reach.

The distributions of turbidity during the first construction phase differed from those during the pre-construction phase, with measurements spanning a greater range as a result of the longer monitoring period compared to pre-construction (fig. 20). Despite differences in distribution properties, patterns between the turbidity distributions during the first construction phase were similar to those observed during the pre-construction phase, with turbidity increasing downstream from RT117 to 13TH and with 9TH and 13TH having nearly identical turbidity distributions (fig. 20); such consistency in patterns provides evidence that construction activities did not alter turbidity, and therefore suspended-sediment transport, during the first construction phase.

The second construction phase had no pre-construction monitoring; therefore, evaluation of the second construction phase is limited to comparison with the understood pattern of downstream increase in turbidity and the assumption that no pre-existing suspended-sediment input source was within the reach. With the exception of the values below 5 FNU, turbidity distributions and patterns between those distributions were similar to those observed during the pre-construction and first construction phases (fig. 20). There was variability in the distributions for values below 5 FNU, and the pattern of

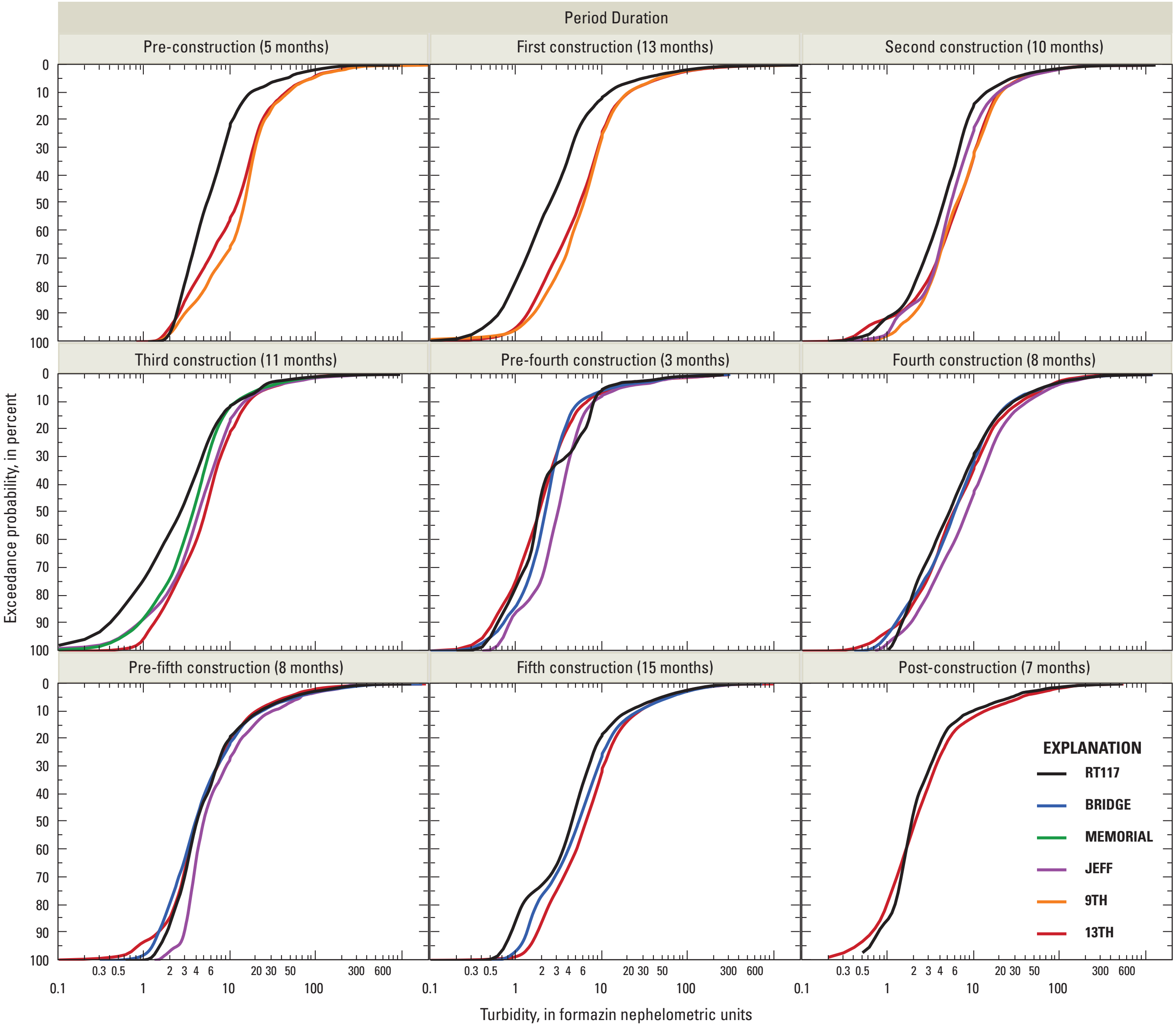


Figure 20. Cumulative distribution frequency plots of continuous turbidity at six monitoring stations, grouped by Roanoke River Flood Reduction Project (RRFRP) phase. [RRFRP phases defined in table 10. Station abbreviations defined in table 9.]

increasing turbidity in the downstream direction was disrupted in this range (fig. 20). This variability is not interpreted as a meaningful signal of differences among sites because (1) the sensors' stated accuracy was ±2 FNU (meaning a measurement of 2 FNU may actually represent a value between 0 FNU and 4 FNU), (2) site-specific characteristics such as lighting/shading and biological activity cause variability in low-level turbidity measurements (U.S. Geological Survey, variously dated), and (3) practically relevant sediment concentrations are not present at such low turbidity.

