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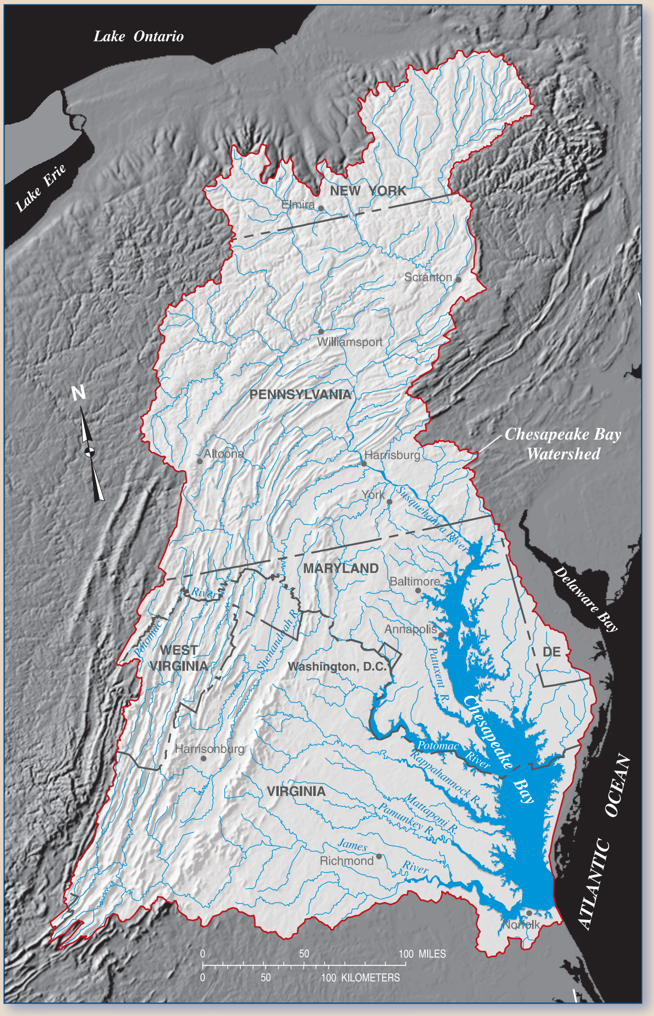
Chesapeake Bay Program
A Watershed Partnership

Sources, Transport, and Storage of Sediment at Selected Sites in the Chesapeake Bay Watershed



Scientific Investigations Report 2008–5186

U.S. Department of the Interior
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Cover. Relief map of the Chesapeake Bay Watershed and photographs of: (top) farming area in the West Branch Little Conestoga Creek Watershed, May 6, 2004; (middle) Old Woman Creek at Bennsville Road, Maryland, view looking downstream; and (bottom) Little Conestoga Creek, Pennsylvania, view looking upstream from Millersville Road Bridge, September 23, 2003. Photographs by Allen Gellis, U.S. Geological Survey.

Inside Cover. Dragon Run, one of the tributaries selected in this study for flood-plain sedimentation analyses, flows 40 miles along and through nontidal and tidal cypress swamp to the headwaters of the Piankatank River in Virginia, and is one of the most pristine waterways in the Chesapeake Bay Watershed. Photograph by Teta Kain.

Sources, Transport, and Storage of Sediment at Selected Sites in the Chesapeake Bay Watershed

By Allen C. Gellis, Cliff R. Hupp, Milan J. Pavich, Jurate M. Landwehr,
William S.L. Banks, Bernard E. Hubbard, Michael J. Langland, Jerry C. Ritchie[1],
and Joanna M. Reuter

[1] U.S. Deparment of Agriculture, Agricultural Research Service

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DIRK KEMPTHORNE, Secretary

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Conversion Factors

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	2.471	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square centimeter (cm^2)	0.1550	square inch (in^2)
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
cubic meter (m^3)	6.290	barrel (petroleum, 1 barrel = 42 gal)
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)

Conversion Factors—continued

Multiply	By	To obtain
	Volume	
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
cubic centimeter (cm^3)	0.06102	cubic inch (in^3)
liter (L)	61.02	cubic inch (in^3)
cubic meter (m^3)	35.31	cubic foot (ft^3)
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
meter per second (m/s)	3.281	foot per second (ft/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
cubic meter per second (m^3/s)	22.83	million gallons per day (Mgal/d)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound, avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
megagram per day (Mg/d)	1.102	ton per day (ton/d)
megagram per year (Mg/yr)	1.102	ton per year (ton/yr)
	Yield	
megagram per square kilometer (Mg/km^2)	2.855	ton per square mile (ton/mi^2)
kilogram per square meter (kg/m^2)	0.2048	pound per square foot (lb/ft^2)
megagram per hectare (Mg/ha)	0.446	tons per acre (ton/acre)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)
gram per cubic centimeter (g/cm^3)	62.4220	pound per cubic foot (lb/ft^3)
	Radioactivity	
becquerel per liter (Bq/L)	27.027	picocurie per liter (pCi/L)

Water year is defined as the 12-month period from October 1 for any given year through September 30 of the following year. The water year is designated by the calendar year in which it ends, and which includes 9 of the 12 months. Thus, the year ending September 30, 1999 is called the “1999” water year.

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

$°F=(1.8\times°C)+32$

Sources, Transport, and Storage of Sediment at Selected Sites in the Chesapeake Bay Watershed

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Abstract

The Chesapeake Bay Watershed covers 165,800 square kilometers and is supplied with water and sediment from five major physiographic provinces: Appalachian Plateau, Blue Ridge, Coastal Plain, Piedmont, and the Valley and Ridge. Suspended-sediment loads measured in the Chesapeake Bay Watershed showed that the Piedmont Physiographic Province has the highest rates of modern (20th Century) sediment yields, measured at U.S. Geological Survey streamflow-gaging stations, and the lowest rates of background or geologic rates of erosion (~10,000 years) measured with *in situ* beryllium-10. In the agricultural and urbanizing Little Conestoga Creek Watershed, a Piedmont watershed, sources of sediment using the "sediment-fingerprinting" approach showed that streambanks were the most important source (63 percent), followed by cropland (37 percent). Cesium-137 inventories, which quantify erosion rates over a 40-year period, showed average cropland erosion of 19.39 megagrams per hectare per year in the Little Conestoga Creek Watershed. If this erosion rate is extrapolated to the 13 percent of the watershed that is in cropland, then cropland could contribute almost four times the measured suspended-sediment load transported out of the watershed (27,600 megagrams per hectare per year), indicating that much of the eroded sediment is being deposited in channel and upland storage.

The Piedmont has had centuries of land-use change, from forest to agriculture, to suburban and urban areas, and in some areas, back to forest. These land-use changes mobilized a large percentage of sediment that was deposited in upland and channel storage, and behind thousands of mill dams. The effects of these land-use changes on erosion and sediment transport are still being observed today as stored sediment in streambanks is a source of sediment. Cropland is also an important source of sediment.

The Coastal Plain Physiographic Province has had the lowest sediment yields in the 20th Century and with sandy soils, contributes little fine-grained sediment. In the agricultural Pocomoke River Watershed, a Coastal Plain watershed, cesium-137 mass-balance results indicate that erosion and deposition are both occurring on cropland fields. Sources of sediment using the sediment-fingerprinting approach for the Pocomoke River were distributed as follows: cropland (46 percent), ditch beds (34 percent), ditch banks and streambanks (7 percent), and forest (13 percent). Cropland was a source of sediment for the two largest peak flow events, which occurred during harvesting when the ground may have been bare. The Pocomoke River Watershed is heavily ditched and channelized, conditions that are favorable for ditch bed and bank erosion. In the mixed land use (forested, agricultural, and urbanizing) Mattawoman Creek Watershed, a Coastal Plain watershed, sources of sediment using the sediment-fingerprinting approach were distributed as follows: streambanks (30 percent), forest (29 percent), construction (25 percent), and cropland (17 percent). Mattawoman Creek Watershed drains a rapidly developing region with 182 hectares (approximately 1.26 percent of the watershed) under construction. Sediment from construction sites was also determined as a source of sediment in the Mattawoman Creek Watershed. The sediment-fingerprinting source results for the three watersheds analyzed, show that in all watersheds, both the stream corridor and agriculture were significant sources of sediment. Forest as a source of sediment in the Mattawoman Creek Watershed may indicate that these forests are being disturbed and forest soils are eroding.

Bare ground can be an important sediment source. Spatial analysis of bare ground in the Little Conestoga Creek Watershed using satellite imagery between 2000 and 2005 showed that the majority of bare ground was classified as pasture. Bare ground was correlated to the growing season with the highest percentages occurring in the early spring (April, 34 percent) and after the fall harvest (December, 38 percent). The lowest percentage of bare ground (10 percent) occurred in August. Results of the sediment-fingerprinting analysis for the Pocomoke River and Mattawoman Creek Watersheds showed cropland as a source during harvesting and before planting. For the Little Conestoga Creek, however, flow may be a more important factor than seasonality in determining sediment sources.

Long-term and short-term flood-plain deposition rates were investigated in several rivers draining the Chesapeake

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Bay Watershed to determine rates of deposition. Results showed that a Piedmont stream and Western Shore Coastal Plain streams had higher sedimentation rates than Eastern Shore Delmarva Peninsula streams. The lowest deposition rates occurred on the channelized reaches of the Eastern Shore Pocomoke River. Extrapolating sedimentation rates to each study river's gross flood-plain area indicated that flood plains trap from 21 to over 100 percent of the river's sediment load. The flood plains of Coastal Plain rivers trap large amounts of sediment that otherwise would be delivered to the Chesapeake Bay.

Introduction

The Chesapeake Bay Watershed, which contains the largest estuary in the United States, has a drainage area of 165,800 km^2 (square kilometers) and drains five major physiographic provinces (Appalachian Plateau, Valley and Ridge Province, Blue Ridge Province, Piedmont Province, and the Coastal Plain Province) (Langland and others, 1995; Sprague and others, 2000) (figs. 1a, b). The Bay was listed as an "impaired water body" in 2000 under the Clean Water Act because of excess sediment and nutrients (Phillips, 2002). Sediment can carry toxic contaminants and pathogens that may negatively impact ecosystems and bury habitats through excess sedimentation (U.S. Environmental Protection Agency, 1997). Excess sediment and nutrients, along with a lack of oysters, reduces water clarity (Phillips, 2002). The poor water clarity has affected submerged aquatic vegetation (SAV), which once covered an estimated 200,000 acres (U.S. Environmental Protection Agency, 2006). In 2005, the Chesapeake Bay had an estimated total of 78,260 acres of SAV (U.S. Environmental Protection Agency, 2006). SAV beds constitute a critical biological resource in estuaries that provide habitat for many species (Langland and others, 2003).

The Chesapeake Bay Program (CBP), a multi-jurisdictional partnership that establishes restoration goals for the Chesapeake Bay and its watershed, enacted an agreement in 2000 to improve water quality, including sediment, in the Bay (Langland and others, 2003). Whereas nutrient sources and transport have been studied since the 1980s, little is known about sediment sources, storage, and delivery to the Bay. To reduce sediment loads to the Bay and assist land-management agencies in developing sediment-reduction strategies, it is useful to target areas with high sediment yields and identify the significant sources of sediment. The U.S. Geological Survey (USGS) has a key role in providing sediment data and interpretations that are utilized to understand sediment sources, storage, and delivery to the Bay and in its watershed.

Sediment is eroded from many points on the landscape, is transported various distances, and is then stored in numerous temporary sinks in a watershed before reaching the ultimate sink of the Chesapeake Bay. Nearly 90 percent of all sediment is trapped for different periods of time along streams before reaching saltwater (Meade and others, 1990). Watershed sediment-storage sinks include but are not limited to colluvial slopes, flood plains, pointbars, channel beds, and impoundments. The sediment-delivery ratio is the proportion of eroded upland soil delivered to a point in the stream relative to the gross erosion within the upstream watershed (Walling, 1983). The sources of sediment in a watershed can be generalized as uplands and channel corridors. Upland source areas include, but are not limited to, land uses and land covers of forest, agriculture, mining, urban, suburban, construction, and landslides. Sources of sediment in the channel corridor include channel banks, channel bars, the channel bed, and the flood plain.

The sources, storage sinks, and transport rates of sediment vary with factors such as flow conditions, sediment grain size, watershed scale, geology, soil type, land-use type, land-use history, upland slope, channel morphology (width, depth, slope, and sinuosity), climate, and climatic events. Sediment in the channel is transported as bedload or suspended load. Bedload is the transport of coarse-grained sediment by rolling, sliding, and saltation (Beschta, 1987). Suspended sediment is the finer-grained sediment that remains in suspension by properties of the fluid, such as turbulence, where the particles' net weight is supported by the density of the fluid (Murphy and Aguirre, 1985). Fine to medium sand can be in transition between both modes of transport (Beschta, 1987). The rate of suspended-sediment transport is related to flow conditions and supply. The transport of sediment is defined as a mass or load over a specific time period in Mg/yr (megagrams per year). A megagram is equal to a metric ton. The average of annual sediment loads, normalized by drainage area, is the sediment yield.

Approaches used to measure the erosion, transport, and storage of sediment vary but can be generalized into three categories: (1) field approaches, (2) surrogate approaches, and (3) modeling approaches. Field approaches include erosion pins and traps that measure soil erosion (Loughran, 1989; Zobisch and others, 1996; Gellis and others, 2006). Field approaches also can include collection of suspended-sediment concentrations and bedload to compute loads and yields (Dunne, 1979; Asselman, 2000; Kattan and others, 1987; Gellis and others, 2003), and documentation of sediment storage by measuring sediment deposition rates (Asselman and Middelkoop, 1995; Hupp, 2000).

Surrogate approaches use methods to infer rates of erosion, sediment transport, and sediment deposition using geochemical tracers such as beryllium-10 (^{10}Be) (Brown and others, 1988), and cesium-137 (^{137}Cs) (Ritchie and McHenry, 1990; Sutherland, 1991; Ritchie and others, 2005); multiple physical and geochemical fingerprints (Walling and Woodward, 1992; Nimz, 1998; Walling, 2005; Whiting and others, 2005); dendrogeomorphic (tree ring) techniques (Carrara and Carroll, 1979; Hupp, 1999; Hupp and Bornette, 2003); and remote sensing (Miller, 1986; Reid and Dunne, 1996; Gellis, 2002).

Approaches for modeling erosion can be categorized into empirical, conceptual, and physically based models (Lane and others, 1988). Empirical models include the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978); the Pacific Southwest Inter-Agency Committee (PSIAC) Method (Pacific Southwest Inter-Agency Committee, 1968); and the spatially referenced regression model (SPARROW) models (Preston and Brakebill, 1999; Schwarz and others, 2001). Physically based models to determine watershed sediment processes include the Agricultural Non-Point Source (AGNPS) model (Young and others, 1995); Water Erosion Prediction Project (WEPP) (Nearing and others, 1989; Lane and others, 1992); and TOPMODEL (Beven and others, 1995). Conceptual models are between empirically and physically based models (Lane and others, 1988) and include the unit sediment graph approach (Rendon-Herrero, 1978).

The selection of an approach to understand the erosion, transport, and storage of sediment involves several factors, including available time to conduct analysis, the time period of interest, costs, and watershed scale. In this study, the sources, transport, and storage of sediment for selected tributaries in the Chesapeake Bay Watershed were determined using field and surrogate approaches.

Sediment eroded from the land surface is stored in the Chesapeake Bay Watershed in three primary places: upland surfaces, in reservoirs behind dams, and in flood plains (Herman and others, 2003). Flood plains in the Chesapeake Bay Watershed can be generally divided into two types: (1) an upland stream-corridor flood plain, and (2) Coastal Plain flood plain and wetlands. The Coastal Plain is characterized by broad, frequently inundated low-gradient flood plains. Although sometimes heavily impacted by land use, these flood plains and their bottomland hardwood systems remain a critical landscape element for the maintenance of water quality by trapping and storing large amounts of sediment and associated contaminants (Hupp, 2000). The Coastal Plain flood plains are the last place of sediment storage for many Chesapeake Bay streams before they enter the critical estuarine ecosystem.

Purpose and Scope

The purpose of this study was to: (1) review the literature on erosion, sediment transport, and sediment storage for the entire Chesapeake Bay Watershed, (2) contrast the spatial variability of soil erosion in the Susquehanna River Watershed using meteoric ^{10}Be erosion and *in situ* ^{10}Be, (3) determine the temporal variation in bare ground in an agricultural watershed, (4) identify or “fingerprint” sources of fine-grained suspended sediment in selected watersheds of the Chesapeake Bay, and (5) determine the role of flood plains and riparian wetlands in sediment storage.

Description of Study Area

The study area encompasses scales from the entire Chesapeake Bay Watershed (165,800 km^2), to major watersheds (such as the Susquehanna River Watershed, 71,250 km^2), to subwatersheds (such as the Pocomoke River, Mattawoman Creek, and the Little Conestoga Creek, 100–200 km^2) (fig. 1a), to farm fields (100 m^2, or square meters), and individual reaches of streams (such as flood plain measurements – tens of m^2). Six main rivers, the Susquehanna, Patuxent, Potomac, Rappahannock, York, and James together drain 70 percent of the Chesapeake Bay Watershed within New York, Pennsylvania, Maryland, Delaware, West Virginia, Virginia, and the District of Columbia (fig. 1a). The morphology of the Chesapeake Bay is tied to changes in sea level, which rose and fell during the late Tertiary and Quaternary Periods (Hobbs, 2004; Colman and others, 1990). In the most recent glaciation (18–20 thousand years before present), the ancestral Susquehanna and Potomac Rivers incised into Coastal Plain strata (Colman and others, 1990). Subsequently, over the past 7,500 years, as sea level rose, the valleys were drowned forming the modern Chesapeake Bay estuary (Bratton and others, 2003).

The climate in the Chesapeake Bay Watershed is humid continental, with average precipitation ranging from 760 mm/yr (millimeters per year) in the northern parts to 1,270 mm/yr in the southern parts (Langland and others, 1995). Elevations range from sea level to over 1,200 m (meters) (Bachman and others, 1998). More than 15 million people lived in the Chesapeake Bay Watershed in 1995 (U.S. Environmental Protection Agency, 2006). In 1987, land use in the Chesapeake Bay Watershed was classified as agriculture (29 percent), urban (10 percent), and forest (60 percent) (Gutierrez-Magness and others, 1997).

Susquehanna River Study Area for Beryllium-10

The Susquehanna River, the largest tributary to Chesapeake Bay, was selected to study the spatial variability of background (geologic) erosion and recent soil erosion (fig. 1b). The Susquehanna’s main stem, at 714 km (kilometers) long, is the longest commercially non-navigable river in North America (Susquehanna River Basin Commission, 2008). The Susquehanna River originates in the Appalachian Plateau of south-central New York and central Pennsylvania and flows into the Valley and Ridge and Piedmont Physiographic Provinces of Southern Pennsylvania and Maryland (fig. 1b). Three major hydroelectric dams are situated on the Susquehanna—from upstream to downstream are Safe Harbor, Holtwood, and Conowingo (fig. 1a). Mean annual temperatures range from 12°C (degrees Celsius) in the lower elevations to 7°C in higher elevations (Sprague and others, 2000). Rainfall in the Susquehanna River Watershed ranges from 838 to 1,219 mm/yr. Major tributaries to the Susquehanna River include the Conestoga River, Chemung River, West Branch Susquehanna River, and the Juniata River. Land use in the Susquehanna River Watershed is primarily forest (67 percent) and agriculture (29 percent), with the Conestoga River Watershed containing the largest percentage of agriculture (Sprague and others, 2000).

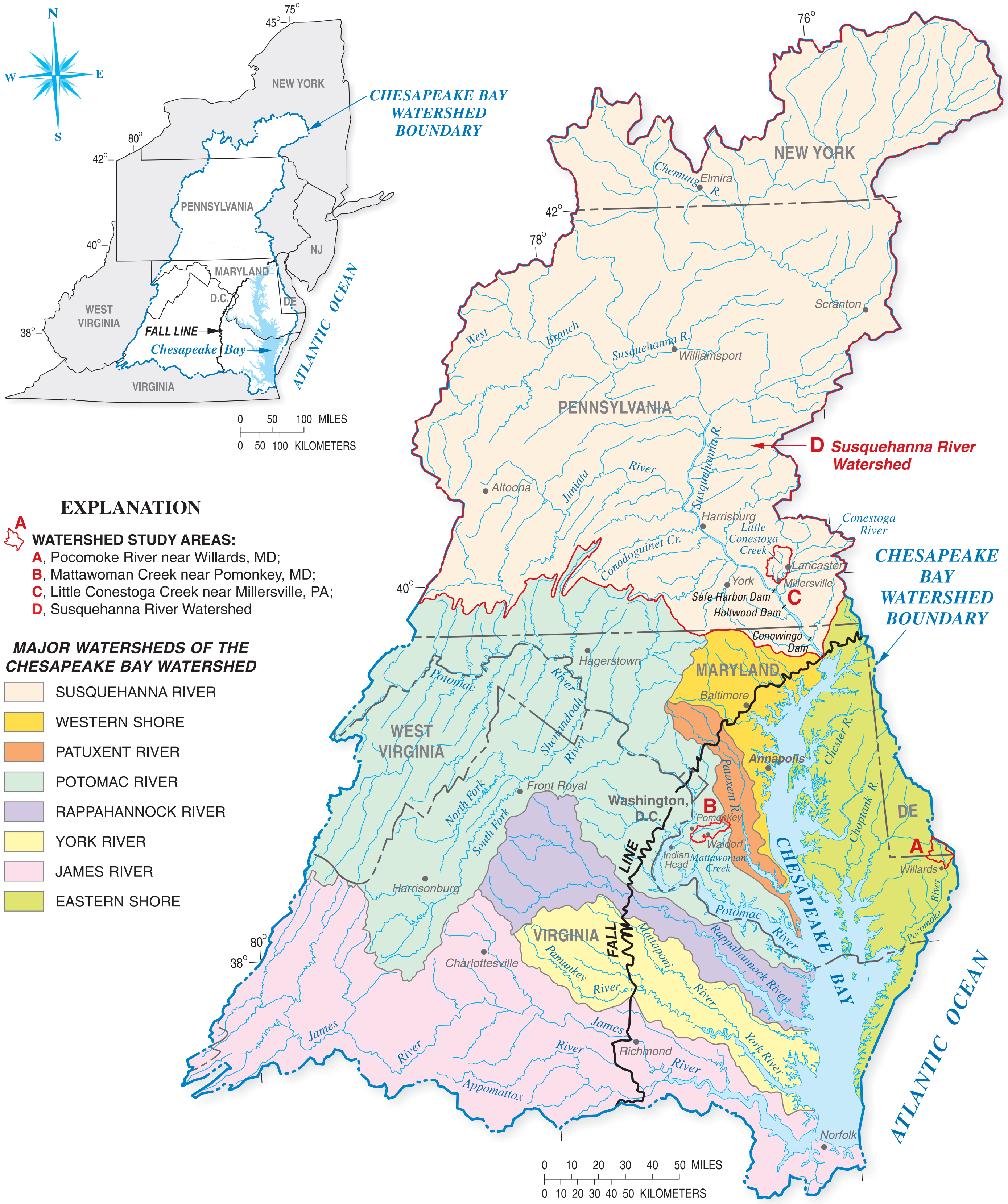

Figure 1a. Major watersheds of the Chesapeake Bay Watershed and watershed study areas: (A) Pocomoke River near Willards, Maryland, (B) Mattawoman Creek near Pomonkey, Maryland, (C) Little Conestoga Creek near Millersville, Pennsylvania, and (D) Susquehanna River Watershed.

