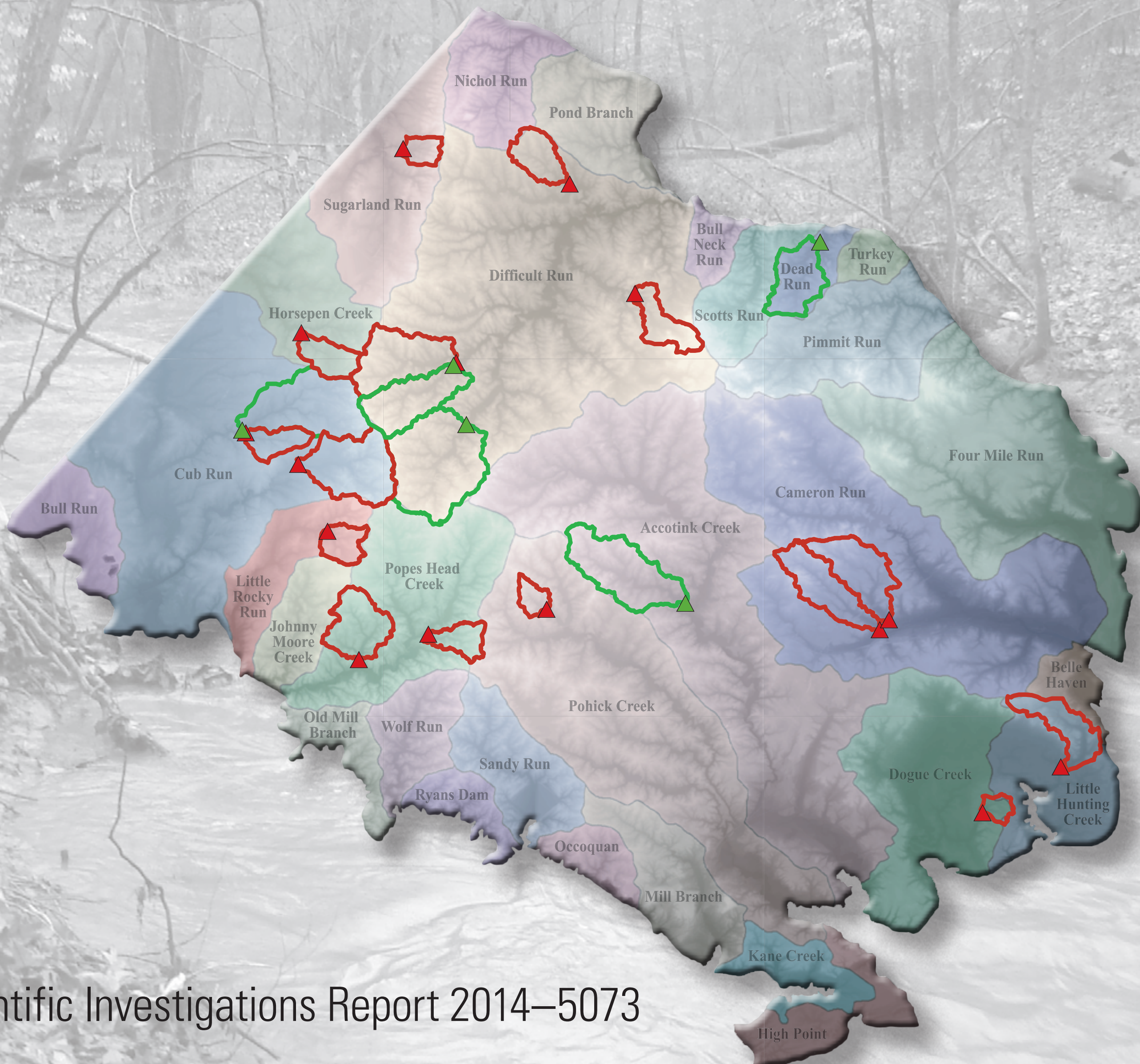
Streamflow, Water Quality, and Aquatic Macroinvertebrates of Selected Streams in Fairfax County, Virginia, 2007–12



Scientific Investigations Report 2014–5073

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Cover. (Front) Map showing watersheds of Fairfax County, Virginia, and monitoring stations with associated watersheds included in the analyses presented herein.

(Background photograph, front and back cover) Dead Run near Mclean, Virginia, during stormflow conditions. Photograph by James McCulla.

(Back cover, left rear photograph) Frog Branch near Chantilly, Virginia, during stormflow conditions. Photograph by James McCulla.

(Back cover, right rear photograph) Big Rocky Run near Chantilly, Virginia, during stormflow conditions. Photograph by James McCulla.

Streamflow, Water Quality, and Aquatic Macroinvertebrates of Selected Streams in Fairfax County, Virginia, 2007–12

By John D. Jastram

Prepared in cooperation with Fairfax County, Virginia

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SALLY JEWELL, Secretary

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This study was designed by Ken Hyer and Doug Moyer of the U.S. Geological Survey (USGS), who continue to contribute to the success of the effort by sharing expertise in water-resources monitoring and data analysis. Numerous USGS hydrologic technicians have spent substantial amounts of time in the field maintaining instrumentation and collecting data, and their efforts are greatly appreciated.

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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)
	Area	
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton per year (ton/yr)	0.9072	megagram per year (Mg/yr)
ton per year (ton/yr)	0.9072	metric ton per year
	Precipitation rate	
inch per year (in/yr)	25.4	millimeter per year
	Yield	
ton per square mile (ton/mi^2)	0.3503	metric ton per square kilometer
pound per square mile (lb/mi^2)	0.1751	kilogram per square kilometer (kg/km^2)

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

$$°F=(1.8\times°C)+32$$

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

$$°C=(°F-32)/1.8$$

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

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

Abbreviations

AEP	annual exceedance probability
AMLE	adjusted maximum likelihood estimator
BM	benthic macroinvertebrates
BMP	best management practices
DCA	Ronald Reagan Washington National Airport
DO	dissolved oxygen
FCSWPD	Fairfax County Stormwater Planning Division
FNU	formazin nephelometric units
IAD	Dulles International Airport
IBI	index of biotic integrity
NRTWQ	National Real Time Water Quality
NWIS	National Water Information System
SCI	stream condition index
SSC	suspended-sediment concentration
USGS	U.S. Geological Survey
WY	water year

Streamflow, Water Quality, and Aquatic Macroinvertebrates of Selected Streams in Fairfax County, Virginia, 2007–12

By John D. Jastram

Abstract

Efforts to mitigate the effects of urbanization on streams rely on best management practices (BMPs) that are implemented with the intent of reducing and retaining stormwater runoff. A cooperative monitoring effort between the U.S. Geological Survey and Fairfax County, Virginia was initiated in 2007 to assess the condition of county streams and document watershed-scale responses to the implementation of BMPs. Assessment of the data collected during the first 5 years of this monitoring program focused on characterizing the hydrologic and ecological condition of 14 monitored streams.

Hydrologic, chemical, and macroinvertebrate community conditions in the streams monitored were found to be consistent, overall, with conditions commonly observed in urban streams. Hydrologically, the monitored streams were found to be flashy, with flashiness positively related to road cover in the watershed. Typical pH values of streams throughout the network centered around neutrality (pH = 7) with strong daily fluctuations apparent in the continuous data. Patterns in specific conductance were largely representative of anthropogenic disturbances—watersheds having the greatest percentage of open space and estate residential land-use had the lowest typical specific conductance values, and specific conductance variability was less than what is observed in watersheds that are more intensively developed. In watersheds having greater road coverage, and more development in general, increases in specific conductance over several orders of magnitude were observed during winter months as a result of the application of de-icing salts on impervious surfaces. Dissolved oxygen conditions were typically within the range required to support healthy biological communities, although occasional departures during summer months at some sites fell below the impairment threshold for streams in Virginia.

Nitrogen (N) and phosphorus (P), concentration patterns were largely consistent across the network, with few exceptions. Nitrogen concentrations in monthly samples were generally low and dominated by nitrate. Exceptions to the generally low N concentrations occurred at Captain Hickory Run, which had a median total N concentration of approximately 4.9 milligrams per liter (mg/L), compared to the network-wide median of approximately 1.7 mg/L, and at Popes Head Creek Tributary, where total N concentrations spiked to 6–8 mg/L during low-flow periods in August or September of each year. Phosphorus concentrations in monthly samples were generally low and dominated by the dissolved fraction. Two monitoring stations in the network, Flatlick Branch and Frog Branch, are notable for having median total P concentrations that were, on average, approximately three times greater than the median total P concentration of 0.02 mg/L observed at the other 12 stations in the network.

Suspended-sediment and nutrient loads and yields were similar to those of urbanized watersheds in other studies, although the yields from these urbanized basins were greater than, or within, the upper quartile of yields observed throughout the Chesapeake Bay watershed. Annual suspended-sediment loads ranged from 289–10,275 tons, with a median of 1,311 tons, and corresponding yields ranged from 107–2,827 tons per square mile (ton/mi^2), with a median of 277 ton/mi^2. Annual total N loads ranged from 8,014–36,413 pounds, with a median of 21,314 pounds, and corresponding yields ranged from 3,361–8,360 pounds per square mile (lb/mi^2), with a median of 6,200 lb/mi^2. Annual total P loads ranged from 380–6,558 pounds, with a median of 1,874 pounds, and corresponding yields ranged from 140–1,562 lb/mi^2, with a median of 543 lb/mi^2.

Benthic macroinvertebrate community metrics indicated that streams throughout Fairfax County are generally of poor health. One station, Castle Creek, was an exception with results indicating relatively high quality aquatic health.

Six additional monitoring stations were added to the network in 2012 to improve spatial coverage throughout Fairfax County. Monitoring activities are expected to continue at all 20 stations for the foreseeable future as BMP implementation is conducted.

Introduction

In the United States, immigration and the migration of populations from rural areas to cities and their surrounding suburbs accelerated during the 20th Century (Kim, 2000), and has continued into the 21st Century (U.S. Census Bureau, 2013a). In Virginia, the percentage of the population residing in urban areas has risen from approximately 35 percent in 1940 to over 75 percent in 2010 (U.S. Census Bureau, 2012). Such urbanization results in extensive landscape changes as residential, commercial, and industrial structures and associated utilities are constructed to support municipal populations. These landscape changes greatly affect natural systems and biotic communities in and around the affected areas. In particular, the degradation of streams and associated ecosystems has consistently been observed in urbanized areas (Paul and Meyer, 2001; Coles and others, 2012).

Common effects of urbanization observed in affected watersheds include altered hydrology, increased nutrient and contaminant transport, decreased channel stability, reduced biotic richness, and increased dominance of perturbation-tolerant organisms. Collectively, these effects have been termed the “urban stream syndrome” (Feminella and Walsh, 2005; Meyer and others, 2005; Walsh and others, 2009). Many of these effects are caused by increased hydraulic efficiency, or more rapid movement of water from the landscape to receiving streams. The increased efficiency alters stream hydrology, which in turn impairs associated ecological systems.

The construction of roads, parking lots, and rooftops, as well as stormwater control structures designed to quickly drain water from the landscape, contributes to increased hydraulic efficiency. Rapid movement of water from the landscape to stream increases the frequency and magnitude of stormflows and (or) floods (Poff and others, 1997; U.S. Environmental Protection Agency, 1997; McMahon and others, 2003), causing stream-channel instability, increased contaminant transport, and degradation of biotic communities. Infiltration is reduced as water is quickly shunted from the landscape to the stream, and consequently, base flows are decreased as the quantity of groundwater in the contributing water table is reduced (Burton and Pitt, 2002). Decreased base-flow levels result in habitat loss and increased vulnerability to rapid thermal changes that further exacerbate the effects of urbanization on aquatic organisms (LeBlanc and others, 1997).

Recent efforts to mitigate the effects of urbanization have relied on the implementation of best management practices (BMPs) to manage urban stormwater and protect or restore the receiving water bodies. These BMPs include a wide range of structural and nonstructural practices aimed at reducing and (or) slowing the transport of stormwater and associated contaminants. Structural BMPs are features installed on the landscape that physically reduce the volume of stormwater runoff generated or retain stormwater for gradual release to the receiving water body and (or) infiltration into the groundwater system, such as stormwater detention ponds and retrofits of existing detention ponds with enhanced wetlands, bioswales, rain gardens, infiltration galleries, tree box planters, green roofs, permeable pavement, and stream and floodplain restorations. Nonstructural BMPs include restoration of riparian stream buffers, stream cleanup events, and outreach and education activities focused on both educating the public about the consequences of various activities and suggesting changes that can be made to those activities to reduce impacts on their local environment.

From 2007 to 2010, over $70 million was spent to protect and restore water quality in developed areas throughout the Chesapeake Bay watershed (Chesapeake Bay Program, 2013). Unfortunately, most watershed-scale efforts to document the effect of BMP implementation have not successfully demonstrated improvements (Meals and others, 2010; Corsi and others, 2013) resulting from such investments, despite widespread documentation of individual BMP efficiencies. The lack of documented improvements associated with BMP implementation has been attributed to several factors, including insufficient implementation intensity, improper selection of implemented BMPs, uncooperative weather and hydrologic conditions during study periods, misunderstood pollution sources and transport processes, and improper study design (Meals and others, 2010).

Fairfax County, Virginia, has experienced rapid population growth since the mid-20th Century (U.S. Census Bureau, 2013c), and consequently, most streams in Fairfax County show symptoms of urban stream syndrome. Within recent decades, Fairfax County has invested substantial resources into the assessment and protection of watersheds and planning for improved management of stormwater (Fairfax County Stormwater Planning Division, 2013). Specifically, watershed planning efforts in Fairfax County have focused on the goals of (1) improving and maintaining watershed functions, including those associated with water quality, habitat, and hydrology; (2) protecting human health, safety, and property by reducing stormwater impacts; and (3) involving stakeholders in the protection, maintenance, and restoration of watersheds (Fairfax County, 2013). Extensive implementation of BMPs is planned throughout Fairfax County watersheds to achieve the goals of the watershed plans.

In 2007, the U.S. Geological Survey (USGS) partnered with Fairfax County to initiate a long-term water-resources-monitoring study to evaluate watershed-scale effects of BMP implementation. This study is specifically designed to address the shortcomings just presented, which have led to inconclusive results about the effectiveness of BMPs at the watershed scale in other studies. During the initial years (2007–12) of this study, little implementation was achieved as a result of diminished tax revenues during the economic downturn that occurred at that time. A substantial amount of data were collected, however, that thoroughly document pre-implementation conditions in the streams monitored. This initial “baseline” characterization is the focus of the analyses presented herein.

Purpose and Scope

The purpose of this report is to summarize streamflow, water quality, and benthic macroinvertebrate community characteristics in Fairfax County, Virginia during 2007–12. To this end, the report also presents the rationale, study design, and initial data analysis performed for the cooperative water-resources monitoring network operated by USGS and Fairfax

County Stormwater Planning Division (FCSWPD) in Fairfax County Virginia. The initial 5 years of data are described and analyzed to provide general characterizations of hydrology, water quality, and stream health of the 14 monitored watersheds, spatial and temporal patterns in water quality and stream health across the 14-station network, and loads and yields of nutrients and sediment at four intensive monitoring stations.

Description of Study Area

Fairfax County is a 395 square mile (mi^2) jurisdiction in northern Virginia (fig. 1). The northern and southeastern boundaries of Fairfax County are defined by the Potomac River, which also defines the local boundary for the Commonwealth of Virginia. The western and southern boundaries are shared with Loudoun County and Prince William County, respectively, and portions of the eastern boundary are shared with Arlington County and the City of Alexandria.

As a result of its proximity to Washington, D.C., Fairfax County has become the most populous jurisdiction in Virginia, with a population of just over 1 million in 2010 (U.S. Census Bureau, 2013b). Much of the growth in population in Fairfax County has occurred since the 1940s, with the population increasing at an average rate of 68 percent per decade from 1940 to 2010 (U.S. Census Bureau, 2013c). Accordingly, land use in Fairfax County is dominated by residential uses, with approximately half of the residences in those areas being single-family detached homes, one-quarter townhomes, and one-quarter multi-family dwellings (Fairfax County, 2011).

Climate—Fairfax County has a humid temperate climate with an average annual precipitation ranging from approximately 39 to 44 inches per year (in/yr) (Southeast Regional Climate Center, 2012). This precipitation is generally well distributed throughout the year, with low-pressure fronts creating rainfall during cool winter months and brief thunderstorms creating rainfall during warm summer months. The average annual temperature ranges from 55 °F to 58 °F, with average January minimums of 23 °F to 28 °F and average July maximums of 83 °F to 88 °F (Southeast Regional Climate Center, 2012).

Physical Setting—Geologic terranes are defined by the type of rock underlying an area, whereas physiographic provinces are defined by landforms at the surface; however, landforms in Virginia are strongly influenced by subsurface geology, and therefore geologic terranes and physiographic provinces are often coincident. Fairfax County is underlain by three major geologic terranes: the Atlantic Coastal Plain, the Piedmont, and the Triassic Lowland (Froelich and Zenone, 1985a). These geologic terranes occur in association with the Coastal Plain physiographic province, Piedmont physiographic province, and Mesozoic Basins physiographic subprovince, respectively (fig. 1). The physical characteristics of these terranes and provinces strongly influence surface water and groundwater flow patterns, as well as water-quality conditions and transport processes.

The majority of Fairfax County lies within the Piedmont terrane, with only the western and eastern extents of the county present in the other terranes (fig. 1). The Piedmont is underlain by highly weathered metamorphic crystalline rock, which has been chemically weathered at the surface to form saprolite (Froelich and Zenone, 1985a). The thickness and permeability of this saprolite vary substantially, from thin and nearly impervious to nearly 200 feet (ft) thick and well-drained, depending upon the parent material from which it was formed (Froelich and Zenone, 1985a). The generally thick overburden of the Piedmont on rolling uplands results in palmate drainage basins having wide alluvial floodplains and narrow, bedrock-controlled stream gorges (Froelich and Zenone, 1985a).

The bedrock of the Triassic Lowland terrane, which occurs along the western boundary of Fairfax County, consists of sedimentary rocks, such as shale and siltstone with local intrusions of igneous diabase (Froelich and Zenone, 1985b). Soils in this province are generally shallow and poorly drained, with topography that is generally of low relief (Froelich and Zenone, 1985a), resulting in dendritic stream networks occurring in very broad and shallow stream valleys (Froelich and Langer, 1983).

The eastern extent of Fairfax County is in the Atlantic Coastal Plain terrane, which is underlain by sedimentary deposits of sand and clay, capped by sheets of gravel (Froelich and Zenone, 1985a). The uplands of this province are relatively flat and low-lying, resulting in streams that flow at low velocities through broad, flat-bottomed valleys (Froelich and Langer, 1983).

Methods of Investigation

This study was designed to provide information to better understand the current condition of streams in Fairfax County and to track changes in stream conditions as BMPs are implemented. Additionally, the data collection and analysis approaches were designed to overcome the following issues, which typically challenge the ability to statistically quantify changes in water quality attributed to the implementation of BMPs:

1. The collection of numerous individual samples needed each year to provide the requisite data from which to calculate trends in water-quality typically comes at a substantial cost, which often limits post-implementation monitoring.

2. Confounding environmental factors, such as streamflow, rainfall distributions, and seasonality, often cause extensive variability in measured water-quality constituents that complicates attempts to quantify improvements attributed to BMP implementation.

3. Lag times between BMP implementation and watershed response may be long, and monitoring programs are often too short in duration to capture the signal of response (Meals and others, 2010).

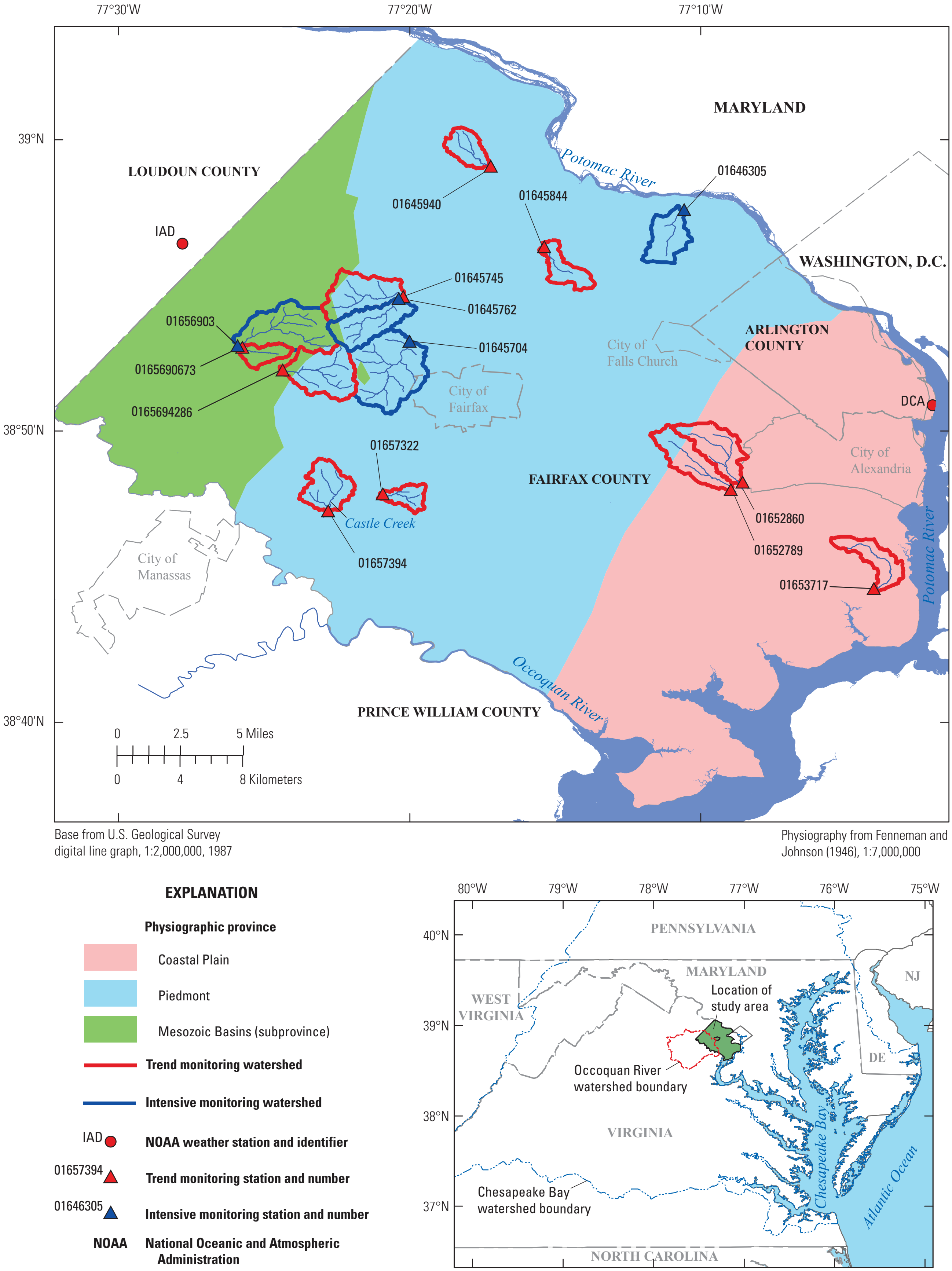

Figure 1. Monitoring stations and watersheds.

Study Design

The challenges just described were addressed through the design of a long-term monitoring program that uses a tiered monitoring intensity across a network of numerous monitoring locations. This network includes 4 intensive water-resources monitoring stations and 10 low-intensity monitoring stations (trend-monitoring stations; fig. 1). These two tiers were designed specifically to address different objectives of the overall effort, and to do so within budgetary constraints.

The intensive monitoring stations were instrumented to provide continuous measurements of streamflow and water-quality parameters, and to provide those data online in near real-time. Automated sampling equipment was operated at the stations to collect discrete samples for laboratory analysis during periods of stormflow. In addition, the stations were visited monthly to collect additional discrete water-quality samples that represent a random distribution of hydrologic conditions. In contrast, the trend-monitoring stations were only visited monthly to collect discrete water-quality samples during random hydrologic conditions, and periodically to measure streamflow.

Selection of Watersheds and Monitoring Locations

Proper design of the monitoring network required careful selection of monitoring locations to accurately represent watersheds in Fairfax County. The monitoring station selection process relied on initial statistical categorization of candidate watersheds with posterior refinement using local knowledge of watersheds and planned implementation activities.

Candidate watersheds were those approximately 6 mi^2 or smaller in area that were included in the first phase of Fairfax County's watershed planning process, which encompassed approximately 50 percent of the land area in Fairfax County; 52 watersheds met both criteria. Watersheds were characterized in terms of land use, average condition of the benthic macroinvertebrate community, percent imperviousness, presence of existing BMPs, and average watershed slope.

Cluster analysis (Shaw, 2003) was performed on the dataset of watershed characteristics to categorize the 52 candidate watersheds for selection. At a coarse scale, this cluster analysis grouped the watersheds into three classes: low-density urban land-uses, high/medium-density urban land-uses, and industrial land-uses, where density of urbanization was primarily defined by residential density. At a finer scale, these coarse classes were separated into 6 clusters of high/medium-density urban land-uses, 5 clusters of low-density urban land-uses, and 1 cluster of industrial land-use. The industrial cluster included two watersheds, both of which drained the grounds of Dulles International Airport. These two watersheds were removed from consideration because of the anomalous conditions presented by the airport facilities and because stormwater management on airport grounds is not within the jurisdiction of Fairfax County.

Final watershed selection was performed through review of the cluster analysis results with County staff who had on-the-ground knowledge of the candidate watersheds. Final study watersheds were selected based on planned BMP implementation within the watersheds and known limitations or advantages of working in particular watersheds. Monitoring station locations within each selected watershed were determined during field inspections of the selected watersheds.

Description of Watersheds and Streams Monitored

The monitoring station selection process resulted in the selection of 14 locations for monitoring stations—4 intensive monitoring locations and 10 trend monitoring locations (table 1). The 14 monitoring stations are distributed throughout Fairfax County and are representative of the physiographic provinces within Fairfax County (fig. 1).

The 14 monitoring stations are located along streams draining a range of land-cover types representative of the land-cover distribution throughout Fairfax County, as determined from Fairfax County Stormwater Planning Division (2007). Monitored watersheds considered to have the least urban impact were those with the greatest proportions of open space and estate and low-density residential, such as Castle Creek, Little Difficult Run, and S.F. Little Difficult Run (fig. 2). Watersheds considered to have the greatest degree of urban impact were those having the greatest proportions of roads, industrial and commercial land-uses, and high-density residential uses, such as Old Courthouse Spring Branch, Big Rocky Run, and Indian Run (fig. 2).

The watersheds monitored are representative of the distribution of physiographic provinces and geologic terranes of Fairfax County. The majority of watersheds are representative of the Piedmont terrane, with 10 watersheds having greater than 60 percent of their watershed area overlying the Piedmont—6 of which are 100 percent Piedmont (table 1). Two watersheds are entirely or nearly entirely within the Triassic Lowlands terrane, and one watershed is entirely within the Coastal Plain terrane (table 1).

Data Collection, Sampling, and Laboratory Analysis

All data-collection activities performed in support of the cooperative monitoring program were conducted in accordance with prescribed methods. Generally, these were established USGS methods intended to ensure the accuracy of the collected data and to promote national consistency in hydrologic data. Data-collection responsibilities were shared between USGS and FCSWPD staff.

Streamgaging activities, which include discrete measurements of streamflow, operation of continuous and noncontinuous streamgaging stations, and streamflow data management, were conducted by USGS staff in accordance

Table 1. Monitoring station identifiers, names, abbreviations, types, watershed areas, and percentage of watershed in geologic terranes.

[mi^2, square mile; –, no value]

Station identifier	Station name	Short name	Station type	Watershed area (mi^2)	Percent Coastal Plain	Percent Piedmont	Percent Triassic Lowland
01646305	Dead Run at Whann Avenue near Mclean, VA	DEAD	Intensive	2.05	–	100	–
01645704	Difficult Run above Fox Lake near Fairfax, VA	DIFF	Intensive	5.49	–	100	–
01656903	Flatlick Branch above Frog Branch at Chantilly, VA	FLAT	Intensive	4.20	–	1	99
01645762	South Fork Little Difficult Run above mouth near Vienna, VA	SF LIL	Intensive	2.71	–	96	4
0165694286	Big Rocky Run at Stringfellow Rd near Chantilly, VA	BRR	Trend	3.40	–	63	37
01645940	Captain Hickory Run at Route 681 near Great Falls, VA	CAPT HICK	Trend	1.38	–	100	–
01657394	Castle Creek at Newman Road at Clifton, VA	CASTLE	Trend	2.21	–	100	–
0165690673	Frog Branch above Flatlick Branch at Chantilly, VA	FROG	Trend	0.99	–	–	100
01652789	Indian Run at Bren Mar Drive at Alexandria, VA	INDIAN	Trend	2.45	14	86	–
01645745	Little Difficult Run near Vienna, VA	LIL DIFF	Trend	2.99	–	97	3
01645844	Old Courthouse Spring Branch near Vienna, VA	OCSB	Trend	1.45	–	100	–
01657322	Popes Head Creek tributary near Fairfax Station, VA	PHCT	Trend	0.95	–	100	–
01653717	Paul Spring Br above North Branch near Gum Springs, VA	PSB	Trend	1.89	100	–	–
01652860	Turkeycock Run at Edsall Road at Alexandria, VA	TRKYCK	Trend	2.59	57	43	–

with standards defined by the USGS Office of Surface Water. Procedures used to collect, process, and store streamflow data are defined in various USGS Techniques of Water-Resources Investigations reports (U.S. Geological Survey, variously dated *b*).

Non-vented internally logging pressure sensors, HOBO U–20 (Onset Computer Corp.) water-level data loggers, were installed at all trend monitoring stations during water year 2009 as a cost-effective approach to generate timeseries stage data at these stations with less intensive data collection. The sensors were configured to record absolute pressure (atmospheric pressure plus water-column pressure) at 15-minute intervals. The absolute pressure data were converted to water level using atmospheric pressure data collected at two monitoring stations within the network and manually measured water level at the time of logger servicing. The 0.015 ft accuracy of these sensors does not meet the USGS Office of Surface Water accuracy requirement of 0.01 ft for stage sensors at streamgaging stations (Sauer, 2002); however, the accuracy is sufficient for the objectives of this component of the data-collection effort, and is consistent with the accuracy of data collected by numerous other recent USGS studies with similar objectives (Gregory and Calhoun, 2006; Moring, 2006; Richards and others, 2006; Sprague and others, 2006; Waite and others, 2006).

Operation of the continuous water-quality monitors and management of the continuous water-quality data were conducted by USGS staff in accordance with Wagner and others (2006) and U.S. Geological Survey (variously dated *a*). In general, the instruments are serviced monthly to clean and re-calibrate the sensors as needed, and data were collected during these visits to support the correction of timeseries data in the event of calibration drift or fouling.

Collection of water samples for laboratory analyses of nutrients and suspended sediments was conducted by USGS and FCSWPD staff in accordance with U.S. Geological Survey (variously dated *a*). The small size and shallow depths

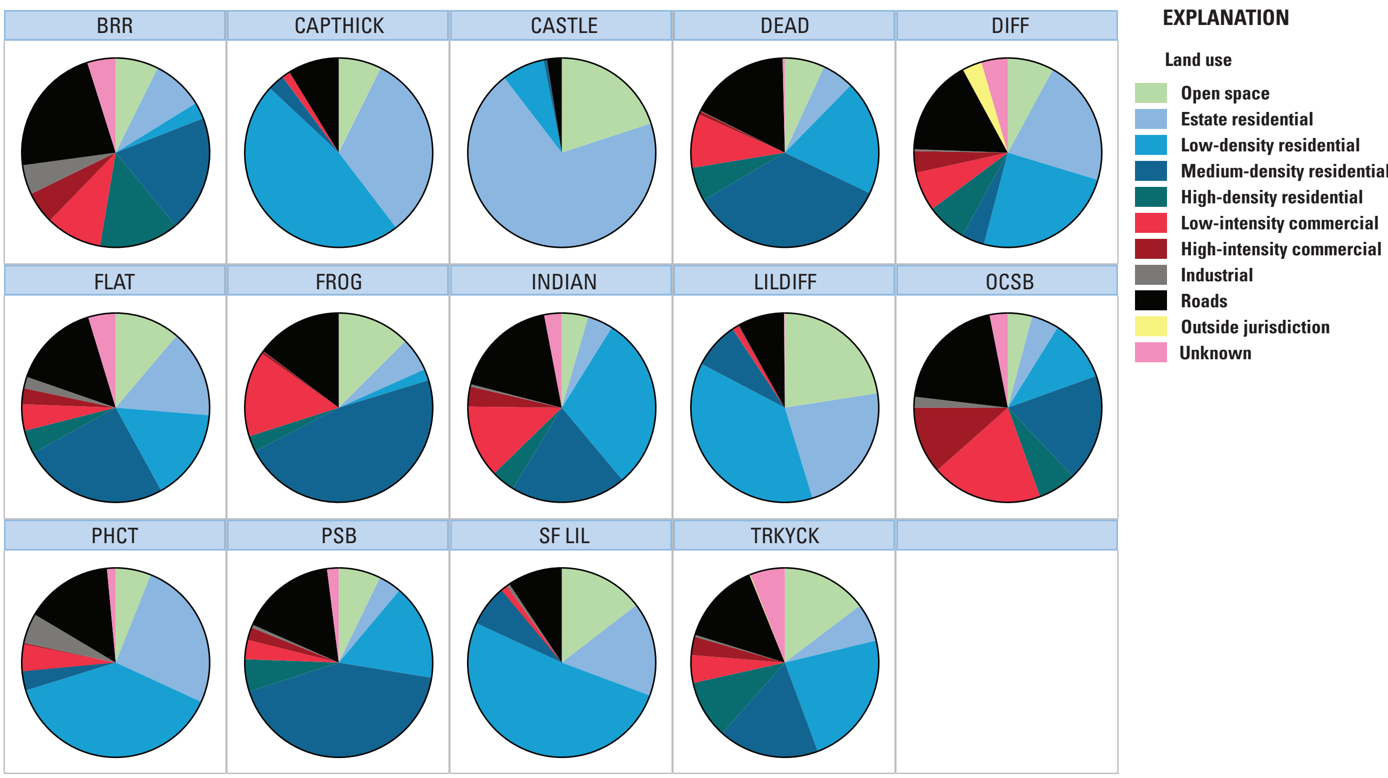

Figure 2. Percentages of land-use types within 14 monitored watersheds in Fairfax County. Station names defined in table 1.

of the streams generally precluded the use of width- and depth-integrating sampling procedures typically employed on larger streams; therefore, most routine sampling was accomplished using a grab (dip) sampling approach. Occasionally, high flow conditions were encountered during manual sampling visits. The flashy nature of these urban streams presents a danger to sampling personnel should they attempt to enter the stream to collect a sample using width- and depth-integrating procedures during these times. In addition, there are generally no suitable stream crossings (such as bridges or culverts) from which to sample from; therefore, grab samples were collected during these conditions as well.