Turbidity distributions during the third construction phase followed the pattern of increasing turbidity with distance downstream nearly perfectly. This pattern provides evidence that construction activities during this phase did not affect suspended sediment and turbidity (fig. 20).

Departures from the pattern of downstream increases in turbidity occurred during the pre-fourth and fourth construction phases, and these departures were not entirely consistent between phases (fig. 20). Turbidity during the pre-fourth construction phase was among the lowest observed during any phase, and as a result of greater sensor fouling effects on low-turbidity measurements, an uncharacteristic turbidity distribution was observed at RT117. Noise in the turbidity data early in this phase artificially elevated the measured turbidity, with some values erroneously recorded as being between 3 and 10 FNU, which resulted in an unusual pattern in the CDF curve for this station. This pattern is not interpreted as a meaningful signal in regards to the effect of construction activities. Additionally, greater turbidity occurred at the downstream extent of the construction reach (JEFF) than at the upstream extent of the construction reach (BRIDGE) or the downstream extent of the RRFRP (13TH) during the pre-construction and construction periods of the fourth phase. This increase in turbidity within the construction reach was consistent between the pre-construction and construction periods, with turbidity in the 25th to 75th percentile increasing by approximately 40 percent in the reach during both periods. This consistency between periods demonstrates that the within-reach increase is the result of a pre-existing condition, not RRFRP activities, and it exemplifies the value of pre-disturbance monitoring to differentiate pre-existing conditions from disturbances induced by other activities.

The fifth, and final, construction phase was associated with the reach between RT117 and BRIDGE. Turbidity distributions for stations bracketing this reach and for the overall project (RT117, BRIDGE, 13TH) were strikingly similar during the pre-fifth construction phase (fig. 20). The JEFF monitoring station remained operational during the pre-fifth construction phase and recorded elevated turbidity similar to that measured during the pre-fourth and fourth construction phases. Turbidity distributions during the fifth construction phase matched the pattern of downstream increases in turbidity observed in most other project phases and, therefore, indicate that construction activities had little or no effect on turbidity and sediment transport in the reach.

Post-construction monitoring was conducted at the two benchmark stations, RT117 and 13TH, for 7 months after construction was complete. Turbidity distributions during this period largely match the pattern of downstream increase observed throughout the study, with the exception of very low, error-prone turbidity values that depart slightly from this pattern (fig. 20). Overall, no construction effects were observed in the turbidity data.

Turbidity–Suspended-Sediment Relations

Simple linear regression models with turbidity as the sole explanatory variable effectively estimated SSC, as demonstrated by the high coefficients of determination (R^2) and strong statistical significance of the turbidity terms (table 13). No change over time in the relation between turbidity and SSC was detected when the decimal time variable was added to the model, as evidenced by the lack of statistical significance of the decimal time term, providing evidence that RRFRP activities did not affect the physical characteristics of suspended sediment transported through the monitored reach.

The ANCOVA performed to evaluate between-site differences in the turbidity-SSC relation demonstrated that there was no statistically significant difference in the relation at the two sites evaluated, RT117 and 13TH, as indicated by the lack of significance of the station indicator (STA) and turbidity—STA interaction term (*ln*Turbidity × STA; table 14). Additionally, the variance explained (R^2) by this pooled model is the same as that of the individual site models, and model error (RMSE) is similar to that of the individual site models (tables 13 14). Overall, results from the ANCOVA provide additional evidence that RRFRP activities did not affect suspended sediment in the construction reach because the turbidity-SSC relation at the inflow to the reach is not statistically different from the relation at the outflow of the reach. The ANCOVA results also support the application of a pooled model from these two benchmark sites to estimate SSC at the sites between RT117 and 13TH where SSC was not measured because no change in the turbidity-SSC relation was detected between locations.

Suspended-Sediment Loads and Yields

Daily mean suspended-sediment loads at each of the six monitoring stations, computed from the pooled SSC estimation model as deemed appropriate in the ANCOVA previously

Table 13. Equations and summary statistics for simple linear regressions to estimate natural logarithm of suspended sediment concentration (SSC) and test for temporal trends in the relation between turbidity and SSC at two monitoring stations on the Roanoke River, Roanoke, Virginia.