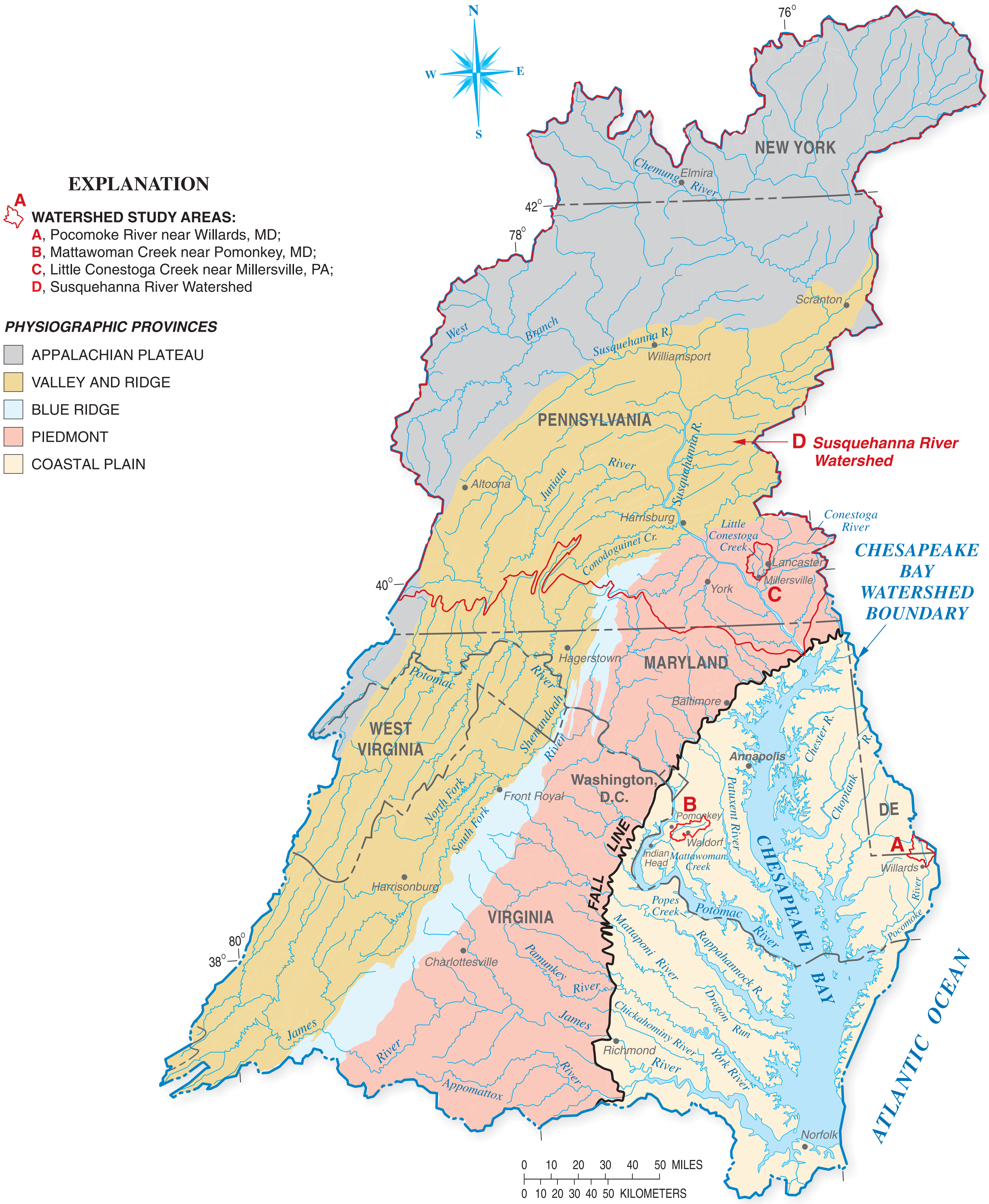

Figure 1b. Physiographic provinces in the Chesapeake Bay Watershed and watershed study areas: (A) Pocomoke River near Willards, Maryland, (B) Mattawoman Creek near Pomonkey, Maryland, (C) Little Conestoga Creek near Millersville, Pennsylvania, and (D) Susquehanna River Watershed (modified from Bachman and others, 1998).

Sediment Source Analysis

Detailed analysis of sediment sources was undertaken in three small tributaries of the Chesapeake Bay Watershed: (1) the Pocomoke River near Willards, Maryland-Delaware (156.7 km^2), (2) Mattawoman Creek above Old Woman Creek near Pomonkey, Maryland (134.5 km^2), and (3) the Little Conestoga Creek near Millersville, Pennsylvania (109.5 km^2) (figs. 1a, b).

Pocomoke River

The Pocomoke River near Willards, Maryland on the Delmarva Peninsula drains parts of Maryland and Delaware entirely within the Coastal Plain Physiographic Province (fig. 1b). Average rainfall for the Pocomoke River Watershed recorded at the Salisbury, Maryland, National Weather Service rain gage (latitude N 38°22’, longitude W 75°35’), which is approximately 20 km from the USGS streamflow-gaging station on the Pocomoke River near Willards, Maryland, from 1916 through 2005 was 1,132 mm/yr (U.S. Department of Commerce, 2007). Surficial geology in the Pocomoke River Watershed consists primarily of unconsolidated sand and some clay-silt of the Parsonsburg Sand and Omar Formations (Denny and others, 1979). Soils in the Maryland part of the Pocomoke River Watershed are mapped as loamy sands of the Klej, Runclint, and Hammonton Soil Series (Demas and Burns, 2004). In the Delaware part of the Pocomoke River Watershed, soils are mapped as loamy sands of the Matawan, Pocomoke, and Fallsington Soil Series (Ireland and Matthews, 1974). The Pocomoke River Watershed drains Wicomico and Worcester Counties in Maryland and Sussex County in Delaware; these counties had a combined estimated population in 2006 of 272,225 (U.S. Department of Commerce, 2006a,b). Land use in the Pocomoke River Watershed in 2001 was 17 percent pasture, 35 percent in cultivated crops, 46 percent forest (8 percent in woody wetland), and less than 1 percent urban (Homer and others, 2007). Cultivated crops in the Pocomoke River Watershed are primarily corn and soy. Corn and soy are rotated in the Pocomoke River Watershed and the type of crop may change from year to year. Depending on soil-moisture conditions, planting for corn and soy can occur from April through May and crop harvesting can occur from August through September. Ditching on agricultural lands in the Pocomoke River Watershed is an extensive practice that has been used to drain wetlands for agriculture (Bell and Favero, 2000). Ditching goes back to the 1840s and much of the land clearing in the Pocomoke River Watershed was completed prior to the 1940s (Bell and Favero, 2000). Ditching occurred at several scales, from ditches on farm fields to straightening and deepening of main-stem rivers and tributaries. Parts of the Pocomoke River main stem were channelized as early as the 1600s, with the main stem of the Pocomoke River channelization from 1939 to 1946 (Bell and Favero, 2000; Ross and others, 2004). In the 1960s, many ditch systems in the Delmarva Peninsula, which includes the Pocomoke River Watershed, were re-engineered and expanded (Bell and Favero, 2000).

Mattawoman Creek

Mattawoman Creek drains entirely within the Coastal Plain Physiographic Province on the Western Shore of the Chesapeake Bay (fig. 1b). Surfaces in the watershed are developed on an upland loam overlying an upland gravel interbedded with sand and cobbles (Cloos, 1951; Hack, 1955; McCartan, 1989). Soils in the Mattawoman Creek Watershed are mapped as silt loams and fine sandy loams of the Beltsville, Leonardtown, and Sassafras Soil Series (Kirby and others, 1967; Hall and Matthews, 1974). Average rainfall recorded at the Upper Marlboro, Maryland, National Weather Service rain gage (latitude N 38°52’, longitude W 76°47’), which is approximately 24 km from the USGS streamflow-gaging station on Mattawoman Creek near Pomonkey, Maryland, from 1957 through 2005 was 1,070 mm/yr (U.S. Department of Commerce, 2007). Land use in the Mattawoman Creek Watershed in 2001 was 11 percent pasture, 7 percent cultivated crops, 19 percent urban, and 60 percent forest (of which 2 percent of the forest was classified as woody wetlands) (Homer and others, 2007). Cultivated crops in the Mattawoman Creek Watershed are primarily corn. Mattawoman Creek drains parts of Charles and Prince Georges Counties, Maryland, which are within commuting distance to Washington, D.C. (45 km). In 2006, the estimated population of both counties was 981,731 (U.S. Department of Commerce, 2006c, d). In Charles County, a 93-percent increase in population occurred from 1980 through 2006 (U.S. Department of Commerce, 2000a). Approximately 20 percent of the population of Charles County is in the city of Waldorf, Maryland (U.S. Department of Commerce, 2000b), part of which drains to Mattawoman Creek. During this study, many construction sites for housing and commercial development were observed in the Mattawoman Creek Watershed downstream of Waldorf. Charles County was recently recognized as the eighth fastest growing county in Maryland (Charles County Government, 2007). The Mattawoman Creek and its tidal and nontidal wetlands were identified in a 1981 Maryland Department of State Planning report as areas of Critical State Concern (Charles County Government, 2007). Wetlands and tributaries in Mattawoman Creek are among the most productive fish spawning and nursery streams in the entire Chesapeake Bay region (Charles County Government, 2007).

Little Conestoga Creek

The Little Conestoga Creek drains part of the Piedmont Physiographic Province in Pennsylvania (fig. 1b). The lower and middle reaches of the Little Conestoga Creek drain early Paleozoic, weakly metamorphosed, silty limestone of the Conestoga Formation (Meisler and Becher, 1971). In the upper reaches of the watershed, the geology is dolomite, limestone, and shale (Meisler and Becher, 1971). Soils in the Little Conestoga Creek Watershed are mapped as silt loams of the Letort, Conestoga, Hagerstown, and Hollinger soil series (Custer, 1985). Average annual rainfall obtained from two National Weather Service rain gages, from 1895–1971 (latitude 40°N

3’ longitude 76°W 17’) and from 1981–2005 (latitude 40°N, 3’ longitude 76°W 16’), both approximately 10 km from the USGS streamflow-gaging station on Little Conestoga Creek near Millersville, Pennsylvania, was 1,065 mm/yr (U.S. Department of Commerce, 2007). Land use in the Little Conestoga Creek Watershed in 2001 was 32 percent pasture, 13 percent cultivated crops, 49 percent urban, and 4 percent forest (Homer and others, 2007). The Little Conestoga Creek is located in Lancaster County, Pennsylvania, which had a population in 2006 of 494,486 persons (U.S. Department of Commerce, 2006e). This represents a 36-percent increase from its population in 1980 (U.S. Department of Commerce, 2000a). Stream water from the Little Conestoga and its tributaries is used for irrigation, livestock, and commercial operations (Loper and Davis, 1998). The largest urban area in Lancaster County is the city of Lancaster, parts of which drain to the Little Conestoga Creek. The city of Lancaster had a population of 56,348 in 2000 (U.S. Department of Commerce, 2000c). Many of the construction sites observed in the Little Conestoga Creek Watershed were for housing and commercial projects.

Flood-Plain Study Areas

Ten streams, tributaries to the Chesapeake Bay, were selected for flood-plain deposition (also referred to as flood-plain trapping) analyses (fig. 2): in clockwise order, the Chickahominy River (tributary to the James River), Pamunkey River (tributary to the York River), Mattaponi River (tributary to the York River), Dragon Run (tributary to the Piankatank River), Popes Creek (tributary to the Potomac River), Mattawoman Creek (tributary to the Potomac River), Patuxent River, Little Conestoga Creek (tributary to the Conestoga River), Choptank River, and Pocomoke River. Except for the Little Conestoga Creek, all of these streams have relatively broad, forested flood plains characteristic of riverine forested wetlands on the Atlantic and Gulf Coastal Plains; one site on the Pocomoke River is a tidal marsh whereas all other sites on the Pocomoke River are forested wetlands. Major Chesapeake Bay tributaries (Susquehanna, Potomac, James, Rappahannock, and York Rivers) are embayed to the Fall Line and do not support large areas of forested bottomlands (Hupp, 2000), although their tributaries may have well-developed flood plains. The Fall Line is the boundary between the crystalline rocks of the Piedmont Province and the unconsolidated Cretaceous and Tertiary sediments of the Coastal Plain Province. A change in topography, usually a scarp, separates the Piedmont Province from the Coastal Plain. Streams flowing across the Fall Line can undergo abrupt decreases in gradient. The Pamunkey, Mattaponi, Patuxent, and Choptank Rivers are part of the Chesapeake Bay River Input Monitoring (RIM) Program, and have long-term records of suspended-sediment loads and concentrations (Gellis and others, 2005). The Chickahominy, Mattawoman, Little Conestoga, and Pocomoke Rivers have either shorter term or less frequent suspended-sediment data. Suspended-sediment data were not available for Dragon Run and Popes Creek. All flood-plain trapping studies were conducted along Coastal Plain reaches of the selected streams, except for the Little Conestoga Creek that flows in the Piedmont (figs. 1b, 2).

Previous Studies on Sediment Processes in the Chesapeake Bay Watershed

Previous studies on sediment erosion, transport, and storage in the Chesapeake Bay Watershed have investigated suspended-sediment concentrations, sediment yields, land-use effects on erosion and sediment, and flood-plain processes. These studies have used a variety of approaches over different spatial and time scales.

Importance of Land Use on Erosion and Sediment Transport

Langland and Cronin (2003) compiled a summary of important sediment processes in the Chesapeake Bay. They recognized that erosion from upland land surfaces and erosion of stream corridors (banks and channels) were the most important sources of sediment in the Chesapeake Bay Watershed. For the entire Chesapeake Bay region, watersheds with the highest percentage of agricultural land use had the highest annual sediment yields, and watersheds with the highest percentage of forest cover had the lowest annual sediment yields.

Langland and others (1995) used suspended-sediment data collected from 127 nontidal sites draining the Chesapeake Bay Watershed to examine the influence of land cover on total suspended solids (TSS) and suspended-sediment concentrations. They found that the largest median concentration of suspended sediment was in the upper Potomac River Watershed, and that the highest concentrations of suspended sediment were in the Susquehanna River Watershed. Correlation of annual sediment yields to land use, computed with a log-linear multiple regression model, indicated that watersheds with the highest percentage of agriculture had the seven highest sediment yields. Watersheds with the highest percentage of forest cover had the lowest annual sediment yields. In an analysis of 42 watersheds in the Potomac River Watershed, Wark and Keller (1963) showed increasing sediment yields with increasing cropland and decreasing sediment yield with increasing forest. When the percentage of land in cropland increased from 20 to 40 percent, the annual suspended-sediment load doubled (Wark and Keller, 1963). Analysis of suspended-sediment loads and yields in the Potomac River Watershed during 1993-95 indicated that two agricultural watersheds, Conococheague Creek at Fairview, Maryland, and the Monocacy River at Reich’s Ford Bridge, Maryland, had the highest sediment yields (Lizarraga, 1997).

The Susquehanna River is a major contributor of sediment to Chesapeake Bay (Gellis and others, 2005). The Susquehanna River transports pollutants attached to the

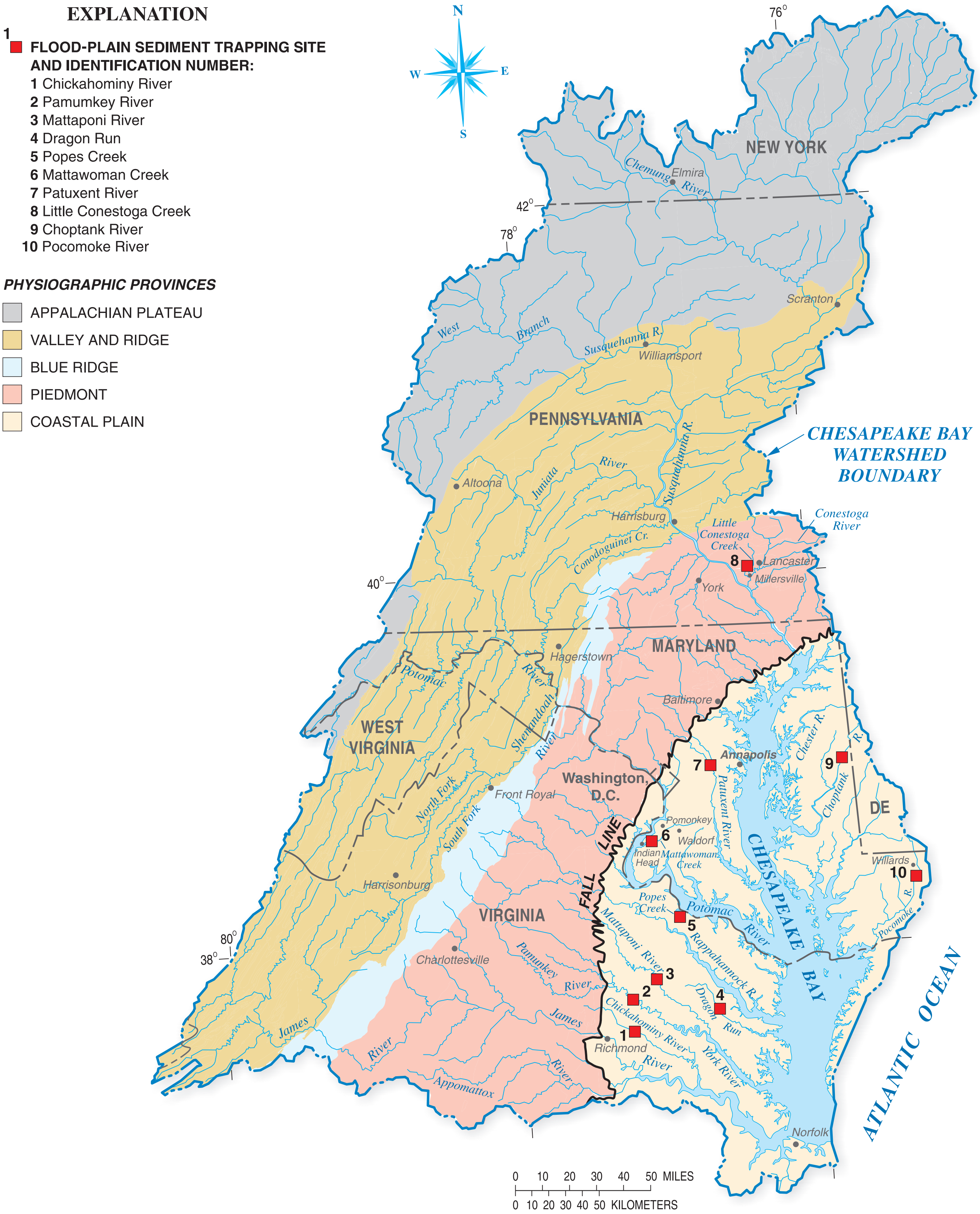

Figure 2. Location of flood-plain sediment trapping sites in the Chesapeake Bay Watershed. [Dates of measurements range from 1996 through 2006 (modified from Bachman and others, 1998).]

sediment and contributes to increased sedimentation in reservoirs and the Bay (Langland and others, 2003). Pollutants and sedimentation are potential threats to the Bay ecosystem. Controlling sediment delivery to the Bay is therefore an important management concern, especially because Susquehanna River reservoirs are at or near their sediment-storage capacity (Langland and Hainly, 1997). Williams and Reed (1972) investigated sediment yields at 33 USGS streamflow-gaging stations in the Susquehanna River Watershed, using data from 1962 through 1967. For watersheds draining more than 259 km^2, sediment yield was related to mining, geologic history, and physiographic region (Williams and Reed, 1972). The highest sediment yields (greater than 70 Mg/km^2, or megagrams per square kilometer) occurred in the Glaciated Low Plateau section of the Appalachian Plateau Province, coal-mining areas of the Valley and Ridge Province, and the Piedmont Province. The lowest sediment yields were found in subwatersheds of the Valley and Ridge Province draining more than 25 percent limestone. Internal drainage, presumably of karst topography, was cited as the cause for the low sediment yields in the limestone terrain.

Land use and changes in land use are also important factors influencing erosion and sediment yields. The Chesapeake Bay Watershed has gone through dramatic land-use changes since European colonization in the 1600s (Wolman and Schick, 1967). During the 18th and 19th centuries, 70–80 percent of the original forest cover in the Chesapeake Bay Watershed was cleared for agriculture (Langland and others, 2003). The loss of forest cover led to an increase in upland erosion and sediment yield (Wolman and Schick, 1967). Since the late 1800s, sedimentation in much of Chesapeake Bay has exceeded pre-land clearance rates (Brush, 1989; Langland and Cronin, 2003). Much of the eroded sediment was not transported out of the source areas, but was deposited on colluvial slopes and flood plains in what is known as “legacy sediment” (Jacobson and Coleman, 1986). In Western Run, a Piedmont watershed in Maryland, Costa (1975) found that 52 percent of sediment eroded from agricultural lands was stored as colluvium. In a series of nested subwatersheds in the York River Watershed (Piedmont and Coastal Plain Physiographic Provinces of Virginia), 57 to 74 percent of upland erosion was stored as colluvium (Herman, 2001). Walter and Merritts (2008) proposed that the impoundment of sediment behind tens of thousands of mill dams in the Mid-Atlantic Region caused a regional base-level rise, which was the dominant cause of aggradation and sediment storage in the channel corridor. As aging mill dams breached or were removed, sediment stored behind the dams was eroded and transported by the newly formed active channel. The effect of small impoundments on sediment budgets has also been reported across the United States (Renwick and others, 2005).

In the 20th Century, land-use changes associated with urbanization led to increased erosion and sediment yields (Wolman and Schick, 1967; Wark and Keller, 1963). Urbanization and development can more than double the natural background sediment yield in the development stages (Langland and others, 2003). Wark and Keller (1963) reported that suspended-sediment yields in streams undergoing urbanization are 10 to 50 times greater than those in rural areas. Comparison of mean annual sediment yields from watersheds draining the Maryland suburbs of Washington, D.C. (Rock Creek, Northwest Branch of the Anacostia River, and the Northeast Branch of the Anacostia), which were undergoing urbanization in 1960–62, showed a two-fold to six-fold decrease in mean annual sediment yields 20 years later, from 1979–81 (Hickman, 1987). The decrease was thought to be due to implementation of erosion-control practices and construction of small reservoirs (Hickman, 1987).

Two urbanized watersheds outside of Washington, D.C., the Northeast Branch of the Anacostia River at Riverdale, Maryland, and the Northwest Branch of the Anacostia River, near Hyattsville, Maryland, had sediment yields that ranged from 131 to 248 $Mg/km^2/yr$ (megagrams per square kilometer per year) during 2004–05 (depending on which sediment computation model was used) (Miller and others, 2007). These sediment yields for the Anacostia River are the second highest compared to sediment yields compiled for the Chesapeake Bay watershed from 1985 through 2001 (Gellis and others, 2003). In urbanized areas, after land development is completed, upland erosion rates are lower; however, sediment yield from urbanized areas can remain high because of increased stream corridor (bed and bank) erosion due to altered hydrology such as an increase in peak flows. Analysis of sediment sources for eight storms in the Anacostia River Watershed between October 2005 and June 2006 showed, on average, that the channel banks (58 percent) were the most important source of sediment, followed by uplands (30 percent), and street residue (13 percent) (Devereux, 2006). If sediment yields from the Anacostia River are representative of other urban areas in the Chesapeake Bay Watershed, then even after land clearance and construction activities cease, sediment transport remains high in urban areas. In urban areas, most erosion-control practices are designed to reduce sediment from construction sites rather than from streambank erosion. (Barrett and others, 1995; Harbor, 1999).