Scheduled monthly sampling was conducted on predetermined dates each month, regardless of hydrologic conditions on the specified sampling day. The intent of this scheduled sampling approach was to randomly represent the range of hydrologic conditions occurring during the study period. All 14 monitoring stations were sampled on the same day to limit variability in conditions across the stations for a given monthly sample.

Targeted storm sampling was accomplished at the four intensive monitoring stations using refrigerated automatic samplers. These samplers, located inside the monitoring station shelter, consist of a peristaltic pump, control unit, and refrigerated sample-storage container. The samplers are capable of collecting 12 discrete samples, with each sample filling two 1-liter polyethylene bottles—one bottle is used for nutrient analyses and the second is used for sediment analyses. Samples were pumped from a single point in the stream channel through a 3/8-in.-diameter vinyl tube. Triggering of the autosampler was accomplished by programming an algorithm into the monitoring station datalogger that was designed to ensure stormflow conditions were occurring and to properly distribute the sampling throughout the stormflow event. The algorithm includes thresholds for turbidity, stream stage, rate-of-change in stage, and time elapsed since last sample collection. The turbidity and time elapsed since last sample collection thresholds are constant across monitoring stations—50 formazin nephelometric units (FNU) and 30 minutes, respectively. Stream stage and rate-of-change in stage are site-specific thresholds, determined through observation of stormflow hydrographs. Sampling data, measured every 15 minutes, were transmitted via satellite and uploaded hourly to the USGS National Water Information System Web interface (NWISWeb; *http://waterdata.usgs.gov/va/nwis*) for evaluation by USGS staff. This information was then relayed to FCSWPD staff, who retrieved the samples for delivery to the appropriate laboratories for analysis.

Nutrient analyses of the water samples were conducted by the Fairfax County Environmental Services Laboratory, as approved through the USGS Laboratory Evaluation Program. Raw (unpreserved) samples were delivered to the laboratory, where laboratory staff promptly filtered and preserved aliquots as required for analyses. Samples were analyzed for total nitrogen and total phosphorus, as well as dissolved and particulate fractions of the totals, in accordance with specified methods (table 2).

Sediment analyses of the water samples were conducted by the USGS Eastern Region Sediment Laboratory in Louisville, Kentucky. All samples were analyzed for suspended-sediment concentration (Guy, 1969; Shreve and Downs, 2005). Storm-event samples were additionally analyzed for sand-fine split—the percentage of material finer than 0.0625 millimeter (mm; Guy, 1969; Shreve and Downs, 2005).

Benthic macroinvertebrate samples were collected annually in the spring by FCSWPD staff, with occasional sampling assistance from USGS staff, in conjunction with the annual sampling performed for the Fairfax County Biological Stream Monitoring Program (Fairfax County Stormwater Planning Division, 2013). Samples of benthic macroinvertebrates were collected, stream-habitat metrics were evaluated, and basic water-quality parameters were measured according to defined procedures (Fairfax County Stormwater Planning Division, 2006). Benthic macroinvertebrate samples were preserved and retained for later sorting and identification by a FCSWPD staff entomologist using the laboratory procedures described by the Fairfax County Stormwater Planning Division (2006). Benthic macroinvertebrate sampling results are summarized using the Fairfax County index of biotic integrity (IBI; Fairfax County Stormwater Planning Division, 1999) and the Virginia stream condition index (SCI; Burton and Gerritsen, 2003). Both metrics are calculated from measures of the benthic macroinvertebrate community and provide scores on a 0–100 (poor to excellent) scale as a relative measure of stream health.

Table 2. Nutrient constituents, abbreviations, and analytical methods for analyses performed by Fairfax County Environmental Services Laboratory.

[USEPA, U.S. Environmental Protection Agency (U.S. Environmental Protection Agency, 2013); SM, Standard Methods (American Public Health Association, 1976)]

Constituent	Abbreviation	Method
Nitrogen		
Total nitrogen	TN	USEPA351.2 + USEPA 353.2
Total dissolved nitrogen	TDN	USEPA 351.2 + USEPA 353.3
Total particulate nitrogen	TPN	USEPA 351.2 - USEPA 353.2
Total Kjeldahl nitrogen	TKN	USEPA 351.2
Dissolved Kjeldahl nitrogen	DTKN	USEPA 351.2
Nitrate + nitrite	NOx	USEPA 353.2
Ammonia	NH_3	USEPA 350.1
Phosphorus		
Total phosphorus	TP	SM425C & 425E
Total dissolved phosphorus	TDP	SM 425C & 425E
Total particulate phosphorus	TPP	SM 425C & 425E
Orthophosphorus	OP	USEPA 365.2

Data collection began in the fall of 2007 with the installation of the four intensive monitoring stations (table 1, fig. 1). Continuous datasets for streamflow and water-quality parameters are available from the beginning of the 2008 water year (WY; October 1, 2007), with the exception of all parameters at Dead Run and dissolved oxygen (DO) at all monitoring stations. Data collection at Dead Run was delayed until November 2007 for water-quality parameters and January 2008 for stage and streamflow. DO was later added to all monitoring stations as additional research was initiated at the stations. All continuous data are available online from NWISWeb at *http://waterdata.usgs.gov/va/nwis*.

Collection of monthly water-quality samples across the 14-station network began in April 2008 and has resulted in the collection of 756 water-quality samples through the end of WY 2012. Storm sample collection at the four intensive monitoring stations also began in April 2008, although initially these samples were analyzed only for suspended sediment. At differing times late in WY 2008, electricity was supplied to the monitoring stations, and nutrient sampling was initiated as the sample refrigerator on the autosampler was powered to preserve the samples. Through the end of WY 2012, a total of 753 storm event samples were collected and analyzed at the four intensive monitoring stations. All water-quality sampling results are available online from NWISWeb.

Annual benthic macroinvertebrate sampling was initiated in the spring of 2008 and has continued through the spring of 2012, resulting in the collection of five benthic macroinvertebrate samples at each of the 14 monitoring stations. Benthic macroinvertebrate sampling results are provided in appendix 1.

Formulation of Suspended-Sediment and Nutrient Load Models

Suspended-sediment and nutrient load models were calibrated using instantaneous loads computed from the discrete monthly and storm sample data as dependent variables, and continuous streamflow and water-quality parameters, including water temperature, specific conductance, pH, and turbidity, as potential explanatory variables. Dependent and explanatory variables were transformed using a natural logarithm (ln) transformation to normalize their distribution as required for linear regression analysis (Helsel and Hirsch, 2002). Model selection was conducted independently for each monitoring station-constituent combination by evaluating all possible models and selecting the model with the lowest Mallows' Cp value (Helsel and Hirsch, 2002) using the software package Load Estimator (S–LOADEST; Lorenz and others, 2011). Selecting a model with the smallest Mallows' Cp value provides a compromise between explaining the most variance possible in the response through incorporation of all relevant regressors and minimizing the variance of the estimates by minimizing the number of regressors (Helsel and Hirsch, 2002). For constituents having censored concentration values, the adjusted maximum likelihood estimator (AMLE) was used to properly fit the model to the censored data (Runkel and others, 2004).

As described by Runkel and others (2004), the general form of the load estimation models is

$$\ln(L) = a_0 + \sum_{j=1}^{NV} a_j X_j \quad (1)$$

where

$\ln(L)$	is the natural logarithm of instantaneous load,
a_0	is the intercept,
NV	is the number of explanatory variables,
a_j	is a model coefficient, and
X_j	is an explanatory variable.

Once an appropriate model was selected, annual (water year), monthly, daily, and instantaneous loads were computed in S–LOADEST using the unit value (15-minute) data as the input file. These loads were then divided by the watershed area of the monitoring station to determine yields.

Formulation of Suspended-Sediment and Nutrient Concentration Models

Methods for regression models using streamflow and water-quality variables (surrogates) to estimate sediment and nutrient loads were presented in the previous section. However, although S–LOADEST generates estimation models with load as the dependent variable (Lorenz and others, 2011), concentration estimation models may also be of interest in some applications. Load- and concentration-estimation models are inherently related, as load is simply the product of concentration and streamflow, and earlier versions of LOADEST programmed in FORTRAN provide both forms of the estimation model (Runkel and others, 2004).

Concentration-estimation models are required for use in the USGS National Real Time Water Quality (NRTWQ; *http://nrtwq.usgs.gov*) Web interface. NRTWQ couples such models with real-time data to display estimates of constituent concentration and load, in near real-time, when such models are available. Additionally, numerous efforts throughout Virginia (Jastram and others, 2009, 2010) and the Nation (Lewis, 1996; Christensen and others, 2000; Lee and others, 2008; Rasmussen and others, 2008; Baldwin and others, 2012; Chanat and others, 2013; Miller and others, 2013) utilize similar models, making regional or larger scale evaluations possible when models are available in comparable forms.

Regression models to estimate suspended-sediment and nutrient concentrations were developed with JMP 10 software (SAS Institute, Cary, N.C.) using procedures similar to those used to develop load estimation models. In addition to determining the best-possible model according to Mallows' Cp, models using a single explanatory variable, turbidity, and models using two explanatory variables, turbidity and streamflow, were developed. These commonly used model forms were developed regardless of their explanatory power to provide a basis for comparison to other locations.

Hydrologic Conditions

Hydrologic conditions, particularly the occurrence of droughts and floods, are primarily affected by precipitation patterns. These conditions are major drivers of the processes that control the transport of nutrients and sediments and the health of aquatic communities. Stormwater management actions seek to mitigate the effects of landscape development on hydrologic conditions in receiving streams, and streamflow statistics are expected to reflect the effectiveness of management actions in mitigating these effects.

Precipitation

Annual and monthly precipitation data (National Oceanic and Atmospheric Administration, 2013) used to characterize precipitation in the study area were obtained from National Weather Service meteorological stations at Dulles International Airport (IAD), located in western Fairfax County, and Ronald Reagan Washington National Airport (DCA), located in Arlington County near the eastern border of Fairfax County. The magnitude and temporal distribution of precipitation during the five water years (2008–12) was variable, as shown by the rainfall data from the two meteorological monitoring stations (fig. 3*A*–*B*).

Water year 2012 had the least total precipitation of the 5 years evaluated at both monitoring stations (fig. 3*A*). Precipitation was below the long-term (1981–2010) average in WYs 2009, 2011, and 2012 at the IAD monitoring station, and in WYs 2009 and 2012 at the DCA monitoring station (fig. 3*A*). Although WY 2009 was drier than average, 43 and 38 percent of the annual total precipitation fell in the months of May and June at IAD and DCA, respectively (fig. 3*B*). Precipitation in WY 2012, however, was much more evenly distributed throughout the year (fig. 3*B*). Water years 2008 and 2010 had the greatest total precipitation of the 5 years evaluated, with totals 11 percent to 29 percent greater than average (fig. 3*B*). Approximately 20 percent of the annual total rainfall at each monitoring station fell within the month of May during WY 2008, whereas the precipitation was more evenly distributed throughout the year in WY 2010 (fig. 3*B*).

As indicated above, some months were notable for high rainfall amounts, and these high precipitation periods have pronounced effects on hydrologic and water-quality conditions. Total precipitation in May 2008 was 9.4 and

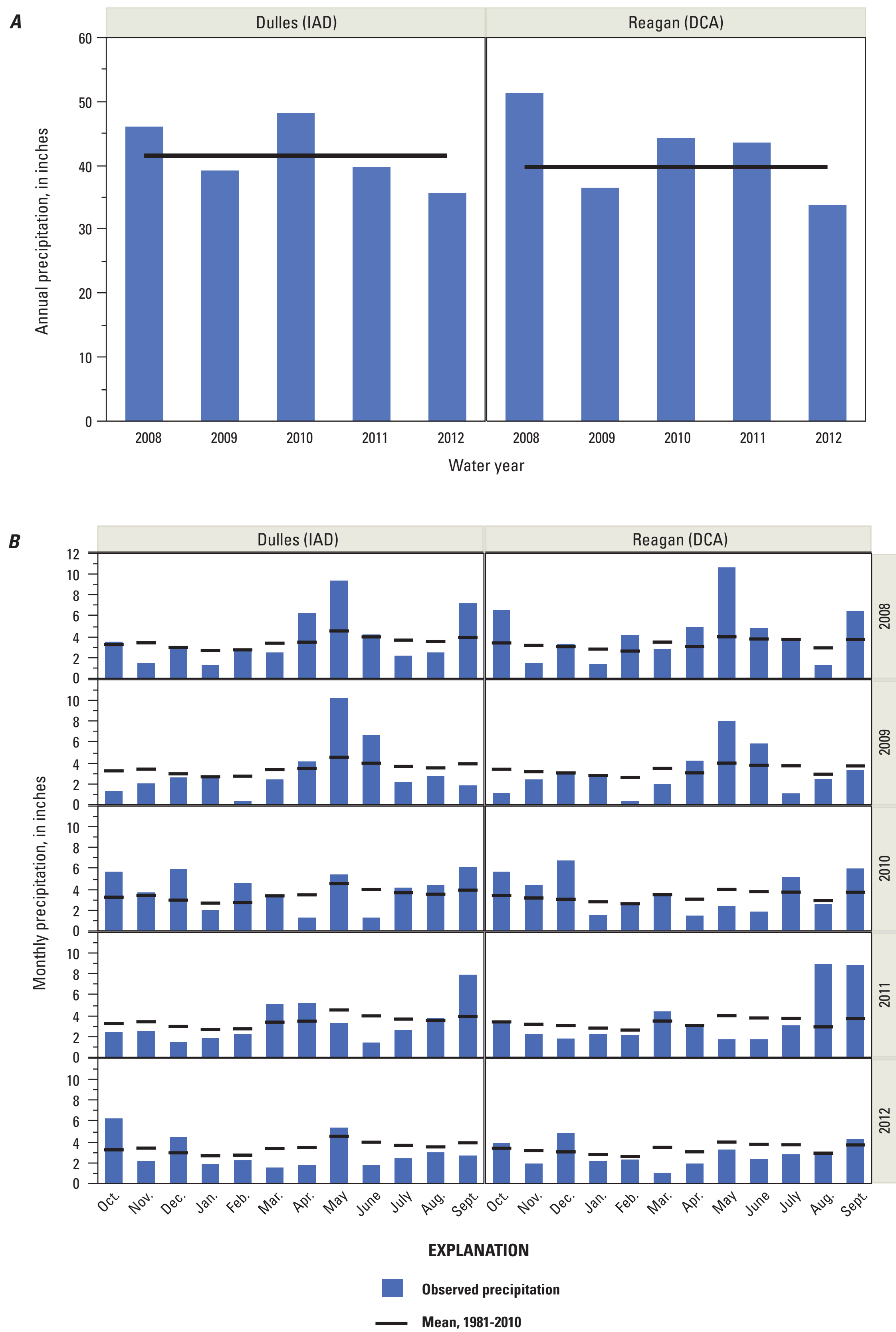

Figure 3. *A*, Annual and *B*, monthly precipitation data from Dulles International Airport and Ronald Reagan Washington National Airport for water years 2008 through 2012 with mean annual and monthly values from the period 1981–2010. Data from National Weather Service.

10.7 inches (in.) at IAD and DCA, respectively (fig. 3*B*), resulting from numerous rainfall events throughout the month. The remnants of Hurricane Hanna brought heavy rains to the study area, accounting for most of the 7.2 and 6.4 in. of precipitation that fell in September 2008 at IAD and DCA, respectively (fig. 3*B*). Total precipitation in May 2009 was 10.3 and 8.1 in. at IAD and DCA, respectively (fig. 3*B*), resulting from numerous rainfall events throughout the month. In August 2011, Hurricane Irene and multiple severe weather systems delivered a total of 8.9 in. of rain at DCA, while areas further west received much less, as indicated by the 3.7 in. that fell at IAD (fig. 3*B*). Tropical Storm Lee brought heavy rain to the area in September 2011, accounting for most of the 7.9 and 8.8 in. that fell at IAD and DCA, respectively (fig. 3*B*).

Streamflow

Streamflow conditions at the four intensive monitoring stations were summarized by computing the cumulative streamflow yield, or volume of streamflow generated per square mile of watershed area, on a daily time step, for each water year (fig. 4*A*). This representation of streamflow allows for comparison of streamflow conditions at a given site across years, clearly depicting dry and wet periods, and for comparisons across stations to evaluate potential differences in streamflow generation across watersheds. Further, the rate of cumulative streamflow yield throughout the year is a major driver of the magnitude of nutrient and sediment loads and yields because discrete, major streamflow events can transport substantially more sediment and associated nutrients than numerous smaller events having a similar total streamflow yield.

The first half of water year 2008 was the driest (lowest cumulative streamflow yield) of the 5 years evaluated, although high flows during the second half of the water year resulted in 2008 having the highest cumulative annual streamflow yield of the 5 years evaluated at Difficult Run and S.F. Little Difficult Run, and the second highest at Flatlick Branch (fig. 4*A*). High-flow events in May, resulting from numerous thunderstorms, quickly increased the cumulative flow yield for the year into the wettest conditions observed over the period, followed by substantial increases in cumulative flow from Tropical Storm Hanna in September (fig. 4*A*). It is important to note that streamflow data were not collected at Dead Run prior to January 10, 2008, resulting in incomplete representation of WY 2008 for Dead Run in figure 4.

Water year 2009 also began dry, and although above-average precipitation in May and June (fig. 3*B*) led to increases in cumulative streamflow yield, the year overall ended among the driest of the 5-year period (fig. 4*A*) as a result of the below-average annual precipitation for the year (fig. 3*A*).

Consistent with the above-average precipitation distributed throughout WY 2010 (fig. 3*B*), cumulative streamflow yield was consistently high throughout the year, with the total annual streamflow yield ranking the highest of the 5 years at Flatlick and second highest at Dead Run and S.F. Little Difficult Run (fig. 4*A*). The high cumulative streamflow yields observed in WY 2010 are unique among the 5 years because of the consistently wet conditions throughout the year, whereas other years with high cumulative streamflow conditions generally resulted from discrete high-flow events or relatively short periods of elevated flows.

Cumulative streamflow yields varied considerably among stations during much of WY 2011, with streamflow yields at Dead Run and Difficult Run among the highest of the 5 years during most of the WY and streamflow yields at Flatlick Branch and S.F. Little Difficult Run yields were among the lowest of the 5 years during most of the WY (fig. 4*A*). In September 2011 the remnants of Tropical Storm Lee delivered substantial precipitation throughout the study area, resulting in the greatest peak streamflows observed during the study period.

Above-average precipitation in early WY 2012 (October and December; fig. 3*B*) resulted in some of the highest streamflow yields observed during the initial few months of the WY. Below-average precipitation throughout the remainder of the remainder of the WY (fig. 3*B*), however, resulted in WY 2012 being among the driest (lowest streamflow yield) of the 5 years for much of the WY (fig. 4*A*).

Comparison of streamflow yields across the four stations was achieved by fitting a smoothing spline (Eubank, 1988) to the 5 years of cumulative streamflow yields for each site (fig. 4*B*). For the 5 years evaluated, Flatlick Branch had the greatest streamflow yield throughout the WY and Difficult Run had the second greatest yield (fig. 4*B*). Streamflow yields at Dead Run and S.F. Little Difficult Run were very similar and the lowest of the four stations (fig. 4*B*). Numerous factors, including physical setting and land use, can affect streamflow yields, although the particular factors affecting differences among the monitored streams are not evaluated herein.

Peak Streamflow Frequency

Streamflow annual exceedance probability (AEP) estimates, which may also be expressed as recurrence intervals, are useful for determining how common or rare a given stormflow event is expected to be. Calculation of these statistics requires 10 years or more of streamflow data (Maidment, 1993). AEP estimates can be made, however, for ungaged watersheds, or watersheds lacking sufficient data to compute the statistics, by adjusting the exceedance probabilities from nearby sites to account for differences in watershed area (Hannum, 1976; Bisese, 1994; Glatfelter, 1984). Austin and others (2011) computed AEPs for nearby sites that could be used to compute such estimates for the four intensive monitoring stations. The nearby sites for which AEPs were computed were only operated during the 1950s, 1960s, and 1970s (Samuel Austin, U.S. Geological Survey, written commun., 2013), and therefore the AEPs for these sites are not representative of current land use in the watersheds. Consequently, reliable estimates of AEPs for the four intensive monitoring stations could not be computed with the available data.

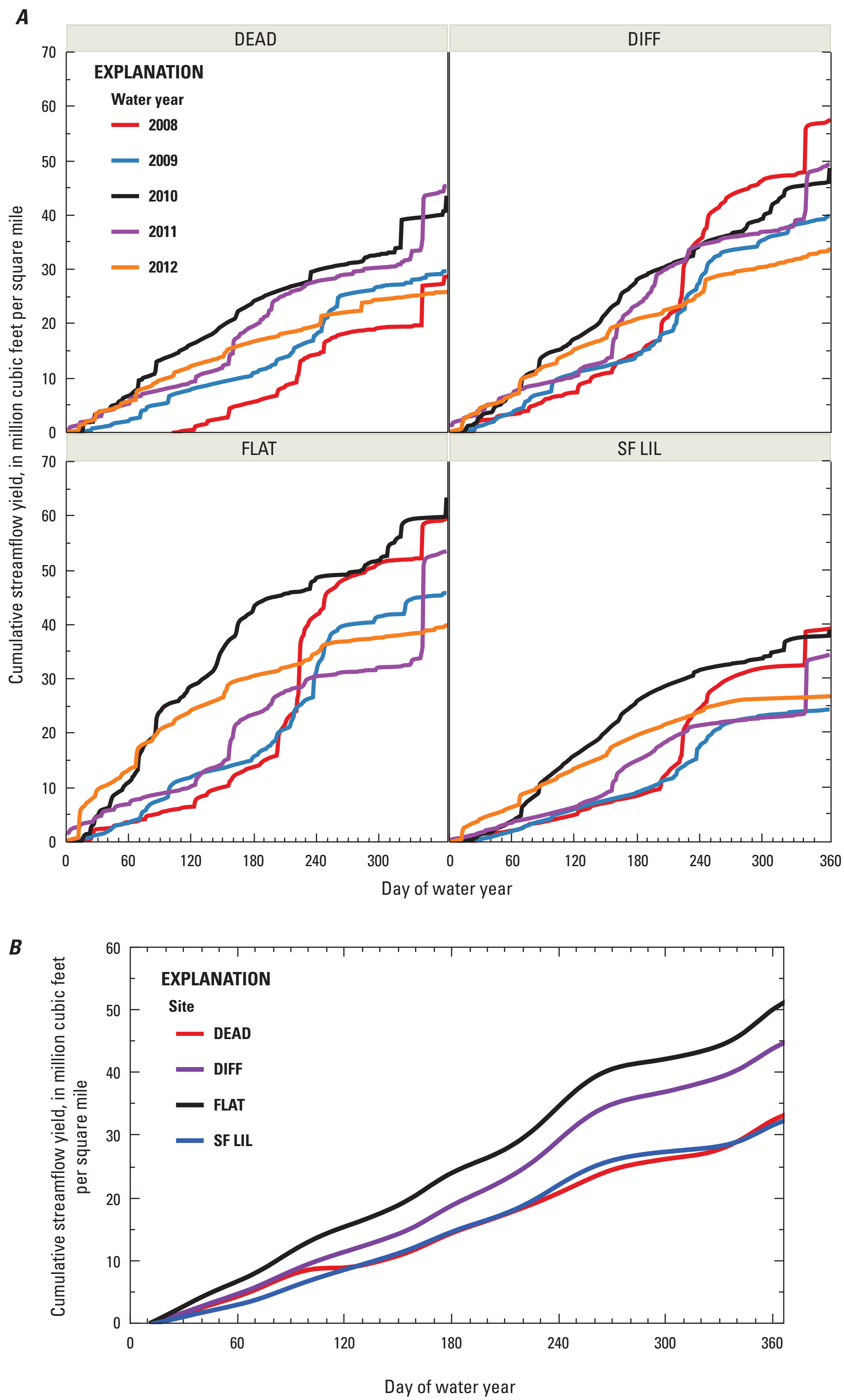

Figure 4. *A*, Cumulative streamflow yield per day of water year, by water year, and *B*, spline smooths of cumulative streamflow yield per day for water years 2008–12, by station. Station names defined in table 1.

Streamflow Variability

In addition to precipitation regimes, watershed characteristics greatly influence hydrologic conditions in streams. In particular, urban development, through the associated increases in impervious cover, can alter streamflow generation processes and consequently change the frequency, duration, and magnitude of extreme flow events (Paul and Meyer, 2001). Flashiness, or the rate of change in streamflow, is a commonly used measure of the rapidity of flow changes in response to precipitation. Streamflow characteristics such as flashiness are typically computed from timeseries records of streamflow, although McMahon and others (2003) demonstrated that the use of stage (or water level) data provides comparable measures of flashiness. Study limitations, such as duration and budget, often limit the amount of streamflow data collection. Within such limitations, the use of stage data alone to compute streamflow characteristics provides a valuable alternative approach to characterize streams.

Stream flashiness was determined for all 14 stations in the monitoring network by using 15-minute-interval stage data from the continuous streamgages at the 4 intensive monitoring stations and from the pressure sensors at the 10 trend-monitoring stations for water years 2010–12. Based on the methods and results of McMahon and others (2003), flashiness was computed as the number occurrences of stage measurements in which the hourly increase in stage was 0.5 ft or greater (PERIODR5). The PERIODR5 value was then divided by the total number of measurements in the analysis period to express flashiness as the percentage of time that PERIODR5 occurs.

Flashiness values generally follow the expected pattern of increased flashiness with increased urbanization, as represented by road coverage in the watershed computed from Fairfax County Stormwater Planning Division (2007; fig. 5). Flashiness was much greater at two stations, Dead Run and Old Courthouse Spring Branch, than the others and both stations were among those having the greatest percentage of watershed area covered by road surfaces in the network (fig. 2). Stations that were the least flashy, Castle Creek, South Fork Little Difficult Run, and Captain Hickory Branch, were among those having the greatest percentage of estate residential and open spaces, and therefore the least impervious cover.

Hydrologic Conditions Represented by Water-Quality Samples

To accurately evaluate water-quality conditions, particularly to compute loads and temporal trends, the samples collected need to represent the range of hydrologic conditions observed over the period of study. This monitoring program utilizes a combination of sampling strategies to achieve the required hydrologic representation—scheduled monthly sampling and targeted stormflow sampling. The entire 14-station monitoring network was sampled monthly on a prescheduled date, regardless of the conditions that day, to generate the requisite data for trend analysis. This “scheduled random” sampling approach is commonly used to ensure an appropriate frequency of sampling events, and by random chance will usually incorporate the range

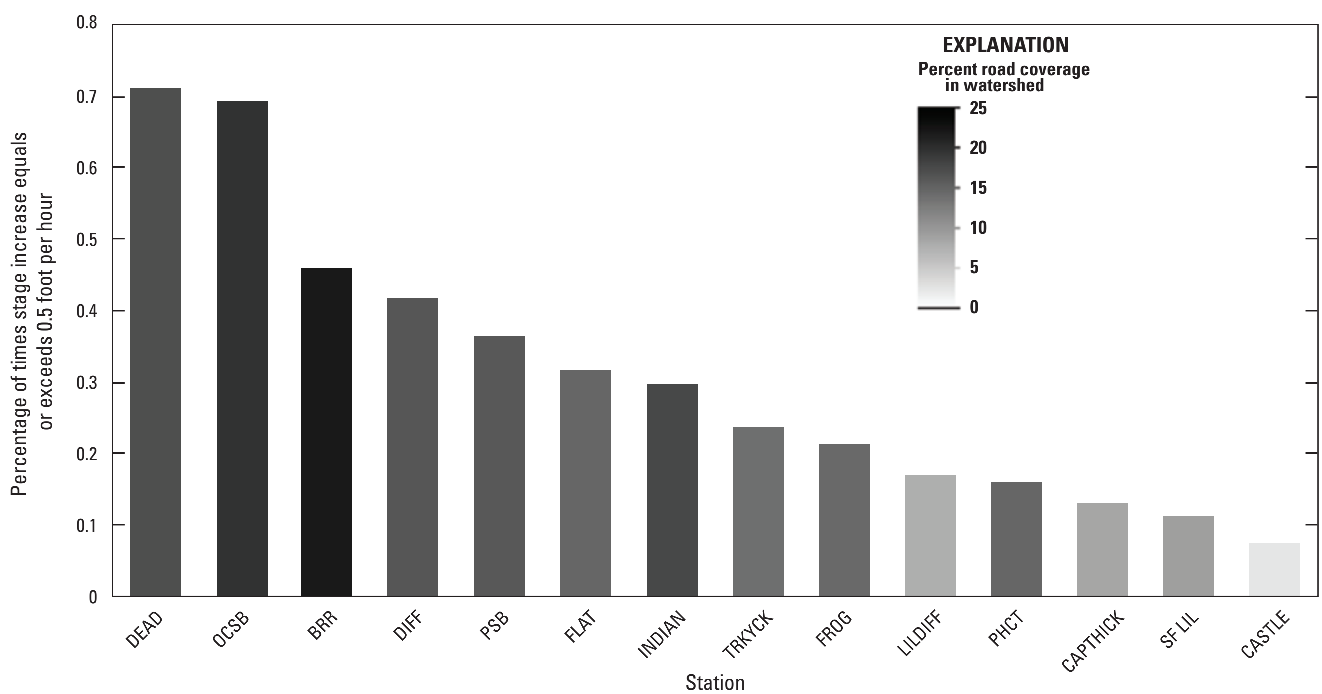

Figure 5. Flashiness, computed as percentage of time stage increases by 0.5 feet per hour or greater, of 14 monitored streams in Fairfax County, shaded by percentage of watershed area covered by road surfaces. Station names defined in table 1.

of hydrologic conditions over a period of multiple years. Stormflow conditions were targeted and sampled at the four intensive monitoring stations to generate the requisite data for load computation—loads were not computed at the trend monitoring stations.

Evaluation of the sample coverage over the range of hydrologic conditions at each of the four intensive monitoring stations showed that the scheduled random sampling approach had effectively represented about 95 percent of the range of streamflow conditions (fig. 6*A*). Because all stations were sampled on the same day each month, it is reasonable to assume that the coverage at the 10 trend monitoring stations was similar—continuous streamflow data were not generated at the trend monitoring stations and therefore this cannot be directly determined. Although the monthly samples represented the majority of observed flow conditions, it is desirable to have more complete coverage of high-flow events to ensure that trend analyses adequately represent the full range of streamflow conditions for the period of study. The scheduled sampling scheme used is generally expected to achieve such coverage through random chance; however high-flow conditions in the small, flashy, streams monitored in this network do not persist for sufficient duration for this approach to be completely effective at representing the full range of streamflow.

Targeted stormflow sampling, in addition to the monthly sampling, was used at the four intensive monitoring stations to collect the requisite data for nutrient and sediment load computation. Evaluation of the monthly and targeted storm-sampling coverage over the range of streamflow conditions showed that the samples collected represented the entire range of observed flow conditions during the study, including periods of highest streamflow when transport of suspended sediment and associated constituents is greatest (fig. 6*B*).

Temporal and Spatial Patterns in Water Quality

A primary long-term objective of this monitoring program is to evaluate change over time. With just 5 years of data, however, temporal trends were not evaluated because longer data sets are needed to evaluate temporal trends with statistical rigor. Although temporal trends were not statistically evaluated, there was sufficient data to evaluate temporal patterns and seasonality in the data. Additionally, sufficient data were available to evaluate spatial patterns in water-quality conditions, and to evaluate potential factors responsible for those patterns.

Patterns in Basic Water-Quality Parameters

Basic water-quality parameters—water temperature, pH, specific conductance, turbidity, and DO—are measured instream concurrently with each monthly water-quality sample, and continuously at each of the four intensive monitoring stations. Analyses of monthly and continuous data were performed to evaluate temporal and spatial patterns, and to determine potential drivers of any patterns that emerged.

pH

pH, the inverse logarithm of the hydrogen-ion concentration, is a measure of the acidity or basicity of a solution. The pH of pure water is 7, or neutral, although natural waters unaffected by pollution typically range between 6.5 and 8.5 (Hem, 1985). Factors affecting pH in stream water include geology, biological processes, anthropogenic disturbances, and precipitation.