[R^2, coefficient of determination; ln, natural logarithm; DecTime, decimal time; NA, not applicable; <, less than]

Station	Equation	Number of observations	Turbidity p-value	DecTime p-value	Root mean square error	R^2
		SSC estimation				
RT117	lnSSC = 0.410 + 0.965(lnTurbidity)	65	<0.0001	NA	0.338	0.95
13TH	lnSSC = 0.437 + 0.952(lnTurbidity)	61	<0.0001	NA	0.320	0.95
		Temporal trend				
RT117	lnSSC = –51.4 + 0.969(lnTurbidity) + 0.026(DecTime)	65	<0.0001	0.20	0.336	0.95
13TH	lnSSC = 17.8 + 0.950(lnTurbidity) – 0.008(DecTime)	61	<0.0001	0.65	0.0322	0.95

discussed, were summed over annual (water year) and RRFRP phases to evaluate potential changes to suspended-sediment loadings (total mass) resulting from RRFRP activities. These loads were also expressed as yields to provide comparisons of the sediment delivery rate in terms of mass per unit area.

Annual suspended-sediment loads were mostly consistent with the pattern of downstream increase observed in the turbidity data (table 15). Interannual variability in suspended-sediment loads was considerable, spanning nearly an order of magnitude at RT117 (table 15), and this variability was generally consistent with variability in streamflow (fig. 21). Annual peak streamflow was most directly related to annual suspended-sediment loads, indicating that the single largest stormflow event each year was most directly responsible for the magnitude of the suspended-sediment load. Total annual streamflow also related well with suspended-sediment loads (fig. 21), particularly in 2009 and 2010 when slight departures from the relation with annual peak streamflow occurred.

Table 14. Summary statistics and model coefficients for analysis of covariance to evaluate differences in the relation between turbidity and suspended sediment concentration at the RT117 and 13TH monitoring stations on the Roanoke River, Roanoke, Virginia.

[R^2, coefficient of determination; NA, not applicable; <, less than; ln, natural logarithm; STA, station indicator]

Item	Value	p-value
Summary statistics		
R^2	0.95	NA
Root mean square error	0.330	NA
Number of observations	126	NA
Model coefficients		
Intercept	0.424	<0.0001
lnTurbidity	0.965	<0.0001
STA	–0.013	0.88
lnTurbidity × STA	–0.013	0.75

Table 15. Annual suspended-sediment loads, in tons, by station and water year, for water years with complete continuous monitoring data, Roanoke River, Roanoke, Virginia.

[Station abbreviations defined in table 9. NA, not applicable.

Water year	RT117	BRIDGE	MEMORIAL	JEFF	9TH	13TH
	Upstream → Downstream					
2006	28,341	NA	NA	NA	32,132	33,462
2007	9,684	NA	NA	NA	10,554	10,177
2008	3,750	NA	NA	4,920	NA	5,287
2009	11,170	12,986	NA	13,810	NA	12,609
2010	29,525	36,412	NA	NA	NA	36,907
2011	13,239	15,497	NA	NA	NA	17,788

Daily suspended-sediment yields from the inflow and outflow of each construction reach were compared for the pre-construction (when available) and construction phases of each reach. These comparisons were accomplished by plotting the daily yield of the inflow against the daily yield of the outflow to assess departures from the line of equality (fig. 22) that would indicate sediment sources (positive departure in y-direction from line of equality) or sinks (negative departure in y-direction from line of equality) within the reach.

Daily suspended-sediment yields of the inflow, measured at 9TH, and outflow, measured at 13TH, in the first construction reach during the pre-construction phase were low compared to those measured during the first construction phase (fig. 22*A,B*) because no major stormflow events occurred during the pre-construction phase. Relations between daily sediment yields at the inflow and outflow of this reach during the pre-construction and first construction phases indicate that there were no practically significant sediment sources or sinks in the reach prior to construction (fig. 22*A*), and this pattern remained through the first construction phase (fig. 22*B*), indicating that construction activities did not contribute additional sediment to the river.

The second and third construction phases had no pre-construction monitoring, thereby precluding the ability to determine pre-existing sediment sources and sinks in the construction reaches. Inflow and outflow monitoring locations evaluated were JEFF and 9TH and MEMORIAL and JEFF, for the second and third construction phases, respectively. Relations between daily sediment yields at the inflow and outflow of each reach during the respective construction phases, however, indicate that there were no practically significant sediment sources or sinks during construction (fig. 22*C,D*), providing evidence that construction activities during these phases did not contribute additional sediment to the river.

Patterns in inflow and outflow suspended-sediment yields were similar between the pre-fourth and fourth construction phases, especially during relevant periods of greater sediment transport (fig. 22*E,F*). Slight differences between the pre-construction and construction phases are observed at the very low end of the sediment yields where such low yields were not observed during the pre-fourth construction phase. These low yields, however, are not of concern because of the exceedingly small mass of sediment transported and magnitude of error included in these estimates.