Although land-use change has been documented on the decadal scale for the Chesapeake Bay region (Wolman, 1967), Smith and others (2003) noted the lack of integrated studies documenting shorter-term (seasonal to annual) impacts of land-use change and best-management practices (crop cover, rotation, and tillage) on the sediment budgets of watersheds at spatial scales smaller than the Chesapeake Bay (at the tributary and subwatershed scales). Upland sediment sources related to land use, such as cropland and construction, may change over time and seasons. On the basis of field observations, Lecce and others (2006a) documented that conditions are most favorable for soil erosion in a small Coastal Plain watershed in North Carolina between the fall harvest of crops and the early spring plowing season, just after snowmelt.

Suspended-Sediment Concentrations and Yields for the Chesapeake Bay Watershed

Gellis and others (2005) analyzed annual suspended-sediment loads (Mg/yr), sediment yields (Mg/km^2/yr), discharge-weighted sediment concentrations (mg/L, milligrams per liter), and instantaneous suspended-sediment concentrations (mg/L) for 65 USGS sediment stations operating in the Chesapeake Bay Watershed for two periods, 1952–1984 and 1985–2001. Examination of average annual sediment yields for the period 1952–84 showed that the three highest sediment yields were for streams draining the suburban Washington, D.C. area (Snakeden Branch at Reston, Virginia, 399 Mg/km^2/yr; Smilax Branch at Reston, Virginia, 346 Mg/km^2/yr; and Northwest Branch Anacostia River near Colesville, Maryland, 246 Mg/km^2/yr) (fig. 3a). The high sediment yields for streams draining the metropolitan Washington, D.C. area may reflect urbanization and construction practices that were occurring in these watersheds when the stations were operating (1963–78) (Wolman and Schick, 1967; Wark and Keller, 1963). Normalizing annual suspended-sediment load by annual runoff to produce an average annual discharge-weighted sediment concentration for the period 1952–84 showed similar results to the average annual sediment yields. The similarity in results is likely due to the fact that runoff is highly correlated to drainage area.

For sediment stations operating from 1985–2001, the Conestoga River Watershed, a tributary to the Susquehanna River, had four of the six highest average annual sediment yields (Little Conestoga Creek near Churchtown, Pennsylvania, 368 Mg/km^2/yr; Little Conestoga Creek site 3A, near Morgantown, Pennsylvania, 116 Mg/km^2/yr; Mill Creek at Eshelman Mill Road near Lyndon, Pennsylvania, 112 Mg/km^2/yr; and Conestoga River at Conestoga, Pennsylvania, 60.9 Mg/km^2/yr)(Gellis and others, 2005) (fig. 3b). The Conestoga River Watershed drains primarily agricultural areas, but other sources of sediment, such as from bank erosion, also may be important in the Conestoga River Watershed (Walter and Merritts, 2008). The Rappahannock River near Fredericksburg, Virginia, had the third highest average annual sediment yield (116 Mg/km^2/yr), and Raystown Branch Juniata River at Saxton, Pennsylvania, a tributary of the Susquehanna River, had the fifth highest average annual sediment yield (90.7 Mg/km^2/yr).

Percentiles (10th, 50th, and 90th) of instantaneous suspended-sediment concentration (mg/L) analyzed at 51 stations, with at least 3 years of data in the period 1985 through 2001, and at least 10 samples in a given year, were examined for the Chesapeake Bay Watershed (Gellis and others, 2005). The 10th percentile of suspended-sediment concentration may reflect low flows, the 50th percentile may reflect intermediate flows, and the 90th percentile may reflect high flows. Streams draining the Susquehanna River Watershed had high suspended-sediment concentrations in each of the percentile categories (10th, 50th, and 90th), (Codorus Creek at Pleasureville; Conestoga River at Conestoga; Little Conestoga Creek near Churchtown; and Pequea Creek at Martic Forge). The lowest suspended-sediment concentration at the 10th, 50th, and 90th percentiles was at Bobs Creek near Pavia, Pennsylvania, in the Susquehanna River Watershed, which drains close to 100 percent forested land (Langland and others, 1995).

Using the data from Gellis and others (2005) for 65 stations operating from 1952 to 2001, sediment yields were determined for five physiographic regions (Coastal Plain, Valley and Ridge, Piedmont, Blue Ridge, and Appalachian Plateau) in the Chesapeake Bay Watershed. The area that each of the 65 stations drains in each physiographic province was delineated using a GIS (Geographic Information System). Watersheds that drained more than one physiographic province were assigned to the province that drained the most area. The average annual suspended-sediment yield for watersheds draining each province was averaged, and results showed that watersheds with a majority of their contributing area designated as Piedmont (n = 21) had the highest average annual suspended-sediment yield (103.7 Mg/km^2/yr) (table 1). Watersheds that have a majority of their contributing areas draining the Coastal Plain (n = 4) have the lowest average annual suspended-sediment yield (11.9 Mg/km^2/yr) (table 1). In an examination of sediment characteristics in North Carolina streams, Simmons (1988) also noted that streams draining the Piedmont had the highest sediment concentrations and yields, and those draining the Coastal Plain had the lowest. Wark and Keller (1963) showed that in the Potomac River Watershed, streams draining the Piedmont and the Great Valley had the finest median suspended-sediment particle sizes in coarse clays to fine silts (0.004 to 0.015 mm) and very fine silts to fine silts (0.0025 to 0.011 mm), respectively.

Flood-Plain Process Studies

Riparian zones in the Chesapeake Bay Watershed are widest along the many low-gradient rivers originating on or flowing across the Coastal Plain Physiographic Province. Two types of rivers occur on the Coastal Plain—alluvial rivers that originate above the Fall Line and blackwater rivers that originate on the Coastal Plain (Hupp, 2000). The term “blackwater rivers” is given to rivers with dark colored water

Table 1. Average annual sediment yields by physiographic province for 65 stations draining the Chesapeake Bay Watershed, 1952–2001.

[Mg/km^2/yr, megagram per square kilometer per year]

Physiographic province	Sediment yield (Mg/km^2/yr)	Number of stations used in the analysis
Appalachian Plateau	58.8	19
Blue Ridge	56.8	2
Valley and Ridge	66.3	19
Piedmont	103.7	21
Coastal Plain	11.9	4

that drain the Coastal Plain. Blackwater rivers are highly organic and contain high amounts of tannin, which gives the river its black color. This type of river has a strong effect on the nature and quantity of the suspended sediment in transport. Alluvial streams that originate above the Fall Line tend to drain a greater area and have higher suspended-sediment loads, typically with a considerable mineral fraction, than rivers that originate on the Coastal Plain. These larger alluvial rivers contribute a significant amount of the particulates and nutrients to the Chesapeake Bay (Langland and others, 2000). Coastal Plain rivers also have a higher frequency of overbank flows, a flatter hydrograph, and longer periods of flood-plain inundation than rivers that originate above the Fall Line. Blackwater rivers are smaller, poorly drained, and have less developed flood plains. Suspended sediments, often with high organic content, are fine-grained (silt to clay-sized). Alluvial rivers construct their flood plains by lateral accretion. Vertical accretion, the accumulation of overbank fines without appreciable lateral channel migration, is the primary process by which lowland flood plains develop, such as Coastal Plain flood plains (Middlekoop and Van Der Perk, 1998; Nanson and Croke, 1992). Coastal Plain flood-plain sediment deposition occurs from two distinct sources: (1) runoff from adjacent uplands (riparian buffer), and (2) streamflow during inundation of bottomlands (riparian retention) (Hupp, 2000).

With minimal erosion caused by lateral migration and little remobilization and export of flood-plain sediments, Leopold and others (1964), Jacobson and Coleman (1986), and Ross and others (2004) verified that riparian retention of sediment in Coastal Plain flood plains is a common and important fluvial process. However, the retention time of sediment may be the most poorly understood, generally unquantified aspect of sediment budgets (Wolman, 1977; R.B. Jacobson, U.S. Geological Survey, written commun., 2004). In a Bottomland Hardwoods sediment retention study, Kleiss (1996) reported that the Cache River, Arkansas transports more than 90 percent of its total annual sediment load during the high-flow period and that more than 14 percent (about 800 $g/m^2/yr$, or grams per square meter per year) of the load is trapped along a 2–3-km-wide, 49-km-long river reach.

Flood-plain deposits of fine-grained sediment typically contain large concentrations of adsorbed contaminants, particularly nutrients (Noe and Hupp, 2005), trace elements, and hydrophobic pesticides from agriculture and urban areas (Johnston and others, 1984; White and Tittlebaum, 1985; Phillips, 1989a, Puckett and others, 1993; Dawson and Macklin, 1998; Liu and others, 2003). This sediment- and contaminant-trapping function of forested flood plains is commonly acknowledged (Kadlec and Kadlec, 1979; Phillips, 1989b; Brinson, 1993; Hupp and others, 1993; Lowrance and others, 1995; Brinson and others,1995; Kleiss, 1996), and in Coastal Plain fluvial systems is especially important because these flood-plain surfaces are the last sites for sediment storage (and biogeochemical cycling) before sediment enters estuaries and their critical nurseries for marine-biological production.

Previous flood-plain deposition studies within the Chesapeake Bay region are consistent with other findings and indicate that flood plains in the Coastal Plain play an important role in trapping sediment and associated contaminants. The lower reaches of the Chickahominy River, Virginia may trap as much as 70,000 kg of sediment per year along a 2-km reach (Hupp and others, 1993). In nutrient retention studies by Noe and Hupp (2005) along Coastal Plain reaches of Chesapeake Bay tributaries, the greatest carbon (C), nitrogen (N), and phosphorus (P) accumulation rates were observed on Chickahominy River flood plains downstream from the growing metropolitan area of Richmond, Virginia.

Channelized or straightened reaches (circa 1946) along the blackwater Pocomoke River, Maryland, trap about 38,000 kg/km/yr (kilograms per kilometer per year) of sediment, whereas unchannelized reaches store up to 860,000 kg/km/yr. Nutrient accumulation rates also were lowest on channelized reaches of the Pocomoke River. Sediment P concentrations and P accumulation rates were much greater on the hydraulically connected flood plain immediately downstream of the limit of channelization. Channelization has disconnected the flood plain from the majority of the Pocomoke River, thus limiting the sediment-trapping efficiency between river channels and flood plains.

Methods of Investigation

The watershed processes that contribute sediment to Chesapeake Bay are highly variable spatially and temporally. A variety of analytical methods were used to measure sediment production, transport, and deposition at spatial scales ranging from flood plains (in tens of square meters), to the entire Chesapeake Bay Watershed, and temporal scales ranging from individual storm events to a 100,000-year time scale. Methods are outlined for each of the major parts of this study.

Erosion Rates Using Beryllium-10

As noted in previous studies, contemporary erosion rates are often affected by land use and sediment storage. To evaluate the impact of increased sediment loads on stream processes and ecosystems, it is important to evaluate contemporary rates in the context of spatial and temporal scale variations that predate land-use disturbances. There are several new approaches to comparing contemporary sediment load and sediment-yield measurements to the geologic and geomorphic background in drainage basins (Bierman and others, 2005; Gellis and others, 2004). Two production pathways of the radionuclide ^{10}Be have been used to estimate rates of erosion in parts of the Chesapeake Bay watershed at the geologic scale using *in situ* ^{10}Be (thousands of years) (Reuter, 2005), and at the historical time scale of accelerated soil erosion, using meteoric ^{10}Be (Brown and others, 1988).

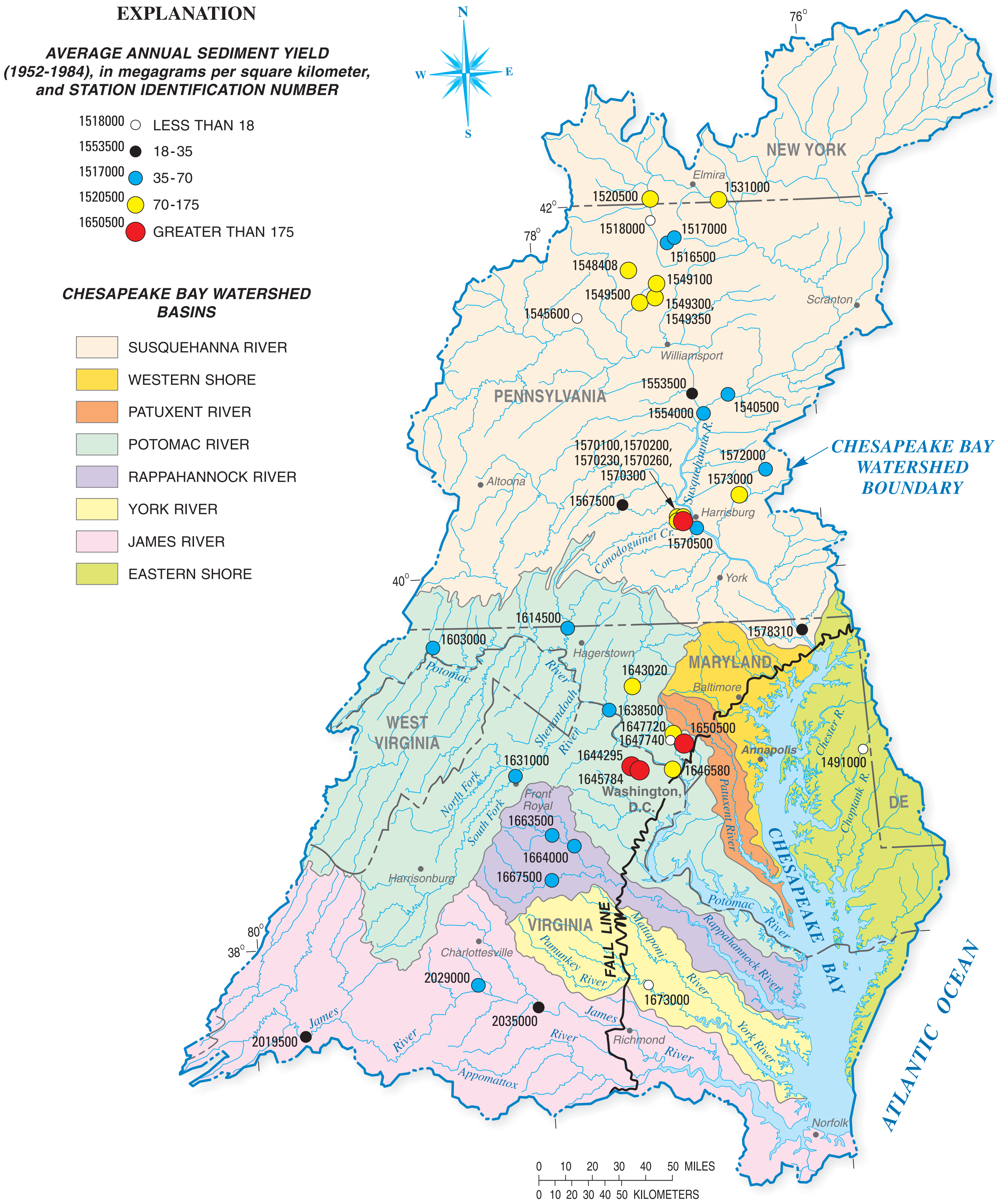

Figure 3a. Average annual sediment yield from 1952 through 1984 for 43 U.S. Geological Survey sediment stations in the Chesapeake Bay Watershed (modified from Gellis and others, 2005).

USGS Station Identification Number	Station Name
01491000	Choptank River near Greensboro, MD
01516500	Corey Creek near Mainesburg, PA
01517000	Elk Run near Mainesburg, PA
01518000	Tioga River at Tioga, PA
01520500	Tioga River at Lindley, NY
01531000	Chemung River at Chemung, NY
01540500	Susquehanna River at Danville, PA
01545600	Young Womans Creek near Renovo, PA
01548408	Wilson Creek above Sand Run near Antrim, PA
01549100	Blockhouse Creek Tributary at Liberty, PA
01549300	Blockhouse Creek at Buttonwood, PA
01549350	Steam Valley Run at Buttonwood, PA
01549500	Blockhouse Creek near English Center, PA
01553500	West Branch Susquehanna River at Lewisburg, PA
01554000	Susquehanna River at Sunbury, PA
01567500	Bixler Run near Loysville, PA
01570100	Conodoguinet Creek Tributary No. 1 near Enola, PA
01570200	Conodoguinet Creek Tributary No. 2 near Enola, PA
01570230	Conodoguinet Creek Tributary No. 2A near Enola, PA
01570260	Conodoguinet Creek Tributary No. 2B near Enola, PA
01570300	Conodoguinet Creek Tributary No. 3 near Enola, PA
01570500	Susquehanna River at Harrisburg, PA
01572000	Lower Little Swatara Creek at Pine Grove, PA
01573000	Swatara Creek at Harper Tavern, PA
01578310	Susquehanna River at Conowingo, MD
01603000	North Branch Potomac River near Cumberland, MD
01614500	Conococheague Creek at Fairview, MD
01631000	South Fork Shenandoah River at Front Royal, VA
01638500	Potomac River at Point of Rocks, MD
01643020	Monocacy River at Reichs Ford Bridge near Frederick, MD
01644295	Smilax Branch at Reston, VA
01645784	Snakeden Branch at Reston, VA
01646580	Potomac River at Chain Bridge at Washington, DC
01647720	North Branch Rock Creek near Norbeck, MD
01647740	North Branch Rock Creek near Rockville, MD
01650500	Northwest Branch Anacostia River near Colesville, MD
01663500	Hazel River at Rixeyville, VA
01664000	Rappahannock River at Remington, VA
01667500	Rapidan River near Culpeper, VA
01673000	Pamunkey River near Hanover, VA
02019500	James River at Buchanan, VA
02029000	James River at Scottsville, VA
02035000	James River at Cartersville, VA

Figure 3a. Average annual sediment yield from 1952 through 1984 for 43 U.S. Geological Survey sediment stations in the Chesapeake Bay Watershed (modified from Gellis and others, 2005).—Continued

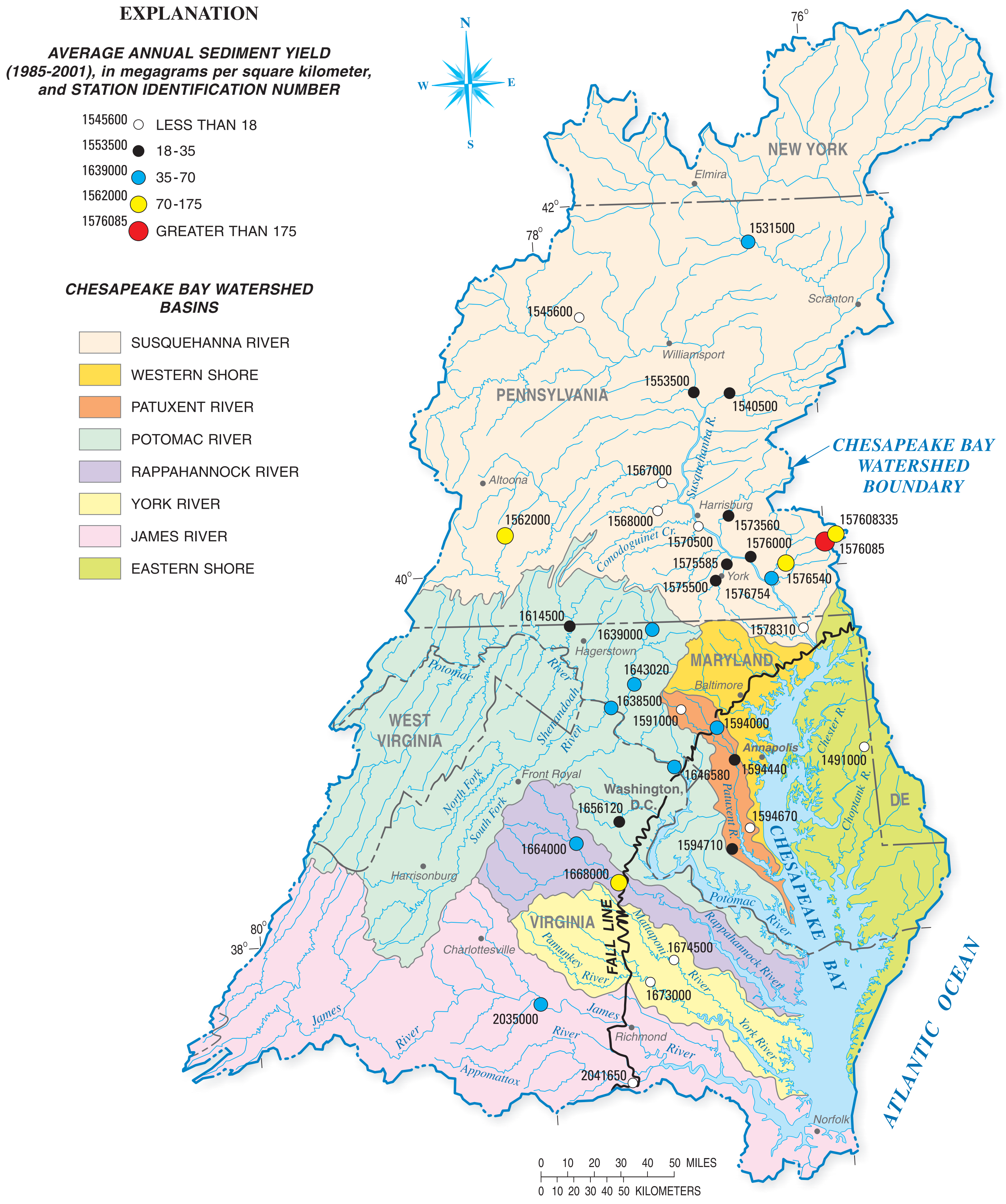

Figure 3b. Average annual sediment yield from 1985 through 2001 for 35 U.S. Geological Survey sediment stations in the Chesapeake Bay Watershed (modified from Gellis and others, 2005).

USGS Station Identification Number	Station Name
01491000	Choptank River near Greensboro, MD
01531500	Susquehanna River at Towanda, PA
01540500	Susquehanna River at Danville, PA
01545600	Young Womans Creek near Renovo, PA
01553500	West Branch Susquehanna River at Lewisburg, PA
01562000	Raystown Branch Juniata River at Saxton, PA
01567000	Juniata River at Newport, PA
01568000	Sherman Creek at Shermans Dale, PA
01570500	Susquehanna River at Harrisburg, PA
01573560	Swatara Creek near Hershey, PA
01575500	Codorus Creek near York, PA
01575585	Codorus Creek at Pleasureville, PA
01576000	Susquehanna River at Marietta, PA
01576085	Little Conestoga Creek near Churchtown, PA
01576540	Mill Creek at Eshelman Mill Road near Lyndon, PA
01576754	Conestoga River at Conestoga, PA
01578310	Susquehanna River at Conowingo, MD
01591000	Patuxent River near Unity, MD
01594000	Little Patuxent River at Savage, MD
01594440	Patuxent River near Bowie, MD
01594670	Hunting Creek near Huntingtown, MD
01594710	Killpeck Creek at Huntersville, MD
01614500	Conococheague Creek at Fairview, MD
01638500	Potomac River at Point of Rocks, MD
01639000	Monocacy River at Bridgeport, MD
01643020	Monocacy River at Reichs Ford Bridge near Frederick, MD
01646580	Potomac River at Chain Bridge at Washington, DC
01656120	Cedar Run at Route 646 near Aden, VA
01664000	Rappahannock River at Remington, VA
01668000	Rappahannock River near Fredericksburg, VA
01673000	Pamunkey River near Hanover, VA
01674500	Mattaponi River near Beulahville, VA
02035000	James River at Cartersville, VA
02041650	Appomattox River at Matoaca, VA
0157608335	Little Conestoga Creek Site 3A near Morgantown, PA

Figure 3b. Average annual sediment yield from 1985 through 2001 for 35 U.S. Geological Survey sediment stations in the Chesapeake Bay Watershed (modified from Gellis and others, 2005).—Continued

Reuter (2005) measured *in situ* ^{10}Be in quartz-rich alluvium from watersheds in all of the bedrock provinces of the Susquehanna Watershed (fig. 4). *In-situ* ^{10}Be is produced in quartz near Earth's surface by cosmic-ray bombardment (Lal and Peters, 1967). In an eroding landscape, grains of quartz function as dosimeters, carrying isotopic inventories that reflect the idiosyncratic near-surface exposure histories of each grain (Bierman and Steig, 1996). Rivers collect, transport, and mix grains from various parts of the watershed. The abundance of cosmogenic isotopes in stream sediments primarily reflects the cosmic-ray dosing of rock and soil on slopes and, to varying degrees, dosing during intermittent storage as material is carried downstream (Bierman and Steig, 1996). The concentration of ^{10}Be in river sediment reflects the integrated erosional history of the watershed over both space and time. The inference of erosion rates relies on a number of assumptions—that the watershed is in isotopic steady state, that quartz distribution in the watershed is uniform, that there is minimal long-term storage of sediment, that sediment from the watershed is well mixed, that mass loss occurs by surface lowering, and that erosion rates are temporally constant (Brown and others, 1995; Bierman and Steig, 1996; Granger and others, 1996).