Median pH at individual monitoring stations ranged from 6.9 to 7.5 and, on average, had a range of about 1.3 pH units. Monitoring stations having the highest median pH were Flatlick Branch (7.5), Frog Branch (7.5), and Big Rocky Run (7.4)—each of which drain watersheds within the Triassic Lowlands terrane. Paul Spring Branch, a Coastal Plain stream, had the lowest median pH at 6.9. All other monitoring stations had median pH values from 7.0 to 7.2. The water-quality standard for pH in Virginia rivers is 6.0 to 9.0 (Commonwealth of Virginia, 1997); data from the monthly sampling events indicate that none of the 14 streams monitored violated this standard. Visual inspection of the pH data collected during the monthly sampling events did not reveal any apparent change over time, including seasonal fluctuations (fig. 7).

In addition to being measured in association with monthly sample collections, pH is measured continuously (15-minute intervals) at the four intensive monitoring stations. Evaluation of these continuous data records reveals patterns that were not captured in the discrete monthly samples. Diurnal (daily) cycles are apparent in the pH data, particularly in the early spring, and especially at Flatlick Branch (fig. 8). These cycles, during which pH peaks in the late afternoon or early evening, are the result of the uptake of carbon dioxide via photosynthesis by aquatic organisms (Hem, 1985)—a process driven by available light and therefore peaking late in the day. This process is most apparent early in the spring in these small streams as the forest canopy has not yet shaded the streams and maximum light levels are available to fuel photosynthesis. The peaks and daily range are greatest, 9.5 and 2.2 units, respectively, at Flatlick Branch, where greater concentrations of the limiting nutrient phosphorus are available (discussed later) than at other sites to support biological activity.

pH is strongly affected by precipitation and the resultant runoff from heavy precipitation events, and such runoff is responsible for the observed periodic sharp decreases in pH (fig. 8). The typical pH of rainwater in Virginia ranges from 4.9 to 5.1 units (National Atmospheric Deposition Program, 2013) as a result of atmospheric pollution to the west. During excessive rainfall events, there is little opportunity for buffering of acidic runoff as it flows across the landscape and enters streams; therefore, pH rapidly decreases when streamflow becomes dominated by runoff.

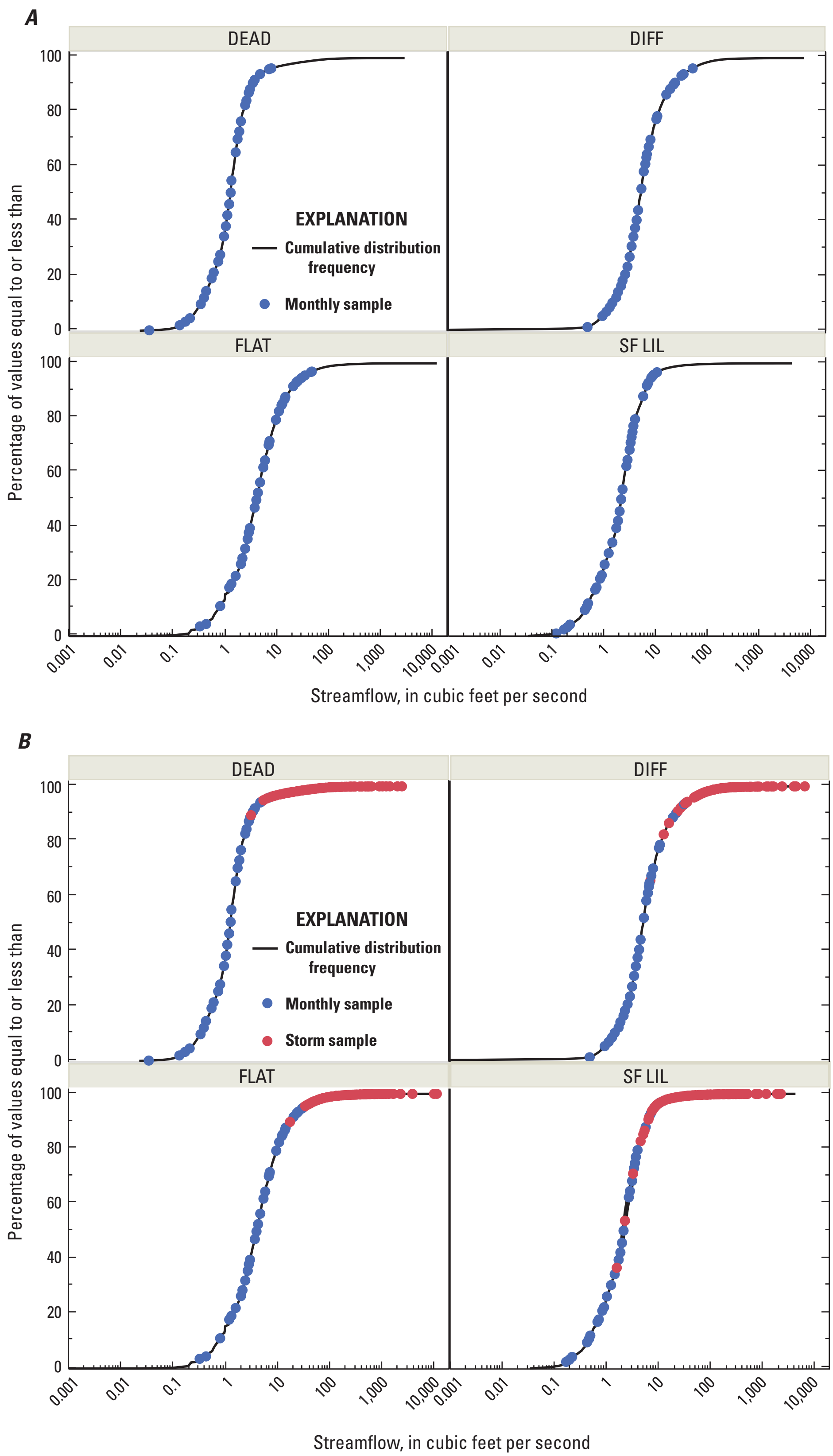

Figure 6. Distribution of streamflow and *A*, monthly samples only, and *B*, monthly plus storm samples, at the four intensive monitoring stations. Station names defined in table 1.

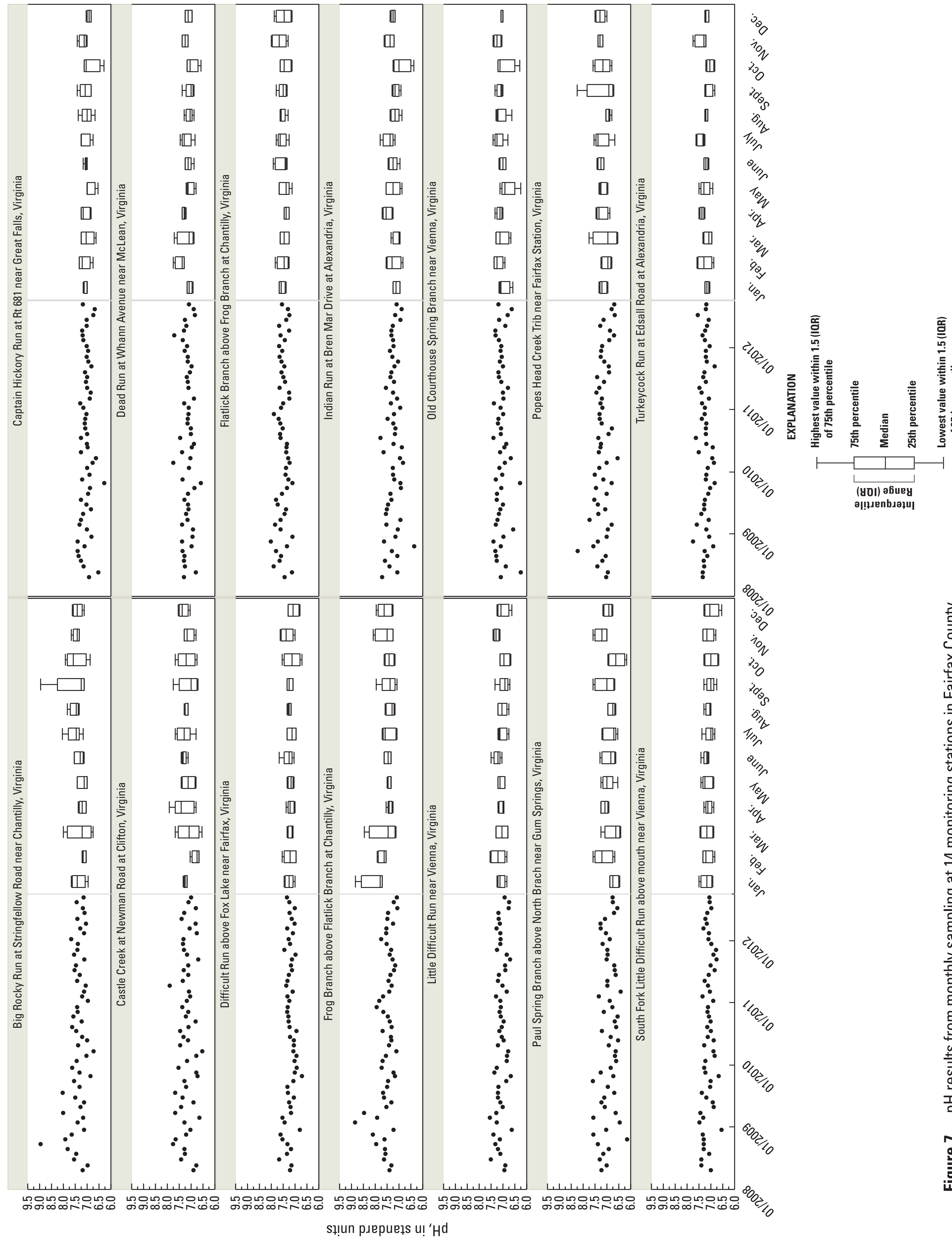

Figure 7. pH results from monthly sampling at 14 monitoring stations in Fairfax County.

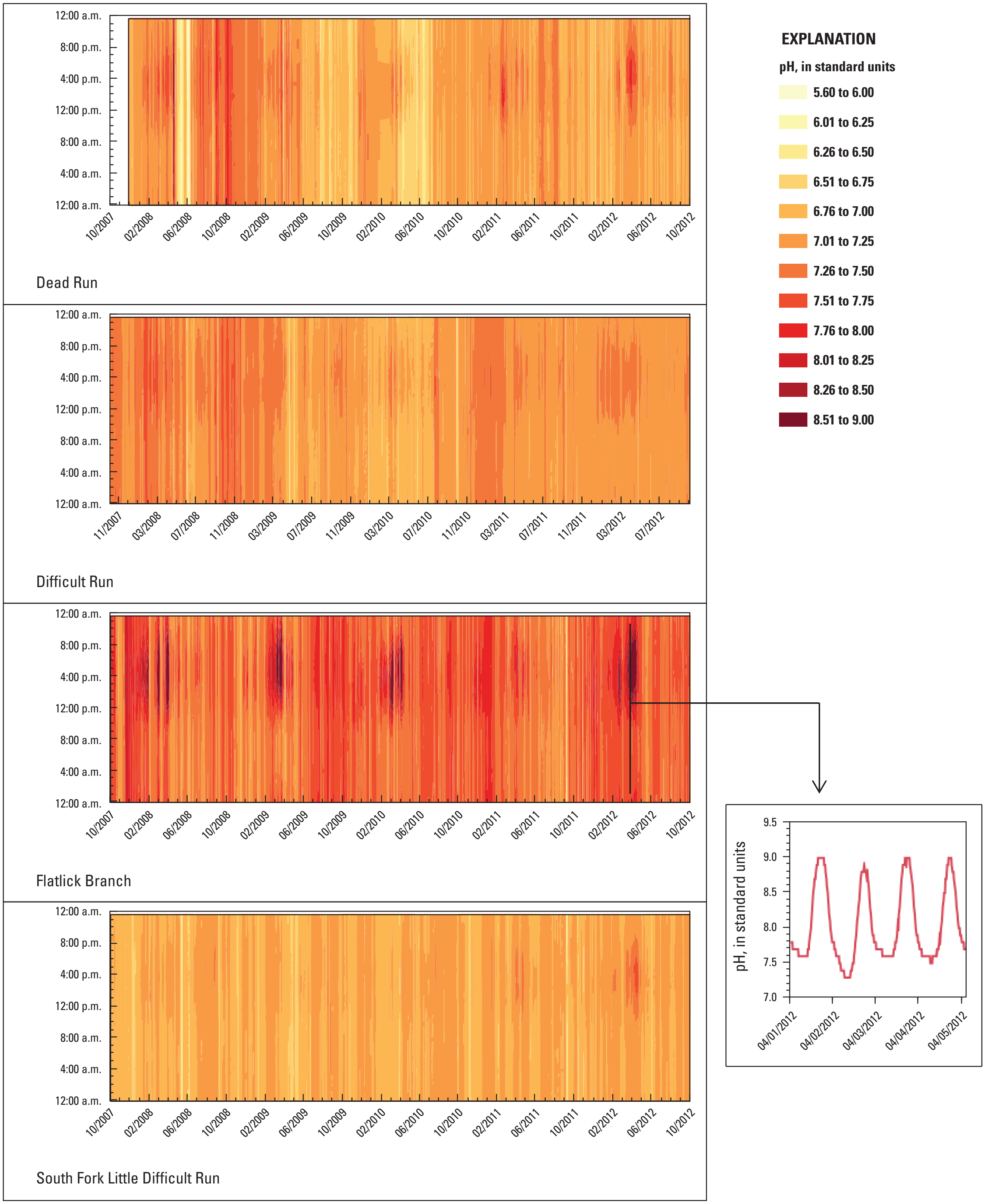

Figure 8. Continuous pH data from the four intensive monitoring stations in Fairfax County with inset detailing a 5-day period of diurnal pH cycles.

Specific Conductance

Specific conductance is a measure of the electrical conductivity of a solution at a specified temperature, typically 25 °C, reported in microsiemens per centimeter (µS/cm; Hem, 1985). The specific conductance of pure water is very low, approximately 0.05 µS/cm, although such water never occurs naturally (Hem, 1985). Charged ionic species in solution impart conductivity, with specific conductance increasing with ion concentration, and therefore specific conductance provides a measure of the total ion concentration in water (Hem, 1985). Stream water specific conductance varies greatly, from about 50 µS/cm or less in areas underlain by geology resistant to weathering and with little anthropogenic influence, to 50,000 µS/cm or more in areas having readily weathered geology and (or) substantial anthropogenic activity (Hem, 1985). Specific conductance generally increases with urbanization (Paul and Meyer, 2001) and, therefore, serves as an indicator of urban impacts in areas where other factors, such as geology and precipitation, are relatively constant.

Specific conductance varied substantially between stations, and especially months, across the monitoring network (fig. 9). The interstation variability is most evident in figure 10; the 4 stations with the least amount of road coverage (used as an indicator of urban intensity) have markedly lower specific conductance values with less variability than the other 10 monitoring stations. Additionally, the maximum specific conductance values at these monitoring stations are much lower than the maximums observed at other stations, where maximum values are often at least an order of magnitude greater than the median (fig. 10).

Specific conductance was greatest during the winter months at all monitoring stations, with maximums usually occurring in January (fig. 9). Thereafter, specific conductance typically declined over several months, with values stabilizing until the following winter. These seasonal spikes in specific conductance are the result of widespread application of de-icing salts on roads, parking lots, sidewalks, driveways, and other surfaces, when snowfall or other frozen precipitation occurs. As the de-icing salts contribute to the melting of the frozen precipitation, the resultant runoff becomes highly concentrated with the salts, and therefore has a very high specific conductance. During the initial melting process, instream specific conductance spikes rapidly to values far exceeding those captured in the monthly samples, as evidenced by comparison of the monthly sampling data to continuous specific conductance data (fig. 11).

Sanford and others (2012) evaluated the relation between specific conductance and chloride (Cl^-) throughout rivers in Virginia, and specifically during a runoff event following the application of road salt in the Difficult Run watershed. They found that where surface salts dominated the stream chemistry during this runoff event, the ratio of Cl^- to specific conductance was 0.33 for samples having a specific conductance greater than 1,000 µS/cm, compared to the typical ratio of 0.03. Cl^- standards for the support of freshwater aquatic life in Virginia dictate that the average Cl^- concentration shall not exceed 860 milligrams per liter (mg/L) during any 1-hour period or 230 mg/L over any 4-day period more than once in a 3-year period (Commonwealth of Virginia, 1997). Application of the 0.33 Cl^- to specific conductance ratio determined by Sanford and others (2012) to the monthly and continuous data indicates that this water-quality standard is probably violated in many of the streams monitored. The rapid increase in specific conductance as snow and ice melts likely produces a shock to the biological communities that inhabit these streams, as chloride concentrations during these events probably exceed impairment thresholds for freshwater aquatic life.

Dissolved Oxygen

The introduction of DO to stream water occurs through physical and biological processes, primarily aeration through the entrainment of air bubbles as the water surface is disturbed and through photosynthesis (U.S. Geological Survey, variously dated *a*). DO is vitally important to organisms whose survival depends on respiration—a process that, in addition to consumption of organic materials and oxidation of inorganics, is a primary sink of DO in streams (Hem, 1985). Because of the dependence on DO by aquatic organisms, it is used as an indicator of stream health, and Virginia has established a minimum criterion of 4.0 mg/L (Commonwealth of Virginia, 1997) for freshwater streams.

DO concentrations across the 14-station network are generally within a healthy range (>4 mg/L), with a few exceptions occurring at two stations during the summer months (fig. 12). The temperature-dependent nature of DO is responsible for the seasonality in the monthly data (fig. 12) and continuous data (fig. 13). Specifically, DO equilibrium is greatest at low temperatures, resulting in maximum concentrations during winter months.

Turbidity

Turbidity is a measure of the optical properties of a volume of water, and therefore is directly related to the quantity and size distribution of particles, such as sediment, suspended in the water column (Davies-Colley and Smith, 2001). Turbidity measurement is not standardized—measures are highly dependent on sensor configuration, and measurements from different sensor configurations are not directly comparable (Anderson, 2005). Turbidity measurements for this study were made using a YSI, Inc. Model 6136 Turbidity Sensor. This turbidity sensor uses near infrared wavelengths with 90-degree detector geometry and is calibrated using formazin-based standards; therefore, data are expressed in FNUs (Anderson, 2005).

Turbidity results from monthly sampling across the 14-station network are generally low, with 75 percent of results below about 6 FNU (fig. 14). These low values result from the monthly samples largely representing base-flow

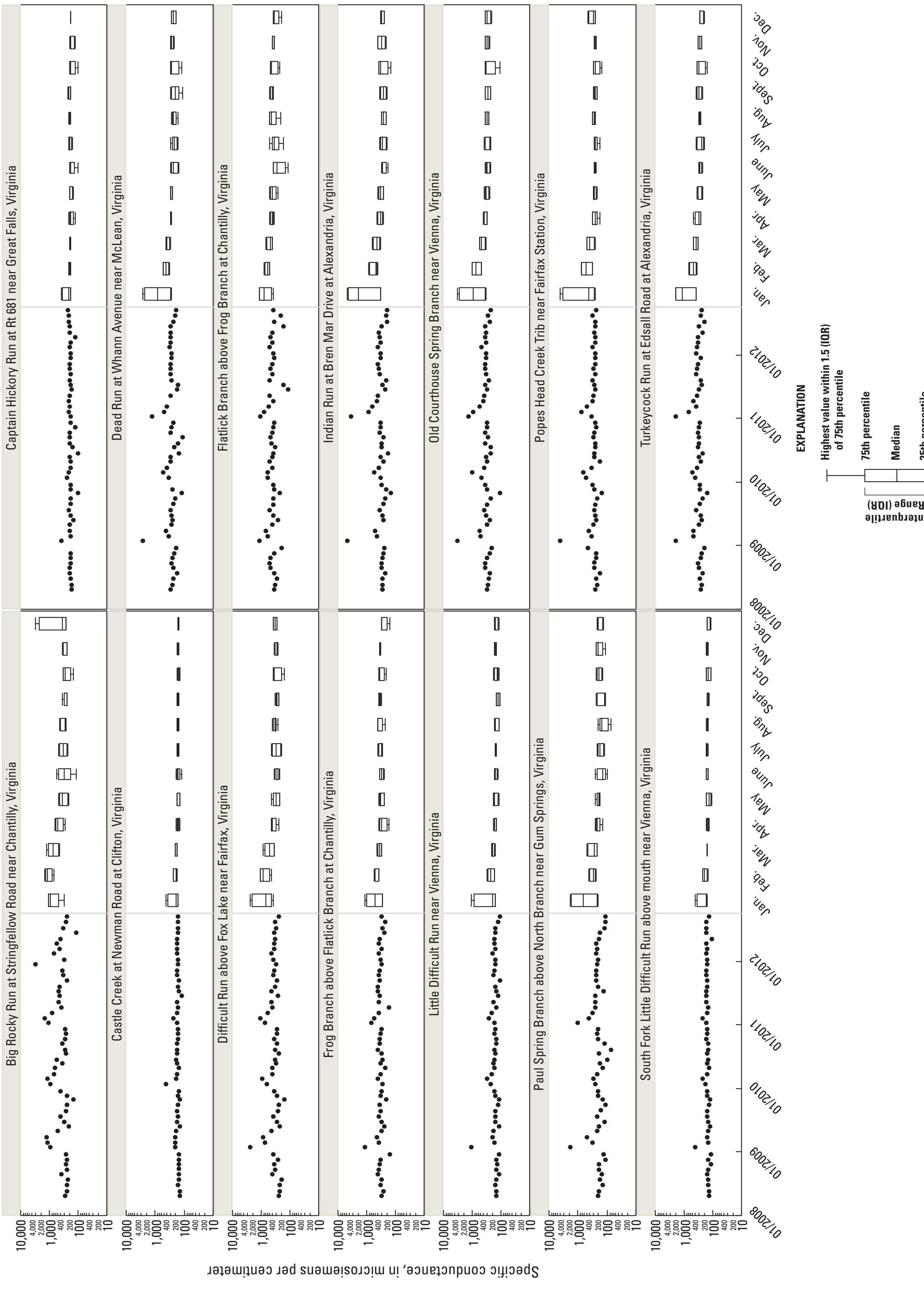

Figure 9. Specific conductance results from monthly sampling at 14 monitoring stations in Fairfax County.

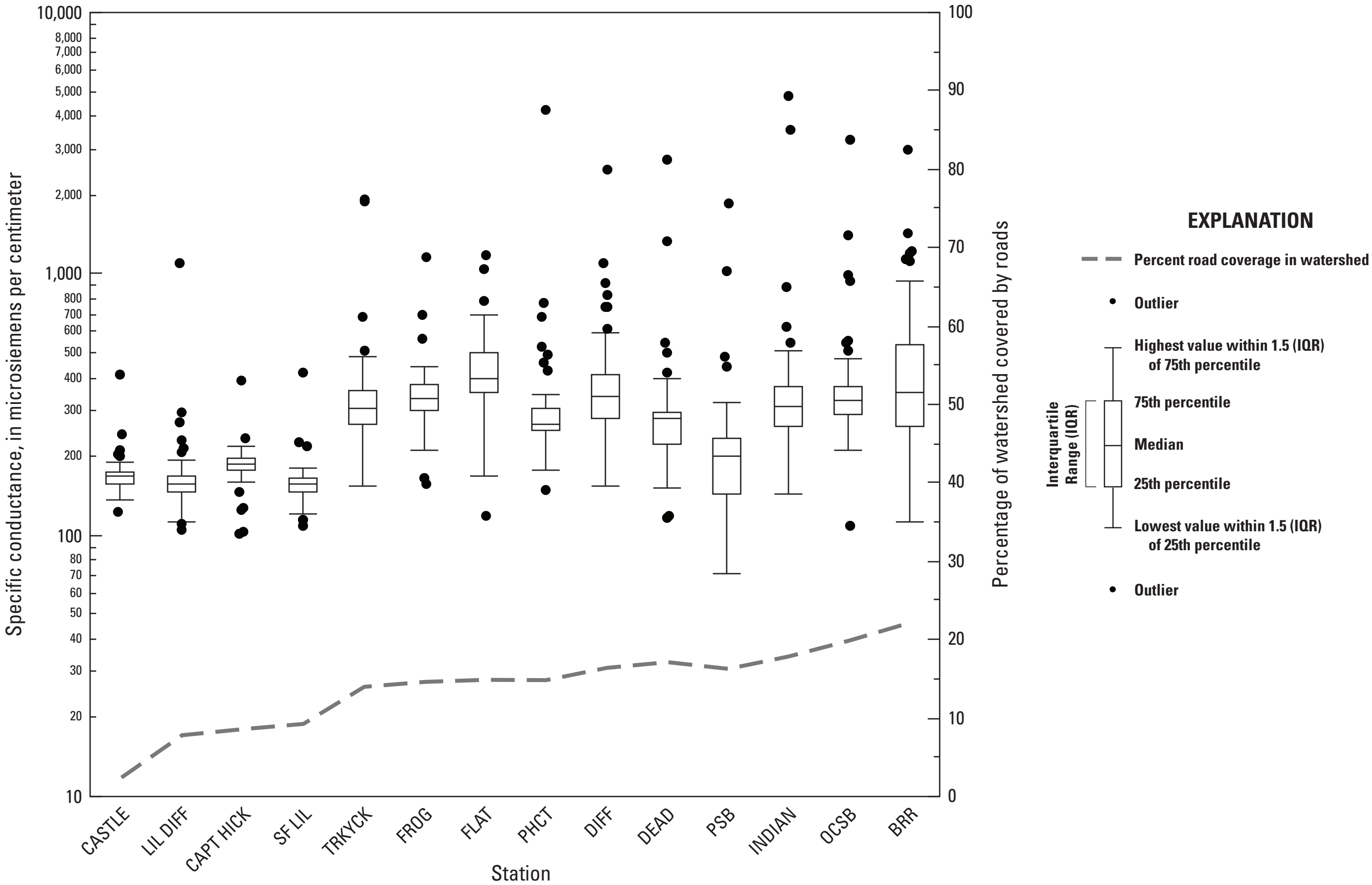

Figure 10. Specific conductance results, with percent road coverage in watershed, by monitoring station, from monthly sampling at 14 monitoring stations in Fairfax County.

conditions and consequently lack of energy to entrain sediment particles and thereby increase turbidity during such flow conditions. Occasionally, low-level stormflows were encountered and higher turbidity values recorded, although the maximum turbidity recorded during the monthly sampling events was only 78 FNU. In contrast to the monthly sampling results, the continuous turbidity data are highly variable across the range of possible turbidity values. Such variability impedes graphical visualization of long periods of data; therefore, only WY 2011 is plotted as an example (fig. 15).

Patterns in Nitrogen

Nitrogen (N) is an essential nutrient for plants and animals that is widely found in the atmosphere, hydrosphere, and biosphere (Hem, 1985). Although agricultural land use is generally associated with greater N concentrations in streams than other land uses, urbanization has been shown to increase N to similarly high concentrations, particularly in areas with faulty or failing wastewater infrastructure or excessive landscape fertilization (Paul and Meyer, 2001).

Patterns in N concentration were evaluated using the monthly sampling results from the entire 14-station network. Median total N (mg/L as N) by monitoring station ranged from 0.88 to 4.88 mg/L, with a median for all monitoring stations of 1.66 mg/L. Measured concentrations of total N were higher at one station, Captain Hickory Run, than at other stations in the network (fig. 16). Occasional high concentrations, greater than or equal to those measured at Captain Hickory Run, were measured at Popes Head Creek tributary (fig. 16). These elevated concentrations at Popes Head Creek tributary have been captured in a single sample per year, collected in either August or September and coincident with the lowest streamflow of the year. With the exception of these two stations, total N concentrations generally show only slight departure from median values, and there is little evidence of seasonal patterns (fig. 16).

The total N concentrations measured in the monthly samples, which typically reflect base-flow conditions, are largely composed of nitrate, as evidenced by the similar concentrations and patterns observed between total N data and the nitrate plus nitrite data (figs 16 and 17). Total dissolved N data mirror the nitrate data more closely than the total N data (not presented), and because these samples largely represent base-flow conditions, during which there is not sufficient energy to entrain particulates, total particulate N concentrations are frequently nondetectable (data not presented).

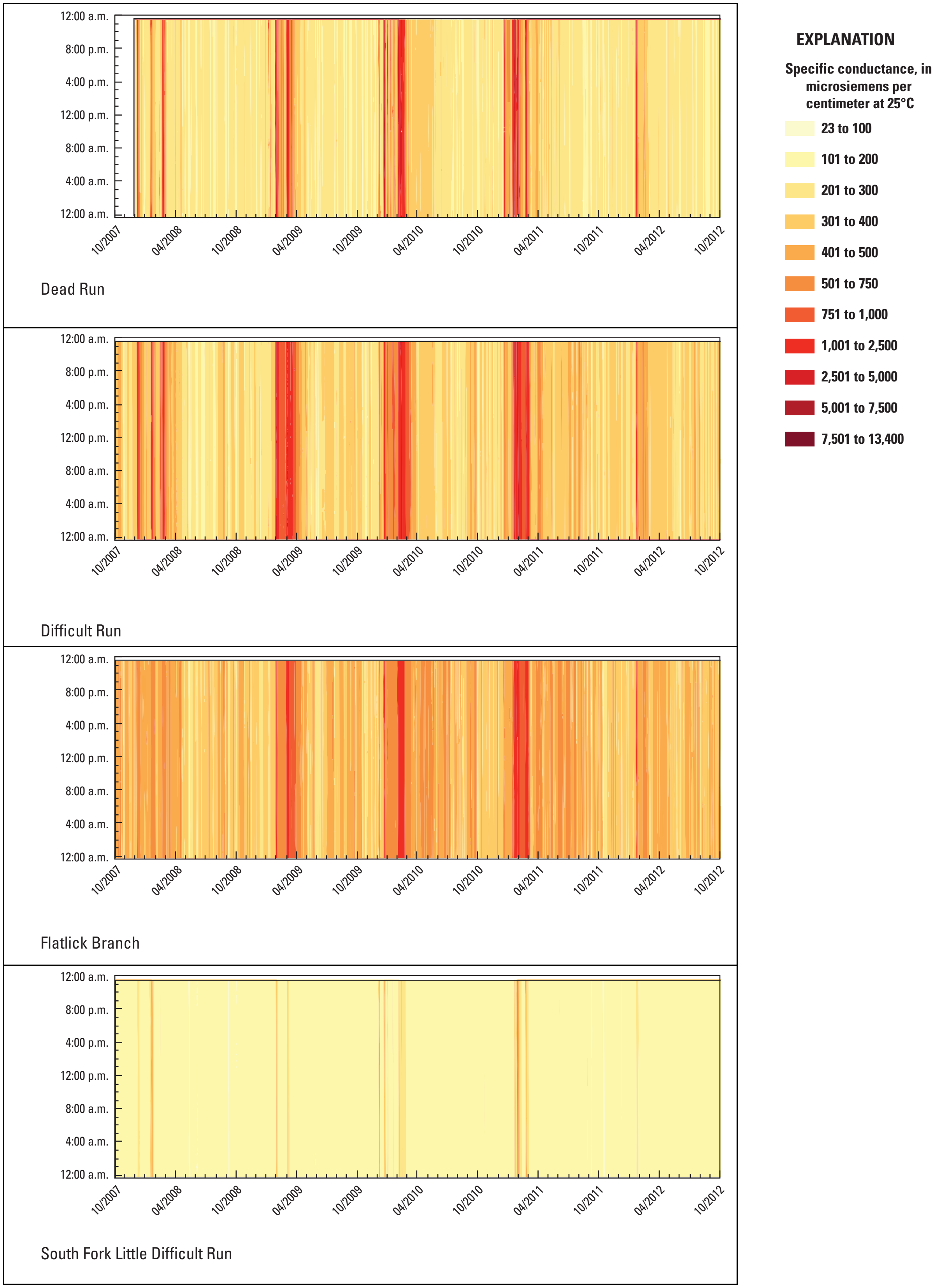

Figure 11. Continuous specific conductance data from the four intensive monitoring stations in Fairfax County.

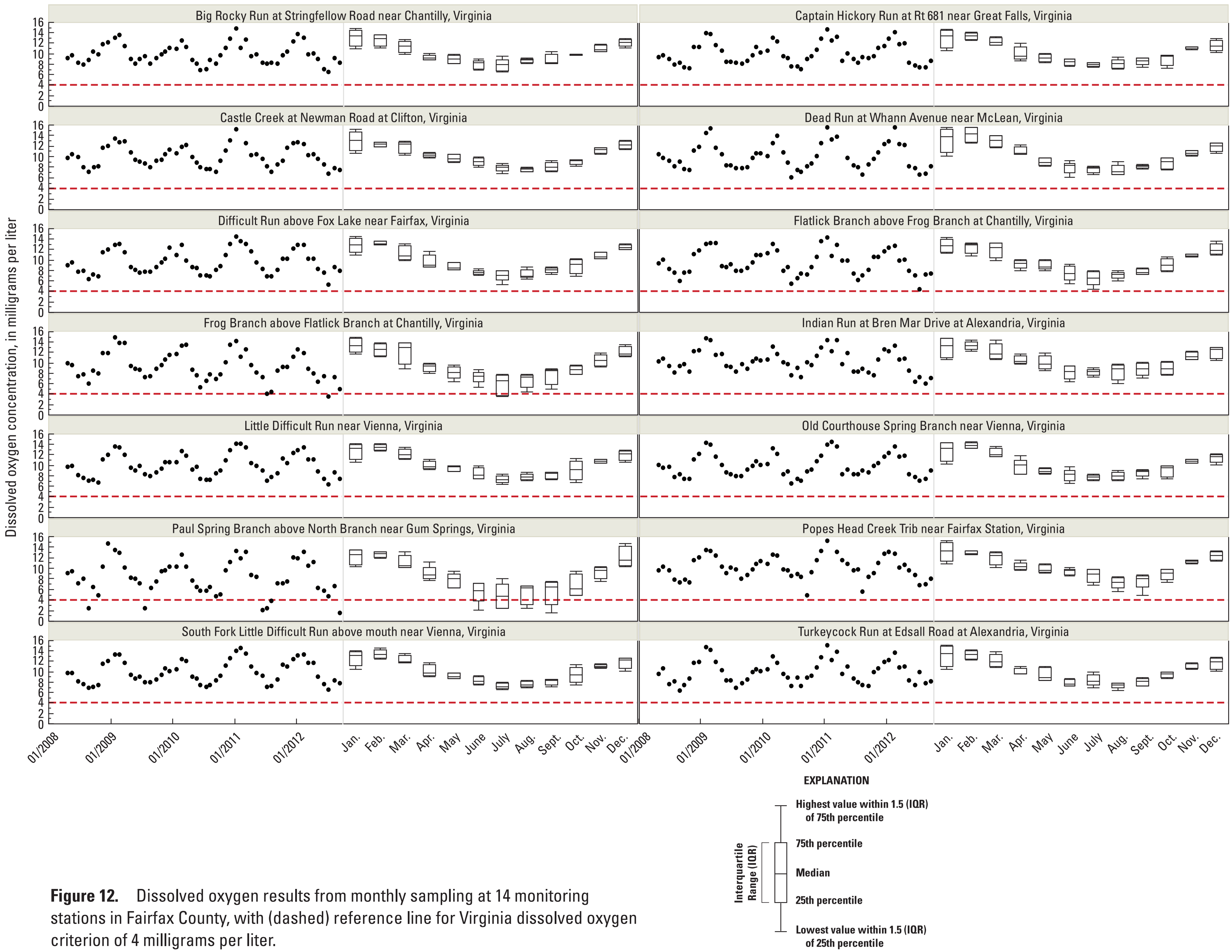

Figure 12. Dissolved oxygen results from monthly sampling at 14 monitoring stations in Fairfax County, with (dashed) reference line for Virginia dissolved oxygen criterion of 4 milligrams per liter.