Inflow and outflow suspended-sediment yields measured at RT117 and BRIDGE during the fifth construction phase were similar and consistent with the pattern observed during the pre-fifth construction phase (fig. 22 *G,H*), providing evidence that construction activities had no measurable effect on sediment transport during the final construction phase.

Synthesis of Study Results

Potential effects of the RRFRP on Roanoke logperch habitat were evaluated through two semi-independent study components—geomorphological change and suspended-sediment transport. These two components, though measured and analyzed independently, are highly interdependent and cumulatively provide a detailed understanding of the sedimentary response, or lack thereof, of the Roanoke River to the RRFRP.

Analysis of bed-sediment composition revealed that though the bed material was usually significantly finer in post-construction cross sections than in pre-construction cross sections, the annual changes in composition were not significantly different; thus, an RRFRP-induced fining of bed materials was not evident. Metrics of bankfull and base-flow channel geometry computed from the cross-sectional surveys revealed variability in these metrics throughout the study, but excluding intentional, designed alterations in channel geometry, no significant differences in this variability were detected between pre- and post-construction measurements.

Analysis of the relations between turbidity and suspended sediment at RT117 and 13TH indicated that those relations were statistically indistinguishable between the two sites, and the relations did not change over time, indicating that there were no significant changes in sediment composition or source in the construction reach during the period of study. Comparisons of patterns in turbidity at each monitoring station indicated slight variability during some construction periods, though such variability was generally minimal and could not be attributed to construction activities.

Results of the geomorphological monitoring and suspended-sediment monitoring components of this study were largely in agreement, indicating that any deleterious effects of the RRFRP were below the level of detection of the methods used. This finding suggests that construction and sediment-control practices employed by the practitioners responsible for constructing the RRFRP sufficiently protected in-stream habitat and the organisms that inhabit those locations, namely the Roanoke logperch.

It is important to note, however, that streamflow conditions during the period of study were relatively dry, with few appreciable stormflow events. Bankfull flow events occurred in only 2 of the 8 years of study, with one occurring early (2006) in the study before much of the construction had been initiated. This lack of channel-forming events limits the ability to fully characterize the stability of the constructed channel and floodplain features; therefore, additional channel surveys may be needed in the future, once sufficient channel-forming events have occurred, to fully assess stability.

Finally, these findings are consistent with those of a related effort which monitored the logperch population before and during RRFRP construction. Roberts and others (2013) reported considerable variability in logperch abundance, habitat quality, and water quality during construction of the RRFRP, but no evidence of RRFRP effects on these measures.

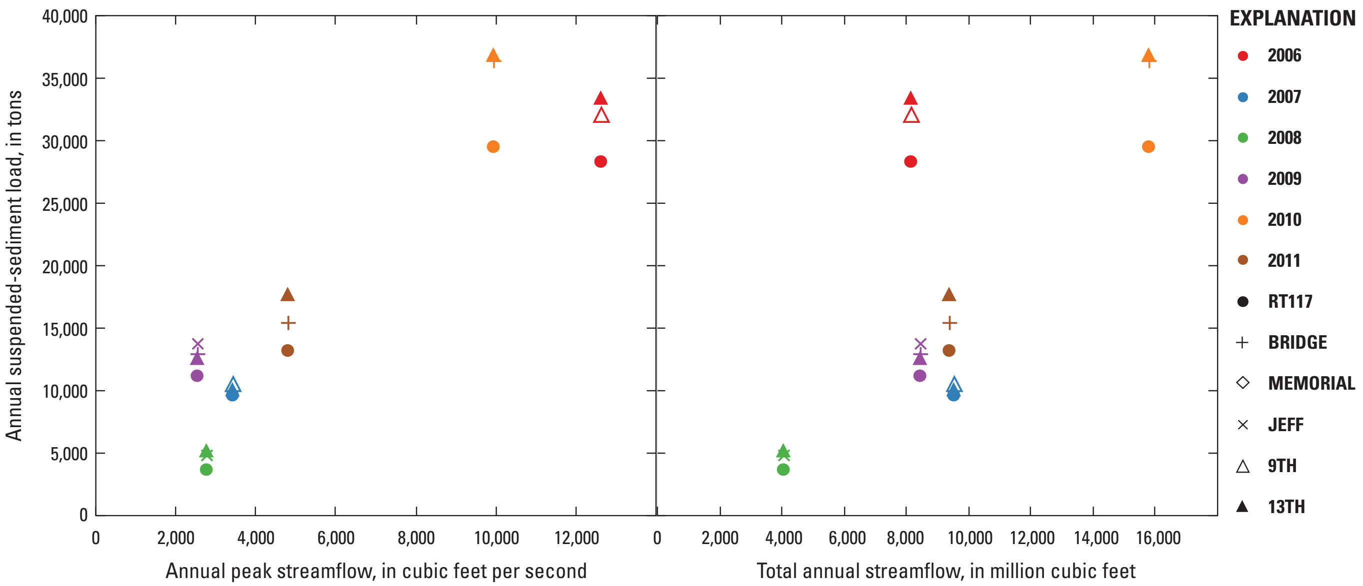


Figure 21. Annual suspended-sediment load and annual peak streamflow and total annual streamflow for six monitoring stations, Roanoke River, Virginia, water years 2006–2011. [Station abbreviations defined in table 9.]