About half of ^{10}Be production occurs within the upper 50 to 100 cm (centimeters) of Earth's surface. Mixing of sediment near the surface homogenizes the ^{10}Be profile. As a result, the method has a relatively low sensitivity to erosion caused by human disturbance or natural episodic change (Bierman and Steig, 1996; Phillips and others, 1998; Heimsath and others, 2002), though gullying and deep erosion can impact ^{10}Be results (von Blanckenburg and others, 2004). The time scale over which cosmogenic analysis is applicable relates to the residence time of material in the near surface where most of the nuclide production takes place. The ^{10}Be-inferred erosion rates are thus averages over time scales long enough to incorporate infrequent geomorphic events. For the Susquehanna River Watershed, the period of integration is between 10,000 and 100,000 years.

Since ^{10}Be erosion rates are integrated over many millennia, these rates provide a relatively long-term background

Site Number	Location
SQ1	Codorus Creek near York, PA
SQ2	West Conewago Creek near Manchester, PA
SQ3	Yellow Breeches Creek near Camp Hill, PA
SQ4	Susquehanna River at Harrisburg, PA
SQ5	Sherman Creek at Shermans Dale, PA
SQ6	Bixler Run near Loysville, PA
SQ7	Juniata River at Newport, PA
SQ9	Spring Creek near Axemann, PA
SQ10	Bald Eagle Creek below Spring Creek at Milesburg, PA
SQ11	West Branch Susquehanna River at Bower, PA
SQ12	Raystown Branch Juniata River at Saxton, PA
SQ13	Dunning Creek at Belden, PA
SQ14	Swatara Creek at Harper Tavern, PA
SQ15	Conestoga River at Conestoga, PA
SQ16	Mill Creek at Eshelman Mill Road near Lyndon, PA
SQ17	Little Conestoga Creek near Churchtown, PA
SQ18	Pequea Creek at Martic Forge, PA
SQ19	Susquehanna River at Danville, PA
SQ20	West Branch Susquehanna River at Lewisburg, PA
SQ29	Chemung River at Chemung, NY
SQ30	Tioga River at Lindley, NY
SQ31	Tioga River at Tioga, PA
SQ32	Corey Creek near Mainesburg, PA
SQ33	Elk Run near Mainesburg, PA
SQ34	Susquehanna River at Towanda, PA
SQ35	Tunkhannock Creek near Tunkhannock, PA

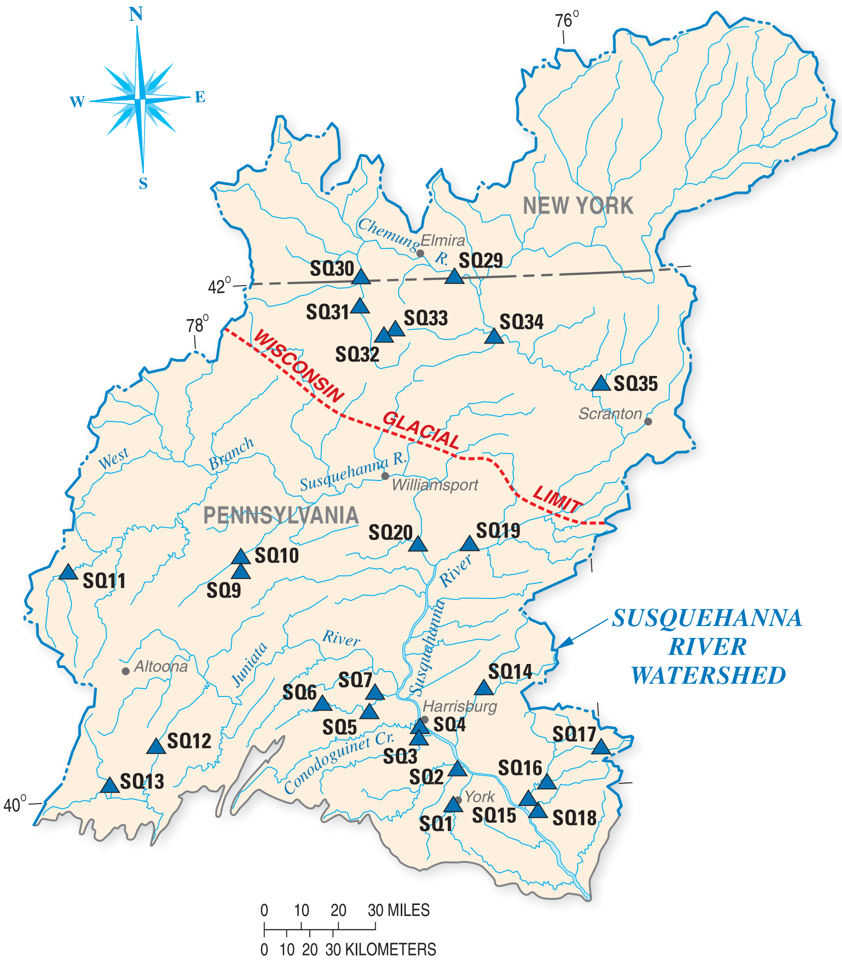

Figure 4. Location of sampling sites at U.S. Geological Survey sediment-gaged stations in the Susquehanna River Watershed for *in situ* beryllium-10 and meteoric beryllium-10.

value with which to compare contemporary sediment yields, such as those determined by suspended-sediment analysis or reservoir filling (Kirchner and others, 2001). Current-day sediment yields have been found to exceed (Clapp and others, 2000; Hewawasam and others, 2003; Gellis and others, 2004; von Blanckenburg and others, 2004), match (Gellis and others, 2004; Matmon and others, 2003), and fall below (Kirchner and others, 2001) the rates of sediment generation inferred from ^{10}Be. In some cases, authors have suggested that the discrepancy results from human impact (Gellis and others, 2004); in other cases, natural variability, including extreme hydrologic events, has been cited as driving the disequilibrium between long-term rates of sediment generation and short-term rates of sediment yield.

In situ ^{10}Be was collected in flood-plain alluvial sediments at USGS sediment stations (fig. 4) and ungaged sites in the Susquehanna River Watershed. An ungaged site refers to a site without a USGS sediment station. These collection sites were distributed across the physiographic and ecoregion subdivisions to provide a representative sampling. In the Appalachian Plateau, collection sites are from both residual and glaciated landscapes. One group of samples came from USGS sediment stations that were chosen based on availability of USGS sediment-yield data (Gellis and others, 2005). A second group of samples came from sites selected with GIS to represent watersheds with a range of lithologies and slopes in each of the major physiographic provinces (Reuter, 2005). All GIS-delineated watersheds that were sampled are south of the glacial margin, range from 0.6 to 25 km^2 in area (the mean ± 1σ is 4.5 ± 3.5 km^2), and are spread among three major physiographic provinces. Each watershed is mapped with a single dominant lithology (Pennsylvania Bureau of Topographic and Geologic Survey, 2001), and the watersheds span a range of mean watershed slopes from 2° to 22°. Reuter (2005) measured the ^{10}Be concentration of 59 fluvial sediment samples (including 3 nested watershed pairs), as well as 4 bedrock samples. Samples were prepared according to standard procedures (Bierman and Caffee, 2001), and ^{10}Be was measured at Lawrence Livermore National Laboratory (LLNL). Erosion rates were calculated using production rates corrected for latitude and altitude considering neutrons only (Lal, 1991), with production factors from pixel-by-pixel calculations.

Another form of ^{10}Be, meteoric ^{10}Be, is produced by cosmic ray spallation in the atmosphere. Along with carbon-14 (^{14}C) and other cosmogenic isotopes, ^{10}Be is well-mixed and has a short residence time in the atmosphere. Unlike the ^{14}C that cycles through a closed organic pathway (represented by the closed system decay of ^{14}C used to date buried organic material), meteoric ^{10}Be follows an inorganic pathway to soils from the atmosphere via rainfall. During slow, background watershed erosion, soil profiles develop on underlying rocks and sediments. In humid climates, clay-rich soil profiles accumulate atmospheric ^{10}Be delivered by rainfall in the soil B-horizon (Pavich and others, 1984). Profile distributions, such as those measured in greater than 100,000-year-old soils near Chesapeake Bay exhibit peak concentrations (atom/g, atom/gram) in clay-rich B-horizons. ^{10}Be is adsorbed and tightly bound at near-neutral pH in soil-exchange complexes. Unless disturbed by erosion, inventories of ^{10}Be (atom/cm^2, atoms per square centimeter) increase through time in clay-rich soils (Pavich and others, 1984; Pavich and Vidic, 1993).

Brown and others (1988) used meteoric ^{10}Be to estimate the spatial variability of soil erosion in 48 watersheds of the eastern United States, including 10 watersheds that drain to the Chesapeake Bay. Interpretations of watershed-wide soil erosion were based on an erosion index defined as the ratio of the annual amount of ^{10}Be leaving a watershed attached to sediment to the annual amount of ^{10}Be deposited over the watershed area. The highest erosion indices were observed in the Piedmont streams, and the lowest rates were observed in Coastal Plain streams (Brown and others, 1988).

The amount of meteoric ^{10}Be leaving a watershed is based on collection of flood-plain sediment where the flood-plain sediment is assumed to represent sediment transported out of the watershed. Meteoric ^{10}Be concentrations (atom/g) were measured in sediments from active flood plains (fig. 4). Small (1m^2 (square meter) x 0.5m deep) trenches were dug, and a roughly 1-kg aliquot was taken from thoroughly mixed sediment removed from the trenches. The analyses were based on the extraction technique of S. Zheng (University of California at Irvine, written commun., 1998). Aliquots (approximately 10 mg) of the less than 2-mm fraction of sediment samples were ground to a fine powder, dried, weighed and spiked with 1-mg ^{9}Be carrier. Samples were dissolved in HF/HClO$_4$ (hydrofluoric acid/perchloric acid). The dried residue was dissolved in 3N (normal) HCl (hydrochloric acid) and Fe (iron), Be (beryllium), and Al (aluminum) precipitated as hydroxides. Be was separated from Al and Fe by complexing with HF; Al and Fe hydroxides precipitate while Be-fluoride remains in solution during titration with ammonium hydroxide. The supernate is decanted and Be is precipitated as an hydroxide, then heated to produce BeO (beryllium oxide). The BeO powder is mixed with silver powder as a binding agent and pressed into sample holders for Accelerator Mass Spectrometer (AMS) analysis of ^{10}Be/^{9}Be ratios. AMS was performed at the Lawrence Livermore National Laboratory-Center for Accelerator Mass Spectrometry (LLNL-CAMS).

Satellite Imagery of Bare Ground in the Little Conestoga Creek Watershed

Agriculture can be an important source of sediment, which can have seasonal variations due to plowing, germination, and harvesting. To determine the seasonal variation in bare ground related to agriculture, the Little Conestoga Creek Watershed, defined at its confluence with the Conestoga River (170 km^2), with 54 percent agriculture in 2001 (40 percent in pasture and 14 percent in cultivated crops) was selected for this analysis. Multi-temporal analysis of cloud-free and nearly cloud-free Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER-Yamaguchi and others, 1998) imagery spanning a 5-year period (April 9, 2000–September 30, 2005) was used to derive maps showing typical seasonal distribution of vegetative cover in agricultural areas over the Little Conestoga Creek Watershed. ASTER measures reflected radiation in three bands between 0.520 and 0.860 µm (micrometers) (visible-near-infrared region-VNIR) at 15-m spatial resolution compared to 30-m spatial resolution of Landsat. ASTER has off-nadir pointing capability, which gives it a repeat coverage (temporal resolution) of 4–16 days. For orbiting satellites, nadir defines the zero angle position of the Earth's surface parallel to (or more precisely, along) its orbital path. In other words, it is the ground directly below the satellite, which is defined by the center of each scan line along an image. "Off-nadir" pixels are away from the center along each scan-line of data. It is also used to refer to the pointing angle of a satellite instrument, when it is not pointing to the ground directly below it along its orbital path. Unlike Landsat, however, which is continually operational and has an 185-km swath-width, ASTER has an 8-percent tasking duty cycle and a 60-km swath-width (Yamaguchi and others, 1998); this is still sufficient for covering the entire Little Conestoga Creek Watershed within a single orbital pass.

Deriving land use and other important information from multispectral remote sensing data that cover mixed land-use watersheds, such as those in the Little Conestoga Creek, is complicated because traditional classification methods cannot effectively handle the mixed-pixel problem in urbanizing landscapes (Madhavan and others, 2001; Wu and Murray, 2003; Lu and Weng, 2006). The conceptual vegetation-impervious surface-soil (V-I-S) model developed by Ridd (1995), which assumes that land cover in urban environments can best be described as linear combinations of three major components, namely vegetation, impervious surfaces (such as roads, parking lots, roof tops) (Arnold and Gibbons, 1996), and soil, was used to determine land use.

Due to difficulty in deriving impervious surface estimates from Landsat and ASTER imagery alone (Madhavan and others, 2001; Wu and Murray, 2003; Lu and Weng, 2006), the percent impervious cover were derived from the most recent National Land Cover Dataset (NLCD; Homer and others, 2004). The NLCD impervious data were derived from 30-m spatial resolution Landsat-7 ETM+ imagery using a regression-tree classification algorithm and training sites based on high spatial resolution imagery sources and scanned aerial orthophotos (Yang and others, 2003). A similar method was used to derive percent canopy coverage using Landsat-7 ETM+ imagery acquired during both "leaf on" and "leaf off" periods (Huang and others, 2001).

Vegetation interpreted from satellite imagery is expressed as standard normalized difference vegetation index (NDVI) values. NDVI values were calculated using the following two ASTER bands as follows:

$$\text{NDVI} = \frac{(\text{ASTER band 3 - ASTER band 2})}{(\text{ASTER band 3 + ASTER band 2})} \qquad (1)$$

Several studies have derived the following relation between scaled NDVI (N) and fractional vegetation cover (Fr) using independent methods:

$$\text{Fr} = \text{N}^2, \text{ where N} = \frac{(\text{NDVI} - \text{NDVI}_o)}{(\text{NDVI}_s - \text{NDVI}_o)} \qquad (2)$$

where the subscripts "s" and "o" denote NDVI values for dense vegetation and bare soil, respectively (Carlson and Arthur, 2000).

Cyr and others (1995) evaluated the utility of several NDVI, NDVI-based and (or) soil-adjusted indices for measuring ground-cover proportions throughout the spring planting to fall harvest season, as compared to ground-truth measurements. They found the best correlations between actual and predicted ground cover throughout the year for corn when using various indices. For other crops such as soy, pasture, and grains, the correlations varied depending on the time of year, with better correlation between actual and predicted cover occurring before the height of the summer growing period for some crops (such as soy) and well after harvest for other crops (such as cereal grains), when senescent vegetation and crop residues begin to decompose and lose their effectiveness in soil-erosion control. Decomposition time varies with crop residue type and other environmental factors (Schomberg and Steiner, 1997), so that some residues tend to decompose rapidly (for example alfalfa, with approximately 36 percent mass loss within first month), whereas others tend to decompose more slowly (such as corn, with less than 16 percent mass loss within first month).

Despite limitations and difficulties in separating senescent vegetation from bare ground, Cyr and others (1995) found that remote-sensing-derived ground cover is still accurate enough for use in assessing ground-cover factors contributing to soil erosion, especially when multi-date imagery are used instead of single scenes, and when other factors such as rainfall and flow intensity are considered as they were in this study. Other researchers have questioned the effectiveness of crop-residue cover in controlling soil erosion altogether without the aid of riparian buffer vegetation, especially over fields in more sloping areas (Kemper and others, 1992). Although it is beyond the scope of this report to assess the role and limitations of senescent vegetation and crop residue in controlling erosion in the Little Conestoga Watershed, future studies may be able to address this issue.

For the NLCD land-use classes, an impervious-cover threshold of greater than 10 percent (Jantz and others, 2005) was used to mask non-agricultural (including low-intensity residential) areas for which the total vegetation-soil fractions remained the most constant between successive imagery. The non-agricultural areas also included areas with a percent canopy threshold greater than 20 percent, which generally corresponds to the distribution of the forest land-use class. Interpretations of bare ground for selected satellite images are expressed as percentages at thresholds of 25 percent and 33 percent, developed by Morgan (2005). Morgan showed soil loss ratio compared to percent vegetation cover plots (fig. 5) for various soil types. Both thresholds lie within the asymptote of these curves, where soil loss increases exponentially with decreasing cover (fig. 5), though the actual chosen values are merely arbitrary representations of 1/4 and 1/3 crop cover, respectively, for each agriculture class pixel.

The use of impervious surface and canopy estimates from a single static period of time will likely introduce a source of error in the estimates of seasonally changing vegetation-soil proportions. Imagery spanning the 1999–2001 period was used to derive impervious estimates for the entire Chesapeake Bay Watershed, for example (Yang and others, 2003). Previous studies, however, reported urban land-use change in 10-year periods between imagery at both the Chesapeake Bay Watershed scale (Jantz and others, 2005) and the Little Conestoga Creek Watershed scale (Hubbard and others, 2004) at around 2- to 5-percent and 1.8-percent-per-year increases, respectively, in impervious surface area. Therefore, +2 percent is a reasonable error estimate.

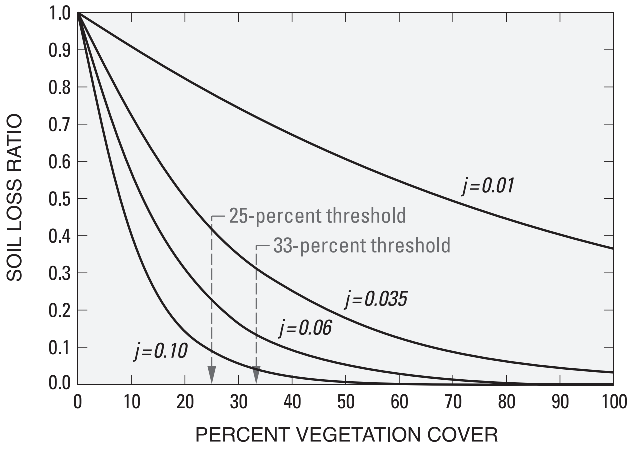

Figure 5. Relation between soil loss ratio (SLR) and percent vegetation cover (fallow or crop cover) (PC). [The curves represent different values of "j" satisfying the equation SLR = e-j(PC), for which "j" are constants derived for different crop and fallow grass types (Morgan, 2005, and references therein). Also shown are the vegetation cover thresholds used to derive seasonally varying bare ground cover. Note the locations of the 25- and 33-percent thresholds on the asymptote of the curves defining exponential soil loss (modified from Morgan, 2005).]

Sediment Source Analysis Using Sediment Fingerprints

Sources of fine-grained sediment for three watersheds draining to the Chesapeake Bay, the Pocomoke River, Mattawoman Creek, and Little Conestoga Creek were assessed using the sediment-fingerprinting approach (figs. 1a, b). The Pocomoke River sediment source analysis was conducted in the watershed draining to USGS streamflow-gaging station 01485000 (Pocomoke River near Willards, Maryland, drainage area 156.7 km^2). Mattawoman Creek sediment source analysis was conducted in the watershed draining above Old Woman Creek (134.5 km^2) at USGS streamflow-gaging station 01658000, Mattawoman Creek near Pomonkey, Maryland. The Little Conestoga Creek sediment source analysis was conducted in the watershed draining to USGS streamflow-gaging station 01576712 (Little Conestoga Creek near Millersville, Pennsylvania (drainage area 109.5 km^2).

Although several approaches to identify sediment sources exist, many approaches rely on visual estimates (Reid and Dunne, 1996), modeling (Foster, 1988), or long-term field-intensive measurements (Gellis and others, 2001; Gellis, Emmett, and Leopold, 2005). The sediment-fingerprinting approach provides a direct method for quantifying watershed sources of fine-grained suspended sediment (Collins and others, 1997; Motha and others, 2003; Walling, 2005; Gellis and Landwehr, 2006). This approach entails the identification of specific sources through the establishment of a minimal set of physical and (or) chemical properties, such as tracers that uniquely define each source in the watershed. Suspended sediment collected under different flow conditions exhibits a composite, or fingerprint, of these properties that allows them to be traced back to their respective sources. Tracers that have successfully been used as fingerprints include mineralogy (Motha and others, 2003), radionuclides (Walling and Woodward, 1992; Collins and others, 1997; Nagle and others, 2007; Whiting and others, 2005); trace elements (Devereux, 2006); magnetic properties (Slattery and others, 2000), and stable isotope ratios (^{15}N/^{14}N and ^{13}C/^{12}C) (Papanicolaou and others, 2003). Sources of watershed sediment include upland sources (such as agriculture, urban construction, and forest), and the channel corridor (beds, banks, ditches, and flood plains). Sampling sediment at these sources and linking the fingerprints to sediment in transport using a statistical mixing model enables quantification of the source(s).

Collection and Analysis of Fluvial Samples

Suspended-sediment samples used for source analysis in the Pocomoke River and Mattawoman Creek were collected during high flows by placing a submersible pump at mid-depth in the center of the channel and pumping the water into 83-L (liter) plastic containers. At the Pocomoke River, water was pumped during high flows from the State Highway 346 bridge located at the streamflow-gaging station near Willards, Maryland. At Mattawoman Creek, water was pumped during high flows from the State Highway 227 bridge located at the streamflow-gaging station near Pomonkey, Maryland. A tributary, Old Woman Creek, joins Mattawoman Creek just below the bridge on the left bank, upstream of the streamflow-gaging station. A sediment deposit (bar) underneath the bridge separates Mattawoman Creek from Old Woman Creek. At high flows, water inundates the bar and connects the two channels upstream of the bridge. Observations of the color of the water during high flows indicated that the two channels were not mixing. A requirement of sediment fingerprinting is that the sampled fluvial sediment is well-mixed. Since the cross section did not appear to be well-mixed, water was only pumped from the center channel of Mattawoman Creek. Water was not pumped from Old Woman Creek; therefore, the sediment-source analysis for this study included only the area draining to Mattawoman Creek upstream of Old Woman Creek. Old Woman Creek drains 14.9 km^2 or 10 percent of the watershed at the streamflow-gaging station (149.4 km^2). Therefore, the watershed analyzed for the sediment study of Mattawoman Creek was 134.5 km^2. USGS-published discharge records and suspended-sediment load estimates (Appendix A2) include the contribution from Old Woman Creek, however.

Water from both the Pocomoke River and Mattawoman Creek was brought back to the laboratory and centrifuged with a Penwalt continuous-flow centrifuge. The centrifuged sediment was dried at 60°C, sieved through a 63-micron sieve to remove sand, split, and sent for appropriate laboratory analysis (discussed later in the text).