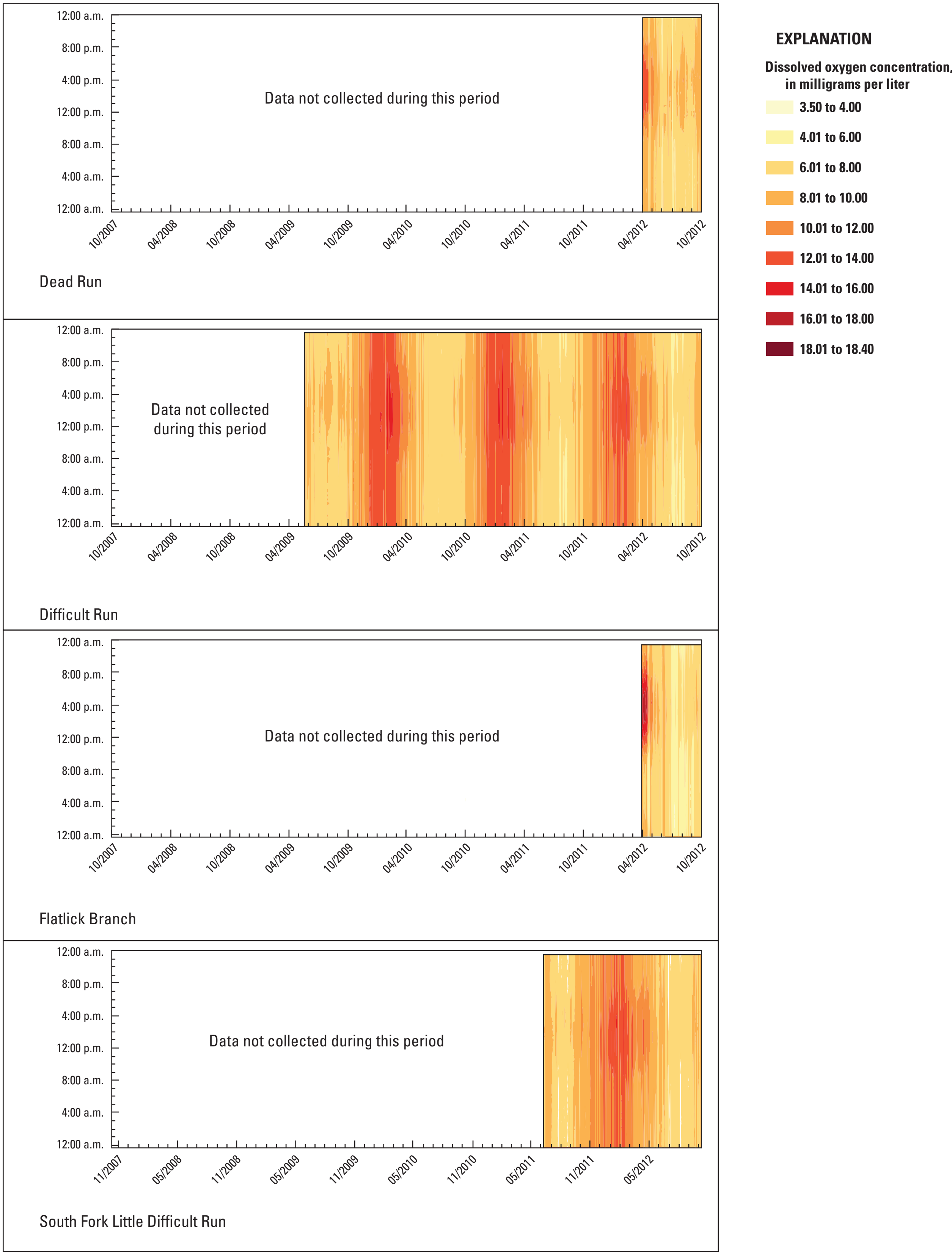

Figure 13. Continuous dissolved oxygen data from the four intensive monitoring stations in Fairfax County.

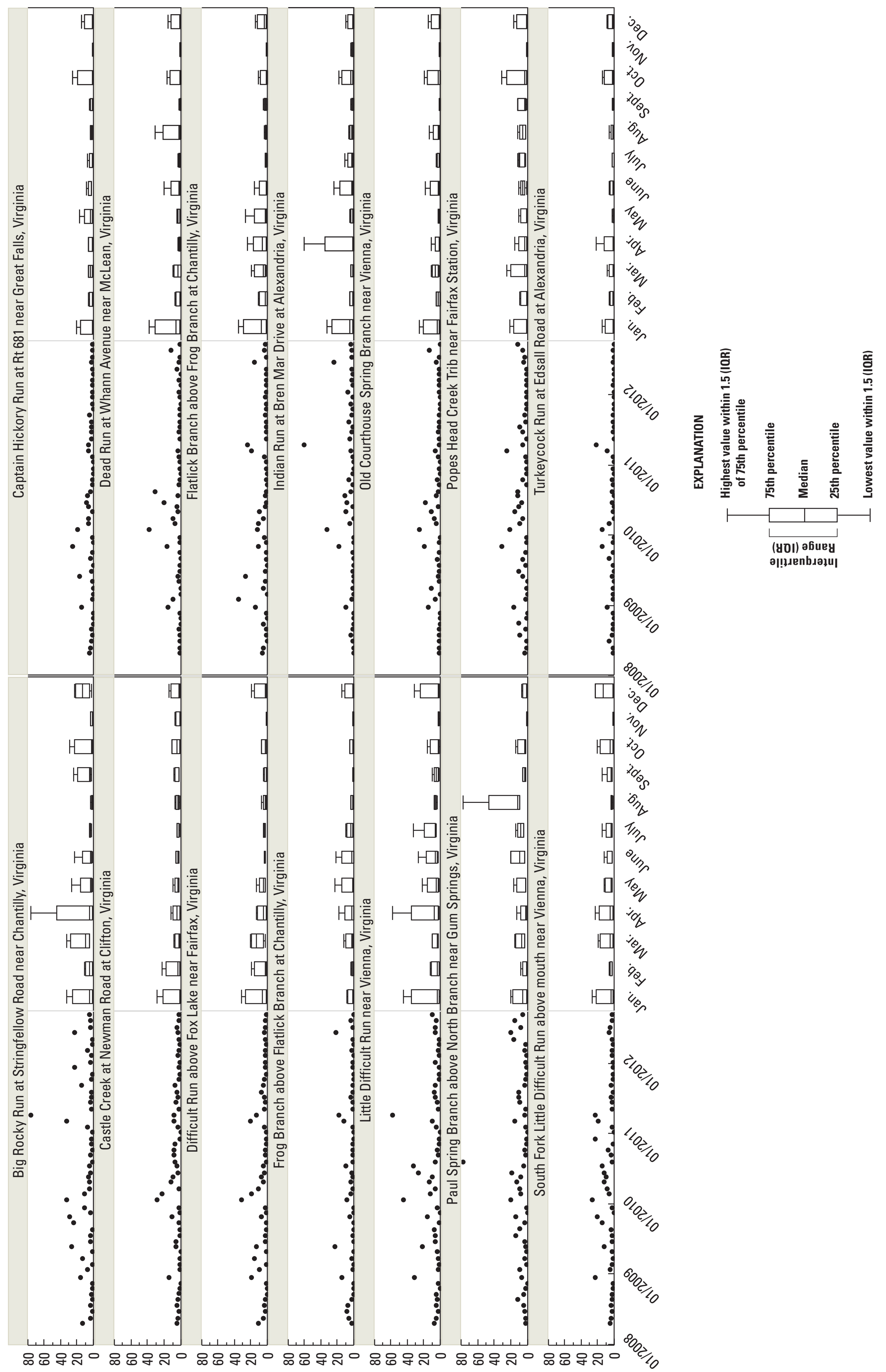

Figure 14. Turbidity results from monthly sampling at 14 monitoring stations in Fairfax County.

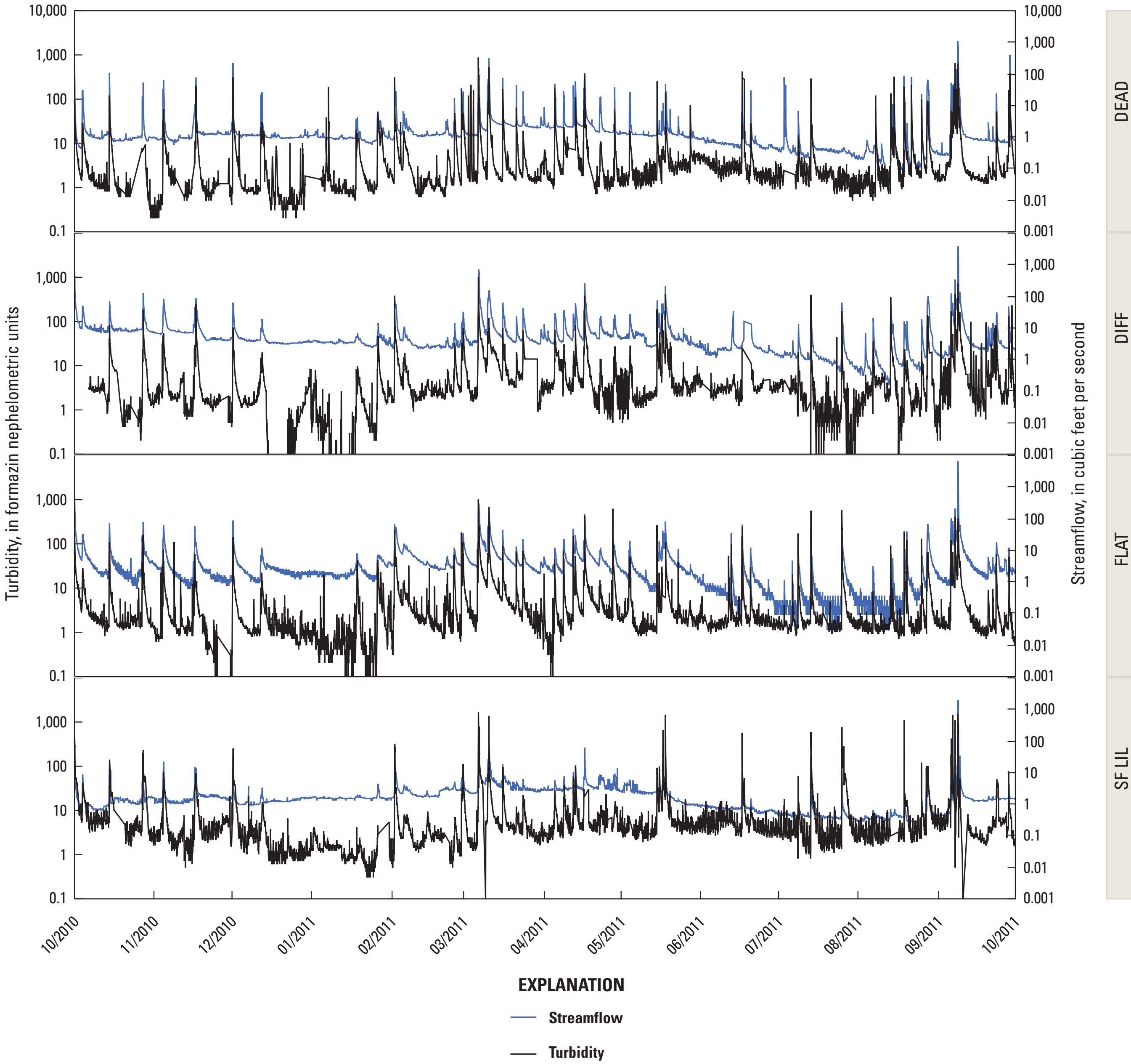

Figure 15. Continuous turbidity and streamflow data from the four intensive monitoring stations in Fairfax County for water year 2011. Station names defined in table 1.

Visual inspection of the N data revealed no readily apparent changes over time, either gradual or as a step function, that would indicate potential trends in N in any of the watersheds. Slight changes may be occurring, however, that will require a longer period of record and formal trend tests to detect.

In general, watersheds having the least road coverage (lower urban intensity) tend to have greater N concentrations than those with greater urban intensity (fig. 18). Additionally, evaluation of the overall distribution of total N results by monitoring station further exemplifies the high concentrations observed at Captain Hickory Run and Popes Head Creek tributary relative to other stations (fig. 18).

Captain Hickory Run is dominated by estate residential (32 percent of watershed) and low-intensity residential (47 percent of watershed area) land uses (fig. 2). Hypotheses regarding the likely source of consistently elevated N in this watershed include (1) fertilizer applied to large residential lawns, (2) human waste from failing or inefficient septic systems (this watershed is not served by municipal wastewater utilities), or (3) groundwater inputs of legacy N from previous agricultural activity. Investigations into the likely sources of N are ongoing (2013) through separate USGS studies in the larger Difficult Run watershed, including Captain Hickory Run.

The Popes Head Creek tributary watershed is also dominated by estate residential (26 percent) and low-density

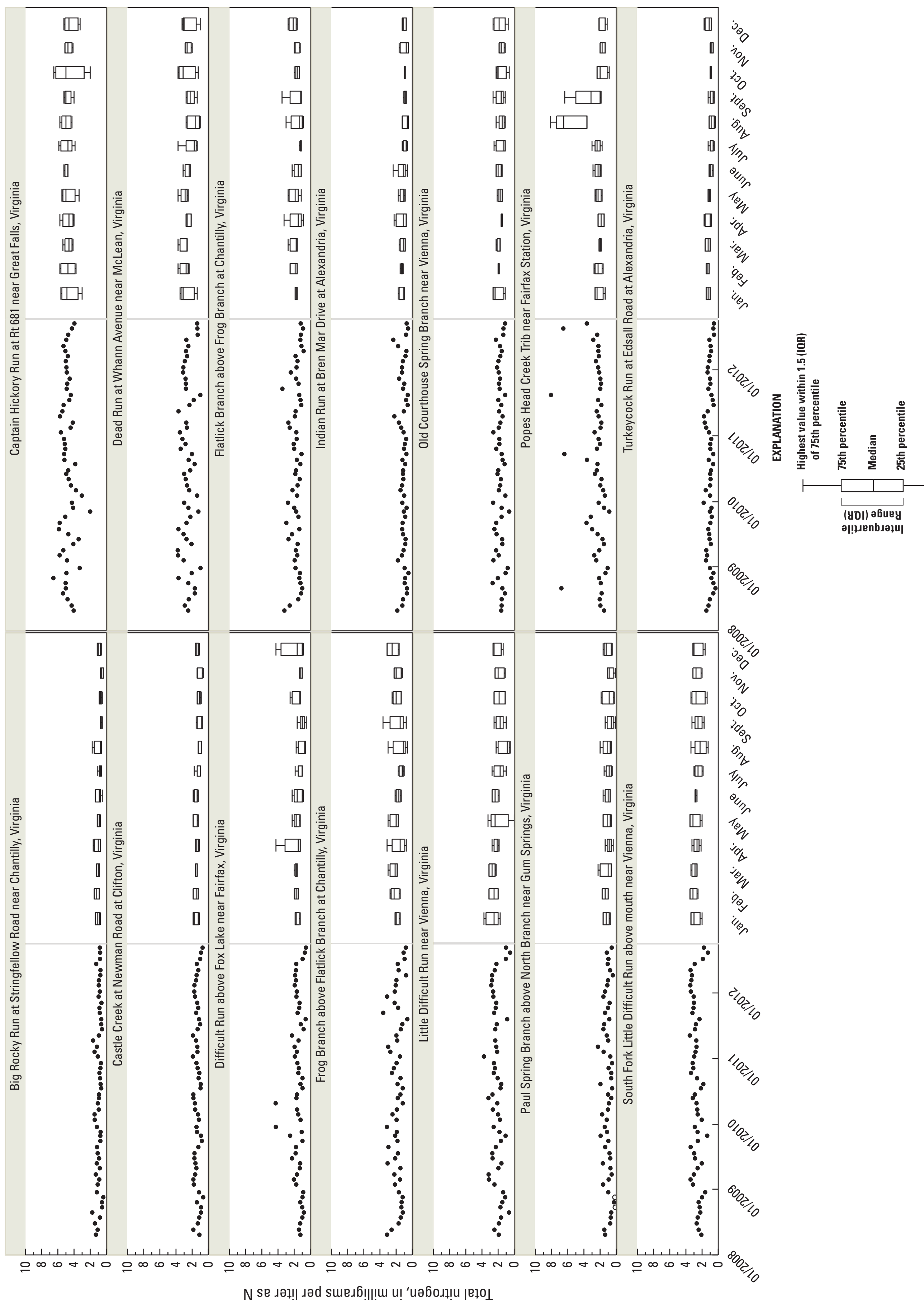

Figure 16. Total nitrogen results from monthly sampling at 14 monitoring stations in Fairfax County.

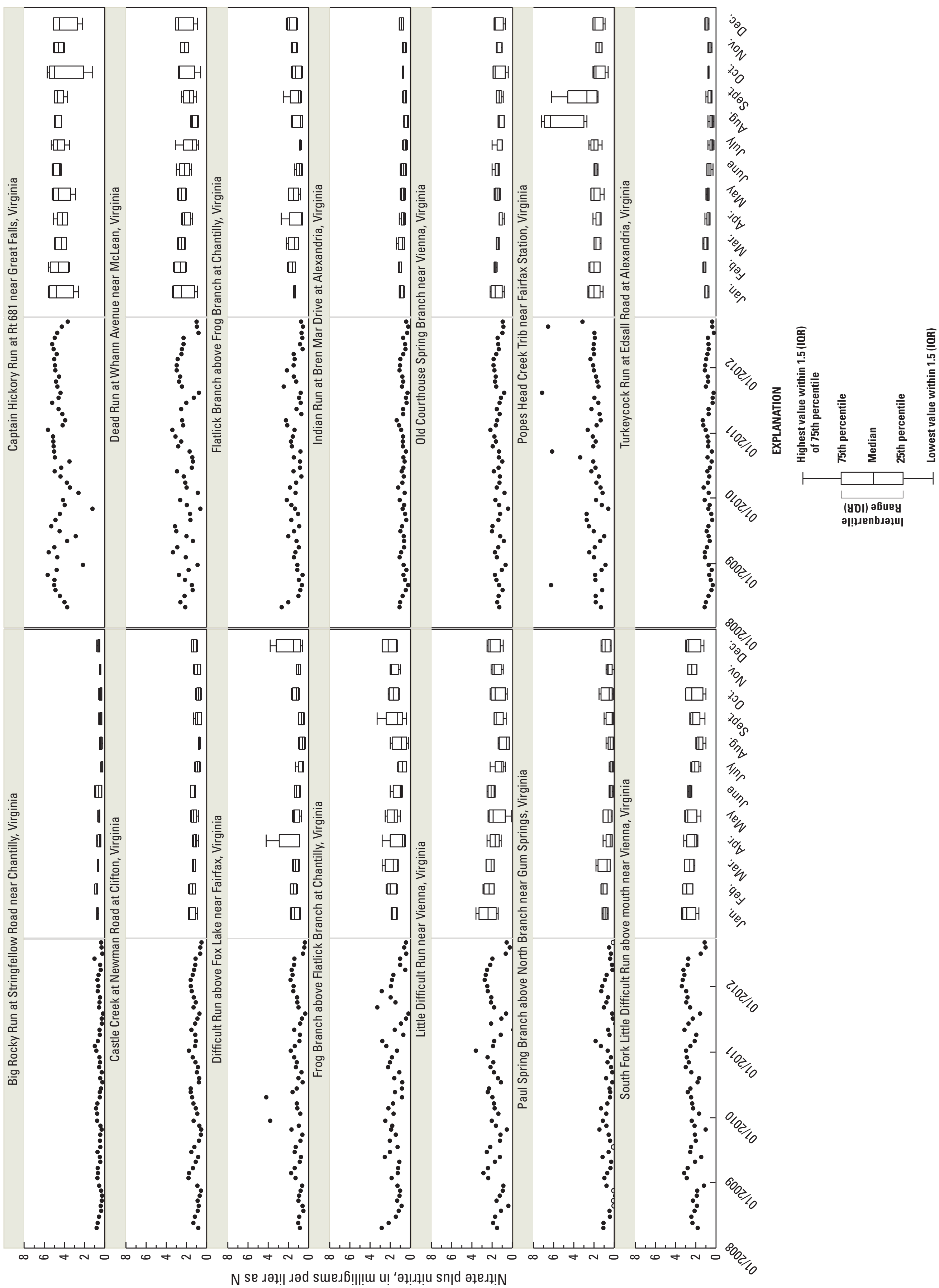

Figure 17. Nitrate plus nitrite results from monthly sampling at 14 monitoring stations in Fairfax County.

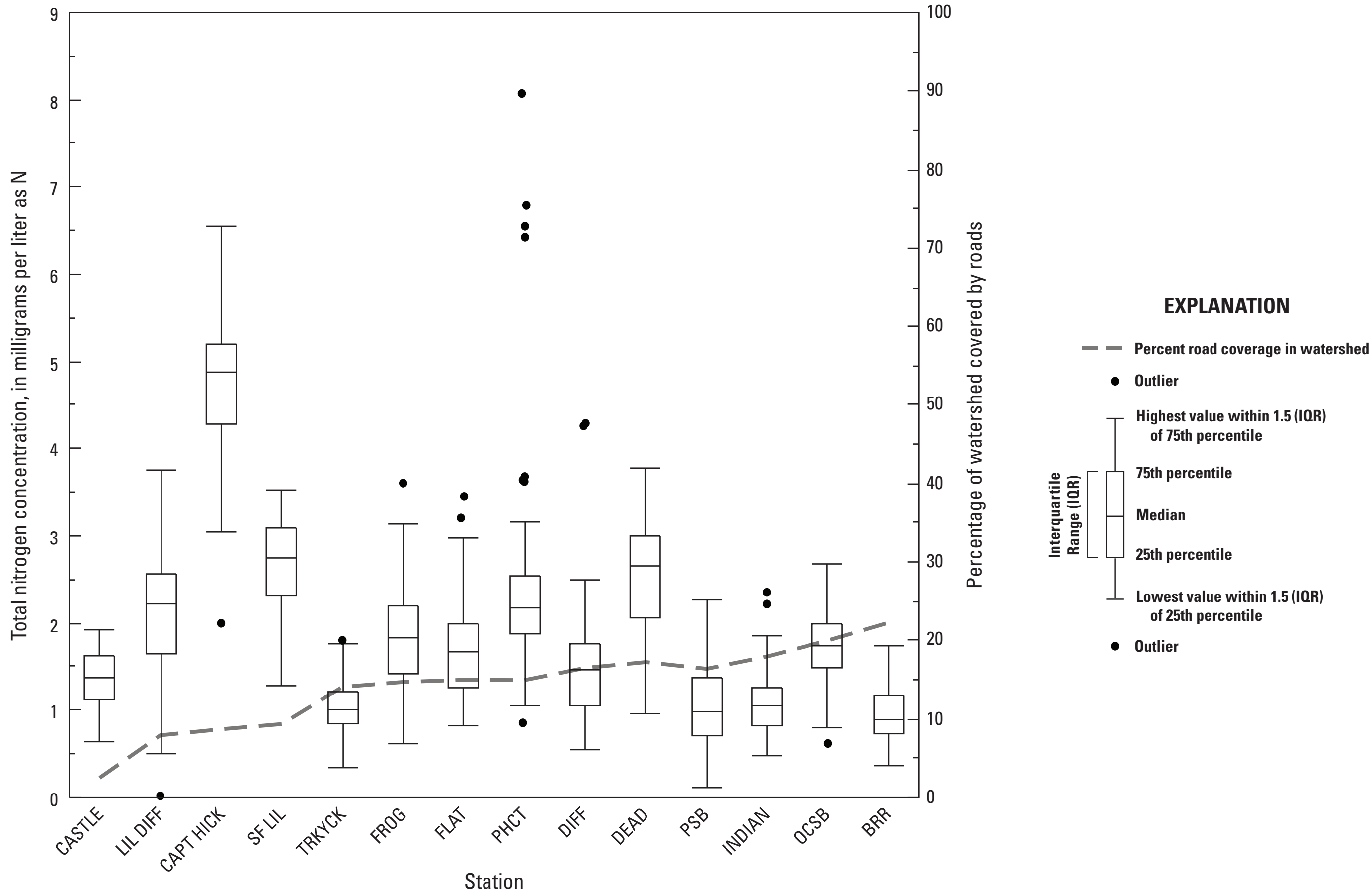

Figure 18. Total nitrogen results, with percent road coverage in watershed, by monitoring station, from monthly sampling at 14 monitoring stations in Fairfax County.

residential (38 percent) land uses, and is not served by municipal wastewater facilities. The occurrence of high N concentrations at this site is limited to the months of August and September (figs. 16 and 17), when streamflows are typically at or near the annual minimum. Hypotheses of N sources are similar to those for Captain Hickory Run (fertilizer, human waste, and animal waste), and N is probably entering the stream continually from a groundwater source that is substantially diluted by all but the lowest streamflows. Efforts to better clarify the source in this watershed are planned, but no results are currently available.

Patterns in Phosphorus

Phosphorus (P) is a primary nutrient required for biological metabolism, although its relative scarcity in typical freshwater environments commonly makes it the limiting nutrient controlling biological activity (Wetzel, 2001; Denver and others, 2010). Natural sources of P include the wastes and remains of plants and animals and weathering of P-bearing minerals in soils and rocks (Litke, 1999; Wetzel, 2001; Filippelli, 2008). In urban environments, anthropogenic sources that commonly increase P concentrations in streams include wastewater and fertilizer (Paul and Meyer, 2001; Denver and others, 2010). P readily combines with other elements to form various phosphate minerals or sorbs strongly to the surface of other minerals, and therefore dissolved P concentrations are typically minimal, with the majority of P transported in association with suspended sediments (Hem, 1985; Litke, 1999; Fillipelli, 2008; Denver and others, 2010). Dissolved P, however, may be transported from groundwater to surface water, where ecological effects of the biologically available P can be pronounced (Kang and others, 2005; Denver and others, 2010).

Patterns in total P were evaluated in a manner similar to those for N. The evaluation of phosphorus was limited by the censoring of some P species, particularly orthophosphorus. Phosphorus concentrations are generally low, particularly during base-flow conditions, and laboratory methods capable of measuring small amounts of P are required to quantify these low levels. Statistical procedures have been developed to analyze datasets with concentrations below laboratory detection levels, commonly referred to as nondetects (Helsel, 2005, and references therein). These procedures typically have thresholds for the maximum proportion of the dataset that are nondetects, and the quality of the statistical analyses degrade as these thresholds are approached or exceeded. Because of the high proportion of nondetects for some P analytes at some stations, the monthly boxplots were not generated for all P analytes at all monitoring stations.

Median total P (mg/L as P) by monitoring station ranges from 0.01 to 0.09 mg/L. Two stations, Flatlick Branch and Frog Branch, have concentrations greater than most other monitoring stations (fig. 19). Most total P measurements in the network reveal concentrations between the laboratory detection limits and reporting limits, and therefore are estimated (E).

The total P concentrations measured in monthly samples typically collected during base-flow conditions are largely composed of dissolved P, as indicated by the similar concentrations and patterns observed between total P data and dissolved P data (figs. 19 and 20). Likewise, total dissolved P is largely composed of orthophosphate (fig. 21), although the higher laboratory detections limits for orthophosphate relative to total dissolved P hinder this evaluation. As was the case with N, there is not typically sufficient energy to entrain particulates under base-flow conditions, and therefore total particulate P concentrations are typically very low (fig. 22).

Seasonal patterns in total P are evident at monitoring stations where P concentrations are greatest—Flatlick Branch, Frog Branch, and Paul Spring Branch (fig. 19). It is likely that similar seasonal patterns occur at stations where concentrations are lower, but these patterns are not discernible because of the highly censored data. Phosphorus concentrations tend to be greatest during the late summer months and lowest during winter months.

The two stations associated with the greatest P concentrations, Flatlick Branch and Frog Branch, drain a landscape formed over Late Triassic shale and siltstone bedrock. These rocks formed from particulate matter (including plant and animal remains) deposited in extensive shallow lakes and are consequently P rich (Lee and Froelich, 1989). The shallow surficial soils formed by the weathering of these rocks are richer in P than soils elsewhere in Fairfax County. Terziotti and others (2010) mapped mean bed sediment P concentrations of 400 to 700 parts per million in these watersheds, whereas the remainder of the monitored watersheds are in areas having mean bed sediment P concentrations of 400 parts per million or less. Natural background sources of P have been shown to contribute to instream P concentrations (Denver and others, 2010), and the elevated P in the Flatlick Branch and Frog Branch watersheds can probably be attributed, in part, to natural sources. Anthropogenic P sources may also be present, however, and further work is needed to determine the relative contributions of natural and anthropogenic sources. Nonetheless, consideration of natural background sources is integral to understanding the probable effects of management activities on P.

Suspended-Sediment and Nutrient Loads and Yields

Suspended-sediment and nutrient loads and yields were computed for the four intensive monitoring stations (Dead Run, Difficult Run, South Fork Little Difficult Run, and Flatlick Branch). Loads and yields were computed for WY 2009–12 at Dead Run, which was not operational until spring 2008, and for WY 2008–12 at the three other monitoring stations.

Suspended-Sediment and Nutrient Load Models

All suspended-sediment load estimation models developed include the natural logarithm of streamflow and the natural logarithm of turbidity, and all models except the one for Dead Run include water temperature (table 3). The significance of streamflow and turbidity in the estimation model reflects the strong influence streamflow has on sediment transport and the strong influence sediment concentration has on turbidity, as described earlier. The significance of water temperature is attributed to seasonal effects on sediment availability, as has been found in other rivers in Virginia (Jastram and others, 2009, 2010). Model results were re-expressed as concentrations to permit direct comparison with measured concentrations – this comparison indicated that all models provide a good fit, particularly at high concentrations, which affect computed total loads the most (fig. 23).

The selected estimation models for N loads—total N, dissolved N, and particulate N—were monitoring-station- and constituent-specific. These models included various combinations of explanatory variables, including natural logarithm of streamflow, natural logarithm of streamflow squared, natural logarithm of turbidity, water temperature, natural logarithm of specific conductance, and pH (table 4). The significance of

Table 3. Number of observations, regression coefficients, and R^2 for suspended sediment load models.