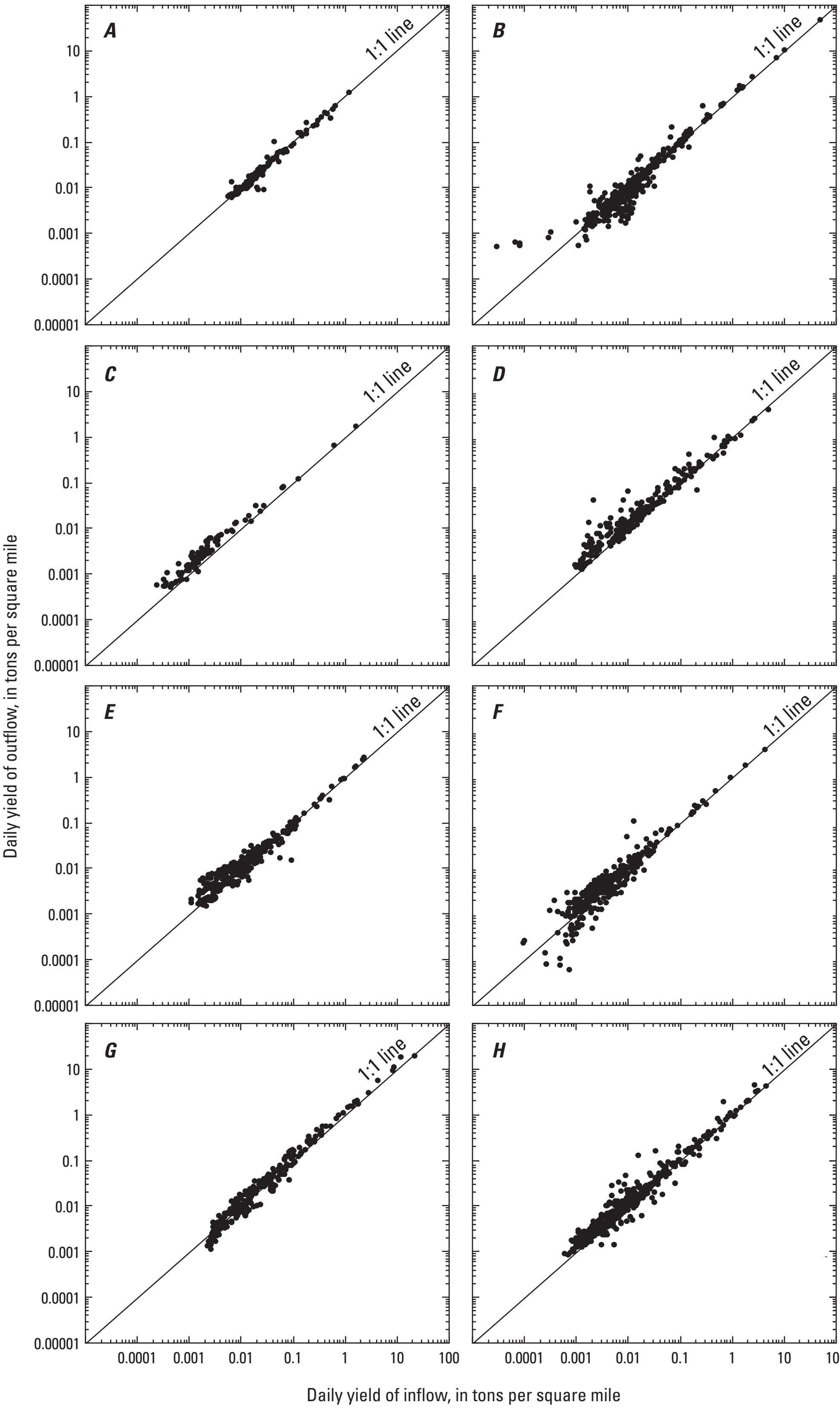


Figure 22. Comparison of inflow and outflow suspended-sediment yields from monitoring stations directly bracketing construction reaches for *A*, pre-construction, *B*, first construction, *C*, second construction, *D*, third construction, *E*, pre-fourth construction, *F*, fourth construction, *G*, pre-fifth construction, and *H*, fifth construction phases, Roanoke River, Virginia, 2005–2012.