Suspended-sediment samples used for source analysis in the Little Conestoga Creek near Millersville, Pennsylvania were collected during high flows using a manual suspended-sediment sampler (DH-59 rope sampler). The DH-59 rope sampler was used on the Millersville Road bridge immediately upstream of the USGS streamflow-gaging station, Little Conestoga Creek near Millersville, Pennsylvania. The DH-59 collects suspended sediment in 0.473-L (1 pint) glass bottles. Several equal-width-increment (EWI) transects were taken across the bridge to obtain the mass required for sediment analysis. When personnel could not reach the station to obtain a sediment sample, an automatic suspended-sediment pump sampler was used. The automatic suspended-sediment sampler is designed to pump the sample into as many as 24 separate 1-L plastic bottles. The pump sampler was pre-programmed to pump samples over the flood hydrograph. The intake for the pump sampler was located near the center of the channel about one-half a meter above the channel bed. All samples were sent to the USGS Kentucky Sediment Laboratory in Louisville, Kentucky for analysis of suspended-sediment concentration. The USGS Kentucky Sediment Lab quality assurance plan can be accessed at *http://ky.water.usgs.gov/technical_info/dist_sedlab_files/sed_lab.htm* (last accessed February 12, 2008).

The suspended-sediment samples were filtered onto Whatman #934-AH glass fiber filters that allow for 1.5-µm (micrometer) retention of suspended solids, and then oven-dried. The filter papers were then returned to the USGS in Baltimore, Maryland, where sediment was removed from the filter paper by scraping and washing, and then composited for each flood hydrograph in a steel bowl. The composited sample is considered a representative sample of the flow event. The sediment was dried at 60°C, dry-sieved through a 62.5-µm sieve (0.0625-mm) sieve to remove the sand, split, and sent for appropriate laboratory analysis for sediment fingerprints.

Collection and Analysis of Upland Samples

In each of the three study watersheds, sediment-source samples were collected from upland source areas and the channel corridor. Upland sources in the Pocomoke River Watershed were identified as cropland and forest. In Mattawoman Creek, upland sources of sediment were identified as cropland, construction sites, and forest. In Little Conestoga Creek, upland sources of sediment were identified as cropland and construction sites. Soil samples from cropland and forest were taken from the top 0.5 cm of the soil surface with a hand shovel. To account for variability in the fingerprint properties at cropland and forested sites, sediment was collected across transects and composited into one sample. Samples from construction sites were taken from housing pads, soil piles, and from sediment ponds (if present) using a hand shovel. Owners or operators of the construction sites were queried as to whether the soil piles were excavated from the site or brought in from elsewhere. At all construction sites, soil piles were native material from the site. At construction sites, housing pads, soil piles, and sediment ponds, samples were collected along transects similar in spacing to the cropland and forest samples, but the lengths of the transects were determined by the size of the construction site. Sediment ponds are erosion-control features that are designed to catch sediment draining from the construction site and thus represent a well-integrated sample of the construction site. Depending on the design and trap efficiency of each sediment pond, however, under high runoff conditions, flow and sediment may be transported out of the pond, and therefore not all sediment from every runoff event is deposited in equal amounts in the sediment pond.

Channel corridor sources in each of the three watersheds represented the banks of the main channel and tributaries. In the Pocomoke River, ditches extend over much of the watershed and because the ditches are deep, straight, and dredged periodically, they were also treated as a potential sediment source. Therefore, in the Pocomoke River Watershed, the potential sediment sources also included the beds and banks of the ditches. The bed of the main stem and tributaries in each watershed were not considered as sediment sources, since in the absence of significant channel incision, sediment mobilized from the channel bed is likely to reflect temporary storage of sediment originating from upstream sources, and is therefore not treated as a separate source (Desmond Walling, University of Exeter, written commun., 2004).

To obtain a representative sample of the channel and ditch banks, the banks were sampled from the bottom to the top of the bank face. Three to five transects spaced 10 m apart were sampled and composited into one sample. If banks were exposed on both sides of the channel, samples were taken on both sides of the river and composited into one sample.

Ditch-bed samples were taken when the ditches were dry or flow was minimal. To obtain a representative sample of the ditch bed, 10 to 20 samples spaced 5 m apart were sampled and composited into 1 sample. Sediment was sampled from the top 0.5 cm of the ditch bed.

Laboratory Analyses for Sediment Fingerprinting

Upland and channel corridor samples were taken back to the laboratory, dried at 60°C, disaggregated using a pestle and mortar, and dry-sieved through a 63-micron sieve to remove the sand. Sample weights before and after sieving were recorded to determine the percent sand in the upland and channel corridor sources. The silt and clay portion (less than 62.5 µm) of suspended sediment, upland, and channel corridor samples was sent for analysis of radionuclides cesium-137 (^{137}Cs) and unsupported lead-210 (^{210}Pb), stable isotopes delta carbon-13 (δ^{13}C) and delta nitrogen-15 (δ^{15}N), and percent of total C, N, and P. The ratio of C to N was used by Papanicolaou and others (2003) to identify sources of sediment in the Palouse Basin, Idaho and Washington. For this study, the ratio of C to N (C : N) was added as another sediment fingerprint.

^{137}Cs is an anthropogenic radionuclide with a 30-year half-life that was introduced into the environment as a result of worldwide, above-ground thermonuclear weapons testing during the 1950s through the 1970s (Ritchie and others, 1974; Ritchie and McCarty, 2003). Fallout peaked around 1963, and since the Nuclear Test Ban Treaty was signed in 1976, there has been negligible fallout of ^{137}Cs. The isotope was globally distributed through atmospheric fallout and is rapidly adsorbed by fine-soil particles on the ground surface. Once adsorbed, it is not easily detached from the soil and moves physically with soil particles that are carried by agents of water and wind. Unsupported ^{210}Pb is derived from radon-222, which diffuses as gas through the soil interstitial pore space into the atmosphere, where it decays to ^{210}Pb. The ^{210}Pb then attaches to aerosol particles and is washed out in rainfall events. The half-life of ^{210}Pb is 22.6 years.

The radionuclides (^{137}Cs and unsupported ^{210}Pb) were analyzed at four different laboratories: Case Western Reserve University in Cleveland, Ohio; U.S. Geological Survey Geologic Division Laboratory in Denver, Colorado; U.S. Geological Survey Geologic Division Laboratory in St. Petersburg, Florida; and the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS), Hydrology and Remote Sensing Laboratory, in Beltsville, Maryland. At the USDA-ARS facility, only ^{137}Cs was analyzed. At all laboratories, the soil samples were dried and sealed for radionuclide analyses. At all four laboratories, radionuclides were analyzed by gamma spectroscopy using either an EG&G Ortec or a Canberra HPGe photon detector and 8192 multi-channel analyzers. The system is calibrated and efficiency determined using an analytic mixed radionuclide standard (10 nuclides) whose calibration can be traced to U.S. National Institute of Standards and Technology. At Case Western Reserve University, an EG&G Ortec also was used. Radionuclide activity is expressed in becquerels per gram (Bq/g). The technique used for counting efficiencies can be found in Wilson and others (2003).

Errors reported in the laboratory analysis of radionuclides are counting errors related to the mass of the sample and the amount of activity. Counting errors of the radionuclides at Case Western Reserve University were computed as follows:

$$Error(Bq/g) = \substack{radionuclide\\activity}\left\{\frac{\left(\left[\frac{\substack{counting\\error}}{\substack{counting\\time}}\right]^2 + \left(\frac{\left(\substack{background\\counts} * \substack{background\\counting\ time}\right)^{1/2}}{\substack{counting\\time}}\right)^2\right)}{\left(\left[\frac{counts}{\substack{counting\\error}}\right] - \substack{background\\counts}\right)^2}\right\}^{1/2} \tag{3}$$

At the USGS St. Petersburg laboratory, the error term for unsupported ^{210}Pb is the counting error which is propagated from the standard error of the gross peak area. At the USGS St. Petersburg laboratory, the error term for ^{137}Cs is calculated by the gamma multi-channel analyzer software, and is calculated by propagating the error from the individual variances of the decay rate, initial activity, net count rate, source volume, and efficiency (Marci Marot, U.S. Geological Survey, written commun., 2006). At the USGS Denver laboratory the error in the unsupported ^{210}Pb data, given in detections per minute per gram (dpm/g), is ±0.2, and for ^{137}Cs (given in dpm/g) is ±0.1 (Jim Budahn, U.S. Geological Survey, written commun., 2005). At the USDA-ARS Laboratory, ^{137}Cs errors are ±4 to 6 percent (Ritchie and others, 2005).

The mass fraction of the sample that was composed by weight (*w*) of C, N, and P was analyzed at the University of Maryland's Chesapeake Biological Laboratory (CBL), Solomons Island, Maryland. Methods of analysis for the CBL laboratory are accessible at their website: *http://www.cbl.umces.edu/nasl/index.htm* (last accessed June 18, 2007).

Samples were analyzed for the ratios of the stable isotopes of C and N (^{13}C/^{12}C, ^{15}N/^{14}N) at the Reston Stable Isotope Laboratory (RSIL) of the U.S. Geological Survey, Reston, Virginia. Methods for analysis are described on the RSIL web site at *http://www.isotopes.usgs.gov* (accessed September 2007). The carbon isotopic results for the sample, δ^{13}C, are reported in per mil relative to VPDB (Vienna Pee Dee belemnite) and normalized on a scale such that the relative carbon isotope ratios of L-SVEC Li_2CO_3 (lithium carbonate reference material prepared by H.Svec) and NBS 19 $CaCO_3$ (National Bureau of Standards Reference Material 19 for calcium carbonate) are -46.6 and +1.95 per mil, respectively (Coplen and others, 2006). Nitrogen isotope ratios, δ^{15}N, also reported in per mil, are expressed relative to N_2 in air using several internationally distributed isotopic reference materials, as discussed in Revesz and Qi (2006). The 2-sigma uncertainty for both δ^{13}C and δ^{15}N analysis is ±0.50 per mil.

RSIL analyzes the entire homogenized sample as received for the mass fraction by weight of the total carbon present, $w(C_T)$, and performs the isotopic analysis on this sample, so that the isotopic analysis can be more specifically labeled $\delta^{13}C_T$. However, the total carbon present may include both inorganic (mineral) and organic materials, and each of these would have different origins and possibly arise in different source areas within the watershed. Furthermore, if carbon is present in both organic and inorganic form, then $\delta^{13}C_T$ just reflects a mixture of the isotopic ratios from two different materials that may have very different isotopic ratios. Consequently, it is necessary to determine in which form carbon is present and which is the appropriate form to be used as a tracer for the fingerprint analysis.

To determine whether the sediments in the three study watersheds contained a significant mixture of inorganic as well as organic C, a subset of samples from each of the watersheds were analyzed at RSIL. The mass fraction by weight of the organic C present, $w(C_O)$, is determined via acid digestion of the inorganic C using hydrochloric acid (Harris and others, 2001). The sample remaining after acid digestion was then analyzed to determine the isotopic content of the organic fraction, $\delta^{13}C_O$.

The mass fraction by weight of the inorganic C present can be calculated as the difference between the total and the organic C fractions, that is, $w(C_I) = [w(C_T) - w(C_O)]$. The estimated value $w(C_I)$ is set equal to 0.0 if $-0.05 < [w(C_I) / w(C_T)] \leq 0.05$ because there is a ±5% uncertainty in the determination of $w(C_O)$. For the samples in which value $w(C_I) = 0$, then total C present was taken not to be a mixture of organic and inorganic forms, so that the relevant tracer variables were just $w(C_T)$ and $\delta^{13}C_T$. When an initial subset of samples yields $w(C_I) > 0.05$, that is, C is found to be present in both inorganic and organic forms, then all samples in a set are analyzed for $w(C_O)$ and $\delta^{13}C_O$. When $[w(C_I) / w(C_T)] \leq -0.05$, then the sample must not have been homogenized properly before RSIL received it, and the sample could not be used in this analysis.

Statistical Methods

Several analytical and statistical steps to determine which tracers were most appropriate in defining sediment sources were used: (1) bracketing the fluvial samples by the source samples, (2) performing a Kruskal-Wallis H-test, and (3) performing a Tukey test.

A requirement of sediment fingerprinting is that the fluvial tracers must be conservative and not change during transport from the source to the sampling point. Consequently, the first step in the statistical analysis was determining that for a given tracer, the fluvial samples were bracketed by the sources, within the range of error for each tracer. Any tracers that did not satisfy this constraint within measurement error were considered to be nonconservative and removed from further consideration.

Another requirement of sediment fingerprinting is that tracers have a unique value for certain sources. To determine which tracers identified a given source, a Kruskal-Wallis H-test and Tukey test were performed. The Kruskal-Wallis H-test (Swan and Sandilands, 1995) determines whether there is a significant difference ($\rho \leq 0.05$) between the medians of the measured tracer values in the source areas. Any tracers that did not satisfy this constraint were considered nondiscriminatory and removed from further consideration. Each tracer should distinguish a specific source, but not necessarily separate all other sources. Conversely, each source should be statistically distinguishable from all others on the basis of at least one tracer. Consequently, a Tukey test (Helsel and Hirsch, 1997) was performed for each tracer between each pair of source areas (significance test at $\rho \leq 0.05$) to confirm that each source area was distinguished from all other source areas by at least one tracer and to identify redundant tracers for elimination. The Tukey test was performed on a rank transformation of the data; rank = 1 for the smallest and rank = N for the largest value. Rank transformations are most useful when performing nonparametric tests (Helsel and Hirsch, 1997). Tracers that distinguish the same sources might bias the results towards those tracers. If tracers were found to discriminate the same source(s), a test of correlation using Spearman's Rho was performed (Helsel and Hirsch, 1997). Spearman's Rho is a test of correlation applied to the ranks of the tracers. If the tracers show a high correlation ($\rho > 0.05$), then use of both tracers is redundant and a decision is made to remove one of the tracers.

The final step in the statistical analysis was determining the significant sources of sediment using an "unmixing model." The literature describes many different mathematical forms by which the fingerprint may be decomposed into the relative contributions by source (Rowan and others, 2000; Motha and others, 2003; Walling, 2005). In this study, the fluvial sample is considered to be composed of a mixture of sediment from the different source areas. To determine the relative source contributions to the fluvial samples, an "unmixing" variable E (equation 4) is defined in terms of normalized scores (Snedecor and Cochran, 1980). E is defined as the average absolute difference between each tracer value measured in the fluvial sample that would occur in the proposed mixture, scaled by the relevant standard deviation of the mixture. The best model is considered to be that set of the relative contributions from each source that will provide the closest match to the fluvial-tracer value, that is, to provide a minimal value for E. The best mixture model was chosen as that set of fractional values (f_s, s=1 to S) which minimizes the expression E, as given below. Note that the f_s must sum to one. The minimizing function E, expressed in standard deviation units, is defined as:

$$E = (1/T)\sum_{t=1}^{T} \left| \; v_t - \sum_{s=1}^{S} f_s A_{st} \; \right| / \sqrt{\sum_{s=1}^{S} f_s^{\,2} (VAR_{st} / n_s)} \qquad (4)$$

where

t = a specific tracer;
T = the total number of tracers;
v_t = the value of the tracer t in the fluvial sample;
s = a specific source area;

S = the total number of source areas;

n_s = the total number samples for an individual source;

f_s = the fraction of the contribution of source s to the entire sample, such that the sum of the S values of f_s is one; and

A_{st} and VAR_{st} = the estimated average and variance of the measured values of tracer t in source area s, respectively.

The sources of sediment for each sampled event are reported as those that show the minimum value of E according to equation 4. The sediment sources for each sampled storm are averaged to describe the sediment sources for that watershed. However, each sampled event may have different flow and sediment conditions and therefore, taking the average of sources for all sampled events may not be the best or most appropriate method to portray the sediment sources for that watershed. For example, one event may transport the majority of sediment and thus may be a more important event in describing sediment sources. To include the importance of high sediment-loading events, the sediment sources of each sampled event were weighted by the total amount of sediment transported by all sampled events. These weighting values were multiplied by the source percentage for each storm and summed to produce a weighted source percentage for each watershed.

During certain times of the year, some sediment sources may be more important than at other times of the year. During the plowing and harvesting seasons, cropland may be bare and may be an important source of sediment. Results of the satellite imagery analysis were used to quantify the area of bare ground over time for Little Conestoga Creek and determine if cropland sources were related to the percent of bare ground.

For the Pocomoke Creek and Mattawoman Creek, fluvial sediment samples were collected at one time in the hydrograph. The timing of sediment samples in relation to the entire storm hydrograph is also an important factor in sediment source identification (Williams, 1989; Walling and Woodward, 1992; Carter and others, 2003). Many rivers show a hysteresis in sediment transport where suspended-sediment concentrations peak before peak discharge. This hysteresis is thought to reflect changes in sediment sources over the storm hydrograph and sediment exhaustion over time (Walling and Webb, 1982). The distance of sediment sources, antecedent conditions, and sediment exhaustion as the event proceeds are some of the factors contributing to changes in sediment concentrations and source areas (Carter and others, 2003). For the sediment source analysis for the Pocomoke River and Mattawoman Creek, it was assumed that the sampled sediment is representative of the entire storm event. However, the timing of the sediment samples, whether they were collected before or after the peak flow, could be a factor in the interpretation of sediment source results. Therefore, sediment source analysis results for each sampled event on the Pocomoke River and Mattawoman Creek were interpreted relative to the sample collection time on the hydrograph. For the Little Conestoga Creek, the sediment samples for source analysis were integrated over the flood hydrograph and the timing of the samples was less important.

The peak flow of the storm event and the total amount of flow are factors that are significant in sediment transport. Guy (1964) analyzed the factors affecting storm-period sediment transport for seven streams in the Atlantic coast area of the United States and determined that the peak flow of the event is an important parameter in describing suspended sediment. Although the sediment samples for the Pocomoke River and Mattawoman Creek may not have been taken precisely at the peak flow, the peak flow of the event is an indication of the intensity of the event, and the amount of sediment mobilized and transported. The sediment source results for each sampled storm are plotted relative to the peak flow of the sampled event and to the daily mean discharge of the event.

Suspended-Sediment Collection and Loads Computation

Suspended sediment was collected at or near the streamflow-gaging stations on the Pocomoke River, Mattawoman Creek, and Little Conestoga Creek (fig. 1a) to compute daily and annual suspended-sediment loads for the water years covering the period of study (2001 through 2004). For the Pocomoke River and Mattawoman Creek, suspended-sediment samples that were used to quantify daily suspended-sediment loads were not used in the sediment-fingerprinting analyses. In Little Conestoga Creek, the suspended-sediment samples used in the computation of daily suspended-sediment loads also were used in the sediment-fingerprinting analyses. At the beginning of this study, the Pocomoke River and Mattawoman Creek were operating stations of streamflow-data collection with records going back to 1950 for both stations. The streamflow-gaging station at the Little Conestoga Creek began operation in February 2003 as part of this study.

Suspended-sediment samples used in the computation of daily suspended-sediment loads were collected at each of the three watersheds, during low flows using a U.S. Series depth-integrating DH-48 hand-held sampler, and at higher flows using a DH-59 rope sampler. Samples of suspended sediment were collected at various points in the cross section using the EWI method (Edwards and Glysson, 1999). During high flows, when suspended-sediment transport rates were assumed to be highest, suspended sediment was collected at the Little Conestoga Creek and Mattawoman Creek using an automatic suspended-sediment pump sampler. There is no automatic pump sampler on the Pocomoke River.

The automatic suspended-sediment sampler is designed to pump samples into 24 separate 1-L plastic bottles. The sampler contains a peristaltic pump to transport the sample from the stream to the sample bottle. The transfer line is purged by the sampler before and after each sample is collected. The timing of the 24 samples was preprogrammed to pump samples over the flood hydrograph. Since the automatic sampler samples sediment at a point in the river cross section, it should be calibrated to cross-sectional samples. During high flows, manual samples were collected using a DH-59 rope sampler deployed at a bridge located near each streamflow-gaging station to calibrate the automatic sampler.

At low flows, suspended-sediment samples at Mattawoman Creek were collected downstream of the confluence of Old Woman Creek with Mattawoman Creek, approximately 300 ft (feet) downstream of the State Highway 227 bridge. The automatic suspended-sediment sampler was located at this sampling site. During high flows, suspended-sediment samples were taken from the State Highway 227 bridge and sampling transects included both Mattawoman Creek and Old Woman Creek. This differed from the sediment-source analysis collection, where samples were only taken from Mattawoman Creek. Since discharge records for Mattawoman Creek near Pomonkey, Maryland included contributions from Old Woman Creek, it was important that the suspended-sediment load reflect contributions from Old Woman Creek.

Suspended-sediment samples from all watersheds were sent to the USGS Kentucky Water Science Center Sediment Laboratory in Louisville, Kentucky for analysis of suspended-sediment concentrations. Determination of suspended-sediment concentration was made by the evaporation or filtration method (Guy, 1969). The concentration of suspended sediment is equal to the ratio of the dry weight of sediment to the volume of the water-sediment mixture. This concentration is computed as a weight-to-weight ratio and is expressed in parts per million (ppm). A conversion factor is used to convert parts per million to milligrams per liter based on the assumption that water density is equal to 1.000 g/mL (grams per milliliter) plus or minus 0.005 g/mL, temperature is from 0° to 29°C, specific gravity of suspended sediment is 2.65, and the dissolved solids concentration is less than 10,000 mg/L (Guy, 1969). For suspended-sediment concentrations less than 15,900 ppm, the conversion factor is equal to 1.0.

Daily suspended-sediment loads were computed at the three study watersheds using two methods. For the Pocomoke River near Willards, Maryland, daily suspended-sediment loads were computed using a regression model of the relation of discharge and suspended-sediment load (Walling, 1977). For Mattawoman Creek and Little Conestoga Creek, suspended-sediment loads were computed using the subdivision method (Porterfield, 1977) with the USGS software program Graphical Constituent Loading Analysis System (GCLAS).

The regression model defines the relation of suspended-sediment and discharge in the following equation:

$$Q_s = Q_c * Q_w * 0.0864 \text{ (Porterfield, 1977)} \qquad (5)$$

where

Q_s = suspended-sediment load (Mg/day);
Q_w = daily mean discharge (m^3/s; cubic meters per second);
Q_c = suspended-sediment concentration (mg/L); and
0.0864 = a coefficient that includes the conversion to Mg/days, and assumes that 1 m^3 of water is equal to 1 Mg.

The relation between discharge and suspended sediment concentration is referred to as a sediment-transport curve (Glysson, 1987). For the Pocomoke River, suspended-sediment concentrations were obtained from suspended sediment collected during the period of this study (October 1, 2000 through September 30, 2003). The sediment-transport curve and the equation for the line of best fit were determined using a standard computer-graphing package (SIGMAPLOT, Version 7.0). The equation of the best-fit line between discharge and suspended-sediment concentration was applied to the daily mean discharge to estimate a daily suspended-sediment concentration for each day during the period of source analysis. Daily mean discharges were obtained from the USGS Automated Data Processing System (ADAPS). Daily suspended-sediment loads were obtained using equation (5).

The relation of discharge and suspended-sediment loads is a log-log relation. Retransformation of load data from log to normal values can result in an error. To correct for this error in calculating daily loads at the Pocomoke River near Pomonkey, a nonparametric Smearing Estimator developed by Duan (1983) was used:

$$\hat{L}_S = \hat{L}_{RC} \frac{\sum_{i=1}^{N} \exp(e_i)}{N} \qquad (6)$$

where

$\hat{L}_S$ = estimated sediment discharge (load) using the smearing estimator;
e_i = residuals from least squares regression of the natural log of discharge versus the natural log of sediment loads;
$\hat{L}_{RC}$ = daily suspended-sediment load estimated from equation 5; and
N = number of samples in the regression equation.