[Station names defined in table 1. Dependent variable is natural logarithm of suspended sediment load. Ln, natural logarithm; Q, streamflow; R^2, coefficient of determination; n/a, not applicable—variable not included in selected model]

Station	Number of observations	Intercept	Ln Q	Ln turbidity	Water temperature	R^2
DEAD	242	–1.832	1.418	0.643	n/a	96.4
DIFF	205	–1.493	1.316	0.829	0.015	97.1
FLAT	242	–2.390	1.310	0.894	0.015	97.1
SF LIL	227	–2.189	1.468	0.762	0.027	97.6

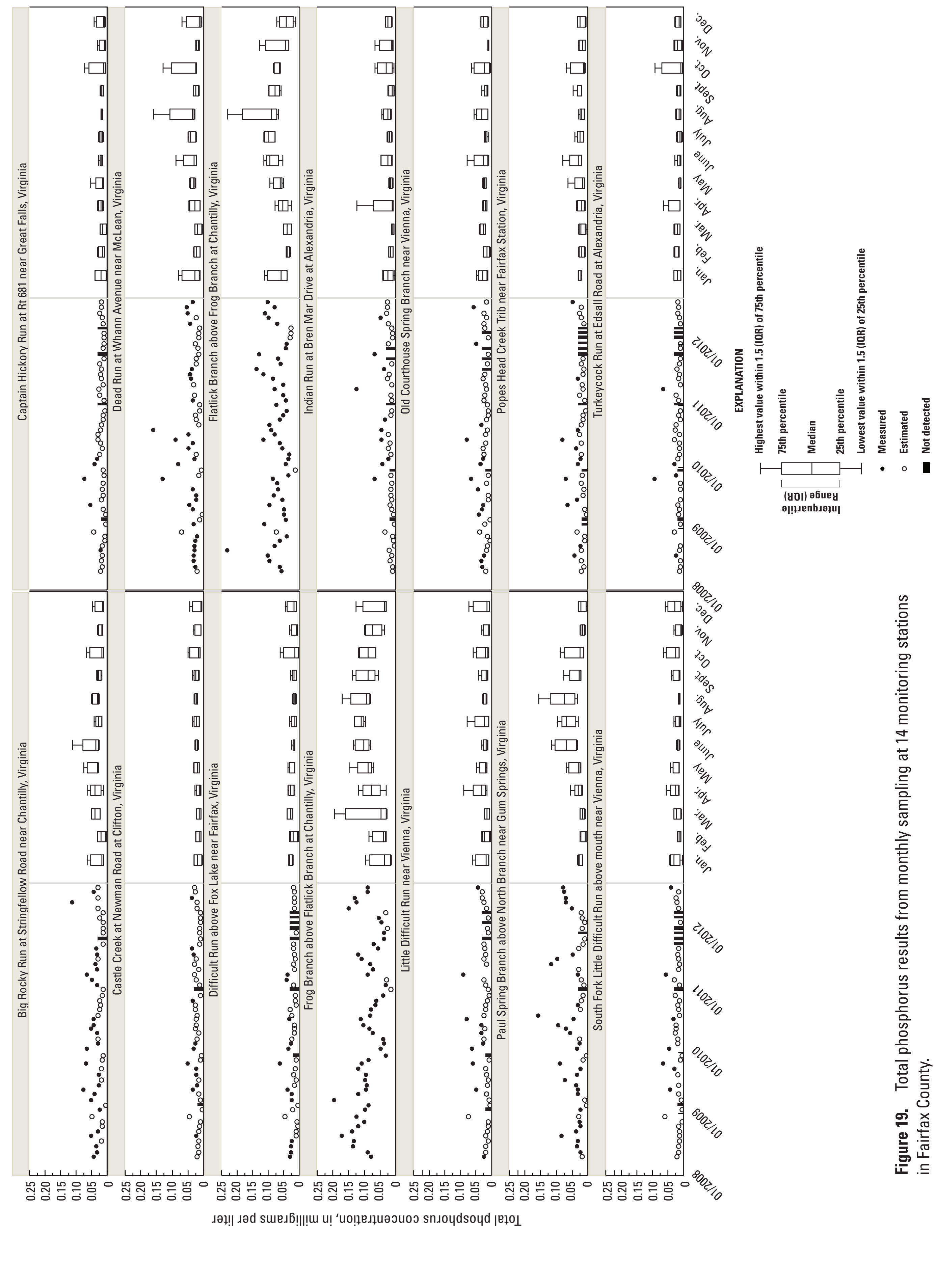

Figure 19. Total phosphorus results from monthly sampling at 14 monitoring stations in Fairfax County.

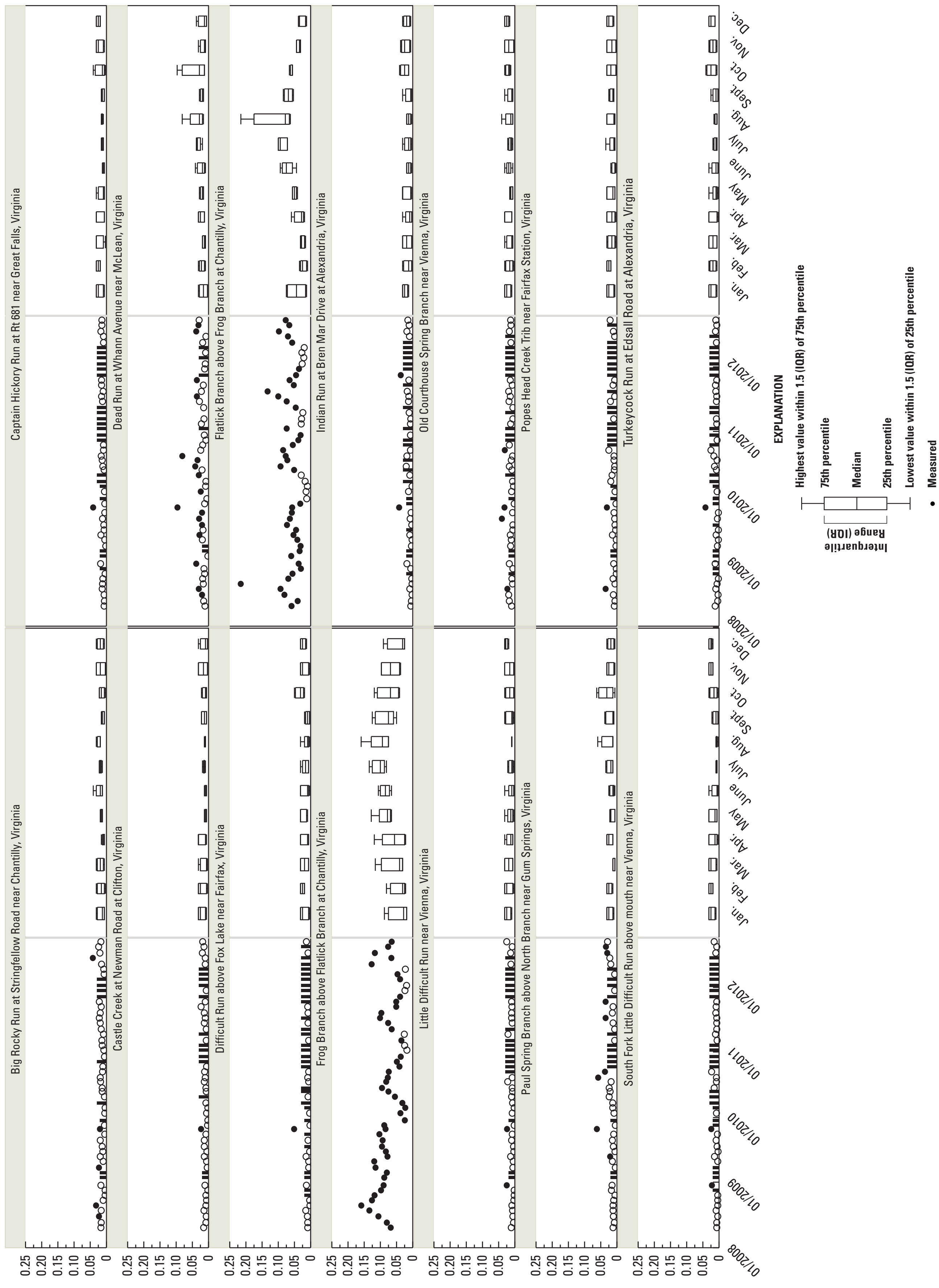

Figure 20. Total dissolved phosphorus results from monthly sampling at 14 monitoring stations in Fairfax County.

Figure 21. Orthophosphate results from monthly sampling at 14 monitoring stations in Fairfax County.

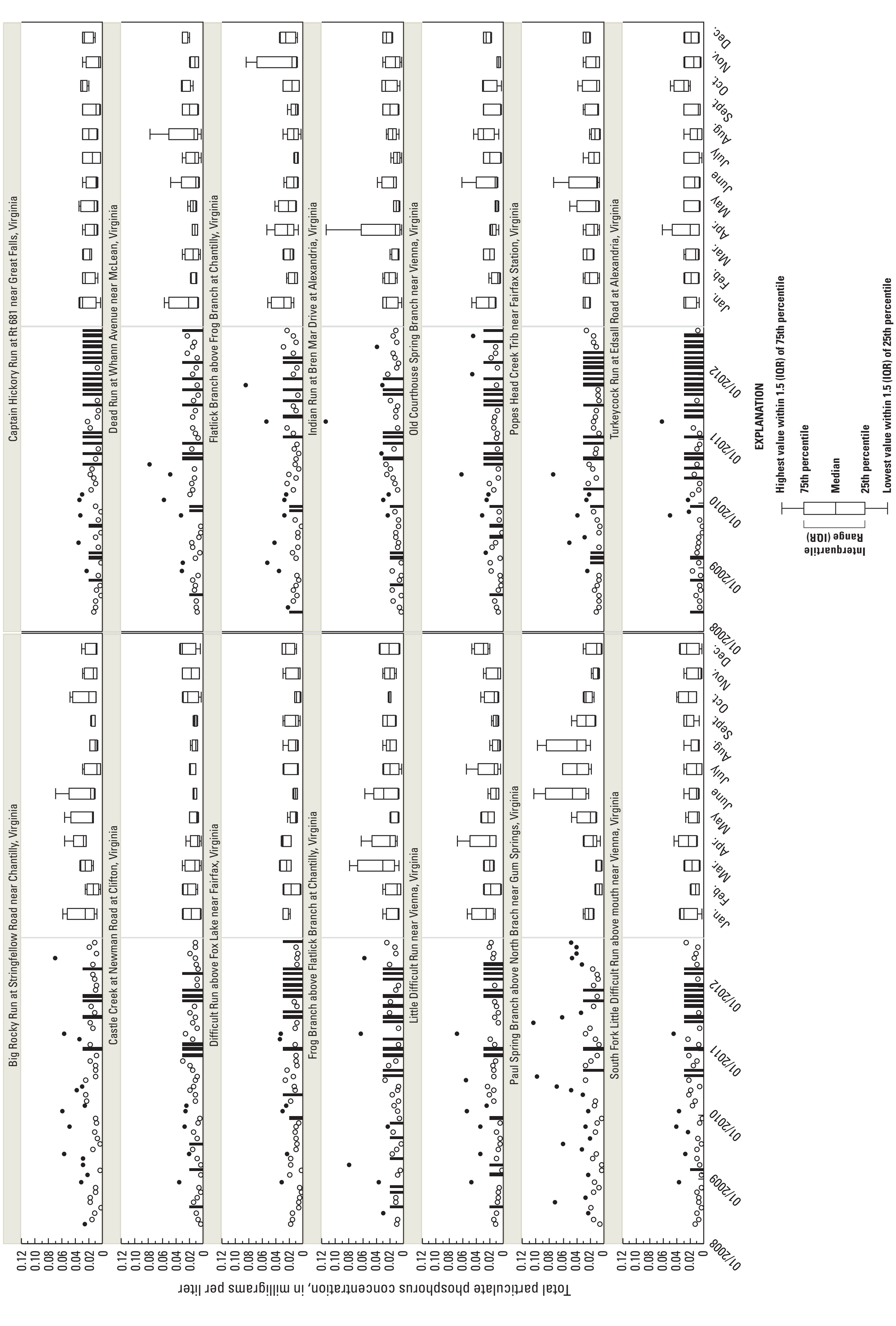

Figure 22. Total particulate phosphorus results from monthly sampling at 14 monitoring stations in Fairfax County.

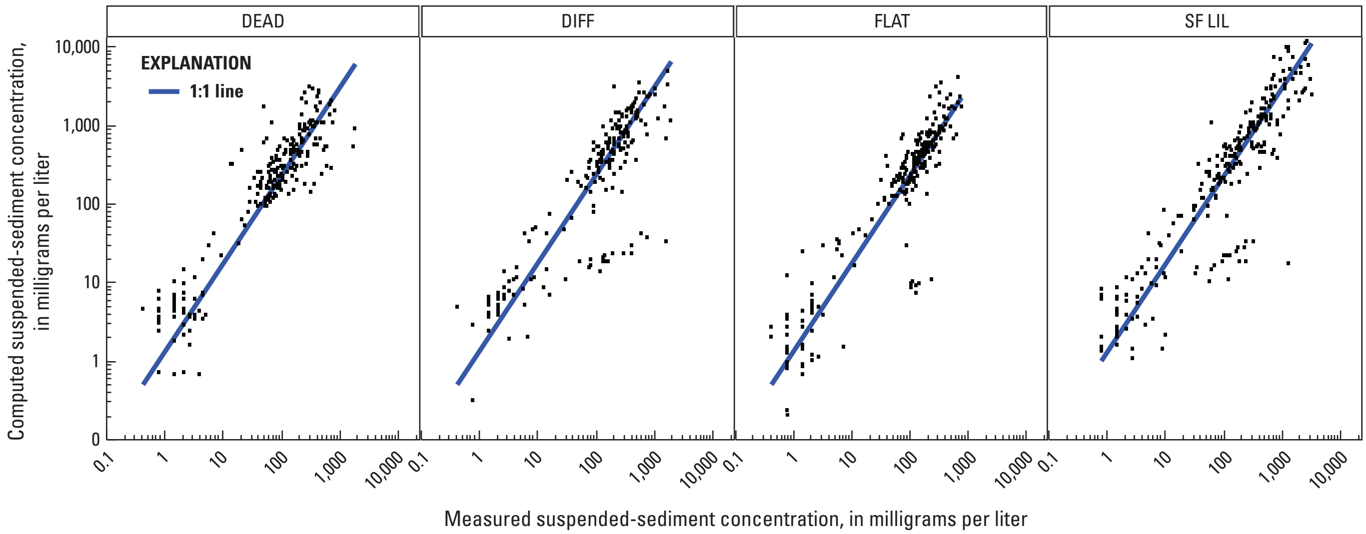

Figure 23. Measured suspended-sediment concentration against computed suspended-sediment concentration for the four intensive monitoring stations. Station names defined in table 1.

these explanatory variables is attributed to various causative and associative relations with N transport. The selected models generally exhibited good fit, with little bias and few outliers in the relation between measured and computed concentrations (fig. 24).

The selected estimation models for P loads—total P, dissolved P, and particulate P—were monitoring station- and constituent-specific. Similar to the N models, the P models include various combinations of explanatory variables, including natural logarithm of streamflow, natural logarithm of streamflow squared, natural logarithm of turbidity, water temperature, natural logarithm of specific conductance, and pH (table 5). The significance of these explanatory variables is attributed to various causative and associative relations with P transport. The selected models generally exhibited good fit, with little bias and few outliers in the relation between measured and computed concentrations (fig. 25).

Annual Suspended-Sediment and Nutrient Loads and Yields

Substantial variability in annual suspended-sediment loads can be seen across monitoring stations and water years (fig. 26). Differences across monitoring stations may be attributed to varying watershed sizes, landscape characteristics within those watersheds, and the localized effects of some rainfall events. Evaluation of yields (load per unit area) is more appropriate for comparisons among monitoring stations because the effect of watershed area is removed. Although interannual variability is still present in the yield values, a clearer picture of the relative contribution of sediment from each watershed may be gained (fig. 26). On average, South Fork Little Difficult Run and Difficult Run yield about as much as twice the mass of sediment (1,074 and 843 tons per square mile (ton/mi^2), respectively) as Flatlick Branch and Dead Run (562 and 461 ton/mi^2, respectively).

Between-year differences are largely attributed to the hydrologic regime in a given year, particularly the effects of storms with high rainfall. For example, most monitoring stations have greater loads in WY 2008 and WY 2011, the years in which Tropical Storms Hanna and Lee, respectively, delivered record rainfall to portions of Fairfax County. The influence of these single, large events is demonstrated by the greater strength of the monitoring-station-specific relation between annual suspended-sediment-concentration (SSC) load and annual peak streamflow, compared to the relation between annual SSC load and total annual streamflow (fig. 27). Here, annual peak streamflow refers to the maximum instantaneous streamflow recorded during each water year and total annual streamflow refers to the total volume of water conveyed in a given water year.

Nitrogen loads generally exhibit less interannual variability than sediment loads, with the exception of the particulate N loads (fig. 28). Dissolved N composes 60 to 85 percent of the total annual N load at the four monitoring stations, and the annual dissolved load is not largely affected by peak-flow events (fig. 29*A*, *C*, *E*), yet is strongly related to the total volume of water conveyed (fig. 29*B*, *D*, *F*), because much of the N is transported during non-stormflow periods that compose the majority of the annual flow. Conversely, particulate N loads exhibit variability very similar to that of sediment loads (figs. 26 and 28), because particulate N is liberated and transported via erosional processes, and the energy of stormflows is required to entrain particulate forms of N. Because of these transport processes, the relations between annual peak flow and particulate N are strongest (fig. 29*E*), whereas the relations between total streamflow and particulate N are weakest (fig. 29*F*).

Across-monitoring-station differences in N loads are apparent, with Difficult Run transporting the greatest N loads, followed by Flatlick Branch, SF Little Difficult Run, and Dead Run (fig. 28). This pattern is less apparent, however, when

Table 4. Number of observations, regression coefficients, and R^2 for nitrogen load models.

[Station names defined in table 1. Dependent variable is natural logarithm of constituent load. Ln, natural logarithm; Q, streamflow; SC, specific conductance; R^2, coefficient of determination; n/a, not applicable—variable not included in selected model]

Station	Number of observations	Intercept	Ln Q	Ln Q^2	Ln turbidity	Water temperature	Ln SC	pH	R^2
				Total nitrogen					
DEAD	206	4.285	1.109	n/a	–0.046	0.013	0.323	–0.172	97.7
DIFF	187	3.855	0.982	n/a	0.145	n/a	0.188	n/a	97.0
FLAT	201	1.698	1.166	n/a	n/a	0.015	0.327	0.174	97.8
SF LIL	199	2.779	1.138	n/a	n/a	0.010	1.868	n/a	97.5
				Total particulate nitrogen					
DEAD	206	0.892	1.219	n/a	0.271	0.015	0.216	n/a	95.5
DIFF	187	-1.530	0.914	0.031	0.606	0.014	n/a	0.432	94.9
FLAT	201	2.049	1.170	n/a	0.289	0.024	n/a	n/a	93.8
SF LIL	199	1.392	1.145	n/a	0.464	n/a	n/a	n/a	94.5
				Total dissolved nitrogen					
DEAD	206	3.140	1.032	–0.017	–0.130	0.015	0.293	n/a	97.8
DIFF	187	7.156	0.942	–0.026	n/a	–0.013	0.109	–0.357	97.1
FLAT	201	3.142	1.083	n/a	–0.071	n/a	0.311	n/a	96.7
SF LIL	199	3.502	1.020	–0.017	–0.073	n/a	0.300	n/a	97.7

Table 5. Number of observations, regression coefficients, and R^2 for phosphorus load models.

[Dependent variable is natural logarithm of constituent load. Ln, natural logarithm; Q, streamflow; SC, specific conductance; R^2, coefficient of determination; n/a, not applicable—variable not included in selected model]

Station	Number of observations	Intercept	Ln Q	Ln Q^2	Ln turbidity	Water temperature	Ln SC	pH	R^2
				Total phosphorus					
DEAD	206	0.107	1.121	n/a	n/a	0.025	n/a	n/a	97.9
DIFF	187	2.280	0.997	n/a	0.645	n/a	–0.402	n/a	97.8
FLAT	201	0.690	1.012	0.032	0.364	0.036	n/a	n/a	96.8
SF LIL	199	–1.431	1.154	n/a	0.623	0.437	n/a	n/a	97.5
				Total particulate phosphorus					
DEAD	206	–0.401	1.180	n/a	0.500	0.011	n/a	n/a	97.1
DIFF	187	1.268	0.975	n/a	0.718	n/a	–0.302	n/a	97.3
FLAT	201	–0.477	1.148	n/a	0.548	0.024	n/a	n/a	96.1
SF LIL	199	–1.686	1.194	n/a	0.667	0.033	n/a	n/a	97.2
				Total dissolved phosphorus					
DEAD	206	2.086	0.959	n/a	0.213	0.017	–0.451	n/a	98.0
DIFF	187	3.181	1.046	n/a	0.142	n/a	–0.578	n/a	94.1
FLAT	201	0.780	0.901	0.017	0.083	0.048	–0.312	0.202	96.8
SF LIL	199	3.814	0.828	–0.016	0.344	n/a	–1.080	n/a	94.8

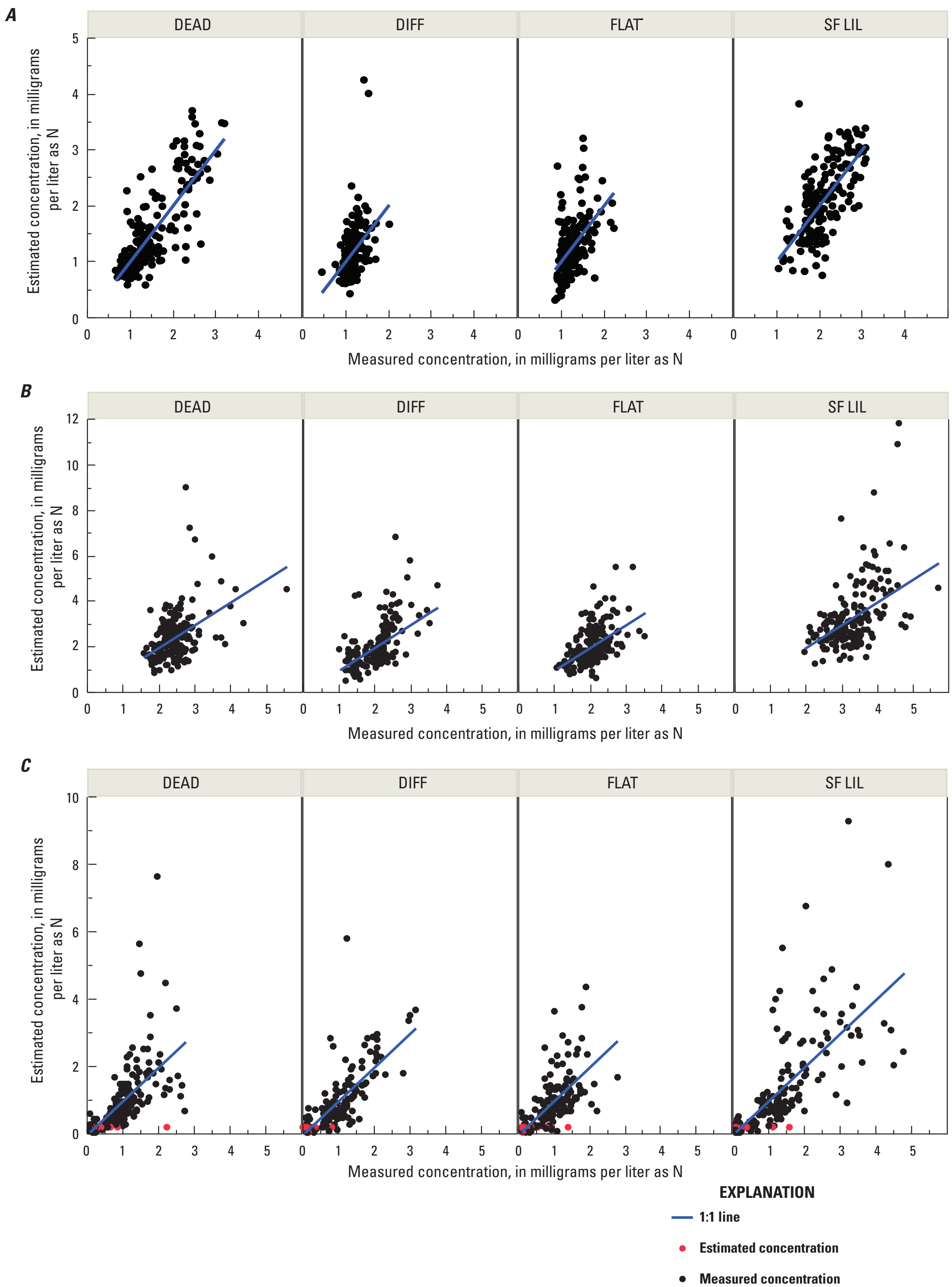

Figure 24. Measured *A*, total dissolved nitrogen, *B*, total nitrogen, and *C*, total particulate nitrogen concentrations against computed concentrations. Station names defined in table 1.

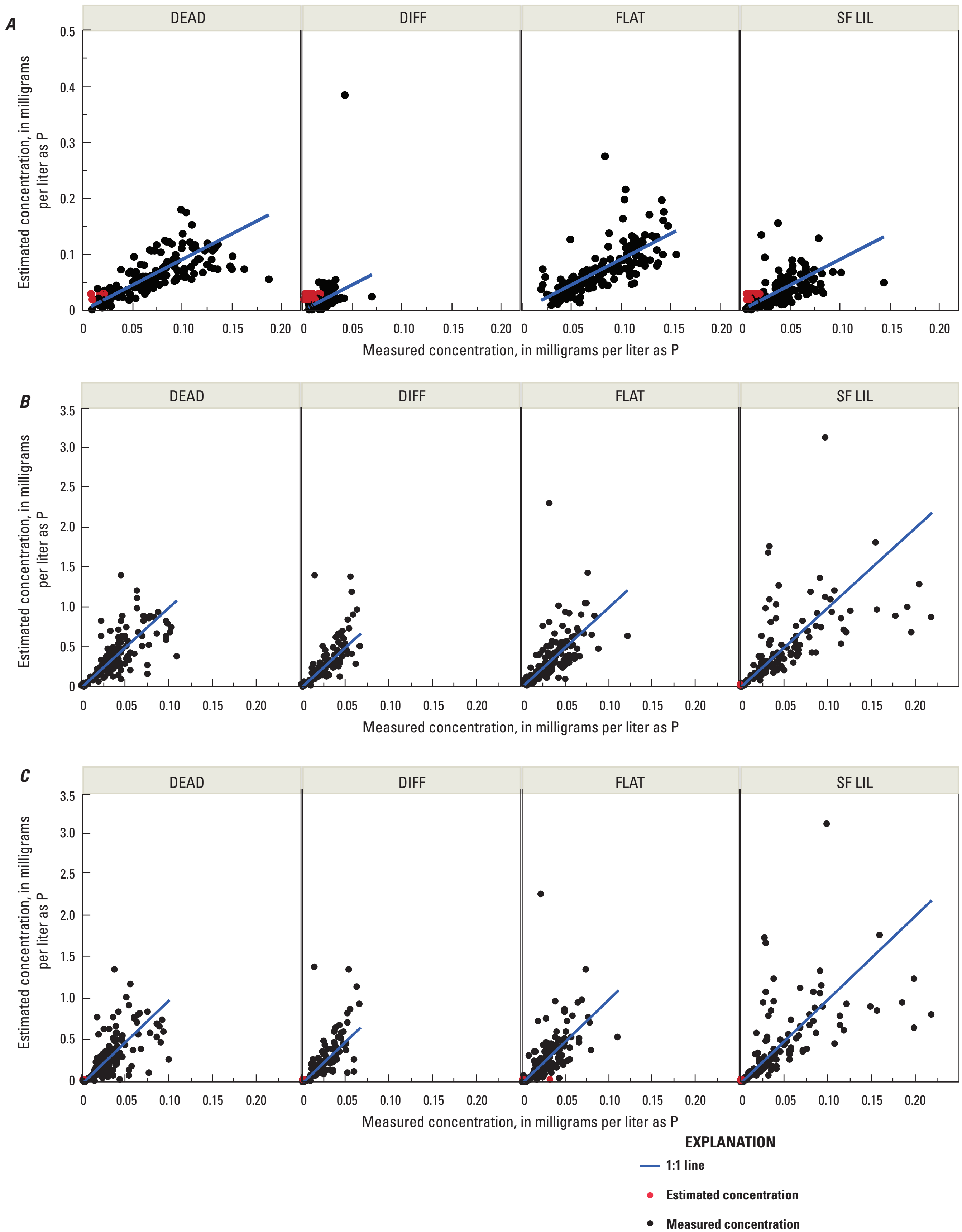

Figure 25. *A*, Total dissolved phosphorus, *B*, total phosphorus, and *C*, total particulate phosphorus concentrations against computed concentrations. Station names defined in table 1.

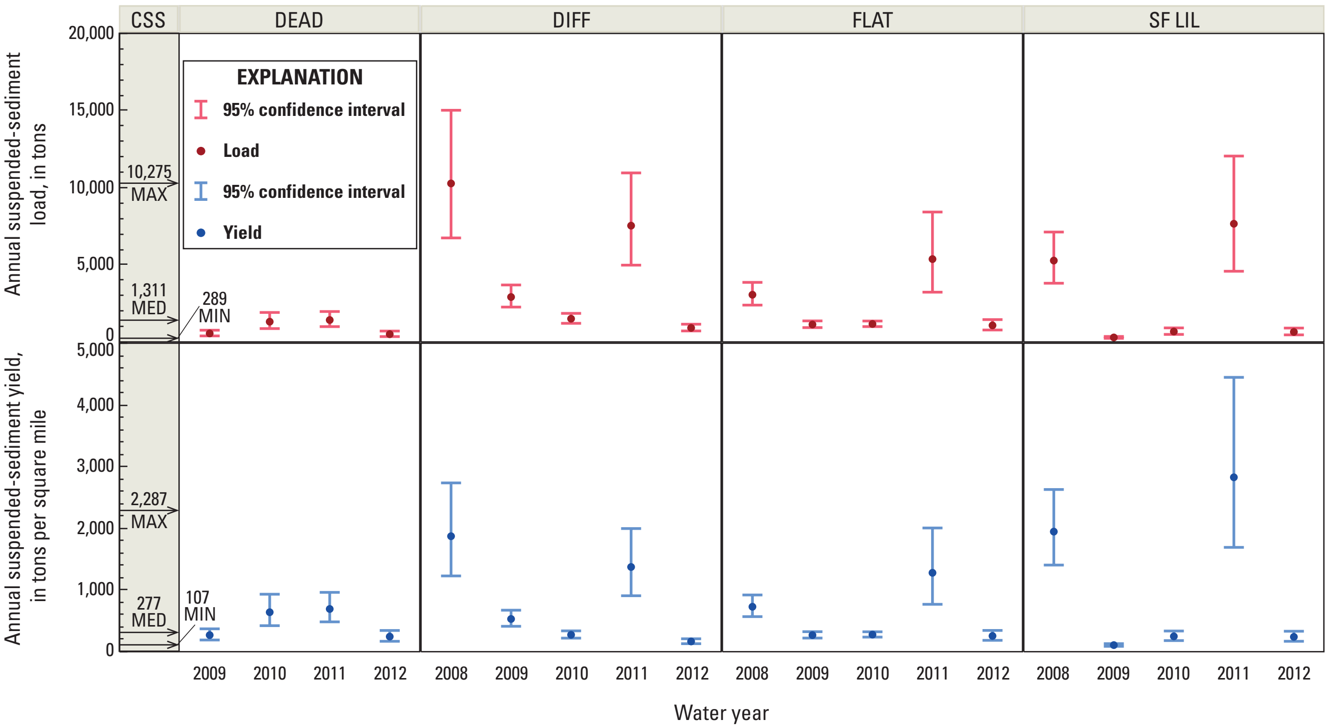

Figure 26. Suspended-sediment loads and yields for water years 2008 through 2012 for the four intensive monitoring stations. Station names defined in table 1. [CSS, combined summary statistics; min, minimum; med, median; max, maximum]

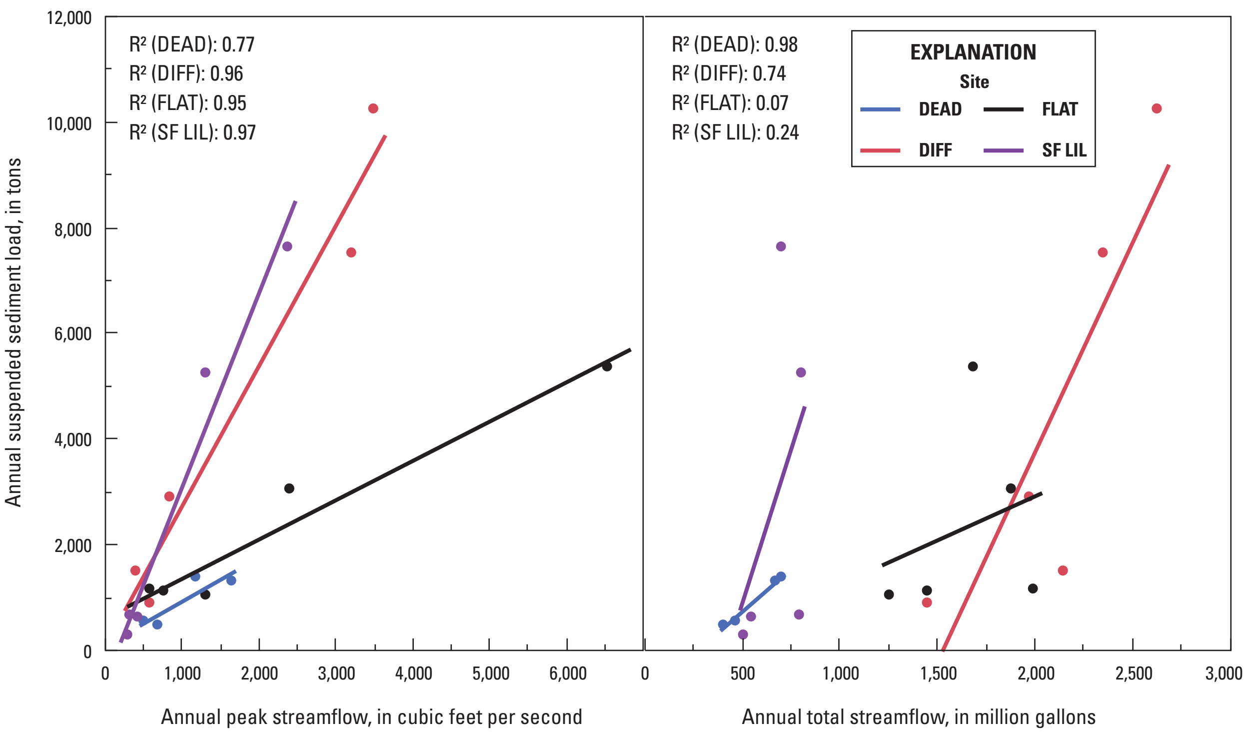

Figure 27. Annual suspended-sediment load against annual peak streamflow and annual total streamflow, with linear regression lines, for the four intensive monitoring stations for water years 2008 through 2012. Station names defined in table 1. R^2 is coefficient of determination.