Summary

Roanoke, Virginia, has been subjected to substantial flood damages, including loss of human life, resulting from its location along the banks of the Roanoke River in mountainous southwestern Virginia. Beginning in 2005, after decades of planning, the U.S. Army Corps of Engineers (USACE) undertook a major construction effort to reduce the effects of flooding on the city—the Roanoke River Flood Reduction Project (RRFRP). Prompted by concerns about the potential for RRFRP construction-induced sediment liberation and geomorphological instability and the detrimental effects these responses could have on the endangered Roanoke logperch (*Percina rex*), the U.S. Geological Survey (USGS) partnered with the USACE to provide a real-time warning network and long-term monitoring to evaluate geomorphological change and sediment transport in the affected river reach.

The objectives of the geomorphological monitoring component of the study were to determine if effects on habitat, including changes in the geomorphic structure of the river channel and changes in bed-material composition, resulted from RRFRP construction activities, as well as to assess the long-term stability of the RRFRP in selected areas. These effects were assessed by using data collected from a combination of annual cross-sectional surveys measuring channel dimensions and pebble counts to characterize bed material at 15 locations within and upstream of the construction reach.

Metrics of bankfull and base-flow channel geometry computed from the cross-sectional surveys were compared in terms of pre- and post-construction condition, with the initial year of construction removed at each site, to determine whether RRFRP activities reduced the stability of geomorphic features. Excluding intentional, designed alterations in channel geometry, these analyses revealed variability in the geomorphic metrics throughout the study, but no significant differences were detected between pre- and post-construction measurements. These findings indicate that the rate of change observed within the RRFRP construction reach was indistinguishable from that upstream of the construction reach and thus represented variability within an expected range given the hydrologic regime during the study period.

The percentage of change in channel dimensions was examined in a few cases to ascertain the effects (if any) resulting from construction activities where greater than 10-percent change was observed. In the vicinity of sites 8 and 9, construction activities were more extensive than in any other area of the RRFRP, and the Wasena Dam was removed. Following the dam removal, there appeared to be channel adjustment with widening in the riffle at site 8 and aggradation in the pool at site 9. While this adjustment indicates a departure from response to the natural variation in hydrology, it does not appear that the RRFRP construction activity could be solely cited as the cause of the changes observed.

Analysis of bed-sediment composition was performed in a similar manner to the geomorphic analysis, focusing on changes in bed-material size class, particularly fines (including silt/clay or sand), between pre- and post-construction measurements. These analyses revealed that though the bed material was usually significantly finer in post-construction than in preconstruction cross sections, the annual changes in composition were not significantly different; thus, RRFRP construction-induced fining of bed materials was not evident. Cumulatively, the findings of the suspended-sediment monitoring and geomorphological monitoring components of this study were largely in agreement, indicating that any deleterious effects of the RRFRP were below the level of detection of the methods used. This finding suggests that construction and sediment-control practices employed by the practitioners responsible for constructing the RRFRP sufficiently protected in-stream habitat and the organisms that inhabit those locations, namely the Roanoke logperch, during the period monitored.

The objectives of the suspended-sediment transport component of this study were to determine what effects, if any, the RRFRP had on suspended-sediment transport through the construction reach and to provide a mechanism to rapidly detect potential increases in sediment transport resulting from construction activities. The approach used to satisfy the objectives of this component of the effort used continuous water-quality monitoring instruments equipped to measure turbidity—an effective surrogate for suspended sediment—to monitor the turbidity of water flowing into and out of the river reach affected by the RRFRP. In addition, manual sampling of the river at these locations was conducted to determine the relation between turbidity and suspended-sediment concentration.

Comparisons of patterns in turbidity at the inflow to the study reach with those at the outflow of the study reach indicated a background pattern of increasing turbidity present prior to construction activities. Monitoring stations also were operated to bracket each 4,000-foot river reach under active construction, and results indicated slight variability during some construction periods, though such variability was generally minimal and could not be attributed to construction activities. Analysis of the relations between turbidity and suspended sediment at the inflow and outflow of the study reach indicated that those relations were statistically indistinguishable between sites, and the relations did not change over time, indicating no significant changes in sediment composition or source in the construction reach during the period of study.

The findings presented herein are consistent with the findings of a related effort which monitored the logperch population before and during the RRFRP. Roberts and others (2013) found considerable variability in logperch abundance, habitat quality, and water quality during construction of the RRFRP, but no evidence of RRFRP effects on these measures.

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Appendix 1. Geomorphic survey benchmark and transect control location coordinates, Roanoke River, Roanoke and Salem, Virginia.