Suspended-sediment loads at Mattawoman Creek and the Little Conestoga Creek were computed using the sediment subdivision method, in which a continual trace of suspended-sediment concentration is developed for the period of interest. A continual trace of suspended-sediment concentration is developed with suspended-sediment concentrations obtained from field sampling and estimates of suspended-sediment concentrations between field samples. Estimates of suspended-sediment concentrations between field samples were made using the sediment-transport curve and turbidity measurements.

Turbidity can be used as a surrogate for suspended-sediment concentration (Ziegler, 2003). Lewis (2003) reported that regressions of suspended-sediment concentration compared with turbidity can be linear with low variance and that sediment flux can be estimated quite accurately. Errors that can arise when turbidity is used as a surrogate for suspended sediment include high suspended-sediment concentrations, sediment size, shape, and color, and biologic fouling of the sensor by algae (Ankcorn, 2003; Landers, 2003).

At the Little Conestoga Creek and Mattawoman Creek, a nephelometer (a device to measure turbidity) was installed and recorded turbidity readings every 15 minutes. Turbidity at Mattawoman Creek was recorded in Formazin Nephelometric Units (FNUs), and at Little Conestoga Creek it was recorded in Nephelometric Turbidity Units (NTUs). Turbidity data were transformed into suspended-sediment concentration using an equation of the line of best-fit between turbidity and suspended-sediment concentrations developed at each station.

In the software package GCLAS, the following data are plotted with time on the computer screen: (1) the hydrograph for the period of interest, (2) sampled suspended-sediment concentrations, (3) the sediment-transport curve, and (4) a background curve of transformed values of turbidity expressed as suspended-sediment concentration (mg/L). The aforementioned data enable the user to create a continual trace of suspended-sediment concentration. Once a satisfactory trace of suspended-sediment concentration is developed, GCLAS computes the suspended-sediment load for each day of interest.

Erosion Rates Using Cesium-137

The ^{137}Cs technique was used to estimate erosion and deposition rates in selected cropland areas of the Pocomoke River and the Little Conestoga Creek Watersheds. The ^{137}Cs technique of estimating soil erosion and deposition has been applied in a variety of locations worldwide (Campbell and others, 1988; Ritchie and McHenry, 1990; Walling and Bradley, 1990; Walling and Quine, 1991; Nagle and others, 2000). The mobility of and redistribution of ^{137}Cs is associated with the mobility and redistribution of soil particles. This redistribution in agro-ecosystems is a cumulative result of tillage, soil erosion, and deposition from the time of fallout to the time of sampling (Zapata, 2003). The loss or gain of ^{137}Cs from a particular site is determined by comparing ^{137}Cs inventories at the site to ^{137}Cs inventories at a reference site, which is stable over time and not eroding. Forests, pastures, and old cemeteries can be used as reference sites. Since there is an established empirical and theoretical relation between the loss and gain of ^{137}Cs and soil, the rates of soil erosion and deposition are readily estimated from ^{137}Cs measurements using conversion models (Walling and He, 1997).

In the Pocomoke River and Little Conestoga Creek Watersheds, soil erosion and deposition for cropland sites was estimated using the Mass Balance Model 2 as described in Walling and He (1997). The Mass Balance Model 2 attempts to account for input and loss of ^{137}Cs, time-variant fallout, and soil redistribution from tillage. This model considers any site with a ^{137}Cs inventory in excess of the reference site to be aggrading, and sites with a ^{137}Cs inventory less than the reference site to be eroding. Using this approach, Walling and He (1997) developed the following equation to quantify erosion as follows:

$$\frac{dA(t)}{dt} = (1-\Gamma)I(t) - (\lambda + P\frac{R}{d})A(t) \qquad (7)$$

where

$A(t)$ = cumulative ^{137}Cs activity per unit area (Bq/m^2);

R = erosion rate (kg/m^2/yr);

d = cumulative mass depth representing the average plough depth (kg/m^2);

λ = decay constant for ^{137}Cs per year = 0.023/yr;

$I(t)$ = annual ^{137}Cs deposition flux (Bq/m^2/yr);

Γ = percentage of the freshly deposited ^{137}Cs fallout removed by erosion before being mixed into the plough layer (percent); and

P = particle size correction factor (unitless).

If an exponential distribution for the initial distribution of ^{137}Cs at the surface can be assumed, then

$$\Gamma = P\gamma\,(1 - e^{-R/H}) \qquad (8)$$

where γ is the proportion of the annual ^{137}Cs input susceptible to removal by erosion, and H (kg/m^2) is the relaxation mass depth of the initial distribution of fallout ^{137}Cs in the soil profile. Values of H were found experimentally by Walling and He (1997) to be 4.0 kg/m^2.

The parameter γ can be estimated in locations of net deposition and where ^{137}Cs extends below the plow depth (Zhang and others, 1999), as:

$$\gamma = \frac{C_m D\rho}{A_0} \qquad (9)$$

where

C_m = the maximum ^{137}Cs concentration in the soil profile (Bq/kg);

D = the plow depth (m);

A_0 = the local ^{137}Cs reference inventory at sampling year n; and

ρ = the average soil bulk density (kg/m^3).

The Mass Balance Model 2 also attempts to correct for particle-size variations. This correction factor acknowledges that ^{137}Cs is preferentially sorbed to fine material (such as clays and silts) and is therefore positively biased toward samples that have preferentially accumulated fines prior to sampling (such as loess deposits).

For sites undergoing deposition, Walling and He (1997) used the following equation:

$$R' = \frac{A_{ex}}{\int_{t_0}^{t} C_d(t')e^{-\lambda(t-t')}dt'} \qquad (10)$$

where

R' = the deposition rate (kg/m^2/yr); and

$C_d(t')$ = the ^{137}Cs concentration of the deposited sediment.

This model accounts for temporal variations and the initial ^{137}Cs concentrations both at the site of interest and from sites upgradient that may contribute ^{137}Cs to the site of interest.

The ^{137}Cs technique was applied to selected cropland fields in the Pocomoke River and Little Conestoga Creek Watersheds. In the Pocomoke River, soil samples were collected in cropland (corn and soy) and at three reference sites (two forested and one cemetery) using a 20-cm (length) by 50-cm (width) by 21-cm (height) steel box coring device (Campbell and others, 1988). A 30-cm aluminum scraper fitted with 1-cm spaced holes down each side allowed soil to be sampled in 1-cm increments. The volume of soil for each increment was analyzed with a Canberra HPGe photon detector at the USGS laboratory in Denver, Colorado and reported in Bq/g. The volume and weight of samples were measured to determine the bulk density of each increment in g/cm^3 (grams per cubic centimeter).

In the Little Conestoga Creek Watershed, there are few forested areas, therefore, a pasture site was chosen as the reference site. Cropland (corn and soy) soils and the pasture site soils were collected using a 3.75-cm diameter coring device to a depth of 25 cm, which was assumed to be the plow depth. At each site, cores were collected along two transects, each running along slope. The volume of soil for each core was analyzed separately for ^{137}Cs using a Canberra HPGe photon detector at the USDA-ARS, Hydrology and Remote Sensing Laboratory, in Beltsville, Maryland, reported in Bq/g. The volume and weight of the entire sample was measured to determine the bulk density, in g/cm^3.

Flood-Plain Sediment Trapping

The analysis of flood-plain sediment trapping involved four main components: (1) site selection and transect establishment, (2) dendrogeomorphic (tree ring) analyses, (3) clay pad installation and analyses, and (4) quantitative integration with other study elements. Discussion in this section will follow the order of these components.

Site Selection and Transect Establishment

Ten streams were selected for flood-plain deposition analyses (fig. 2). Each study reach was sampled along flood-plain transects (typically three), parallel to the river and separated by 50 to 100 m. Transects, aligned normal to the stream, began on the channel edge (usually a levee) and continued for a few hundred meters into the low backswamp area (fig. 6). Each transect typically had four to six monitoring points generally spaced by about 50 m where periodic measurements were made of deposition rate, and sediment texture and composition. These sampling points were numbered consecutively, starting with the lowest number nearest the channel. All transects were surveyed using an optical or laser level and tied to a temporary benchmark.

Dendrogeomorphic Analyses

Dendrogeomorphic techniques use tree-ring information to age and interpret various geomorphic processes (Sigafoos, 1964; Shroder, 1978; Hupp, 1988; Hupp and Bornette, 2003). These techniques were used in the present study to determine the net rate of flood-plain sediment deposition (and in some cases, rates of erosion and subsidence). Typically, six or more trees were sampled at each monitoring point. Replication is necessary to account for local depositional variation and to ensure the determination of a mean rate with an acceptable standard error (SE less than the mean). Specimen trees are partly excavated down to the top of normally horizontally radiating root mass, a level that is established at the time of germination. The amount of burial above the top of major roots to the present ground surface provides a conservative estimate of net sediment deposition during the life of a tree. The tree is then cored with an increment borer (fig. 7a), core

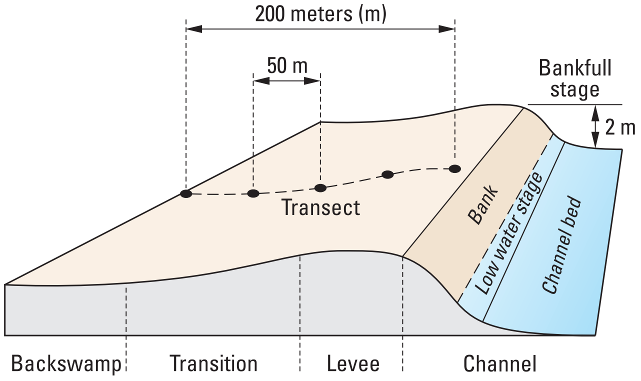

Figure 6. Generalized layout of a transect for flood-plain sediment trapping. [Stops along transect are locations for clay pad installation and adjacent dendrogeomorphic sampling. Study sites typically have three or more parallel transects separated by 50 to 100 meters.]

extracted, and the sample is returned to the laboratory for cross dating and age determination. The age of the tree is then divided into the depth of burial to provide an estimate of net deposition rate. This technique has been used with considerable success along streams in the Coastal Plain (Hupp and others, 1993; Hupp, 2000; Jolley and Lockaby, 2006) and Great Plains (Friedman and others, 1996; Scott and others, 1996) regions of the United States, and in Europe (Piégay and others, 2008). Although dendrogeomorphic analyses are not as precise as other techniques in measuring erosion and deposition, they are relatively inexpensive and may provide long-term erosion and deposition rates wherever ring-producing trees grow, often with considerable spatial and temporal detail. More descriptions of dendrogeomorphic techniques are provided in Shroder (1978), Hupp (1988), and Hupp and Bornette (2003).

Clay Pad Installation and Measurement

Artificial marker layers (clay pads) (fig. 7b) were placed at each monitoring station. The markers, powdered white feldspar clay approximately 20 mm in thickness, were placed over an area of about 0.5 m^2 on the soil surface that had been cleared of coarse organic detritus. The clay becomes a fixed plastic marker after absorption of soil moisture that permits accurate measurement of short-term net vertical accretion above the clay surface (Baumann and others, 1984; Hupp and Bazemore, 1993; Kleiss, 1996; Ross and others, 2004). During the period of this study, the clay pads were examined for depth of burial annually and at selected times after flooding events. Depth of burial was measured by coring the ground surface above the clay pads, and measuring the vertical depth of sediment above the artificial clay layer. Measurements from all clay pads were averaged. Sediment adjacent to the clay pad was assumed to correspond to the depth of deposition during the course of study, and was analyzed for percent sand (greater than 0.63 microns), bulk density, and percent organics (loss on ignition, or LOI). The LOI Test is designed to measure the amount of organics lost when the sample is ignited. Approximately 5 grams of each soil sample were dried for 24 hours at 110°C. The samples were then allowed to cool in a dessicator, weighed to within 0.01 g precision, and burned for 16 hours at 400°C in a muffle furnace. The cooled sample was re-weighed and the percent mass lost was recorded as the organic content of the sample. Deposition rates measured from the clay pads and dendrogeomorphic analyses provided net rather than gross values.

Quantitative Integration

Net deposition rates (mm/yr) obtained from both dendrogeomorphic and clay-pad measurements, were averaged for three scales (1) transect, (2) reach, and (3) river. Dendrogeomorphic measurements provide relatively long-term sedimentation rates whereas clay-pad measurements provide short-term sedimentation rates. Sedimentation rates (mm/yr) were converted to sediment volumes (kg/unit area/yr) using measured bulk density information (kg/m^3) and by estimating the total flood-plain area. Flood-plain area was obtained by digitizing maps for each stream of interest using USGS 1:24,000 series topographic maps. The total amount of sediment deposited on the flood plain each year was compared to the sediment transported at the streamflow-gaging station to estimate a crude sediment budget.

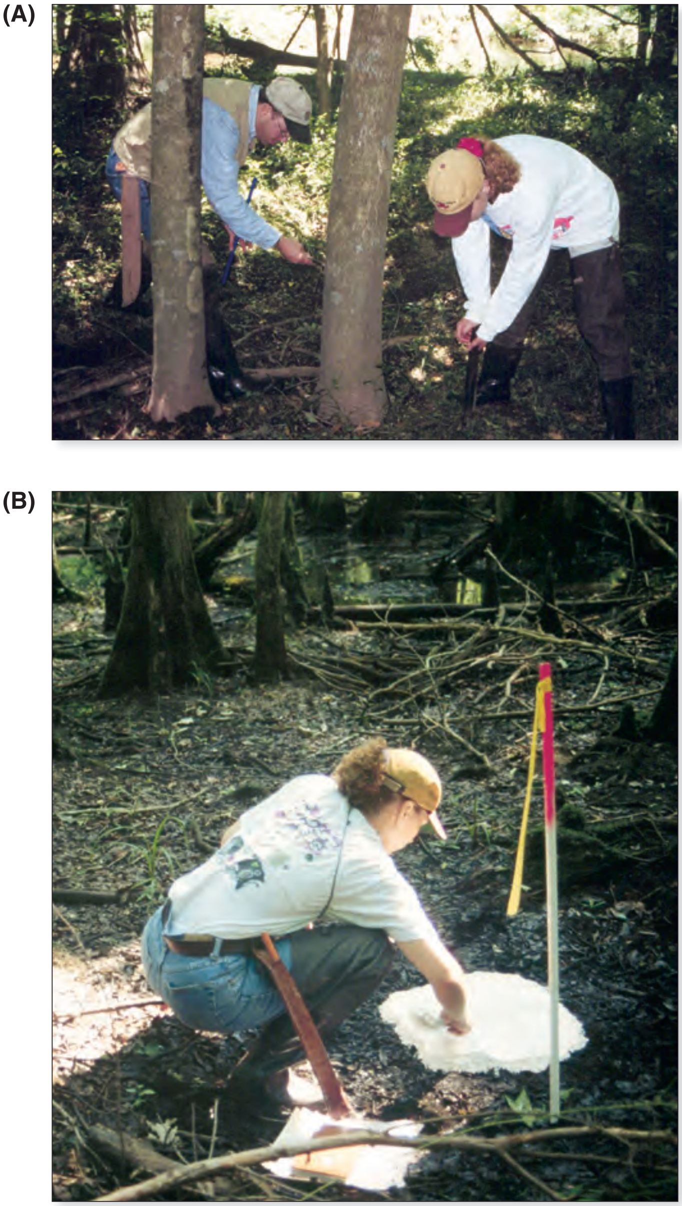

Figure 7. (A) Dendrogeomorphic and (B) clay pad techniques, long and short term, respectively, for estimation of sediment deposition rates. [(A) shows one person coring a tree for age determination and another probing for depth of root burial. (B) demonstrates the placement of the white feldspar clay pads on the flood-plain surface.] Photographs by Cliff R. Hupp, U.S. Geological Survey.

Susquehanna River Watershed Erosion Rates Using *in situ* Beryllium-10

Reuter (2005) presented data for background, geologic timescale (10,000 to 100,000 years) erosion for Susquehanna subwatersheds of various drainage areas measured using *in situ* ^{10}Be (Bierman and Steig, 1996; Matmon and others, 2003). The erosion rates measured with this technique (table 2) range from a few m/My (meters per million years) to greater than 50 m/My. Reuter (2005) sampled 68 watersheds and found that rates vary significantly for small watershed areas (less than 100 km^2) as a function of rock type, watershed climate, and slope. Background erosion is most strongly related to slope (Reuter, 2005). For the Appalachian Plateau and Valley and Ridge Provinces, background erosion is well correlated with slope ($r^2 = 0.66$) (Reuter, 2005). Except for the Piedmont, background erosion rates determined by this method correspond well to short-term erosion rates calculated from instrumental sediment-yield measurements (fig. 8). Background rates for large watersheds represent integrated contributions from tributaries and correspond to long-term regional

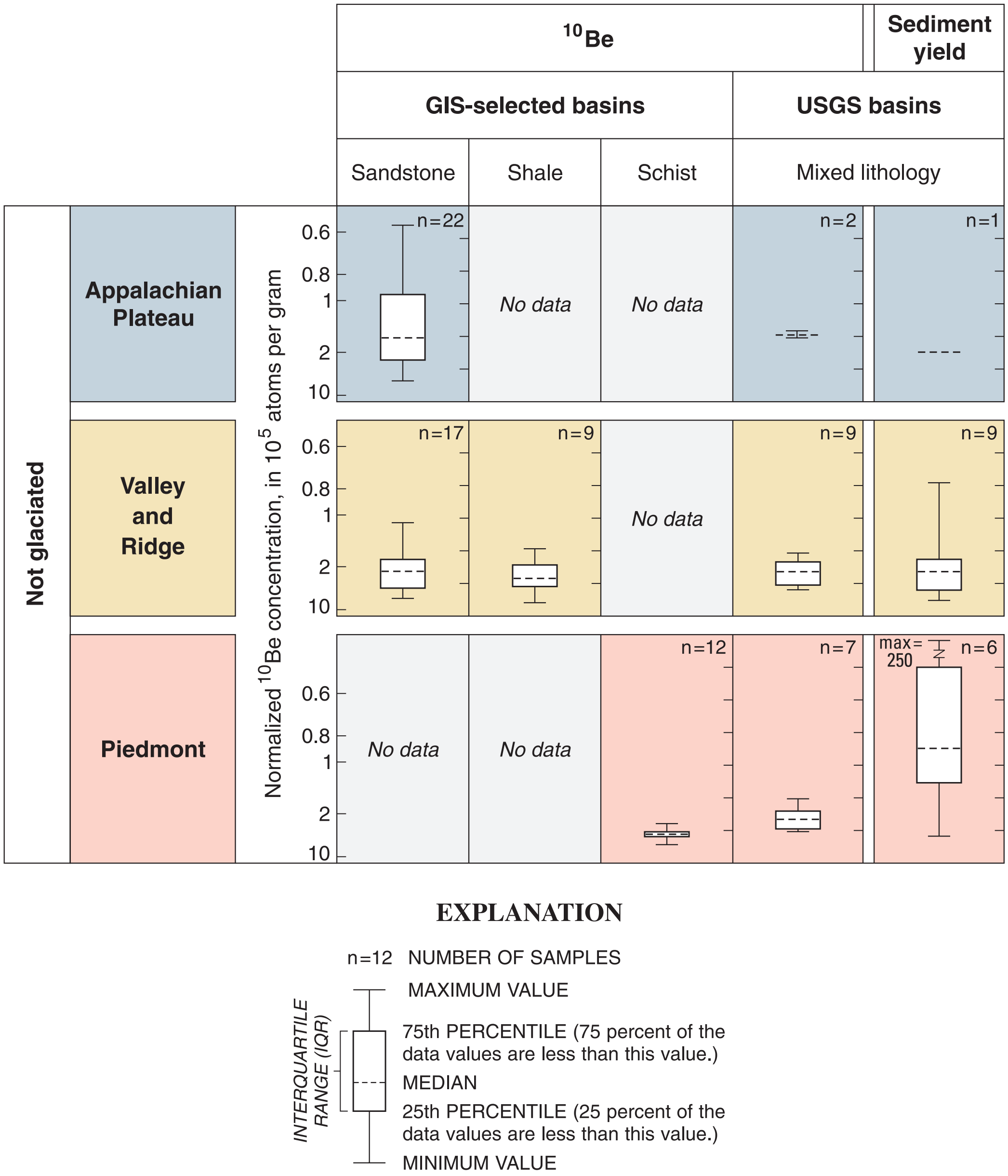

Figure 8. Background and geologic timescale rates of erosion for Susquehanna tributary watersheds using *in situ* beryllium-10 delineated by physiographic province and dominant lithology (modified from Reuter, 2005). [Sediment yields from 20th century U.S. Geological Survey streamflow-gaging stations converted to millimeters per 1,000 years are presented as a comparison to the geologic rates.]

denudation rates determined from post-orogenic thermal evolution of the Appalachians, as shown for the Great Smokies by Matmon and others (2003). Reuter (2005) also showed that in the Susquehanna River Watershed, background erosion rates are independent of the percentage of cleared land, an important factor affecting contemporary erosion.

Susquehanna River Watershed Erosion Indices Using Meteoric Beryllium-10

Results of meteoric ^{10}Be analyses from 12 tributaries of the Susquehanna River are presented in figure 9 and table 2. The Erosion Index (EI) for each watershed is calculated from watershed area, rainfall delivery of ^{10}Be, sediment yield, and ^{10}Be sediment concentrations (Brown and others, 1988) (table 2), and is shown in equation 11.

$$\mathrm{EI} = \frac{\text{watershed area (cm}^2\text{) x }^{10}\text{Be (atoms/cm}^2\text{/yr)}}{\text{sediment yield (g/yr) x }^{10}\text{Be concentration (atoms/g)}} \qquad (11)$$

Index values less than or equal to 1 indicate a net accumulation of ^{10}Be, and low net export of sediment out of the watershed. Values greater than 1 indicate soil erosion and net export of sediment by alluvial transport. The indices of 21 of the 26 samples (86 percent) ranged from 0.5 to 5.9 (fig. 9; table 2), which are similar to results obtained from other Atlantic slope rivers (Brown and others, 1988). Erosion indices are highest (close to 20) in the Piedmont parts of the Susquehanna River Watershed, particularly in small watersheds in Lancaster County, Pennsylvania that drain to the Conestoga River. Tributary watersheds in the Valley

Figure 9. Meteoric beryllium-10 erosion indices for sampling sites in the Susquehanna River Watershed. [Site locations and identifiers are shown in figure 4.]

Table 2. Summary of *in situ* and meteoric beryllium-10 analyses for Susquehanna River Watershed samples.