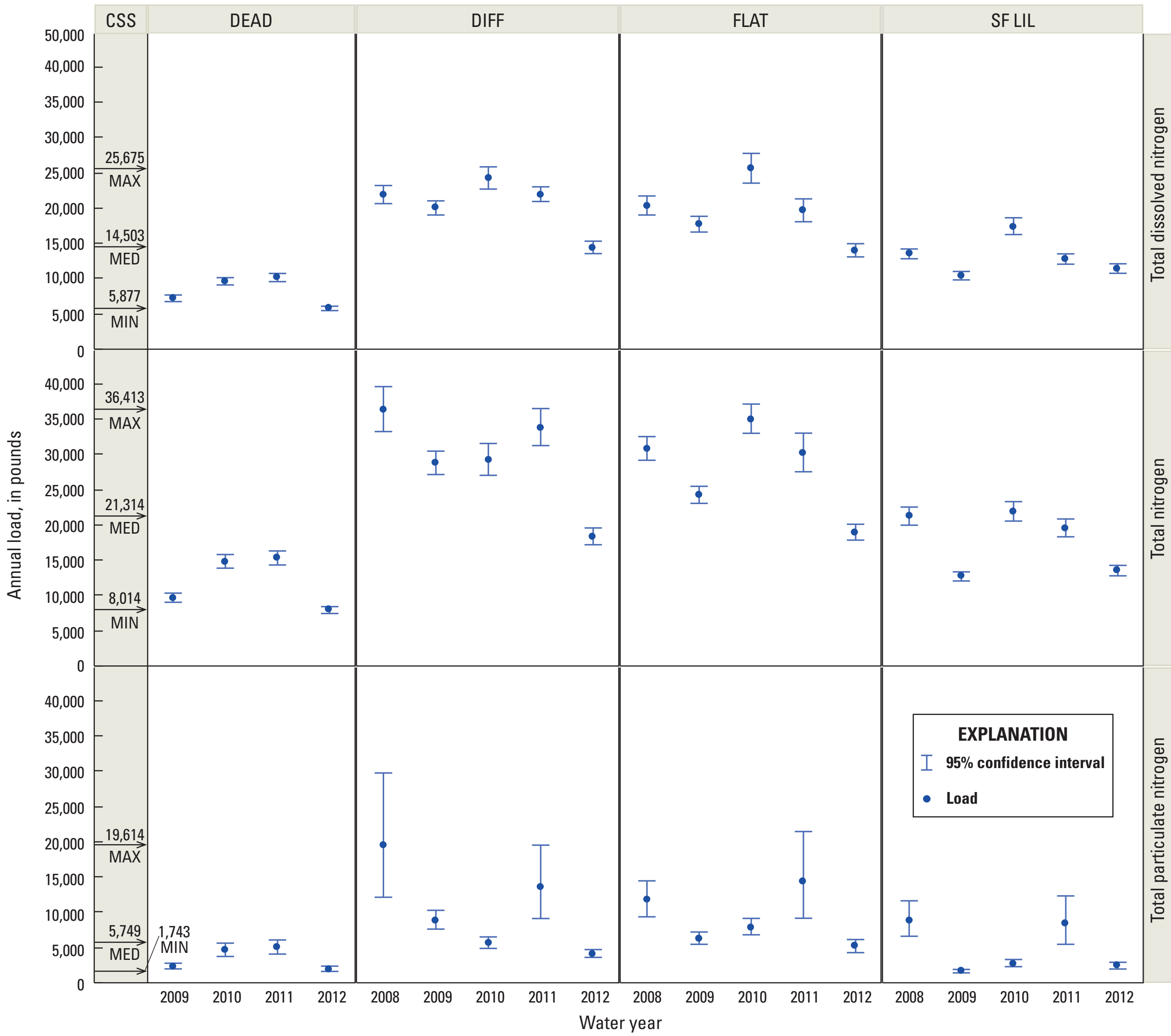

Figure 28. Annual loads of total dissolved nitrogen, total nitrogen, and total particulate nitrogen for water years 2008 through 2012 at the four intensive monitoring stations. Station names defined in table 1. [CSS, combined summary statistics; min, minimum; med, median; max, maximum]

watershed area is accounted for, as indicated by the annual N yields (fig. 30). On average, total N yields across the monitoring stations are comparable, with average annual yields that range from approximately 5,350 to 6,650 pounds per square mile (lb/mi^2) and an overall average of approximately 6,200 lb/mi^2 (fig. 30).

Annual loads and yields of total P and total particulate P show inter-monitoring station and annual variability comparable to the variability in suspended-sediment loads and yields (figs. 26, 31 and 32). Total P loads are largely composed of sediment-associated P transported during stormflow, resulting in the strong relations between total P and annual peak streamflow (fig. 33*C*), and therefore patterns in P loads mimic patterns in sediment loads. Although dissolved P contributes a relatively small amount of P to the total load, and little interannual variability is evident in dissolved P, there is inter-monitoring station variability in the dissolved loads. Dissolved P loads in Flatlick Branch are greater than the other monitoring stations (fig. 32), probably as a result of elevated concentrations during base-flow conditions (fig. 20). As described previously, the Flatlick Branch watershed is located in the Triassic Lowland, a terrane underlain by sedimentary deposits, some of which contain P, and this natural source of P probably contributes to the P concentrations in Flatlick Branch.

Regional Comparison of Yields

Monitoring of nutrient and sediment loads and yields in small, urbanized, watersheds is relatively rare (for example, Chesapeake Bay Program, 2009), and therefore opportunities

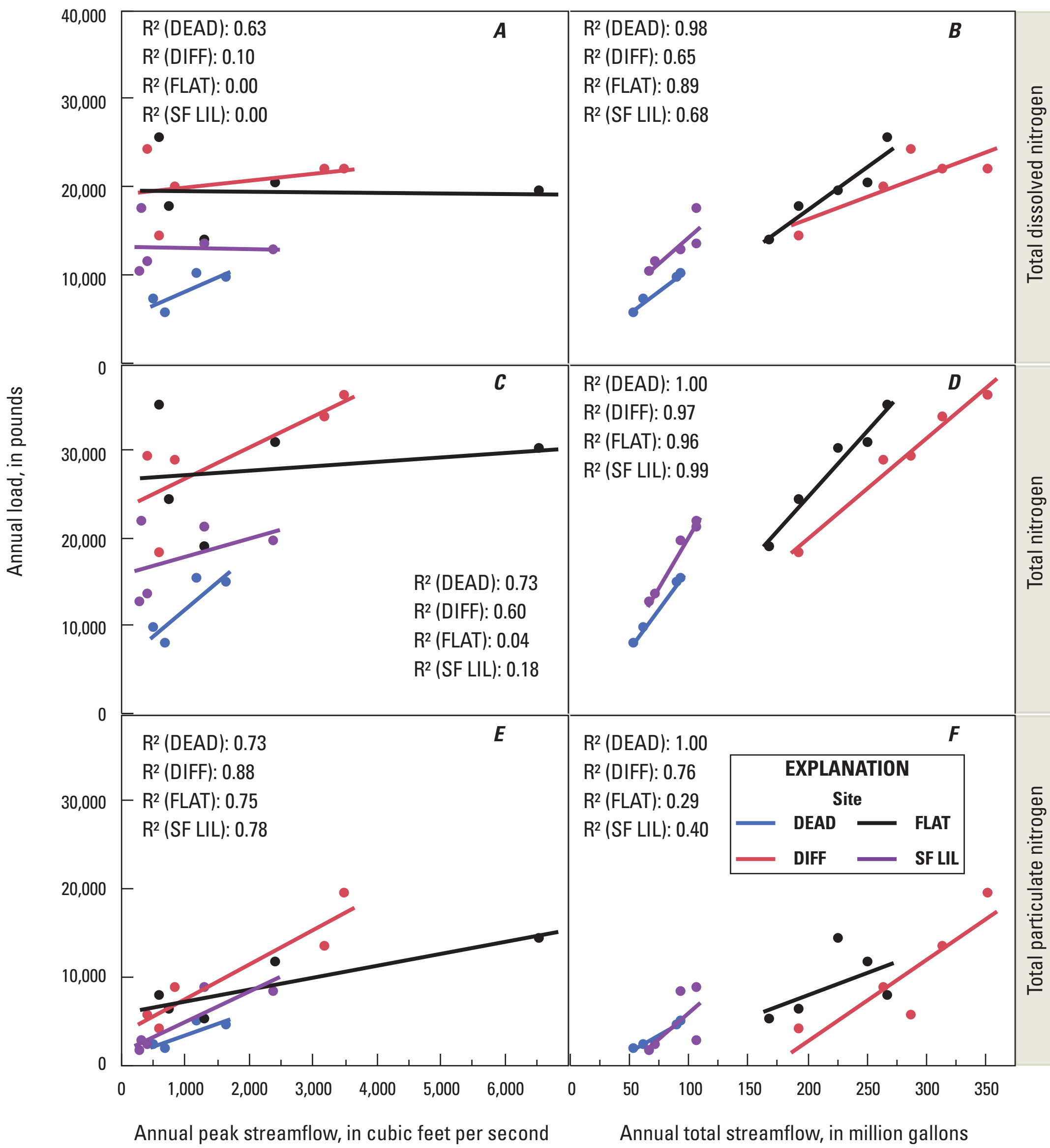

Figure 29. Annual (*A*, *B*) total dissolved nitrogen, (*C*, *D*) total nitrogen, and (*E*, *F*) total particulate nitrogen load against annual peak streamflow and annual total streamflow, with linear regression lines, for the four intensive monitoring stations for water years 2008 through 2012. Station names defined in table 1. R^2 is coefficient of determination.

for comparison with other urban areas are limited. Two studies from the eastern United States that provide such data for comparison with the yields measured in Fairfax County were completed in Gwinnett County, Georgia (Landers and others, 2007), in the Atlanta metropolitan area, and Central and Eastern North Carolina (Harden and others, 2013). In addition to comparisons with other urbanized areas in the eastern United States, yields are compared with those of nearby watersheds draining into the Occoquan River (Dougherty and others, 2006) and numerous other watersheds in the Chesapeake Bay watershed (U.S. Geological Survey, 2013). Although the watersheds included in the Occoquan and Chesapeake Bay yields are much larger and incorporate many different land uses, this comparison provides an important perspective on how urban watersheds, which are under-represented in Chesapeake Bay monitoring activities (Chesapeake Bay Program, 2009), compare with other watersheds draining into Chesapeake Bay.

A comparison of sediment yields from Fairfax County watersheds to those from urban watersheds in the Atlanta metropolitan area demonstrates that the Fairfax County yields are generally comparable to those from another urban area (fig. 34). Comparison of sediment yields from Fairfax County watersheds with those from the larger Occoquan watersheds nearby, however, show that a much greater amount of sediment is being exported from the small watersheds of Fairfax County than these larger watersheds that drain predominantly forested areas. The yields from the Atlanta area and the

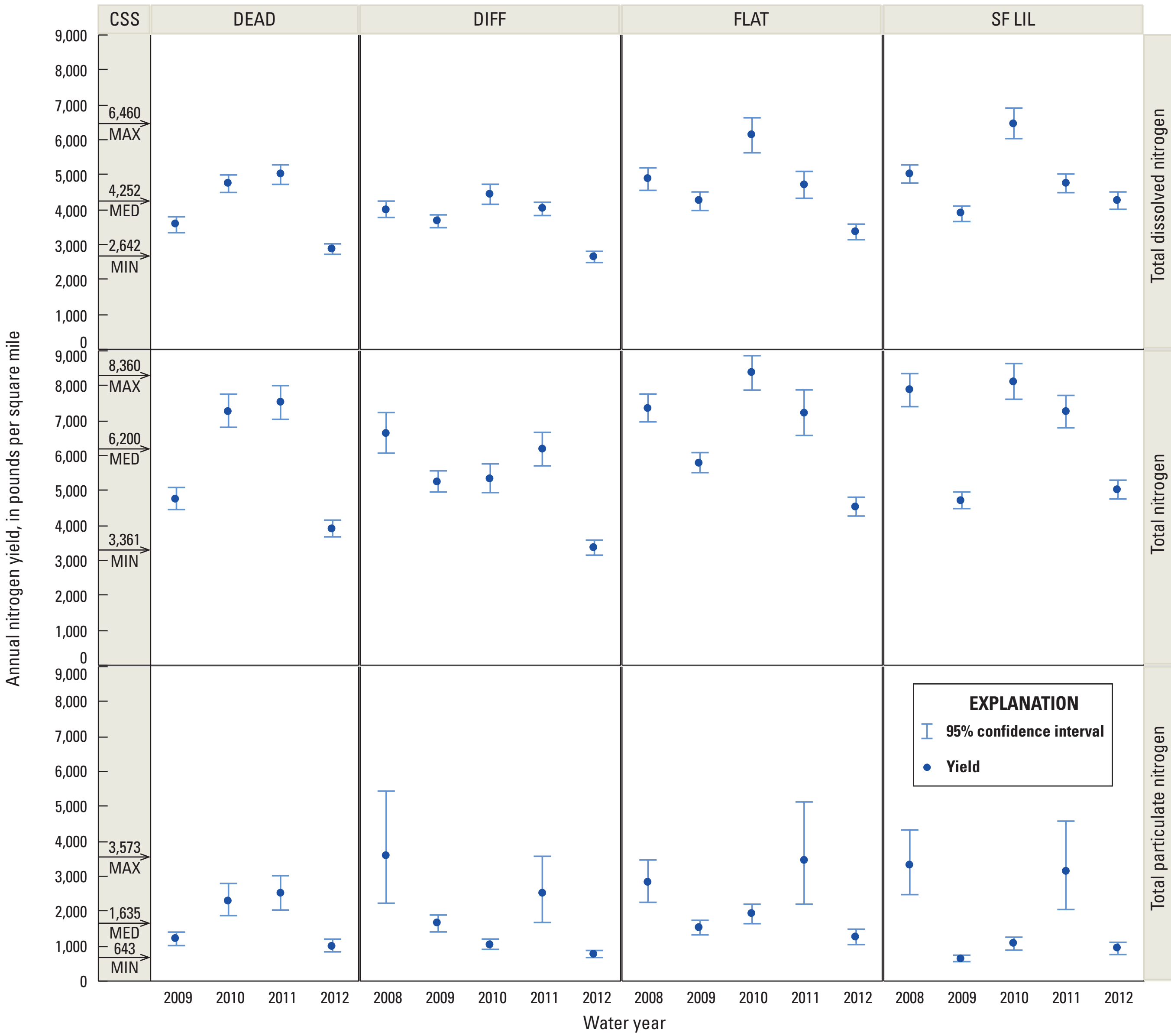

Figure 30. Annual yields of total dissolved nitrogen, total nitrogen, and total particulate nitrogen for water years 2008 through 2012 at the four intensive monitoring stations. Station names defined in table 1. [CSS, combined summary statistics, min, minimum; med, median; max, maximum]

Occoquan watersheds are probably greater than what is represented in figure 34, however, because the yields shown in the figure are for total suspended solids, a measure of sediment concentration that has been demonstrated to underrepresent actual concentrations as a result of the method used for analysis (Gray and others, 2000).

A comparison of sediment yields for Fairfax County watersheds to those from other watersheds in the Chesapeake Bay watershed reveals that, on average, the Fairfax watersheds deliver greater masses of sediment per unit of watershed area than most monitored Chesapeake Bay watersheds (fig. 34). This result is probably a result of multiple factors related to watershed characteristics that are diminished over the larger areas of the Chesapeake Bay monitoring watersheds. For example, the Fairfax County watersheds are higher-gradient headwater systems that, regardless of land-use, produce higher sediment yields than other watersheds as a result of the energy available for entrainment of sediments. The larger watersheds represented in the Chesapeake Bay dataset encompass a range of topographic gradients and the effect of the headwater areas is averaged over larger areas, thereby reducing the overall yield of these watersheds. Additionally, because of the location and size of the watersheds in Fairfax County, these watersheds more exclusively represent anthropogenically disturbed areas, where the Chesapeake Bay watersheds incorporate larger proportions of undisturbed areas along with the disturbed areas, thereby reducing the effect of disturbance.

Total N yields from the Fairfax County watersheds were comparable to yields from the Atlanta area, although yields from both areas were greater than those determined for

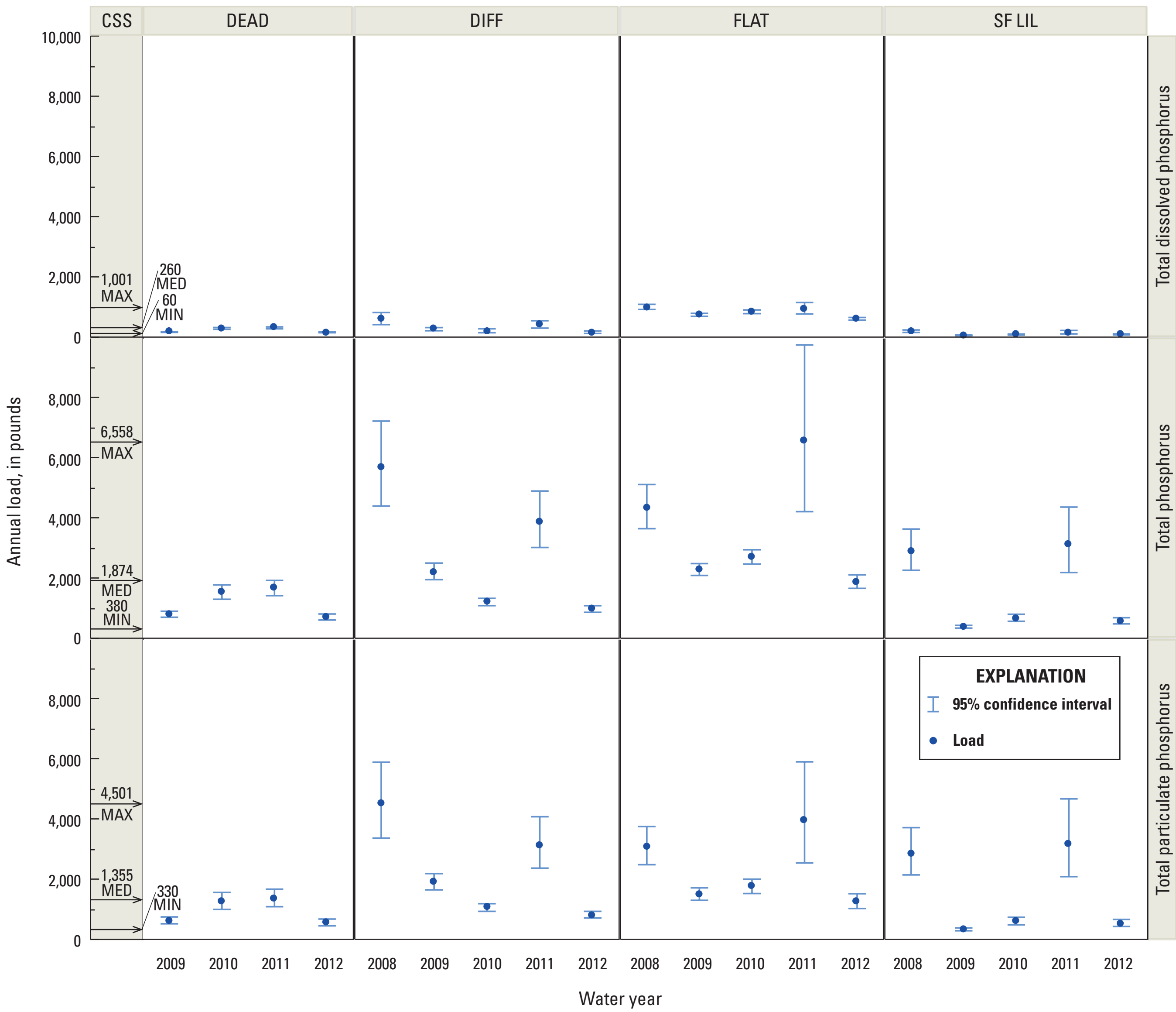

Figure 31. Annual loads of total dissolved phosphorus, total phosphorus, and total particulate phosphorus for water years 2008 through 2012 at the four intensive monitoring stations. Station names defined in table 1. [CSS, combined summary statistics, min, minimum; med, median; max, maximum]

developed watersheds in North Carolina and the Occoquan watersheds (fig. 35). Total N yields in the Chesapeake Bay watershed span a much greater range than the yields observed in the three studies representing developed watersheds, with the yields from Fairfax County ranging between the 50th and 75th percentiles of yields from the Chesapeake Bay watershed. Although the Fairfax County yields are greater than those for over 50 percent of the Chesapeake Bay watersheds, over 25 percent of Chesapeake Bay watersheds yield greater masses of N, with the highest yield being over three times greater than the highest average yield in Fairfax County (fig. 35).

Total P yields from Fairfax County watersheds, like the N yields, were comparable to yields from the Atlanta area, although typically greater than those determined for watersheds in North Carolina and the Occoquan watershed (fig. 36). As with Total N, Total P yields in the Chesapeake Bay watershed span a much greater range than the yields observed in three studies representing developed watersheds, with the yields from Fairfax County ranging between the 75th and 90th percentiles of yields from the Chesapeake Bay watershed. Although the Fairfax County yields are within the top quartile of yields from Chesapeake Bay watersheds, the highest yield in the Chesapeake Bay watersheds is over two times greater than the highest average yield in Fairfax County. The elevated P yields from the Fairfax County watersheds match expectations, given the elevated sediment yields and the fact that the majority of P transported is typically bound to sediment particles (Hem, 1985).

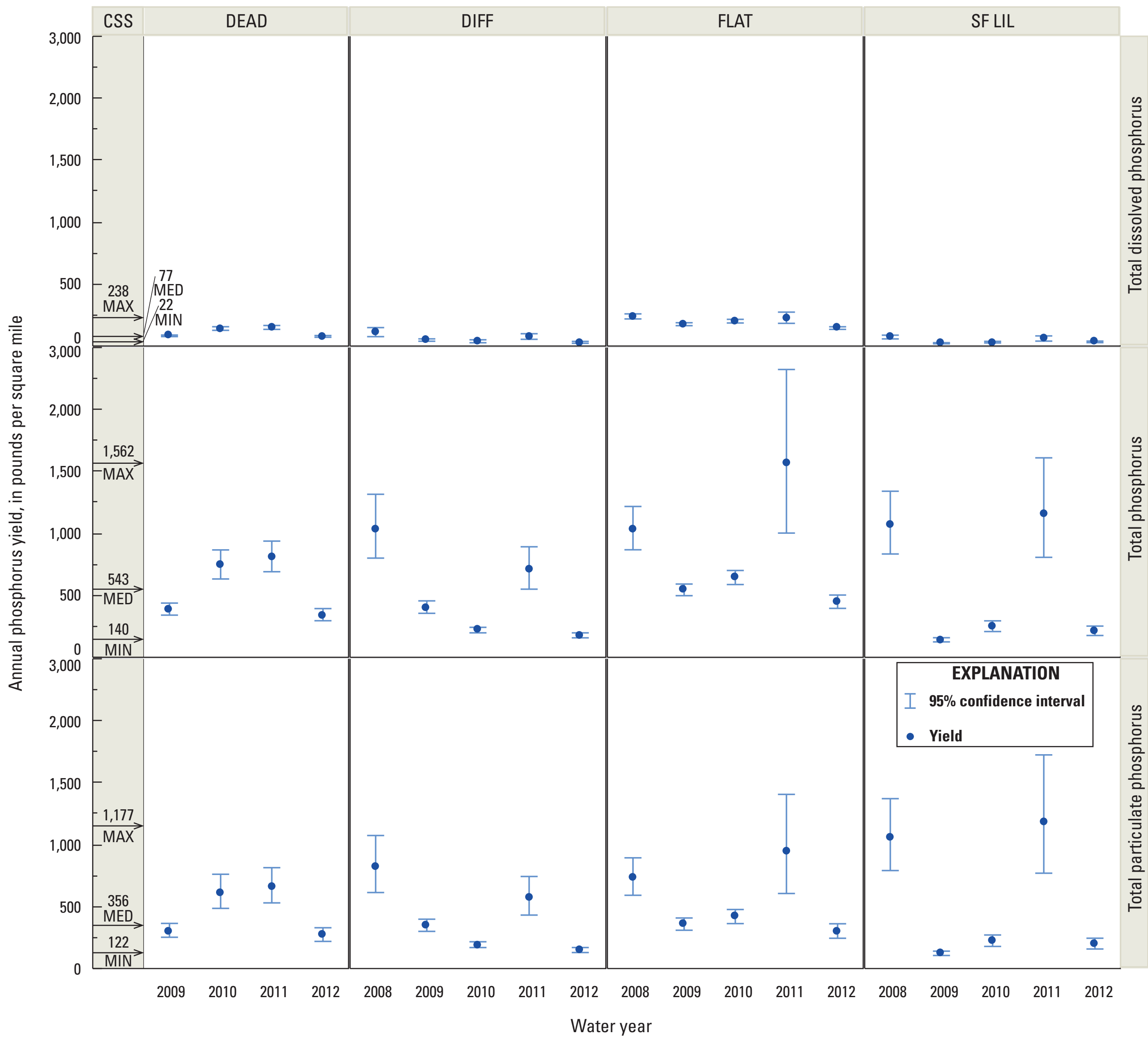

Figure 32. Annual yields of total dissolved phosphorus, total phosphorus, and total particulate phosphorus for water years 2008 through 2012 at the four intensive monitoring stations. Station names defined in table 1. R^2 is coefficient of determination. [CSS, combined summary statistics, min, minimum; med, median; max, maximum]

Suspended-Sediment and Nutrient Concentration Models

Suspended-sediment and nutrient concentration models were generated to support potential future applications and analyses, such as inclusion in the NRTWQ system and comparison with concentration models developed for other locations. Although these models are not directly used in analysis herein, the models presented are valid for use in the aforementioned applications and analyses.

For most cases, little additional explanatory power (increase in adjusted R^2) was achieved through the addition of streamflow to the univariate model using turbidity as the sole explanatory variable (table 6). In all cases, except for Dead Run, the best possible model included turbidity, streamflow, and water temperature as explanatory variables (table 6), although the variability explained by these models was similar to that of the bivariate turbidity and streamflow models.

Concentration models for nutrients were developed for total N and P concentrations (tables 7 and 8). The high number of censored values for dissolved nutrients, particularly dissolved P, precluded modeling of those constituents. The regression models developed to estimate total N concentrations are much less effective than the models developed to estimate suspended sediment and total P concentrations. The turbidity-only model for total N at Dead Run was not statistically significant ($\alpha = 0.05$), and the variability explained

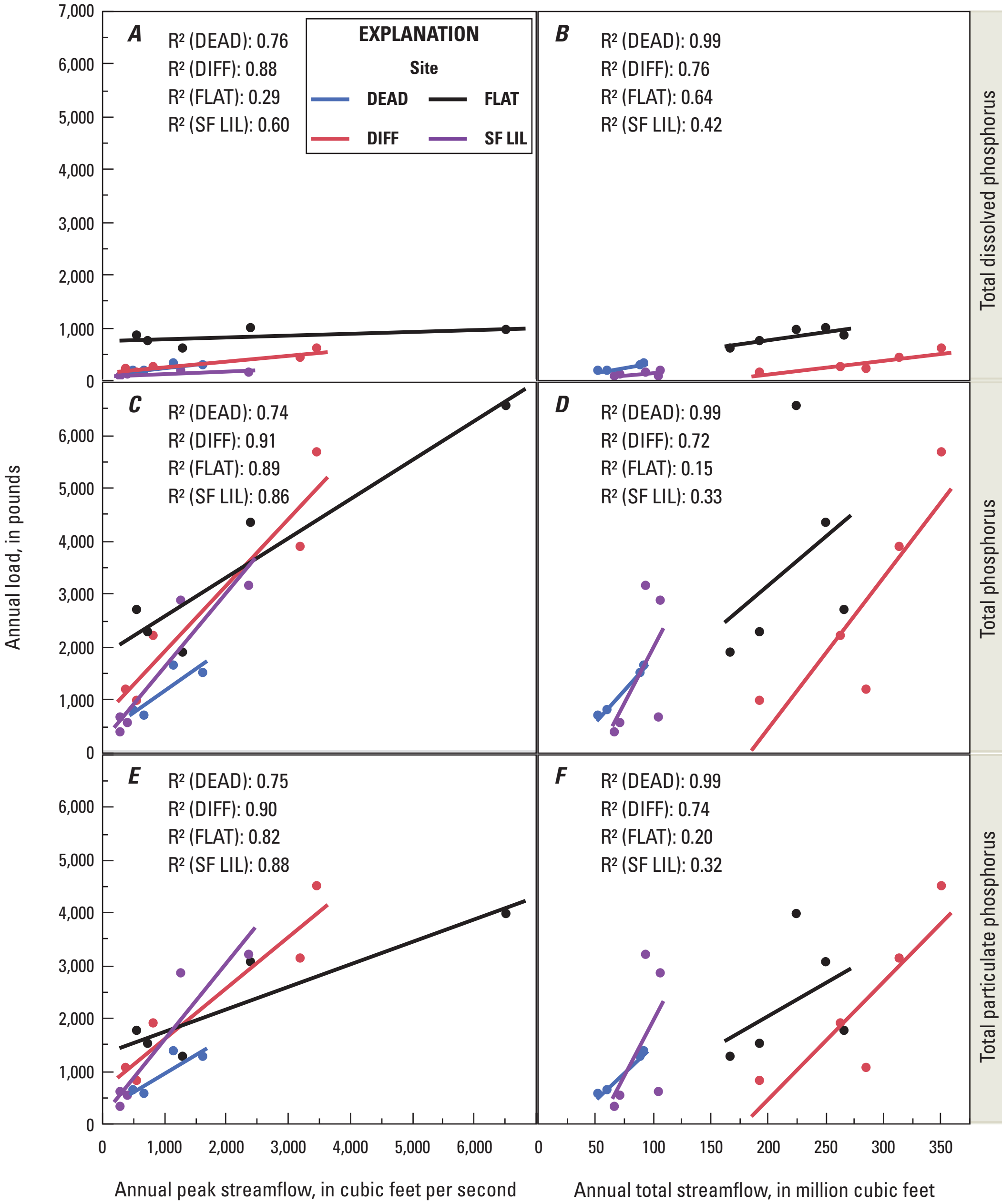

Figure 33. Annual loads of (*A*, *B*) total dissolved phosphorus, (*C*, *D*) total phosphorus, and (*E*, *F*) total particulate phosphorus against annual peak streamflow and total annual streamflow, with linear regression lines, at the four intensive monitoring stations for water years 2008 through 2012. Station names defined in table 1. R^2 is coefficient of determination.

by the models at the other three monitoring stations was low (adjusted $R^2 = 0.15$–0.30; table 7). The models having turbidity and streamflow as explanatory variables were not statistically valid because of the lack of statistical significance ($\alpha = 0.05$) of one of the explanatory variables in each model. The explanatory variables included in the best possible models were unique to each monitoring station, using some combination of streamflow, turbidity, water temperature, specific conductance, and pH (table 8). Although these multivariate models were the best of all potential models, they only explained 23 percent to 37 percent of the variability in total N. The inability to more effectively model total N concentration is probably a result of the majority of N occurring in dissolved form, and the lack of correlation between patterns in dissolved N transport and measured water-quality parameters.

The turbidity-only model effectively described total P concentrations, and little or no improvement was gained through the addition of streamflow (table 8). The explanatory variables included in the best possible models were unique to each monitoring station, using some combination of streamflow, turbidity, water temperature, and specific conductance (table 8). Slight improvements in explanatory power of the models were made through the addition of these explanatory variables when compared to the univariate and bivariate models.

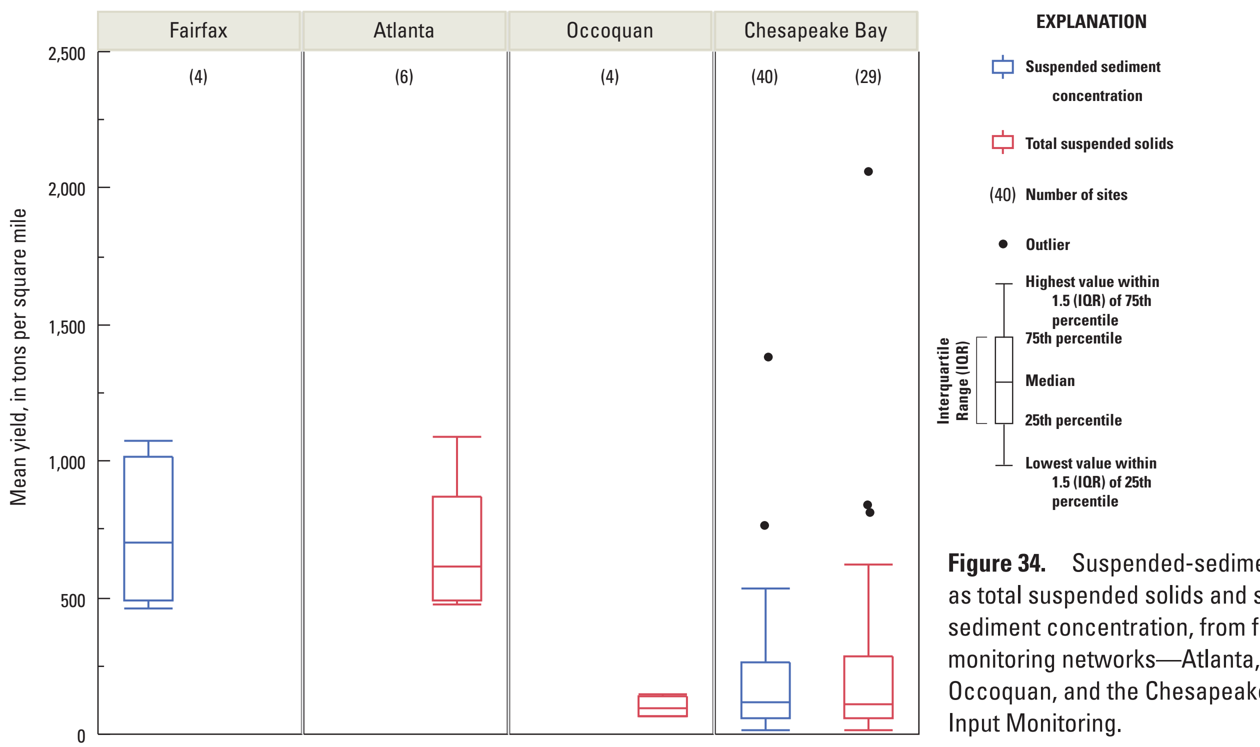

Figure 34. Suspended-sediment yields, as total suspended solids and suspended-sediment concentration, from four monitoring networks—Atlanta, Fairfax, Occoquan, and the Chesapeake Bay River Input Monitoring.