[Values reported represent the most recent coordinates from the 2012 survey. BM, benchmark; TC, transect control; m, meters]

Site[1]	Description	Control type	Date last surveyed	Northing[2] (m)	Easting[2] (m)	Elevation (m)	Comments
1	TC-01f	TC	6/19/2012	1,106,623.944610	3,361,493.34177	305.6982	Installed 2012
1	TC-01e	TC					Destroyed 2012
1	TC-01d	TC	6/19/2012	1,106,615.277030	3,361,487.68526	306.7082	Found
1	TC-01c	TC	6/19/2012	1,106,657.556030	3,361,514.94626	305.4810	Found
2	BM-02a	BM	6/18/2012	1,106,478.050000	3,361,540.19000	307.8338	Found
2	BM-02b	BM	6/18/2012	1,106,454.670000	3,361,474.47000	307.9801	Found
2	BM-02e	BM	6/18/2012	1,106,484.799480	3,361,448.16247	308.8711	Found
2	TC-02f	TC					Destroyed 2012
2	TC-02d	TC					Destroyed 2012
2	TC-02a	TC	6/18/2012	1,106,513.106510	3,361,668.71764	304.8328	Found
2	TC-02c	TC	6/18/2012	1,106,542.045370	3,361,692.85739	305.2864	Found
2	TC-02e	TC	6/18/2012	1,106,453.271910	3,361,618.82592	306.8702	Found
3	BM-03a	BM	6/18/2012	1,105,390.070000	3,363,463.34000	301.2195	Found
3	BM-03b	BM	6/18/2012	1,105,448.224880	3,363,412.52832	302.0937	Found
3	BM-03c	BM	6/18/2012	1,105,426.622730	3,363,458.42839	299.9764	Found
3	TC-03c	TC	6/18/2012	1,105,409.425250	3,363,480.46309	299.7222	Found
3	TC-03b	TC	6/18/2012	1,105,445.761730	3,363,512.17691	300.3568	Found
4	BM-04a	BM	6/18/2012	1,105,303.190000	3,363,467.37000	301.8230	Found
4	BM-04b	BM	6/19/2012	1,105,268.143020	3,363,506.80812	303.1424	Found
4	TC-04a	TC	6/19/2012	1,105,304.565020	3,363,508.93570	301.1229	Found
4	TC-04b	TC	6/19/2012	1,105,304.951510	3,363,521.52865	298.3991	Found
4	TC-04c	TC	6/19/2012	1,105,306.302230	3,363,555.95403	298.4119	Found
5	BM-05a	BM	6/18/2012	1,104,671.780000	3,364,506.47000	302.4052	Found
5	BM-05b	BM	6/18/2012	1,104,796.140000	3,364,555.53000	302.4174	Found
5	BM-05e	BM	6/18/2012	1,104,712.668350	3,364,530.23316	302.3140	Found
5	BM-05c	BM	6/18/2012	1,104,656.312350	3,364,450.52146	302.3270	Found
5	TC-05e	TC	6/18/2012	1,104,604.709230	3,364,484.80486	297.1488	Found
5	TC-05f	TC	6/18/2012	1,104,575.578730	3,364,505.08876	297.5734	Found
5	TC-05c	TC	6/18/2012	1,104,543.769480	3,364,512.62808	297.1026	Found
6	BM-06c	BM	6/19/2012	1,105,056.450000	3,365,909.86500	299.4460	Found
6	BM-06e	BM	6/19/2012	1,105,055.955000	3,365,815.12400	297.8650	Found
6	BM-06f	BM	6/19/2012	1,105,075.218600	3,365,850.27549	297.3635	Found

Appendix 1. Geomorphic survey benchmark and transect control location coordinates, Roanoke River, Roanoke and Salem, Virginia.—Continued

[Values reported represent the most recent coordinates from the 2012 survey. BM, benchmark; TC, transect control; m, meters]