[Site locations are shown in figure 4. km^2, square kilometer; kg/km^2, kilogram per square kilometer; ^{10}Be, beryllium-10; atom/kg, atoms per kilogram; atom/km^2, atoms per square kilometer; atom/yr, atoms per year; m/Ma, meters per million years; N.D., not determined]

Site number	Sampling site	U.S. Geological Survey streamflow-gaging station ID	Latitude (degree minute second)	Longitude (degree minute second)	Drainage area (km^2)	Sediment yield (kg/km^2 x 10^4)	^{10}Be concentration (atom/kg x 10^{11})	^{10}Be output (atom/km^2 x 10^{15})	^{10}Be input (atom/yr x 10^{17})	Index (Output/Input)	*In situ* ^{10}Be erosion rate[1,2] (m/Ma)	Data source for sediment yields
SQ1	Codorus Creek near York, PA	01575500	39 56 46	76 45 20	575	2.27	5.64	12.8	39.5	1.9	13.5	3
SQ2	West Conewago Creek near Manchester, PA	01574000	40 04 56	76 43 13	1,321	7.70	6.35	48.9	172	3.8	14.1	4
SQ3	Yellow Breeches Creek near Camp Hill, PA	01571500	40 13 29	76 53 54	559	4.55	5.65	25.7	73.1	2.0	19.1	4
SQ4	Susquehanna River at Harrisburg, PA	01570500	40 15 17	76 53 11	62,419	3.29	2.39	7.90	8,150	0.6	N.D.	3
SQ5	Sherman Creek at Shermans Dale, PA	01568000	40 19 24	77 10 09	536	1.29	6.24	8.10	67.6	0.6	11.1	3
SQ6	Bixler Run near Loysville, PA	01567500	40 22 15	77 24 09	39.0	2.33	6.00	14.0	5.10	1.1	7.70	3
SQ7	Juniata River at Newport, PA	01567000	40 28 42	77 07 46	8,687	1.15	7.11	8.20	1,130	0.6	18.9	3
SQ9	Spring Creek near Axemann, PA	01546400	40 53 23	77 47 40	226	3.85	4.87	18.8	29.4	1.4	13.3	4
SQ10	Bald Eagle Creek below Spring Creek at Milesburg, PA	01547200	40 56 35	77 47 12	686	3.51	1.86	6.50	90.0	0.5	16.4	USGS Water Resources Data Reports for Pennsylvania, 1956–58
SQ11	West Branch Susquehanna River at Bower, PA	01541000	40 53 49	78 40 38	816	4.11	3.69	15.2	106	1.2	19.4	USGS Water Resources Data Reports for Pennsylvania, 1964–67
SQ12	Raystown Branch Juniata River at Saxton, PA	01562000	40 12 57	78 15 56	1,958	9.08	4.01	36.4	255	2.8	9.30	3
SQ13	Dunning Creek at Belden, PA	01560000	40 04 18	78 29 34	445	2.03	4.15	8.40	58.1	0.6	9.10	4
SQ14	Swatara Creek at Harper Tavern, PA	01573000	40 24 09	76 34 39	873	10.81	3.85	41.6	114	3.2	13.7	USGS Water Resources Data Reports for Pennsylvania, 1960–79
SQ15	Conestoga River at Conestoga, PA	01576754	39 56 47	76 22 5	1,217	6.09	7.76	47.3	159	3.6	18.2	3

Table 2. Summary of *in situ* and meteoric beryllium-10 analyses for Susquehanna River Watershed samples.—Continued

[Site locations are shown in figure 4. km^2, square kilometer; kg/km^2, kilogram per square kilometer; ^{10}Be, beryllium-10; atom/kg, atoms per kilogram; atom/km^2, atoms per square kilometer; atom/yr, atoms per year; m/Ma, meters per million years; N.D., not determined]

Site number	Sampling site	U.S. Geological Survey streamflow-gaging station ID	Latitude (degree minute second)	Longitude (degree minute second)	Drainage area (km^2)	Sediment yield (kg/km^2 x 10^4)	^{10}Be concentration (atom/kg x 10^{11})	^{10}Be output (atom/km^2 x 10^{15})	^{10}Be input (atom/yr x 10^{17})	Index (Output/ Input)	*In situ* ^{10}Be erosion rate[1,2] (m/Ma)	Data source for sediment yields
SQ16	Mill Creek at Eshelman Mill Road near Lyndon, PA	01576540	40 00 36	76 16 39	140	11.24	6.87	77.2	18.3	5.9	11.0	3
SQ17	Little Conestoga Creek near Churchtown, PA	01576085	40 08 41	75 59 20	15.0	36.70	7.18	264	2.00	19.9	9.70	3
SQ18	Pequea Creek at Martic Forge, PA	01576787	39 54 21	76 19 43	383	68.43	3.64	249	50.0	19.1	19.4	USGS Water Resources Data Reports for Pennsylvania, 1977–79
SQ19	Susquehanna River at Danville, PA	01540500	40 57 29	76 37 10	29,060	3.18	4.27	13.6	3,792	1.00	N.D.	3
SQ20	West Branch Susquehanna River at Lewisburg, PA	01553500	40 58 03	76 52 36	17,734	1.98	6.35	12.6	2,314	1.00	N.D.	3
SQ29	Chemung River at Chemung, NY	01531000	42 00 08	76 38 06	6,491	11.57	1.43	16.6	844	1.30	N.D.	3
SQ30	Tioga River at Lindley, NY	01520500	42 01 43	77 07 57	1,997	14.10	1.07	15.1	260	1.20	N.D.	3
SQ31	Tioga River at Tioga, PA	01518000	41 54 30	77 07 47	730	1.39	0.70	0.97	95.0	0.10	N.D.	3
SQ32	Corey Creek near Mainesburg, PA	01516500	41 47 27	77 00 54	32.0	3.90	1.63	6.40	4.20	0.50	N.D.	3
SQ33	Elk Run near Mainesburg, PA	01517000	41 48 54	76 57 55	26.0	5.66	1.76	10.0	3.40	0.80	N.D.	3
SQ34	Susquehanna River at Towanda, PA	01531500	41 45 55	76 26 28	20,194	3.63	1.15	4.20	2,625	0.30	N.D.	3
SQ35	Tunkhannock Creek near Tunkhannock, PA	01534000	41 33 30	75 53 42	992	0.64	1.56	0.99	129	0.10	N.D.	USGS Water Resources Data Reports for Pennsylvania, 1966

[1] Reuter, 2005.

[2] Glaciated basins are reported as N.D. for *in situ* erosion rate as sediment dosing has been affected by glacial contributions at ~20ka.

[3] Gellis and others, 2003.

[4] Williams and Reed, 1972.

and Ridge and Appalachian Plateau have low erosion indices, often less than 1, despite higher watershed slopes than in the Piedmont (Reuter, 2005). This may reflect the large percentage of forest cover and low percentage of agricultural and urban land use in the Appalachian Plateau and Valley and Ridge, relative to the Piedmont Province.

The high erosion indices in the Piedmont part of the Susquehanna River Watershed support the hypothesis that agriculture is an important factor in erosion. The Piedmont has had two centuries of farming that has disturbed upper soil horizons, including clay rich B-horizons, and has led to accelerated soil erosion, producing sediment with high concentrations of ^{10}Be. Annual pre-colonization sediment yields for the Piedmont are estimated to be 12 Mg/km^2, a value that closely matches the lowest sediment yields in Chesapeake Bay (table 1) (Gellis and others, 2005).

Meteoric ^{10}Be has accumulated in soil B-horizons of the Atlantic Coastal Plain and Appalachian soils over the past million years (Pavich and others, 1984; Pavich and others, 1985). Agricultural disturbance causes erosion of the ^{10}Be-rich B-horizon. In the headwaters of Chesapeake Bay, sediment cores taken by Valette-Silver and others (1986) demonstrated that peaks of ^{10}Be-enriched sediment correlated with periods of agricultural disturbance of upland soils. Their results from Principio Creek and Furnace Bay at the head of Chesapeake Bay show ^{10}Be peaks for periods of colonial (circa 1700 to 1850 A.D.) and mechanized soil erosion (after circa 1850 A.D.) contributing to increased sediment loads.

Satellite Imagery Assessment of Bare Ground in Agricultural Areas of Little Conestoga Creek

Resulting vegetation fractions derived from the ASTER image acquisition for the Little Conestoga Creek Watershed, April 9, 2000 to December 6, 2006, are shown in figure 10 and table 3. In the agricultural areas, percent bare ground is simply the inverse of the vegetation proportions derived from the NDVI equations 1 and 2 (fig. 10). The seasonally changing distribution of bare ground using vegetation cover thresholds at less than 25 percent and less than 33 percent, respectively, is shown in figures 11 and 12. The results exclude NLCD-based urbanized and forested areas using the impervious and canopy thresholds described in the previous section. In addition, the results have been filtered to reduce noise and misclassified pixels, while preserving the boundaries of individual fields and the spatial patterns resulting from contour plowing and other tillage methods used. Both sets of results (figs. 11 and 12) yield similar spatial patterns and surface area distributions, which suggest that either of the two thresholds are suitable for distinguishing bare soils from crop- and fallow-covered fields. Because of poor satellite coverage from November through March, the percent bare ground could only be estimated for one snow-free scene acquired in early December (December 6, 2006; table 3).

Changes in bare ground for the dates of satellite scenes are shown in figure 13. Bare ground is classified into cropland and pasture (fig. 13). Although the percentages of bare cropland and bare pasture change over time, the majority of land in bare ground is pasture, averaging 67 percent and 69 percent for the 25-percent and 33-percent thresholds, respectively. Taking averages of bare ground by month shows a correlation of bare ground to the growing season (fig. 14). The highest percentage of bare ground is in the early spring “plow season” and after “fall harvest” (fig. 14). The lowest percentage of bare ground occurs in August, when most fields are in full cover and only about 10 percent of the watershed is in bare ground. The 10-percent value of bare ground may reflect variability in crop cover and areas other than agriculture that are bare ground such as construction sites.

Many farmers in Lancaster County, Pennsylvania have crops planted in the late spring and harvested in late summer. The two maximum percentages of bare ground at both the 25-percent and 33-percent threshold on April 2, 2003 and September 30, 2005 correspond to these two periods (table 3). If an average of bare ground is determined from September and October (30 percent) and this value is assumed to be constant through the winter until planting starts in April, then close to one-third of the Little Conestoga Creek Watershed could be in bare ground for 6 months of the year. This may represent a large source of available sediment.

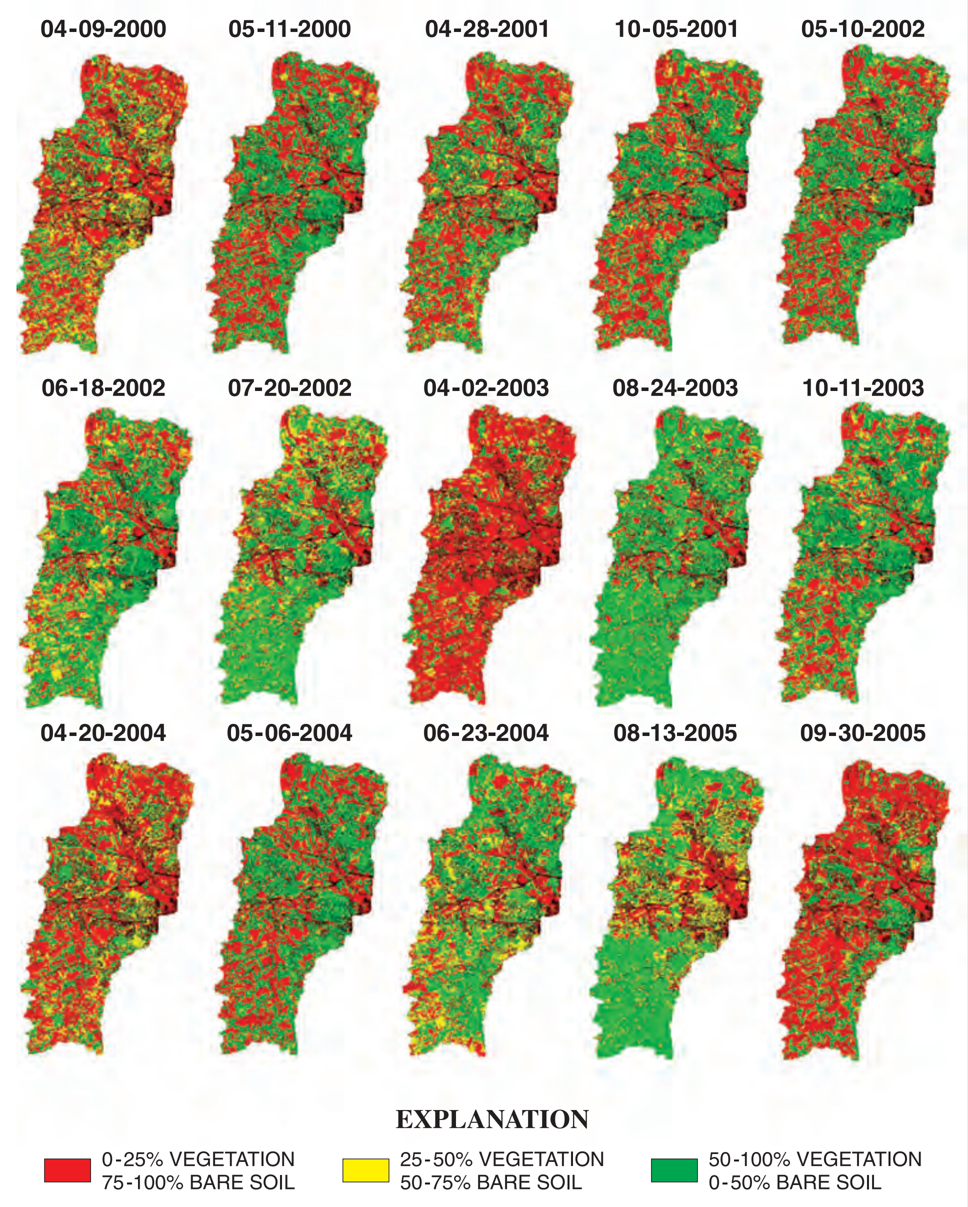

Figure 10. Normalized Difference Vegetation Index (NDVI)-derived estimates of percent vegetation and percent bare-soil cover in agricultural areas of the Little Conestoga Creek Watershed, Pennsylvania, that drain to the Conestoga River with superimposed county roads, driveways, and parking lots data from false color composite images of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes acquired from 15 different dates from April 9, 2000–December 6, 2006 (See table 3) (Yamaguchi and others, 1998).

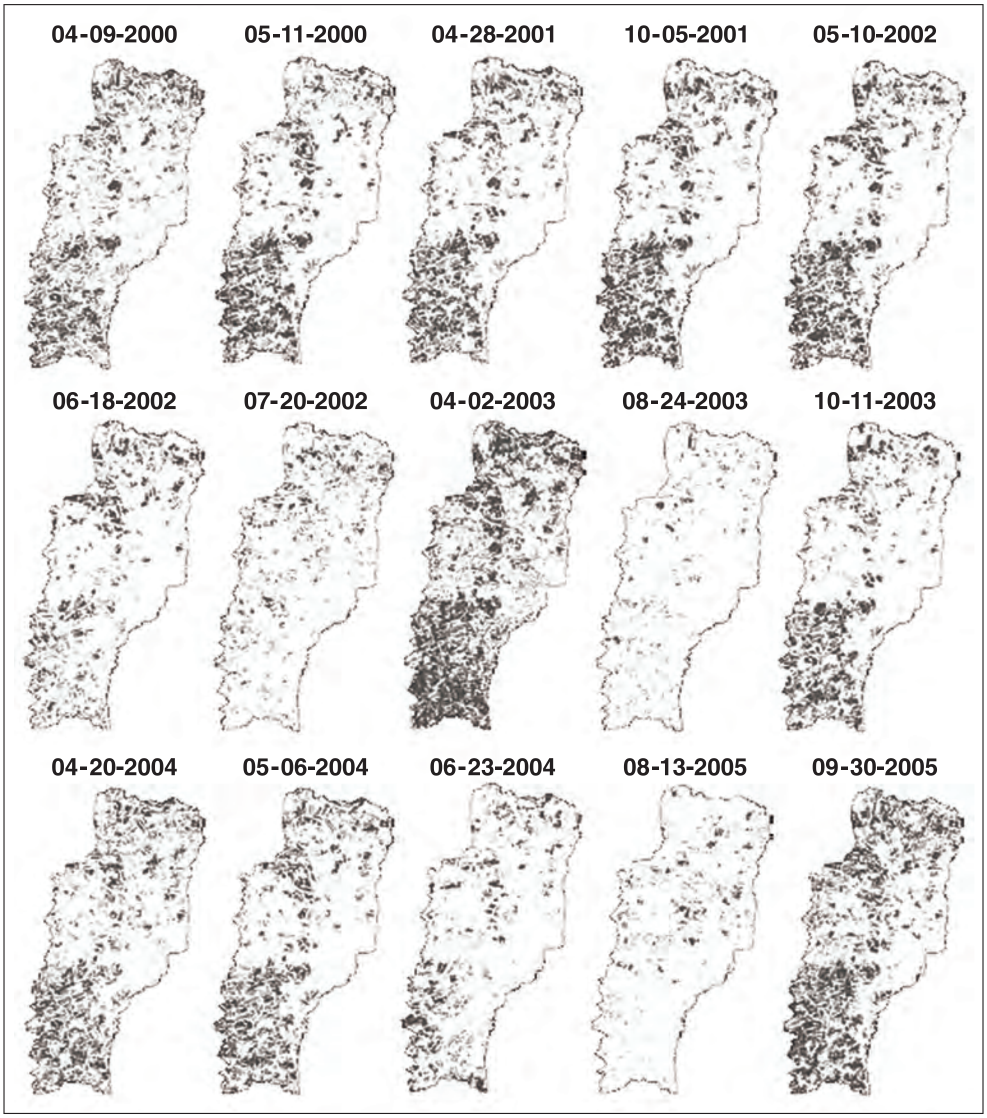

Figure 11. Seasonally changing bare-soil cover in agricultural areas of the Little Conestoga Creek Watershed, Pennsylvania, that drain to the Conestoga River derived from 15 different Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes, April 9, 2000–December 6, 2006, using a less than 25-percent vegetation cover threshold. [Gray areas indicate bare ground. Non-agricultural or non-fallow areas have been excluded, as discussed in detail in the text.]

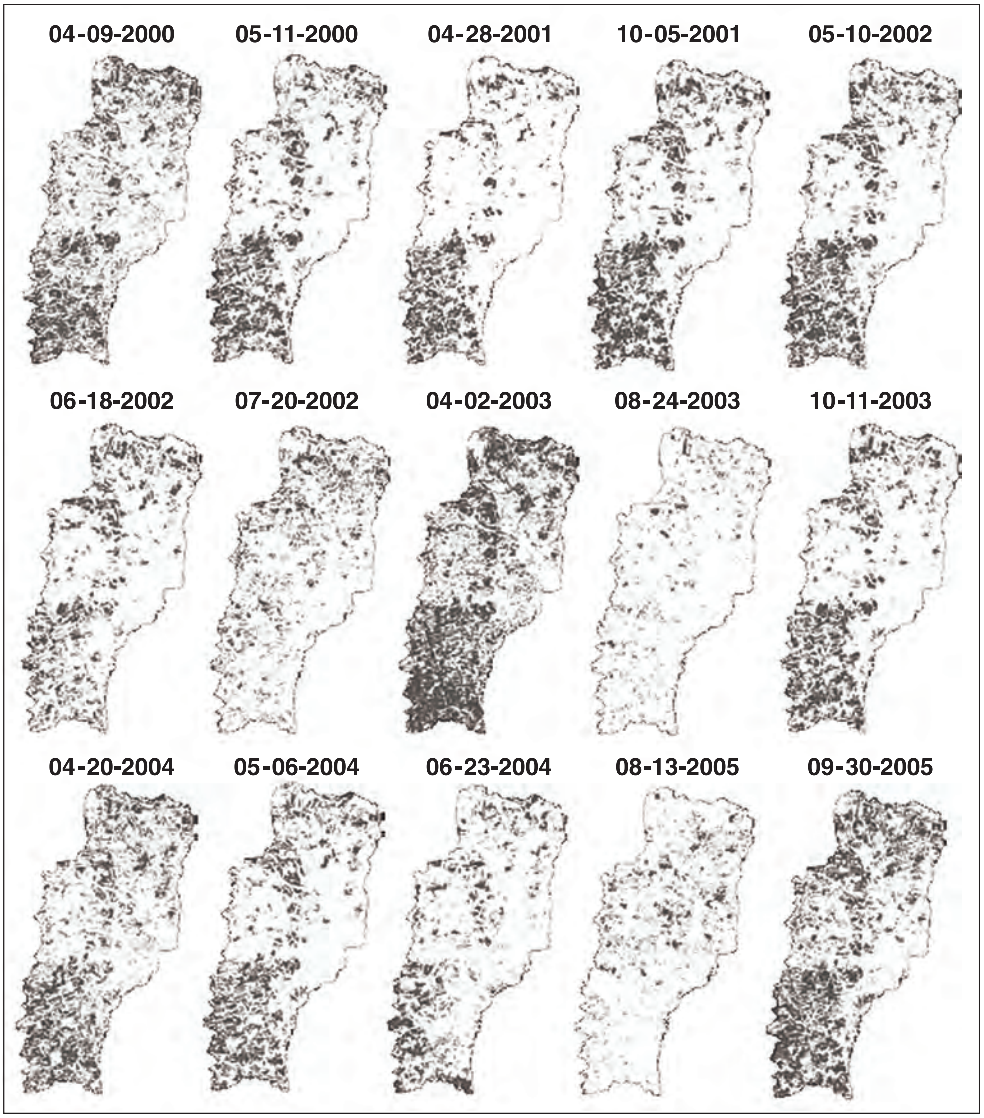

Figure 12. Seasonally changing bare-soil cover in agricultural areas of the Little Conestoga Creek Watershed, Pennsylvania, that drain to the Conestoga River derived from 15 different Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes, April 9, 2000–December 6, 2006, using a less than 33-percent vegetation cover threshold. [Gray areas indicate bare ground. Non-agricultural or non-fallow areas have been excluded, as discussed in detail in the text.]

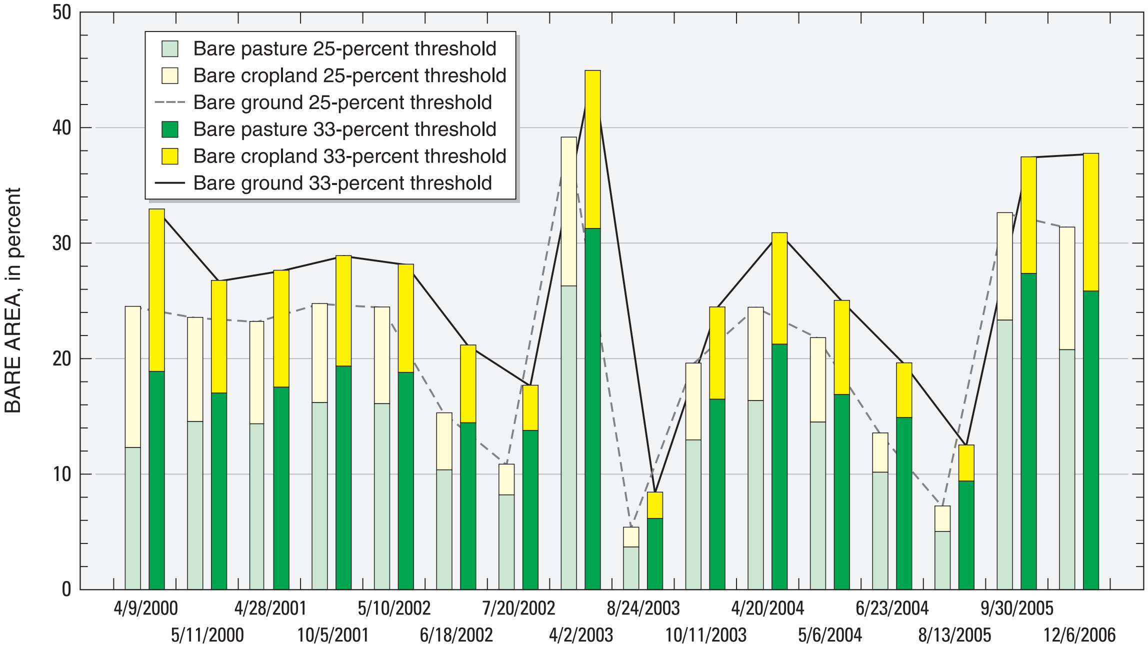

Figure 13. Analysis of bare ground (pasture and cropland) derived from 15 different Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes, April 9, 2000–December 6, 2006, for the Little Conestoga Creek Watershed, Pennsylvania, separated into 25- and 33-percent thresholds.