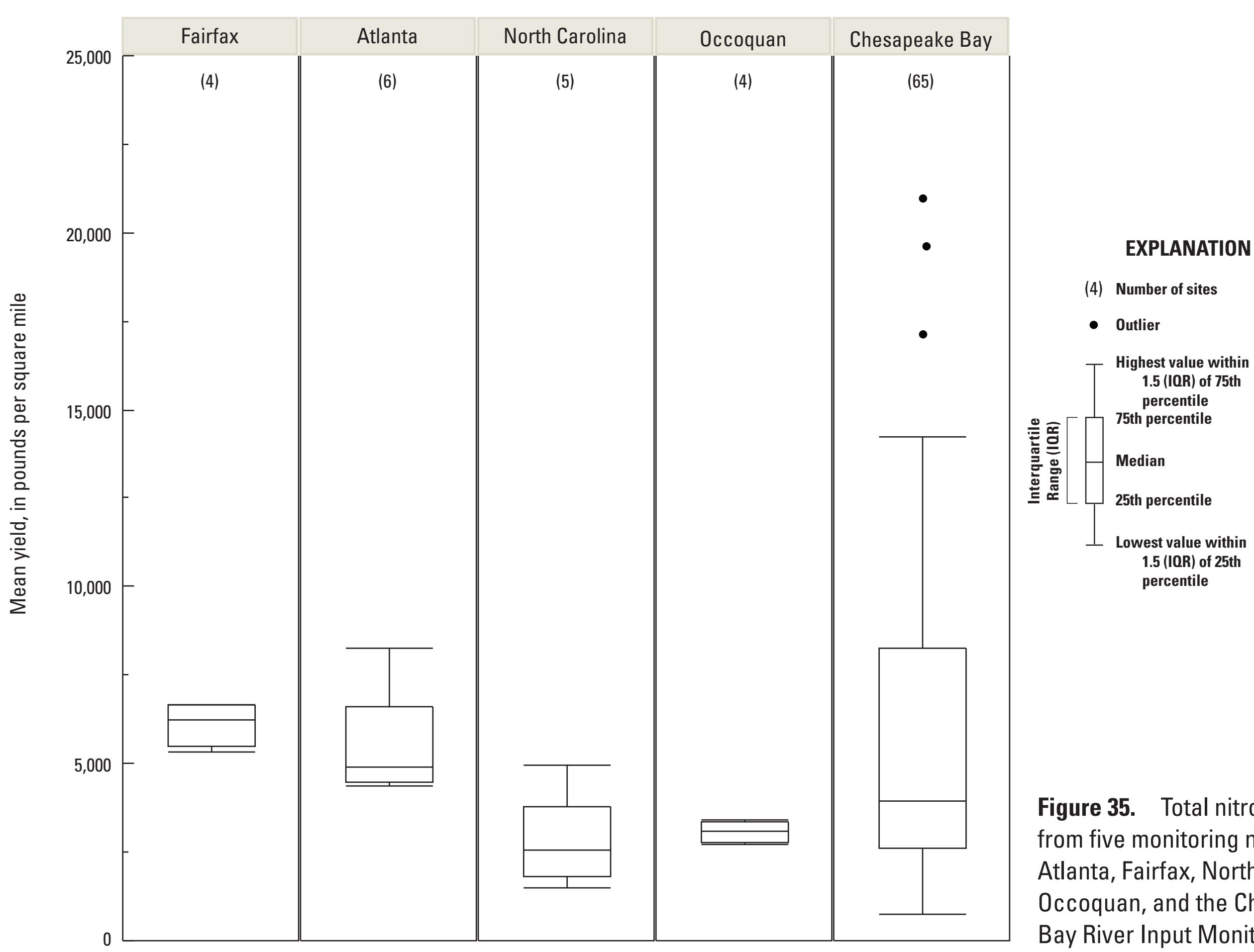

Figure 35. Total nitrogen yields from five monitoring networks—Atlanta, Fairfax, North Carolina, Occoquan, and the Chesapeake Bay River Input Monitoring.

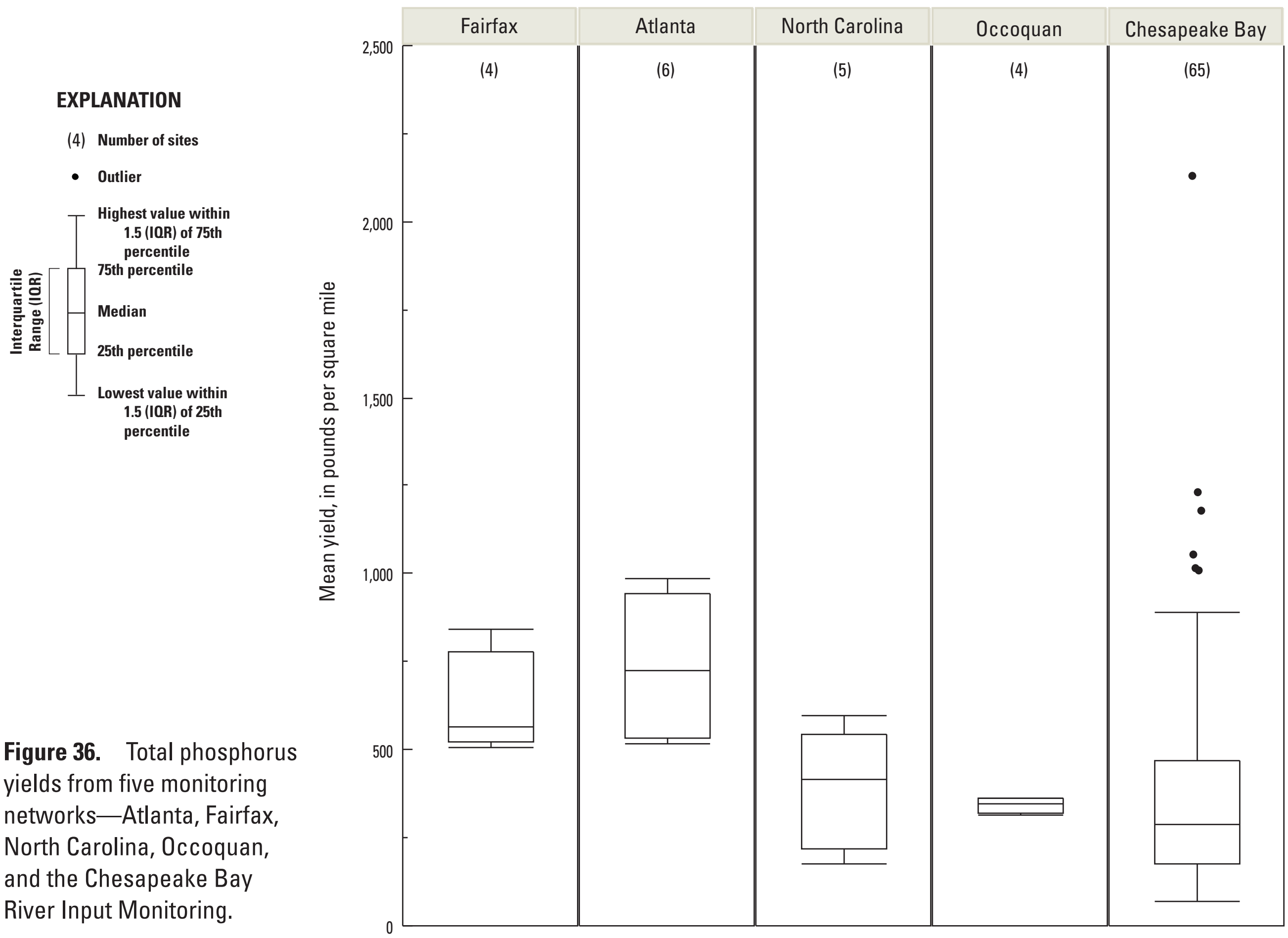

Figure 36. Total phosphorus yields from five monitoring networks—Atlanta, Fairfax, North Carolina, Occoquan, and the Chesapeake Bay River Input Monitoring.

Benthic Macroinvertebrate Data and Stream Health

Benthic macroinvertebrates (BM) are invertebrate organisms that inhabit the stream channel bottom and other stable instream structures (such as vegetation, roots, and fallen trees) for some portion of their lifecycle (Hauer and Resh, 1996). These organisms are ubiquitous in stream environments, and some can even inhabit severely polluted streams (Hauer and Resh, 1996). Because these organisms are residents of the aquatic environment, measurements of BM communities provide a measure of stream health that is integrated over time, as opposed to the snapshot of conditions acquired through chemical sampling and physical measurements (Resh and others, 1996). This time-integrated representation of conditions, along with the ubiquity and varied tolerance to perturbation, has led to widespread use of BM community metrics as measures of stream health (Resh and others, 1996; U.S. Environmental Protection Agency, 2002; Blocksom and Winters, 2006; Cuffney and others, 2010).

The IBI scores are all higher than the corresponding SCI scores (fig. 37) because the Fairfax County IBI metric was developed using reference sites in Fairfax County where areas of minimal anthropogenic impact are scarce, and the SCI metric was developed using reference sites throughout Virginia and, therefore, includes many pristine locations. Collectively, the results for both metrics show a general decrease in stream health with increasing urban intensity (fig. 37).

Evaluation of the IBI and SCI scores reveals that the health of the streams monitored is generally poor. A single value criterion of 61 has been suggested to demonstrate biological impairment using the SCI score (Burton and Gerritsen, 2003). All SCI scores at the 14 stations over 5 years were equal to (1 result) or less than (69 results) this criterion (fig. 37). A descriptive scale of very poor (0–20), poor (21–40), fair (41–60), good (61–80), and excellent (81–100) was used for the Fairfax County IBI scores; using this scale, 84 percent of the scores obtained denote fair, poor, or very poor conditions, all of which indicate biological impairment. Castle Creek, which drains the least intensively developed watershed in the monitoring network (fig. 2), is the only stream in the monitoring network supporting a balanced and highly diverse macroinvertebrate community, resulting in IBI scores classified as excellent.

Evaluation of temporal patterns in the BM metrics indicates some interannual variability at individual monitoring stations (fig. 38). The small number of samples per monitoring station (n = 5) precludes statistical analysis of temporal trends, and elucidation of any temporal trends through visual observation of the data is complicated by interannual variability.

Table 6. Number of observations, regression coefficients, and R^2 for suspended sediment concentration models.

[Dependent variable is natural logarithm of suspended sediment concentration. Ln, natural logarithm; Q, streamflow; R^2, coefficient of determination; n/a, not applicable—variable not included in selected model]

Station	Number of observations	Intercept	Ln Q	Ln turbidity	Water temperature	Adjusted R^2
Best possible model						
DEAD	233	0.889	0.426	0.636	n/a	0.88
DIFF	205	0.214	0.319	0.823	0.016	0.91
FLAT	242	–0.468	0.310	0.891	0.016	0.91
SF LIL	212	–0.001	0.471	0.756	0.029	0.93
Turbidity and streamflow model						
DEAD	233	0.889	0.426	0.636	n/a	0.88
DIFF	205	0.445	0.274	0.867	n/a	0.91
FLAT	242	–0.257	0.300	0.911	n/a	0.91
SF LIL	212	0.321	0.438	0.804	n/a	0.93
Turbidity only model						
DEAD	233	0.690	n/a	0.981	n/a	0.84
DIFF	205	0.651	n/a	1.071	n/a	0.90
FLAT	242	–0.217	n/a	1.179	n/a	0.89
SF LIL	212	0.023	n/a	1.129	n/a	0.90

Table 7. Number of observations, regression coefficients, and R^2 for total nitrogen concentration models.

[Dependent variable is natural logarithm of total nitrogen concentration. Ln, natural logarithm; Q, streamflow; SC, specific conductance; R^2, coefficient of determination; n/a, not applicable—variable not included in selected model]

Station	Number of observations	Intercept	Ln Q	Ln turbidity	Water temperature	Ln SC	pH	Adjusted R^2
Best possible model								
DEAD	206	0.092	0.109	–0.046	0.013	0.323	–0.172	0.23
DIFF	187	–0.986	n/a	0.132	n/a	0.193	n/a	0.37
FLAT	201	–3.207	0.166	n/a	0.015	0.327	0.174	0.30
SF LIL	199	–1.141	0.138	n/a	0.011	0.432	n/a	0.27
Turbidity and streamflow model								
DEAD	Models are not statistically valid.							
DIFF								
FLAT								
SF LIL								
Turbidity only model								
DEAD	206	n/a	Model not statistically significant					
DIFF	187	0.162	n/a	0.117	n/a	n/a	n/a	0.30
FLAT	201	0.335	n/a	0.081	n/a	n/a	n/a	0.17
SF LIL	199	0.843	n/a	0.068	n/a	n/a	n/a	0.15

Table 8. Number of observations, regression coefficients, and R^2 for total phosphorus concentration models.

[Dependent variable is natural logarithm of total phosphorus concentration. Ln, natural logarithm; Q, streamflow; SC, specific conductance; R^2, coefficient of determination; n/a, not applicable—variable not included in selected model]

Station	Number of observations	Intercept	Ln Q	Ln turbidity	Water temperature	Ln SC	Adjusted R^2
Best possible model							
DEAD	206	-4.113	0.121	0.435	0.025	n/a	0.87
DIFF	187	-2.495	n/a	0.598	n/a	-0.377	0.86
FLAT	201	-3.693	n/a	0.372	0.040	n/a	0.73
SF LIL	199	-5.251	0.205	0.541	0.036	n/a	0.87
Turbidity and streamflow model							
DEAD	206	-3.804	0.091	0.470	n/a	n/a	0.85
DIFF	187	-4.813	0.107	0.547	n/a	n/a	0.84
FLAT	201	-3.142	-0.021	0.412	n/a	n/a	0.65
SF LIL	199	-4.851	0.150	0.605	n/a	n/a	0.85
Turbidity only model							
DEAD	206	-3.847	n/a	0.546	n/a	n/a	0.85
DIFF	187	-4.735	n/a	0.627	n/a	n/a	0.83
FLAT	201	-3.147	n/a	0.394	n/a	n/a	0.65
SF LIL	199	-4.937	n/a	0.708	n/a	n/a	0.85

Changes to the Monitoring Program

The 14-station network described herein has successfully provided abundant information about surface-water resources in Fairfax County since its inception in 2007. However, monitoring station selection for this network was performed using only watersheds included in the first of two phases of watershed planning within Fairfax County and, therefore, only represents about 50 percent the spatial extent of Fairfax County. Additionally, although some consideration of planned BMP implementation intensity was included in the monitoring-station selection process, the selected monitoring stations represent a range of implementation intensities. In 2012, the decision was made to expand the monitoring network to include watersheds from the remaining 50 percent of Fairfax County, included in the second phase of watershed planning, and to focus that expansion on small watersheds (less than 1 mi^2) with high rates of planned implementation; that is, watersheds where responses to implementation are expected to be greatest. The approach and objectives for implementing these additional monitoring stations are identical to those for the network used in the original monitoring program.

Using monitoring station-selection procedures similar to those presented for the original network on a list of potential watersheds selected for high rates of planned implementation, an additional 6 stations were chosen for expansion of the network. Of these 6 stations, 1 was established as an intensive monitoring station and 5 were established as trend monitoring stations (table 9; fig. 39). Data collection at the 6 new stations was initiated in October 2012, and given the short period of record for these sites, no analysis of their data is presented herein.

Along with the addition of the new monitoring stations at the beginning of WY 2013, a change was made to the monthly sampling program in an attempt to improve the representation of hydrologic conditions by the monthly dataset. As described previously, the monthly sampling approach has not fully represented the range of hydrologic conditions, and consequently is largely composed of base-flow samples (fig. 6). Targeted wet-weather samples were added to the monthly sampling program to address this issue. Four months are randomly selected each water year for wet-weather sampling. During these 4 months, the scheduled sampling date is replaced with a targeted wet-weather sampling event to improve the coverage of high-flow conditions.

Future Directions

The monitoring activities described herein are expected to continue largely unchanged for the foreseeable future to continue to record water-quality, streamflow, and aquatic macroinvertebrate conditions of streams throughout Fairfax County. Implementation of management efforts is ongoing, and has increased during the latter portion of the monitoring period discussed. It is expected that implementation of management activities will continue at current rates or greater. Future efforts will focus on recording pertinent measures of the implementation activities to support the analysis of watershed-scale responses resulting from these management activities.

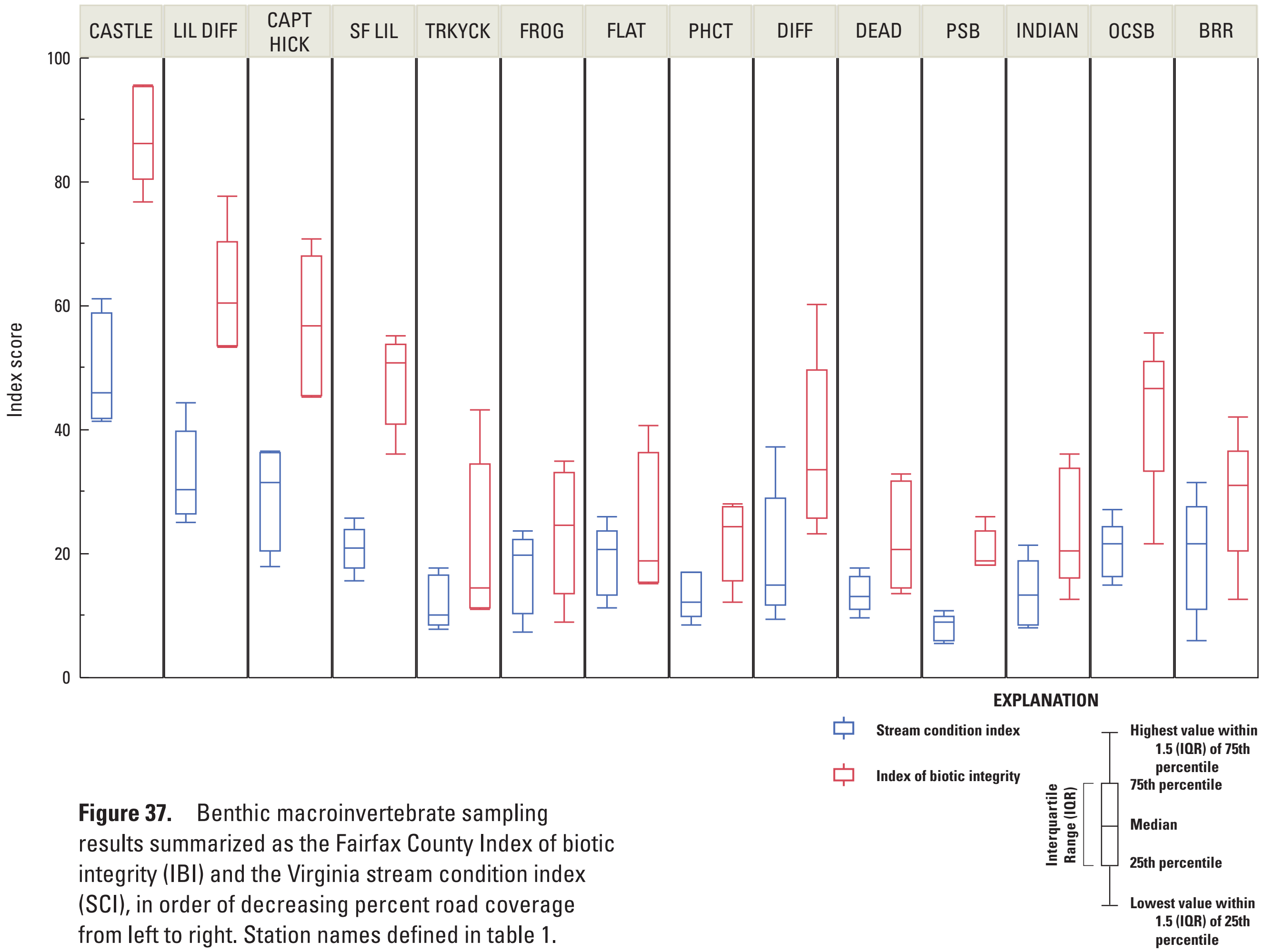

Figure 37. Benthic macroinvertebrate sampling results summarized as the Fairfax County Index of biotic integrity (IBI) and the Virginia stream condition index (SCI), in order of decreasing percent road coverage from left to right. Station names defined in table 1.

Summary

Fairfax County, in northern Virginia, has experienced great population growth and urbanization since the middle of the 20th Century. As a result of the changing landscape to accommodate this growth, streams in Fairfax County have become impaired because they are frequently inundated with excessive volumes of stormwater runoff. Efforts to mitigate these detrimental effects through the implementation of best management practices (BMPs) are underway, and a study of the watershed-scale response to BMP implementation has been initiated. Results from the first five water years (2008–12) of this study show that the impacts of urbanization are apparent in water-quality, hydrologic, and biological metrics determined at all 14 stations of the monitoring network implemented for the study.

Spatial and temporal patterns in basic water-quality parameters measured monthly at all 14 stations and continuously at the 4 intensive monitoring stations reflect seasonal and other natural patterns and processes, as well as some patterns indicative of anthropogenic activities. Typical pH values of streams throughout the network centered around neutrality (pH = 7), particularly in streams draining watersheds within the Piedmont physiographic province. Streams draining the Triassic Lowland had higher typical pH values, and streams draining the Coastal Plain tended to have lower pH values. Strong daily fluctuations in pH are apparent in the continuous pH data, particularly at Flatlick Branch, where elevated phosphorus (P) concentrations fuel photosynthetic organisms. Additionally, pH decreases periodically in intensively monitored streams in response to rainfall events.

Spatial and temporal patterns in specific conductance were largely representative of anthropogenic disturbances. Watersheds having the greatest percentage of open space and estate residential land-use had the lowest typical specific conductance values, and specific conductance variability was less than what is observed in watersheds that are more intensively developed. Application of de-icing salts on impervious surfaces during the winter months is apparent in the specific conductance data. In watersheds having greater road coverage, and more development in general, increases in specific conductance over several orders of magnitude are present in the monthly sampling data and the continuous data. In these watersheds, when frozen precipitation occurs, elevated specific conductance is observed through the winter months, gradually deceasing through the spring and summer. The rapid increase in specific conductance as snow and ice melts likely produces a shock to the biological communities

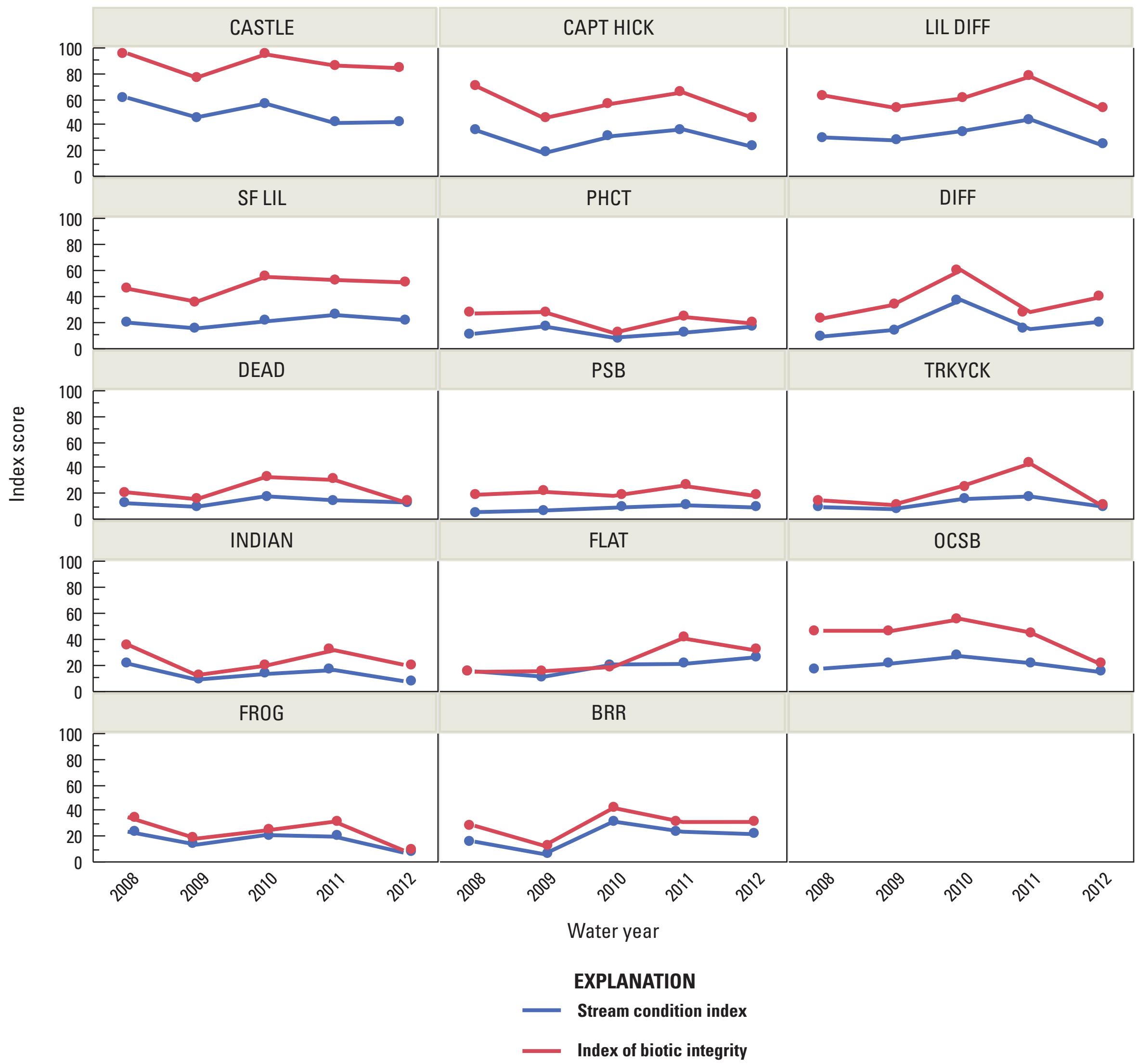

Figure 38. Benthic macroinvertebrate sampling results summarized as the Fairfax County index of biotic integrity (IBI) and the Virginia stream condition index (SCI). Station names defined in table 1.

Table 9. Station information for six stations added to the monitoring network in 2012.

[mi², square mile]

Station identifier	Station name	Type	Watershed area (mi²)
01654500	Long Branch at Route 620 near Annandale, VA	Intensive	3.72
01655305	Rabbit Branch tributary above Lake Royal near Burke, VA	Trend	0.57
0164425950	Horsepen Run above Horsepen Run tributary near Herndon, VA	Trend	1.19
01644343	Sugarland Run tributary below Crayton Road near Herndon, VA	Trend	0.64
01653844	Dogue Creek tributary at Woodley Drive at Mount Vernon, VA	Trend	0.43
01657100	Willow Springs Branch at Highway 29 near Centreville, VA	Trend	0.96
01657100	Willow Springs Branch at Highway 29 near Centreville, VA	Trend	0.96

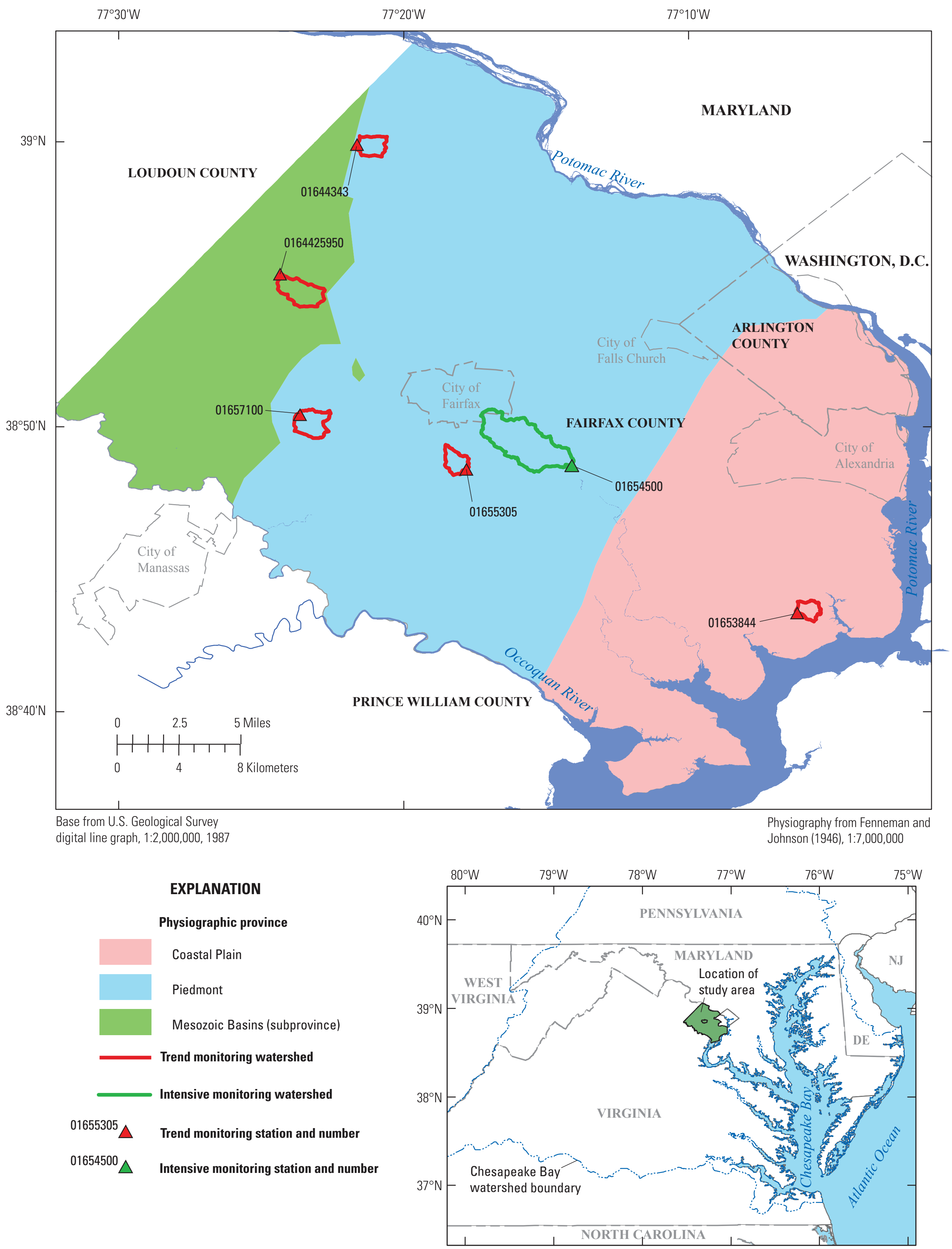

Figure 39. Monitoring stations and watersheds added to the monitoring network in 2012.

that inhabit these streams, as chloride concentrations during these events probably exceed impairment thresholds for freshwater aquatic life.

Patterns in dissolved oxygen (DO) concentration are largely indicative of expected seasonal patterns driven by temperature dependent solubility relations and biological activities. DO concentrations were generally much greater in the colder months when solubility is greatest, and concentrations were lowest during summer months when water temperatures are maximized and solubility is minimized. In general, DO conditions were typically within the range required to support healthy biological communities, although occasional departures during summer months fell below the impairment threshold for streams in Virginia. These impaired conditions occurred most frequently at Paul Spring Branch, a Coastal Plain stream that typically has minimal flow during the summer.

Evaluation of patterns in nitrogen (N) concentrations revealed two monitoring locations, Captain Hickory Run and Popes Head Creek tributary, as having anomalous conditions not fully explained by the available data, whereas the other stations were typically characterized by low N concentrations with low variability. Captain Hickory Run had a median total N concentration of approximately 4.9 mg/L, compared to the network-wide median of approximately 1.7 mg/L. The consistently elevated N concentrations in Captain Hickory Run, which has a watershed primarily composed of estate residential land-use, are hypothesized to result from (1) faulty septic systems, (2) excessive fertilizer application on residential landscapes, or (3) a legacy source of N in the local groundwater. Additional USGS studies are currently focused on determining the source of N in this watershed. Popes Head Creek Tributary also had an anomalous pattern of N concentration, although different from the pattern observed in Captain Hickory Run. In this stream, N concentrations spiked to approximately three times their typical value during low-flow periods in August or September of each year. This isolated annual spike in concentration is probably the result of groundwater input that is always present, but diluted in all but the lowest streamflows. Additional work is needed to clarify the source of this N.

Phosphorus concentrations in monthly samples were generally low and dominated by the dissolved fraction. Two monitoring stations in the network, Flatlick Branch and Frog Branch, are notable for having median total P concentrations that were, on average, approximately three times greater than the median total P concentration observed at the other 12 stations in the network. These two watersheds are unique in the network because of their location in the Triassic Lowland terrane. This terrane is underlain by sedimentary rocks formed by the deposition of particulate materials, including remains of plants and animals, resulting in P-rich formations. This naturally occurring P source is probably responsible for much of the elevated P concentrations observed in these streams, and highlights the importance of understanding the effects of natural setting in making decisions about management needs.