Site[1]	Description	Control type	Date last surveyed	Northing[2] (m)	Easting[2] (m)	Elevation (m)	Comments
6	TC-06a	TC	6/19/2012	1,105,079.631710	3,365,893.73116	297.0695	Found
6	TC-06b	TC	6/19/2012	1,105,124.377660	3,365,888.23717	293.9080	Found
7	TBM-07a	BM	6/19/2012	1,105,527.240000	3,368,596.81000	291.5786	Found
7	BM-07b	BM	6/19/2012	1,105,573.560000	3,368,721.92000	292.7216	Found
7	BM-07c	BM	6/19/2012	1,105,515.111310	3,368,559.81982	291.9702	Found
7	TC-07b	TC	6/19/2012	1,105,503.118170	3,368,601.28780	288.2032	Found
7	TC-07d	TC	6/19/2012	1,105,458.876820	3,368,609.52214	286.6884	Found
8	BM-08a	BM	6/20/2012	1,104,677.070000	3,370,287.06000	286.0586	Found
8	BM-08b	BM	6/20/2012	1,104,605.590000	3,370,273.89000	287.8843	Found
8	BM-08c	BM	6/20/2012	1,104,704.821430	3,370,339.81439	287.1000	Found
8	TC-08b	TC	6/20/2012	1,104,723.820430	3,370,213.02480	286.9602	Found, was bent
9	BM-09a	BM	6/20/2012	1,104,713.130000	3,370,616.95000	286.4457	Found
9	BM-09b/C-12	BM	6/20/2012	1,104,524.510000	3,370,526.38000	292.4930	Found
9	BM-09c	BM	6/20/2012	1,104,617.837210	3,370,721.61788	286.1851	Found
9	BM-CITY DISK	BM	6/20/2012	1,104,682.684980	3,370,663.43727	286.3274	Found
9	TC-09d	TC	6/20/2012	1,104,743.007270	3,370,636.08414	282.7454	Found
10	BM-10a	BM	6/20/2012	1,103,980.600000	3,370,803.82000	281.9467	Found
10	BM-10b	BM	6/20/2012	1,103,846.480000	3,370,803.54000	283.1081	Found
10	TC-10a	TC	6/20/2012	1,103,979.457050	3,370,813.57984	282.4605	Found
10	BM-10c	BM	6/20/2012	1,103,996.344290	3,370,806.56957	282.2184	Found
10	TC-10b	TC	6/20/2012	1,103,984.553900	3,370,770.77137	282.3701	Found
11	BM-11c	BM	6/20/2012	1,103,587.250000	3,372,366.83000	280.1390	Found
11	BM-11b	BM	6/20/2012	1,103,459.530000	3,372,271.10000	278.9719	Found
11	BM-11g	BM	6/20/2012	1,103,562.457600	3,372,403.68846	281.6321	Found
11	BM-11f	BM	6/20/2012	1,103,455.475050	3,372,300.76241	281.0834	Found
11	TC-11d	TC	6/20/2012	1,103,562.804020	3,372,360.13729	280.5355	Found
11	TC-11a	TC	6/20/2012	1,103,570.329400	3,372,348.26986	280.0777	Found
11	BM-11e	BM	6/20/2012	1,103,546.388890	3,372,396.75687	281.9497	Found
11	TC-11b	TC	6/20/2012	1,103,577.330000	3,372,337.26241	278.2089	Found
11	TC-11c	TC	6/20/2012	1,103,596.933550	3,372,306.42493	277.5390	Found
12	BM-12a	BM	6/20/2012	1,103,469.170000	3,372,991.51000	280.4837	Found
12	BM-12b	BM	6/20/2012	1,103,549.530000	3,372,904.45000	281.4469	Found
12	BM-12c	BM	6/20/2012	1,103,453.781250	3,373,027.82241	280.7790	Found
12	TC-12c	TC	6/20/2012	1,103,490.111050	3,373,026.20531	279.1968	Found
12	TC-12d	TC	6/20/2012	1,103,495.102420	3,373,034.53421	277.4650	Found
12	TC-12e	TC					Not found

Appendix 1. Geomorphic survey benchmark and transect control location coordinates, Roanoke River, Roanoke and Salem, Virginia.—Continued

[Values reported represent the most recent coordinates from the 2012 survey. BM, benchmark; TC, transect control; m, meters]

Site[1]	Description	Control type	Date last surveyed	Northing[2] (m)	Easting[2] (m)	Elevation (m)	Comments
13	BM-13a	BM	6/21/2012	1,102,984.690000	3,374,376.43000	277.2619	Found
13	BM-13b	BM					Destroyed 2012
13	TC-13d	TC	6/21/2012	1,102,996.921190	3,374,358.88632	275.2207	Found
13	TC-13b	TC	6/21/2012	1,103,000.467980	3,374,353.79902	273.9411	Found
13	TC-13c	TC	6/21/2012	1,103,024.658010	3,374,319.10231	273.9860	Found
13	BM-13c	BM	6/21/2012	1,103,046.663440	3,374,411.35703	275.6346	Found
13	BM-13d	BM	6/21/2012	1,102,975.622340	3,374,341.75432	274.8264	Found
14	BM-14a/TC-14a	BM/TC	6/21/2012	1,103,691.960000	3,374,672.13000	276.1158	Found
14	BM-14b	BM	6/21/2012	1,103,893.000000	3,374,647.03000	276.4725	Found
14	TC-14d	TC	6/21/2012	1,103,695.759340	3,374,647.19224	273.6381	Found
14	TC-14c	TC	6/21/2012	1,103,703.160270	3,374,598.47265	273.8814	Found
15	BM-15c	BM	6/21/2012	1,104,048.795000	3,374,591.58600	276.5980	Found
15	BM-15a	BM	6/21/2012	1,104,129.277520	3,374,586.93473	277.2433	Found
15	BM-15d	BM	6/21/2012	1,104,028.764160	3,374,623.42430	276.5073	Found
15	TC-15f	TC	6/21/2012	1,104,067.960190	3,374,609.72419	276.7495	Found
15	TC-15a	TC	6/21/2012	1,104,058.454460	3,374,586.37269	276.7103	Found
15	TC-15e	TC	6/21/2012	1,104,054.241250	3,374,575.99971	273.2026	Found
15	TC-15d	TC	6/21/2012	1,104,035.036480	3,374,528.74337	272.5248	Found

[1] Site numbers correspond to site numbers from table 1 and figure 1.

[2] Coordinates reported in the same projection and coordinate system used for surveys: State Plane Virginia South FIPS 4502, Lambert Conformal Conic, North American Datum 1983.

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