Annual loads and yields of suspended sediment and nutrients were computed at the four intensive monitoring stations using continuous water-quality data as explanatory variables. Yields were compared to other study areas to provide context for the relative contributions to downstream loading from the four small urban watersheds that were intensively monitored in this study.

Suspended sediment loads and yields were highly variable across water years and across monitoring stations. Water years (WY) 2008 and 2011 generally produced the greatest suspended-sediment loads as a result of tropical storm systems that produced large runoff events. Annual peak streamflow, or single highest flow event of the year, was strongly related to suspended-sediment load, whereas the total streamflow for the year was less strongly related to annual suspended-sediment load. Suspended-sediment yields were generally greatest at Difficult Run and South Fork Little Difficult Run, which were about twice the yields observed at Dead Run and Flatlick Branch, on average. Overall, suspended-sediment yields from the intensively monitored small urban watersheds were comparable to yields from similar urban watersheds in Atlanta, Georgia, although the yields were much greater than yields observed from other, larger watersheds throughout the Chesapeake Bay watershed.

Nitrogen loads and yields are generally less variable across water years than suspended-sediment loads and yields because N transport is dominated by dissolved forms of N that are less influenced by peak streamflow events. Nitrogen loads are more strongly related to total annual streamflow, however, with years of greatest total flow transporting the greatest amounts of total N. Nitrogen loads were greatest from Difficult Run and Flatlick Branch, followed by South Fork Little Difficult Run, and Dead Run, although these differences in load are largely attributed to the size of the contributing watershed. When adjusted for watershed area, it is apparent that these watersheds yielded comparable amounts of N, approximately 6,200 pounds per square mile, on average. Total N yields from the stations monitored in Fairfax County were similar to the N yields observed in urban streams in Atlanta, Ga., although they were greater than N yields from urban and suburban streams in North Carolina and the nearby Occoquan River watershed. Yields of N from throughout the Chesapeake Bay watershed span a much wider range than the yields observed in Fairfax County, with Fairfax County yields ranging within the 50th to 75th percentiles of yields throughout the Chesapeake Bay watershed.

Patterns in P loads and yields are very similar to those in suspended-sediment yields as a result of the transport processes involved; much of the P is bound to sediment particles and therefore transported in association with suspended sediments. As with suspended sediment, much greater P loads were observed in 2008 and 2011 than in other years as a result of tropical storms inundating the area with large volumes of precipitation. Dissolved P accounts for only a small fraction of the total P transported, and the dissolved fraction load is more closely related to the total annual streamflow, whereas total P and the particulate fraction loads are more closely related to the annual peak streamflow. Phosphorus yields, and the dissolved P yield in particular, were greatest at Flatlick Branch as a result of the P-rich parent material in the Triassic physiographic province. Total P yields from the streams in Fairfax County were comparable to the yields observed in urban Atlanta, Ga., although they were greater than the yields observed in the developed watersheds of North Carolina and the Occoquan River watershed. The Fairfax County P yields were among the highest (75th to 90th percentile) of the yields observed throughout the Chesapeake Bay watershed.

Evaluation of the health of the aquatic communities in the streams monitored was assessed through annual benthic macroinvertebrate sampling. Benthic macroinvertebrate communities were summarized using the Fairfax County index of biotic integrity (IBI) and the Virginia stream condition index (SCI). The IBI metric results indicate that the aquatic communities in the majority of streams monitored are in poor condition, with just one stream, Castle Creek, having results indicating relatively high quality aquatic health. The SCI metric results, which are based on condition observed throughout Virginia, indicate that all but one of the samples collected were below the threshold indicating an impaired condition.

Although most measures indicate that conditions in streams throughout Fairfax County are generally poor, the conditions are consistent with the current understanding of the effects of urbanization on stream health. Efforts to mitigate the detrimental impacts of urbanization are being implemented throughout Fairfax County, and this monitoring program uniquely positions Fairfax County to be able to directly assess the effectiveness of these implementation activities.

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Appendix 1

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
01644343									
Annelida	Oligochaeta				No samples collected 2008–10			98	21
Arthropoda	Crustacea	Amphipoda	Crangonyctidae	*Crangonyx*				2	–
Arthropoda	Insecta	Coleoptera	Dryopidae	*Helichus*				1	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Oulimnius*				1	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*				2	–
Arthropoda	Insecta	Diptera	Chironomidae					108	190
Arthropoda	Insecta	Diptera	Empididae	*Chelifera*				1	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*				–	4
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*				–	2
Arthropoda	Insecta	Plecoptera	Leuctridae	*Leuctra*				–	1
Arthropoda	Insecta	Plecoptera	Nemouridae	*Amphinemura*				1	1
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*				6	–
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Dolophilodes*				–	1
Mollusca	Gastropoda	Limnophila	Lymnaeidae					1	–
01645704									
Annelida	Oligochaeta				–	–	44	1	–
Annelida	Oligochaeta	Oligochaeta			–	4	–	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	–	–	10	–	9
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia*	–	–	1	–	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Macronychus*	–	–	1	–	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Microcylloepus*	–	3	15	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Optioservus*	–	–	4	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Oulimnius*	2	–	–	–	2
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	2	2	30	20	33
Arthropoda	Insecta	Diptera	Ceratopogonidae	*Mallochohelea*	–	1	–	–	–
Arthropoda	Insecta	Diptera	Chironomidae		223	209	81	177	148
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	2	5	1	5
Arthropoda	Insecta	Diptera	Tipulidae	*Antocha*	–	1	–	–	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	–	–	1	–	–
Arthropoda	Insecta	Odonata	Aeshnidae	*Boyeria*	1	–	–	–	–
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	1	–	1	–	1
Arthropoda	Insecta	Odonata	Coenagrionidae		–	–	1	–	1
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	–	–	1	–	–
Arthropoda	Insecta	Odonata	Libellulidae		–	–	–	–	1
Arthropoda	Insecta	Trichoptera	Hydropsychidae		–	–	1	–	–

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
01645704—Continued									
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	3	13	5	5	3
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	2	2	4	1	1
Arthropoda	Insecta	Trichoptera	Limnephilidae	*Ironoquia*	–	–	1	–	–
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	–	–	1	–	–
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Wormaldia*	–	1	–	–	–
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*	–	–	–	1	–
Mollusca	Bivalvia	Pelecypoda	Sphaeriidae	*Pisidium*	–	–	1	–	–
Platyhelminthes	Turbellaria	Tricladida	Planariidae		–	–	–	4	–
01645745									
Annelida	Oligochaeta				–	–	6	1	1
Annelida	Oligochaeta	Oligochaeta			3	2	–	–	–
Arthropoda	Crustacea	Amphipoda	Crangonyctidae		–	–	1	–	–
Arthropoda	Crustacea	Amphipoda	Crangonyctidae	*Crangonyx*	–	–	1	–	–
Arthropoda	Crustacea	Decapoda	Cambaridae		–	–	1	–	1
Arthropoda	Insecta	Coleoptera	Dryopidae	*Helichus*	1	–	–	1	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	2	3	2	3	12
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia*	3	6	–	4	2
Arthropoda	Insecta	Coleoptera	Elmidae	*Macronychus*	1	–	–	–	3
Arthropoda	Insecta	Coleoptera	Elmidae	*Optioservus*	17	4	19	–	4
Arthropoda	Insecta	Coleoptera	Elmidae	*Oulimnius*	2	2	–	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	1	–	2	–	–
Arthropoda	Insecta	Diptera	Ceratopogonidae	*Dasyhelea*	1	–	–	–	–
Arthropoda	Insecta	Diptera	Chironomidae		149	161	140	105	150
Arthropoda	Insecta	Diptera	Empididae	*Clinocera*	1	–	–	5	–
Arthropoda	Insecta	Diptera	Empididae	*Hemerodromia*	1	–	–	–	–
Arthropoda	Insecta	Diptera	Simuliidae	*Prosimulium*	3	1	1	–	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	–	–	1	1
Arthropoda	Insecta	Diptera	Tipulidae	*Dicranota*	3	1	–	–	1
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	2	–	1	–	1
Arthropoda	Insecta	Ephemeroptera	Baetidae		–	1	–	–	–
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae	*Eurylophella*	–	–	–	2	–
Arthropoda	Insecta	Ephemeroptera	Heptageniidae		–	–	–	–	2
Arthropoda	Insecta	Ephemeroptera	Heptageniidae	*Maccaffertium*	3	6	7	28	4
Arthropoda	Insecta	Ephemeroptera	Heptageniidae	*Stenonema*	–	–	–	2	–
Arthropoda	Insecta	Megaloptera	Corydalidae	*Nigronia*	1	–	–	–	–
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	–	–	–	–	1
Arthropoda	Insecta	Odonata	Coenagrionidae		–	–	–	–	1
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	–	–	1	–	–
Arthropoda	Insecta	Odonata	Gomphidae	*Gomphus*	1	–	–	1	–
Arthropoda	Insecta	Plecoptera	Leuctridae		–	–	–	1	–

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
				01645745—Continued					
Arthropoda	Insecta	Plecoptera	Nemouridae	*Amphinemura*	–	–	1	–	–
Arthropoda	Insecta	Plecoptera	Nemouridae	*Shipsa*	1	3	–	–	–
Arthropoda	Insecta	Plecoptera	Taeniopterygidae		–	–	–	1	–
Arthropoda	Insecta	Plecoptera	Taeniopterygidae	*Oemopteryx*	1	–	1	–	–
Arthropoda	Insecta	Trichoptera			–	–	2	–	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	1	12	6	36	15
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	–	–	2	–	–
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	2	8	12	9	4
Arthropoda	Insecta	Trichoptera	Uenoidae	*Neophylax*	–	–	–	1	–
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*	–	1	–	–	–
Mollusca	Bivalvia	Pelecypoda	Sphaeriidae		1	–	–	–	–
Mollusca	Gastropoda	Limnophila	Planorbidae		–	–	–	1	–
				01645762					
Annelida	Oligochaeta				–	–	2	13	11
Annelida	Oligochaeta	Oligochaeta			1	2	–	–	–
Arthropoda	Crustacea	Amphipoda	Crangonyctidae	*Crangonyx*	–	–	2	–	3
Arthropoda	Crustacea	Decapoda	Cambaridae		–	1	1	1	–
Arthropoda	Crustacea	Decapoda	Cambaridae	*Cambarus*	2	–	–	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	–	–	1	2	8
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia*	3	2	1	–	3
Arthropoda	Insecta	Coleoptera	Elmidae	*Macronychus*	–	–	1	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Oulimnius*	3	–	–	1	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	1	1	–	1	2
Arthropoda	Insecta	Coleoptera	Hydrophilidae	*Tropisternus*	1	–	–	–	–
Arthropoda	Insecta	Diptera	Chironomidae		185	192	164	148	154
Arthropoda	Insecta	Diptera	Empididae	*Chelifera*	–	–	1	–	–
Arthropoda	Insecta	Diptera	Empididae	*Clinocera*	–	–	4	1	1
Arthropoda	Insecta	Diptera	Empididae	*Hemerodromia*	–	–	–	–	1
Arthropoda	Insecta	Diptera	Simuliidae	*Prosimulium*	1	1	2	–	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	–	–	–	7
Arthropoda	Insecta	Diptera	Stratiomyidae	*Odontomyia*	–	–	–	1	–
Arthropoda	Insecta	Diptera	Tipulidae	*Antocha*	–	–	–	1	–
Arthropoda	Insecta	Diptera	Tipulidae	*Dicranota*	–	–	1	–	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	2	1	2	–	1
Arthropoda	Insecta	Ephemeroptera	Baetidae		2	1	–	–	–
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae	*Eurylophella*	–	–	–	–	1
Arthropoda	Insecta	Ephemeroptera	Heptageniidae	*Maccaffertium*	–	–	–	1	–
Arthropoda	Insecta	Odonata	Aeshnidae	*Boyeria*	1	–	–	–	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	–	–	3	–	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Enallagma*	–	–	1	1	–

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
01645762—Continued									
Arthropoda	Insecta	Odonata	Gomphidae	*Hagenius*	–	–	–	1	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	10	5	4	17	6
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Diplectrona*	–	–	–	1	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	–	4	3	–	1
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	5	2	13	10	2
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Wormaldia*	1	–	–	–	2
Arthropoda	Insecta	Trichoptera	Uenoidae	*Neophylax*	–	–	–	1	–
01645844									
Annelida	Oligochaeta				–	–	12	10	29
Annelida	Oligochaeta	Oligochaeta			1	3	–	–	–
Arthropoda	Crustacea	Amphipoda	Crangonyctidae	*Crangonyx*	–	–	1	–	–
Arthropoda	Crustacea	Isopoda	Asellidae	*Caecidotea*	–	1	–	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	–	–	1	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	–	1	–	–	–
Arthropoda	Insecta	Diptera			–	–	–	1	–
Arthropoda	Insecta	Diptera	Chironomidae		56	147	123	130	176
Arthropoda	Insecta	Diptera	Empididae	*Chelifera*	–	–	3	–	–
Arthropoda	Insecta	Diptera	Empididae	*Hemerodromia*	–	3	2	1	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	–	2	2	3
Arthropoda	Insecta	Diptera	Tipulidae	*Antocha*	–	1	4	–	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	3	4	1	1	–
Arthropoda	Insecta	Lepidoptera			–	–	1	–	–
Arthropoda	Insecta	Megaloptera	Corydalidae	*Corydalus*	–	–	–	1	–
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	1	1	1	19	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	2	1	4	20	2
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	4	9	7	8	1
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	6	6	24	4	–
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	1	10	12	3	–
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Wormaldia*	–	–	–	–	1
Mollusca	Bivalvia	Pelecypoda	Sphaeriidae	*Pisidium*	–	–	1	–	–
Mollusca	Gastropoda	Limnophila	Physidae		1	1	2	–	1
Mollusca	Gastropoda	Limnophila	Planorbidae	*Menetus*	–	1	–	–	–
01645940									
Annelida	Oligochaeta				–	–	28	31	–
Annelida	Oligochaeta	Oligochaeta			2	–	–	–	–
Arthropoda	Crustacea	Amphipoda	Crangonyctidae	*Crangonyx*	1	–	–	–	–
Arthropoda	Crustacea	Decapoda	Cambaridae	*Cambarus*	–	1	–	–	–
Arthropoda	Crustacea	Isopoda	Asellidae	*Lirceus*	1	–	–	–	–
Arthropoda	Insecta	Coleoptera	Dytiscidae		–	–	–	1	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	–	–	1	–	1

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
01645940—Continued									
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia*	–	–	–	7	7
Arthropoda	Insecta	Coleoptera	Elmidae	*Macronychus*	–	–	–	1	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Optioservus*	1	3	1	2	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Oulimnius*	23	3	3	1	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	2	–	1	–	–
Arthropoda	Insecta	Diptera	Chironomidae		114	184	135	125	189
Arthropoda	Insecta	Diptera	Empididae	*Chelifera*	–	2	1	–	–
Arthropoda	Insecta	Diptera	Empididae	*Clinocera*	1	–	–	1	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	1	2	–	8
Arthropoda	Insecta	Diptera	Tipulidae	*Antocha*	3	–	–	–	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	2	–	–	–	–
Arthropoda	Insecta	Ephemeroptera	Baetidae		–	–	1	2	1
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae		–	–	–	1	–
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae	*Ephemerella*	–	–	–	1	–
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae	*Eurylophella*	–	–	1	1	1
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae	*Serratella*	3	–	–	–	–
Arthropoda	Insecta	Ephemeroptera	Heptageniidae	*Maccaffertium*	4	–	2	1	1
Arthropoda	Insecta	Ephemeroptera	Leptophlebiidae	*Triaenodes*	–	1	–	–	–
Arthropoda	Insecta	Odonata	Aeshnidae		–	–	–	1	–
Arthropoda	Insecta	Odonata	Aeshnidae	*Boyeria*	2	–	1	–	2
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	2	–	–	3	2
Arthropoda	Insecta	Odonata	Gomphidae		–	–	–	1	–
Arthropoda	Insecta	Plecoptera	Nemouridae	*Amphinemura*	7	–	18	12	–
Arthropoda	Insecta	Plecoptera	Perlidae		–	–	1	2	–
Arthropoda	Insecta	Plecoptera	Perlodidae		–	1	–	1	1
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	42	9	5	9	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	–	2	–	–	1
Arthropoda	Insecta	Trichoptera	Leptoceridae		–	–	–	–	1
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	2	2	–	–	–
Mollusca	Gastropoda	Limnophila	Lymnaeidae		–	–	–	1	–
01646305									
Annelida	Oligochaeta				–	–	16	31	22
Annelida	Oligochaeta	Oligochaeta			25	4	–	–	–
Arthropoda	Crustacea	Isopoda	Asellidae	*Lirceus*	1	–	–	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	–	–	1	1	–
Arthropoda	Insecta	Diptera	Chironomidae		170	220	150	155	185
Arthropoda	Insecta	Diptera	Empididae	*Hemerodromia*	–	1	–	–	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	–	6	–	2
Arthropoda	Insecta	Diptera	Tipulidae	*Antocha*	–	–	1	–	1
Arthropoda	Insecta	Diptera	Tipulidae	*Brachypremna*	–	–	1	–	–

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
01646305—Continued									
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	1	1	–	–	–
Arthropoda	Insecta	Ephemeroptera	Baetidae		–	–	–	–	1
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	–	1	2	–	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Enallagma*	–	–	1	–	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae		–	1	–	–	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	3	2	9	13	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	1	3	10	2	2
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	1	–	1	3	–
Mollusca	Gastropoda	Limnophila	Ancylidae		–	–	1	–	–
01652789									
Annelida	Oligochaeta				–	–	35	3	1
Annelida	Oligochaeta	Oligochaeta			9	7	–	–	–
Arthropoda	Crustacea	Amphipoda	Crangonyctidae	*Crangonyx*	2	–	–	–	–
Arthropoda	Crustacea	Isopoda	Asellidae	*Caecidotea*	1	–	–	–	–
Arthropoda	Insecta	Coleoptera	Dytiscidae		–	–	–	–	1
Arthropoda	Insecta	Diptera	Chironomidae		22	200	151	29	65
Arthropoda	Insecta	Diptera	Empididae	*Chelifera*	–	–	1	–	–
Arthropoda	Insecta	Diptera	Empididae	*Hemerodromia*	–	1	–	–	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	1	–	–	–	–
Arthropoda	Insecta	Diptera	Tipulidae	*Antocha*	–	1	4	–	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	1	–	2	2	–
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	1	1	1	4	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	2	–	–	2	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	1	–	2	–	1
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	2	–	1	1	–
Mollusca	Gastropoda	Limnophila	Lymnaeidae	*Pseudosuccinea*	–	1	–	–	–
Mollusca	Gastropoda	Limnophila	Physidae		–	1	1	–	–
01652860									
Annelida	Oligochaeta				–	–	67	2	23
Annelida	Oligochaeta	Oligochaeta			5	2	–	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	–	–	1	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	–	–	1	–	–
Arthropoda	Insecta	Diptera	Chironomidae		189	208	132	36	191
Arthropoda	Insecta	Diptera	Empididae	*Hemerodromia*	–	1	–	–	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	–	1	–	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	1	–	1	2	–
Arthropoda	Insecta	Lepidoptera	Pyralidae		–	–	–	1	–
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	1	–	1	1	1
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	–	–	1	–	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	2	–	1	3	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	4	3	4	2	1
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	–	–	–	1	–

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
01653717									
Annelida	Oligochaeta				–	–	43	30	28
Annelida	Oligochaeta	Oligochaeta			10	7	–	–	–
Arthropoda	Crustacea	Isopoda	Asellidae	*Caecidotea*	–	–	–	1	–
Arthropoda	Insecta	Diptera	Chironomidae		193	205	166	180	178
Arthropoda	Insecta	Diptera	Tipulidae	*Rhabdomastix*	–	–	–	1	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	–	1	1	1	1
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	–	–	1	1	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	–	–	–	1	–
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*	–	1	–	–	–
01653844									
Annelida	Oligochaeta							82	61
Arthropoda	Crustacea	Amphipoda	Gammaridae	*Gammarus*				3	–
Arthropoda	Crustacea	Decapoda	Cambaridae					2	–
Arthropoda	Insecta	Diptera	Chironomidae			No samples collected 2008–10		117	157
Arthropoda	Insecta	Odonata	Coenagrionidae					1	–
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*				2	–
Mollusca	Gastropoda	Limnophila	Planorbidae	*Planorbella*				3	–
01654500									
Annelida	Oligochaeta							147	12
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*				–	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*				–	1
Arthropoda	Insecta	Diptera	Chironomidae			No samples collected 2008–10		60	191
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*				2	8
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*				–	8
Mollusca	Gastropoda	Limnophila	Physidae					–	1
01655305									
Annelida	Oligochaeta							102	33
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*				2	–
Arthropoda	Insecta	Diptera	Chironomidae					92	176
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*				1	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*		No samples collected 2008–10		2	–
Arthropoda	Insecta	Megaloptera	Corydalidae	*Corydalus*				2	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*				1	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*				–	1
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*				1	–
Mollusca	Gastropoda	Limnophila	Physidae					1	–
01656903									
Annelida	Oligochaeta				–	–	174	15	80
Annelida	Oligochaeta	Oligochaeta			19	9	–	–	–
Arthropoda	Crustacea	Amphipoda			–	–	–	1	–
Arthropoda	Crustacea	Amphipoda	Crangonyctidae	*Crangonyx*	–	–	–	1	–

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
01656903—Continued									
Arthropoda	Crustacea	Isopoda	Asellidae	*Caecidotea*	–	–	1	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	–	–	3	2	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia*	–	–	–	2	2
Arthropoda	Insecta	Coleoptera	Elmidae	*Microcylloepus*	–	–	–	4	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	–	–	–	3	4
Arthropoda	Insecta	Coleoptera	Haliplidae	*Peltodytes*	–	–	–	6	–
Arthropoda	Insecta	Coleoptera	Hydrophilidae		–	–	–	–	1
Arthropoda	Insecta	Diptera	Chironomidae		38	184	35	144	114
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	–	3	4	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	–	1	–	–	–
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae	*Ephemerella*	–	–	–	–	3
Arthropoda	Insecta	Lepidoptera	Pyralidae		–	–	–	1	–
Arthropoda	Insecta	Odonata	Coenagrionidae		–	–	–	–	1
Arthropoda	Insecta	Odonata	Coenagrionidae	*Enallagma*	–	1	3	5	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	–	2	–	8	5
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	1	3	–	–	–
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*	2	–	–	3	3
Mollusca	Bivalvia	Pelecypoda	Sphaeriidae		–	–	1	–	–
Mollusca	Gastropoda	Limnophila	Ancylidae		1	–	–	–	–
Mollusca	Gastropoda	Limnophila	Physidae		1	1	1	1	–
Mollusca	Gastropoda	Limnophila	Planorbidae		–	2	–	–	–
Mollusca	Gastropoda	Limnophila	Planorbidae	*Menetus*	–	–	–	1	–
01657100									
Annelida	Oligochaeta							74	8
Arthropoda	Insecta	Coleoptera	Dryopidae	*Helichus*				1	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*				1	2
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia*				2	4
Arthropoda	Insecta	Diptera	Chironomidae					136	186
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*				–	3
Arthropoda	Insecta	Odonata						1	–
Arthropoda	Insecta	Odonata	Coenagrionidae			No samples collected 2008–10		1	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*				1	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Enallagma*				–	5
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*				2	1
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*				2	–
Mollusca	Gastropoda	Limnophila	Ancylidae					1	–
Mollusca	Gastropoda	Limnophila	Lymnaeidae					1	–
Mollusca	Gastropoda	Limnophila	Physidae					3	–

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
01657322									
Annelida	Oligochaeta				–	–	24	6	67
Annelida	Oligochaeta	Oligochaeta			3	76	–	–	–
Arthropoda	Insecta	Coleoptera	Dryopidae	*Helichus*	–	–	–	–	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	4	1	–	1	1
Arthropoda	Insecta	Diptera	Chironomidae		173	120	181	197	140
Arthropoda	Insecta	Diptera	Empididae	*Clinocera*	1	–	–	–	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	6	4	4	5	4
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	–	–	–	1	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	–	2	–	1	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	–	2	–	–	–
Arthropoda	Insecta	Trichoptera	Limnephilidae	*Ironoquia*	–	–	–	1	–
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	–	1	–	–	–
Mollusca	Bivalvia	Pelecypoda	Sphaeriidae		1	–	–	–	–
Mollusca	Gastropoda	Limnophila	Physidae		1	1	1	–	–
Platyhelminthes	Turbellaria	Tricladida	Planariidae		1	–	–	–	–
01657394									
Annelida	Oligochaeta				–	–	2	–	1
Annelida	Oligochaeta	Oligochaeta			–	2	–	–	–
Arthropoda	Crustacea	Amphipoda	Crangonyctidae	*Crangonyx*	1	–	6	3	–
Arthropoda	Crustacea	Isopoda	Asellidae	*Caecidotea*	–	–	1	–	–
Arthropoda	Crustacea	Isopoda	Asellidae	*Lirceus*	1	–	–	–	–
Arthropoda	Insecta	Coleoptera	Dryopidae	*Helichus*	–	–	3	–	–
Arthropoda	Insecta	Coleoptera	Dytiscidae		–	–	–	–	1
Arthropoda	Insecta	Coleoptera	Elmidae		–	–	–	–	2
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia*	2	1	3	1	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Microcylloepus*	–	–	3	1	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Optioservus*	5	–	–	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Oulimnius*	5	2	7	2	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	4	1	2	2	3
Arthropoda	Insecta	Coleoptera	Hydrophilidae	*Hydrobius*	–	–	1	–	–
Arthropoda	Insecta	Coleoptera	Hydrophilidae	*Tropisternus*	–	–	2	–	–
Arthropoda	Insecta	Coleoptera	Psephenidae	*Ectopria*	1	–	–	–	–
Arthropoda	Insecta	Coleoptera	Psephenidae	*Psephenus*	–	–	–	–	1
Arthropoda	Insecta	Coleoptera	Ptilodactylidae	*Anchytarsus*	–	–	5	1	1
Arthropoda	Insecta	Diptera	Ceratopogonidae	*Bezzia*	–	–	2	1	–
Arthropoda	Insecta	Diptera	Ceratopogonidae	*Dasyhelea*	–	–	1	–	–
Arthropoda	Insecta	Diptera	Ceratopogonidae	*Mallochohelea*	–	–	–	–	1

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
				01657394—Continued					
Arthropoda	Insecta	Diptera	Chironomidae		56	129	90	132	121
Arthropoda	Insecta	Diptera	Empididae	*Chelifera*	–	–	1	–	–
Arthropoda	Insecta	Diptera	Empididae	*Clinocera*	7	1	6	4	–
Arthropoda	Insecta	Diptera	Simuliidae	*Prosimulium*	5	–	–	1	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	1	4	6	12
Arthropoda	Insecta	Diptera	Tipulidae	*Antocha*	–	1	–	1	–
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	–	–	3	5	–
Arthropoda	Insecta	Ephemeroptera	Ameletidae	*Ameletus*	–	1	–	–	–
Arthropoda	Insecta	Ephemeroptera	Baetidae	*Acentrella*	–	–	–	–	1
Arthropoda	Insecta	Ephemeroptera	Baetidae	*Centroptilum*	–	7	–	–	–
Arthropoda	Insecta	Ephemeroptera	Caenidae	*Caenis*	–	–	8	1	–
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae	*Ephemerella*	1	–	–	–	–
Arthropoda	Insecta	Ephemeroptera	Ephemerellidae	*Eurylophella*	–	1	–	–	–
Arthropoda	Insecta	Ephemeroptera	Heptageniidae		1	–	–	2	–
Arthropoda	Insecta	Ephemeroptera	Heptageniidae	*Maccaffertium*	–	3	4	1	–
Arthropoda	Insecta	Ephemeroptera	Isonychiidae	*Isonychia*	–	–	–	1	–
Arthropoda	Insecta	Megaloptera	Corydalidae	*Corydalus*	–	–	–	1	–
Arthropoda	Insecta	Megaloptera	Corydalidae	*Nigronia*	–	1	3	–	–
Arthropoda	Insecta	Odonata	Gomphidae		1	1	–	4	–
Arthropoda	Insecta	Odonata	Gomphidae	*Stylogomphus*	–	–	2	–	–
Arthropoda	Insecta	Plecoptera			–	–	2	–	–
Arthropoda	Insecta	Plecoptera	Leuctridae		–	1	–	–	5
Arthropoda	Insecta	Plecoptera	Nemouridae	*Amphinemura*	99	5	14	14	51
Arthropoda	Insecta	Plecoptera	Perlidae	*Eccoptura*	–	–	1	–	–
Arthropoda	Insecta	Plecoptera	Perlodidae	*Isoperla*	2	–	–	–	2
Arthropoda	Insecta	Trichoptera	Hydropsychidae		–	2	–	–	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	6	13	7	8	3
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	1	4	2	2	–
Arthropoda	Insecta	Trichoptera	Limnephilidae		–	–	–	1	–
Arthropoda	Insecta	Trichoptera	Philopotamidae	*Chimarra*	–	24	11	10	1
Arthropoda	Insecta	Trichoptera	Polycentropidae		2	–	–	–	–
Arthropoda	Insecta	Trichoptera	Polycentropidae	*Neureclipsis*	–	3	–	–	–
Arthropoda	Insecta	Trichoptera	Polycentropidae	*Polycentropus*	–	–	1	–	–
Arthropoda	Insecta	Trichoptera	Rhyacophilidae	*Rhyacophila*	–	–	–	–	1
Arthropoda	Insecta	Trichoptera	Uenoidae	*Neophylax*	1	6	3	4	–
Mollusca	Bivalvia	Pelecypoda	Sphaeriidae		1	–	–	–	–
Mollusca	Gastropoda	Limnophila	Physidae		–	–	1	–	–
Mollusca	Gastropoda	Limnophila	Planorbidae		–	–	1	–	–

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
0164425950									
Annelida	Oligochaeta				No samples collected 2008–10			119	16
Arthropoda	Insecta	Diptera	Chironomidae					81	205
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*				1	–
0165690673									
Annelida	Oligochaeta				–	–	81	65	11
Annelida	Oligochaeta	Oligochaeta			22	1	–	–	–
Arthropoda	Crustacea	Amphipoda	Talitridae	*Hyalella*	1	–	–	1	–
Arthropoda	Crustacea	Isopoda	Asellidae	*Caecidotea*	–	–	1	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Dubiraphia*	–	–	2	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	–	1	–	2	–
Arthropoda	Insecta	Diptera	Ceratopogonidae	*Monohelea*	–	–	–	3	–
Arthropoda	Insecta	Diptera	Chironomidae		33	194	104	119	210
Arthropoda	Insecta	Diptera	Simuliidae	*Prosimulium*	–	–	–	1	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	1	1	3	1
Arthropoda	Insecta	Diptera	Tipulidae	*Tipula*	–	–	–	1	–
Arthropoda	Insecta	Ephemeroptera	Baetidae		–	–	1	–	–
Arthropoda	Insecta	Lepidoptera	Pyralidae		–	1	–	–	–
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	1	–	–	–	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	2	–	–	–	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Enallagma*	–	–	1	1	–
Arthropoda	Insecta	Odonata	Coenagrionidae	*Ischnura*	–	–	–	2	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Cheumatopsyche*	3	1	–	15	–
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	6	3	–	1	–
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*	7	4	1	–	–
Mollusca	Bivalvia	Pelecypoda	Sphaeriidae		–	–	3	–	–
Mollusca	Gastropoda	Limnophila	Ancylidae		1	1	–	–	–
Mollusca	Gastropoda	Limnophila	Lymnaeidae		–	–	2	–	–
Mollusca	Gastropoda	Limnophila	Lymnaeidae	*Pseudosuccinea*	–	1	–	–	–
Mollusca	Gastropoda	Limnophila	Physidae		1	3	9	1	1
0165694286									
Annelida	Oligochaeta				–	–	18	51	33
Annelida	Oligochaeta	Oligochaeta			40	2	–	–	–
Arthropoda	Insecta	Coleoptera	Elmidae	*Ancyronyx*	–	–	4	–	1
Arthropoda	Insecta	Coleoptera	Elmidae	*Stenelmis*	12	2	92	45	24
Arthropoda	Insecta	Diptera	Chironomidae		147	208	103	120	155
Arthropoda	Insecta	Diptera	Empididae	*Chelifera*	–	–	1	–	–
Arthropoda	Insecta	Diptera	Empididae	*Hemerodromia*	1	–	–	–	–
Arthropoda	Insecta	Diptera	Simuliidae	*Simulium*	–	–	2	–	1
Arthropoda	Insecta	Odonata	Calopterygidae	*Calopteryx*	–	–	–	–	1
Arthropoda	Insecta	Odonata	Coenagrionidae	*Argia*	1	–	–	–	1

Table 1–1. Counts of benthic macroinvertebrates for each annual sample, by station identifier.—Continued

[Station identifiers shown in spanner rows are defined in tables 1 and 9. –, organism not found in sample]

Phylum	Class	Order	Family	Genus	2008	2009	2010	2011	2012
0165694286—Continued									
Arthropoda	Insecta	Trichoptera	Hydropsychidae	*Hydropsyche*	2	–	1	1	1
Mollusca	Bivalvia	Pelecypoda	Corbiculidae	*Corbicula*	1	–	–	–	3
Mollusca	Gastropoda	Limnophila	Planorbidae		–	–	1	–	–
Nematomorpha					–	–	–	–	1

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For more information about this publication, contact:
Director
USGS Virginia Water Science Center
1730 East Parham Road
Richmond, Virginia 23228
(804) 261-2600
email: dc_va@usgs.gov

or visit our website at
http://va.water.usgs.gov/

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