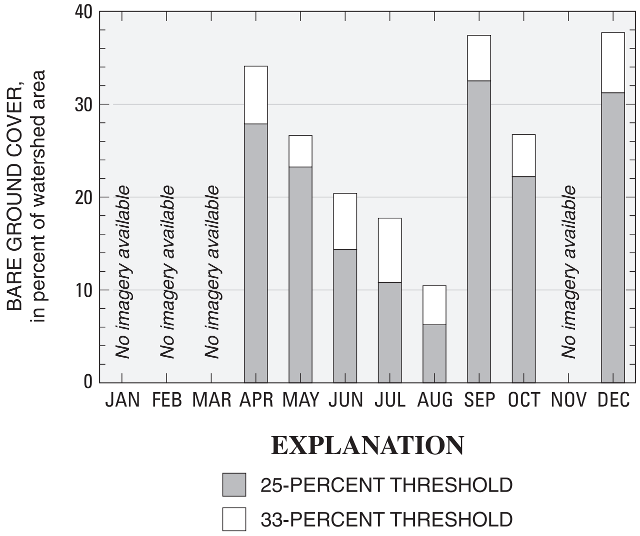

Figure 14. Monthly averages of bare ground cover derived from 15 different Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) scenes, April 9, 2000–December 6, 2006, for the Little Conestoga Watershed, Pennsylvania, at 25- and 33-percent thresholds. [Satellite imagery was not available for January, February, March, and November.]

Table 3. Satellite imagery analysis of bare ground in the Little Conestoga Creek watershed, April 9, 2000 through December 6, 2006.

[Satellite imagery was not available for November, January, and February.]

Date of scene	Number of pixels at 25-percent threshold	Percent of watershed in bare ground at 25-percent threshold	Number of pixels at 33-percent threshold	Percent of watershed in bare ground at 33-percent threshold
4/9/2000	151,717	24.6	203,505	33.1
5/11/2000	145,657	23.7	165,078	26.8
4/28/2001	143,580	23.3	170,280	27.7
10/5/2001	152,639	24.8	178,255	29.0
5/10/2002	151,006	24.5	173,143	28.1
6/18/2002	93,950	15.3	130,435	21.2
7/20/2002	66,443	10.8	109,202	17.7
4/2/2003	240,906	39.1	276,082	44.8
8/24/2003	32,601	5.3	51,649	8.4
10/11/2003	120,423	19.6	150,538	24.5
4/20/2004	150,788	24.5	189,729	30.8
5/6/2004	134,256	21.8	153,801	25.0
6/23/2004	83,326	13.5	120,469	19.6
8/13/2005	44,079	7.2	76,746	12.5
9/30/2005	200,354	32.5	230,137	37.4
12/6/2006	192,809	31.3	232,251	37.7

Sediment Sources and Transport in Selected Small Watersheds

Sediment source results are presented for the Pocomoke River Watershed near Willards, Maryland; Mattawoman Creek near Pomonkey, Maryland; and the Little Conestoga Creek near Millersville, Pennsylvania. Results of ^{137}Cs inventories to quantify upland erosion rates are presented for the Pocomoke River and Little Conestoga Creek.

Pocomoke River Watershed

Results are presented in this section on soil erosion using ^{137}Cs, sediment transport, and sediment source analysis in the Pocomoke River Watershed.

Erosion Rates Using Cesium-137

Using the ^{137}Cs technique (Walling and He, 1997), three reference sites (two forested and one cemetery) and five cropland sites (three soy and two corn fields) were cored to determine erosion and deposition rates in and near the Pocomoke River Watershed (fig. 15; table 4). The forested reference sites had trees that appeared to be older than 50 years. The cemetery site, located on a farm, had headstones from the early 20th Century and appeared undisturbed. Soil cores in the cropland and forested sites were taken in increments ranging from 3 to 18 cm, and to depths ranging from 24 to 48 cm (table 4). Profiles of the ^{137}Cs distribution with depth are shown in figure 16. The two forested reference sites had an organic, leafy layer from 0–8 cm deep that was not used in the ^{137}Cs analysis. The majority of ^{137}Cs activity at all reference sites was between 8 to 20 cm. Below this depth, activity decreases exponentially. The wide range of ^{137}Cs activity with depth at the three reference sites may indicate that the soil has been mixed, presumably from biologic activity. Although the three reference sites do not show a typical exponential decrease with depth, it is assumed that no erosion has occurred at these sites. The average ^{137}Cs inventory from all reference sites was 2,729 Bq/m^2, ranging from 2,265 to 3,212 Bq/m^2 (table 4).

Erosion and deposition rates were determined for the five cropland sites (equation 7). In the cropland sites, a noticeable change in soil structure occurred at 24 cm, which was

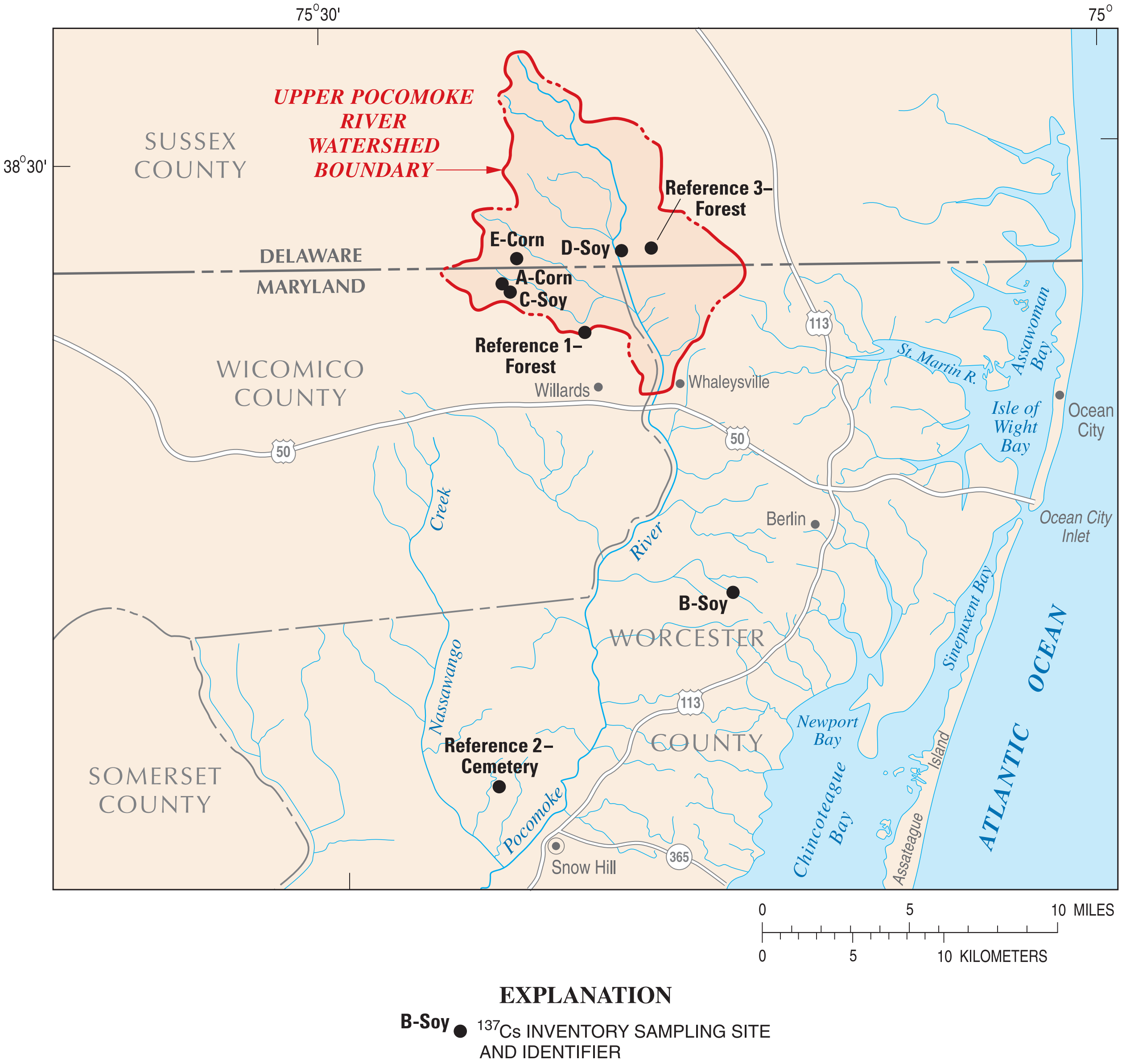

Figure 15. Location of cesium-137 inventory samples in the Pocomoke River Watershed. [Samples collected from October 3, 2001 to August 6, 2002.]

Table 4. Results of cesium-137 technique for selected cropland sites in the Pocomoke River Watershed.

[Site locations are shown in figure 15. Samples collected from October 3, 2001 to August 6, 2002. cm, centimeters; ^{137}Cs, cesium-137; Bq/m^2, becquerels per square meter; g/cm^3, grams per cubic centimeter; kg/m^2, kilograms per square meter; Mg/ha/yr, megagrams per hectare per year]

Site Identifier	Sampling date	Depth of core (cm)	Total ^{137}Cs activity (Bq/m^2)	Average bulk density[1] (g/cm^3)	Mass depth[2] (kg/m^2)	Mass Balance Model II results[3] (Mg/ha/yr) (+ = aggradation)
REF 1-Forest reference site	10/4/2001	38	3,212	1.01		
REF 2-Cemetery reference site	10/4/2001	24	2,710	1.04		
REF 3-Forest reference site	8/6/2002	26	2,265	0.77		
Reference site average			**2,729**			
A-Corn	10/3/2001	24	8,209	1.09	261.6	140.1
B-Soy	10/4/2001	24	3,174	1.07	256.8	11.3
C-Soy	7/25/2002	40	1,842	1.36	295.6	-13.2
D-Soy	8/6/2002	28	631	1.00	148.7	-50.7
E-Corn	8/6/2002	48	3,588	1.26	320.7	23.5
Cropland Average						**22.2**

[1] Average bulk density for the forested site is an average of the bulk density for all increments.

[2] Based on a tillage depth of 24 cm.

[3] γ, the proportion of the annual ^{137}Cs input susceptible to removal by erosion, is estimated using equation (8) on page 25 as 0.76.

used as the plow depth. The value of γ (proportion of the annual ^{137}Cs input susceptible to removal by erosion; equation 9) was determined using the core at Corn E (fig. 15), which showed a ^{137}Cs activity higher than the reference value and ^{137}Cs activity below the plow layer, was estimated at 0.76. The Mass Balance 2 model predicted erosion at Soy C (13.2 Mg/ha/yr, Megagrams per hectare per year) and Soy D (50.7 Mg/ha/yr) and deposition at Corn A (140.1 Mg/ha/yr), Soy B (11.3 Mg/ha/yr), and Corn E (23.5 Mg/ha/yr) (table 4).

Results from the ^{137}Cs technique indicate that erosion and deposition are both occurring on cropland fields in the Pocomoke River Watershed. There are, however, limitations to this technique. Although the collection of the ^{137}Cs data was detailed with respect to depth, a robust spatial sampling scheme was lacking. The slopes of the sampled cropland fields are low, but even in low slope environments, ^{137}Cs activity may be highly variable. Bachhuber and others (1987) determined that the ^{137}Cs activity in 100 samples collected in a cropland site in Germany (150 m by 100 m), ranged from 4.8 to 17 Bq/kg and averaged 7.45 Bq/kg. A more satisfactory sampling scheme in the Pocomoke River Watershed would involve capturing the spatial variability of ^{137}Cs.

Sediment Transport in the Pocomoke River

Suspended-sediment loads were computed for water years 2001 through 2003 using a regression model of daily mean discharge (m^3/s) to suspended-sediment load (Mg) (Appendix A1). The average water-year discharge at the Pocomoke River near Willards, Maryland for the period of study (2001–03) was 2.13 m^3/s, which was within 2 percent of the historical average water-year discharge (1951–2004) of 2.09 m^3/s (USGS-National Water Information System-Web Interface Database; NWIS, 2007). Therefore, streamflow conditions during the period of study were close to historical averages.

The low suspended-sediment concentrations of this Coastal Plain river are apparent in the sediment-transport curve shown in figure 17. Even during high-flow events, suspended-sediment concentrations seldom were above 100 mg/L. The average annual suspended-sediment load for water years 2001 through 2003 was 3,360 Mg/yr or 21.5 Mg/km^2/yr. Comparison of the Pocomoke River Watershed sediment yield of 21.5 Mg/km^2/yr to the average sediment yield for other Coastal Plain streams (average = 11.9 Mg/km^2/yr; table 1), indicates that it is a high sediment-yielding stream relative to other Coastal Plain streams (table 1).

Sediment Source Assessment Using Sediment Fingerprints in the Pocomoke River

At the Pocomoke River near Willards, Maryland, seven runoff event suspended-sediment samples were collected for sediment-source analysis during water years 2001 through 2003 (tables 5a, b). Samples for six of the seven events were collected from 2 to 21 hours after the peak flow (table 5a). The

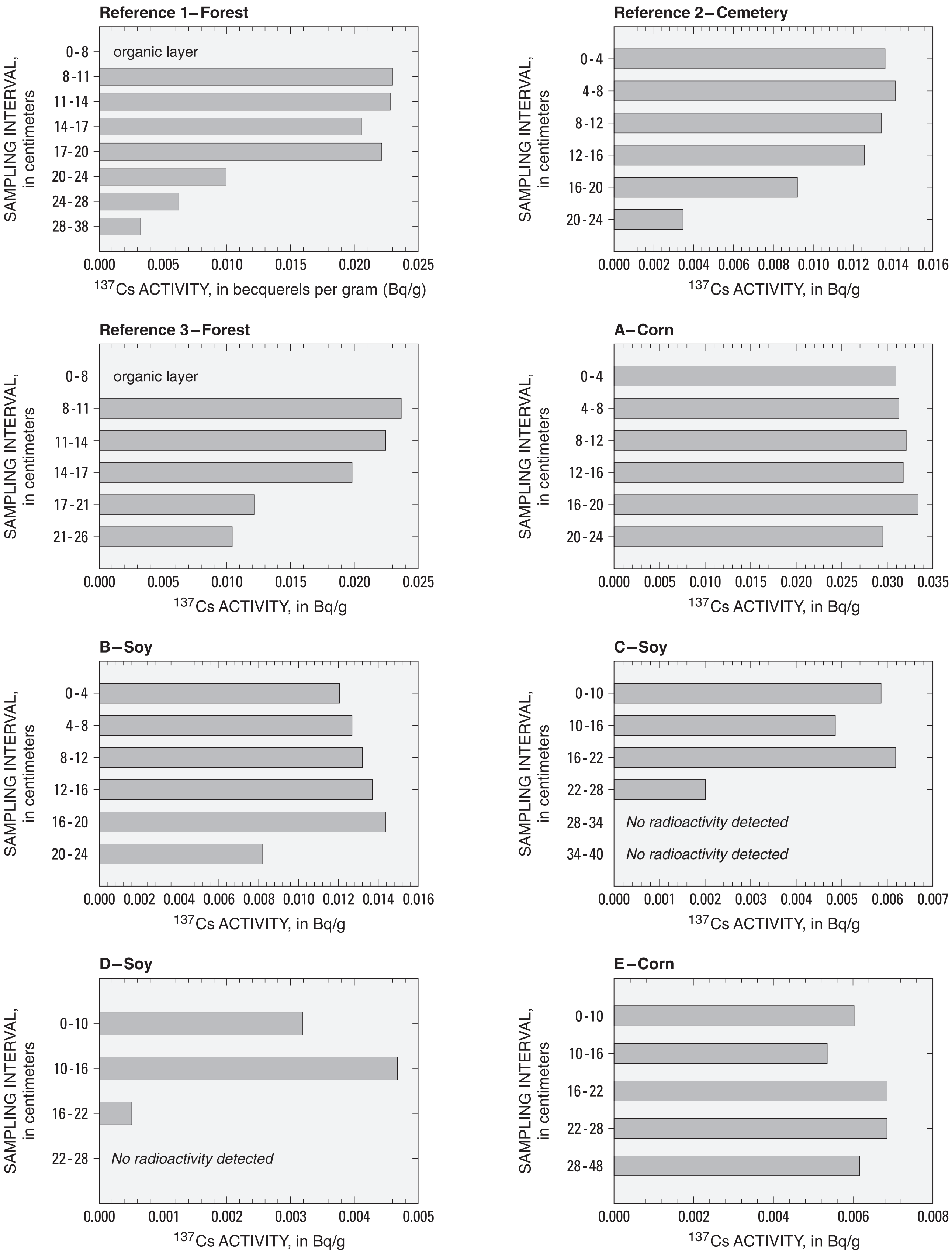

Figure 16. Cesium-137 profiles with depth for soil cores taken at eight sites in and near the Pocomoke River Watershed, Maryland and Delaware. [See figure 15 for location of soil profiles.]

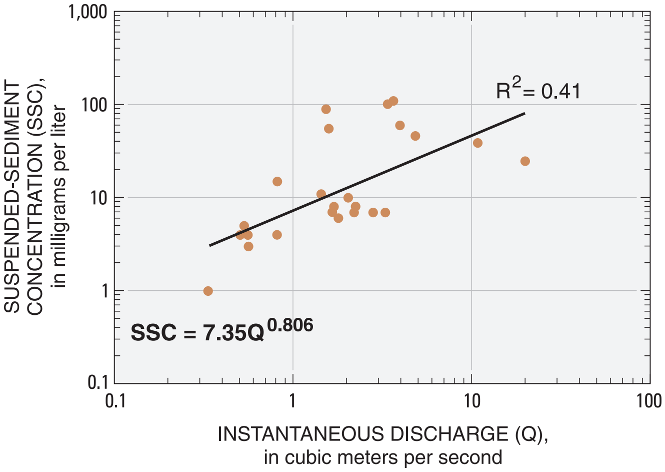

Figure 17. Sediment-transport curve for U.S. Geological Survey streamflow-gaging station 01485000, in the Pocomoke River near Willards, Maryland, during water years 2001–2002.

sediment sample for the event on November 6, 2002 was collected 6½ hours before the peak flow (table 5a). The samples on August 29 and 30, 2002 were collected for the same runoff event (August 28–30, 2002) but because the samples were collected 17 hours apart, the sediment sources for these samples are not averaged but are determined separately.

To determine the sediment sources for these 7 events, 43 samples from 5 source areas (main stem Pocomoke River channel banks, ditch banks, ditch beds, croplands, and forest) were taken at n = 3, 6, 8, 22, and 4 sites, respectively (fig. 18; table 6). The amount of sand in the Pocomoke River Watershed source samples was high, averaging 81 percent ± 23 percent for banks, 89 percent for ditch beds, 87 percent for croplands, and 94 percent for forest (table 6). The high sand content in the source samples reflects the high sand composition of the Coastal Plain sediments.

The low suspended-sediment concentrations in the Pocomoke River provided low mass for chemical analyses. Three grams was determined as the lowest mass suitable for ^{137}Cs analysis (Gerald Matisoff, Case Western Reserve University oral commun., 2003). Three of the seven fluvial samples had mass below 3 g and therefore, ^{137}Cs was not used as a tracer in the Pocomoke River. For three of the fluvial samples, unsupported ^{210}Pb activity was not detected and a value of 0.0001 was assigned to these samples. Since there was no detected unsupported ^{210}Pb activity, it was not possible to report error terms for these samples (table 5b). Unsupported ^{210}Pb for 1 fluvial sample (August 30, 2002) (table 5b) had an error term that was greater than the unsupported ^{210}Pb activity for that sample and was removed from sediment source analysis. The high error may be related to mass, counting time, and activity (see equation 3). RSIL analysis for a subset of Pocomoke samples showed that $w(C_T)$ was not significantly different than $w(C_O)$, as shown in table 7, and the appropriate tracers to be used in this watershed were $w(C_T)$ and $\delta^{13}C_T$.

Examination of the fluvial tracers compared to the source samples showed that the measured values for two tracers, $w(P)$ and $w(C_I)$: $w(N)$ were outside the range of measured source values in six and five cases, respectively. These tracers were determined not to be conservative tracers and therefore were not used. One fluvial sample collected on November 6, 2002 had a $\delta^{15}N$ value that was outside the range of the source $\delta^{15}N$ values, but it was within the range of measurement error and was retained. Results for one fluvial sample—that of August 29, 2002—had an outlier for unsupported ^{210}Pb, and unsupported ^{210}Pb was not used in the analysis for this date. A Kruskal-Wallis test performed for each of the remaining five potential tracers (unsupported ^{210}Pb, $w(C_T)$, $w(N)$, $\delta^{13}C_T$, and $\delta^{15}N$) for the five sources confirmed that there were statistically significant differences between the medians of the measured tracer values in the five source areas (table 8).

Results of the Tukey test indicated that the Pocomoke River main-stem banks and the ditch bank could not be distinguished by any of the five remaining tracers. The Pocomoke River main-stem banks and the ditch bank samples were combined into one source (banks). Results of the Tukey test indicated that the five tracers could distinguish between the four sources (main stem and ditch banks, cropland, forest, and ditch beds) in the Pocomoke River (table 9). Using the Tukey test at a significance level of 0.05, the five tracers could distinguish between all sources except ditch bed and banks. When the significance level was raised to 0.07, unsupported ^{210}Pb distinguished between ditch beds and banks (table 9).

Both $w(N)$ and $w(C_T)$ identified the same sources. Results of Spearman's Rho showed a high correlation between $w(N)$ and $w(C_T)$ (correlation coefficient = 0.90; ρ less than 0.0001), so that use of both tracers was redundant. Since there is greater precision and accuracy in the analysis of $w(C_T)$ than $w(N)$ (Nancy Simon, USGS, written commun., 2006), $w(N)$ was eliminated. The number of tracers remaining after the Tukey test was $T = 4$ (unsupported ^{210}Pb, $w(C_T)$, $\delta^{13}C_T$, and $\delta^{15}N$).

Results of the unmixing model for the four tracers showed variations in sediment sources with respect to flow, sediment loads, and time of year (fig. 19; table 10). Averaging sediment sources for the seven events indicated that the channel corridor (channel and ditch banks, and ditch beds) were important sources of sediment (76 percent) (table 10). Weighting the sources by the sediment transported for each sampled event showed that cropland (46 percent) was the most important source of sediment, followed by the channel corridor (channel and ditch banks and ditch beds; 41 percent). Cropland was an important source of sediment for the two highest peak-flow events, the two highest event daily-mean discharges, and the two highest sediment-loading events (September 2, 2002 and November 18, 2002) (fig. 19; table 10). For all events, except for November 6, 2002, ditch beds were a source of sediment. Forest contributed sediment during the

Table 5a. Hydrologic characteristics for sampled flow events in the Pocomoke River near Willards, Maryland, water years 2001–03.

[m^3/s, cubic meters per second; Mg, megagrams; <, less than]

Sample date	Sample time[1]	Discharge at time of sample (m^3/s)	Dates of runoff event	Daily mean discharge of event period (m^3/s)	Total sediment load for event period (Mg)	Weighted value = event sediment load divided by cumulative load of all events	Peak flow (date and time[1])	Peak flow, (m^3/s)	Peak flow recurrence interval (years)
7/19/2001	1000	1.59	7/18–20/2001	0.86	1.3	0.0024	7/19/2001 0800	1.61	<1.05
3/21/2002	0945	3.03	3/20–22/2002	2.21	7.0	0.0132	3/21/2002 0500	3.14	<1.05
[2]8/29/2002	1615	0.29	8/28–30/2002	0.17	0.06	0.0001	8/29/2002 1200	0.31	<1.05
[2]8/30/2002	0900	0.17	8/28–30/2002	0.17	0.06	0.0001	8/29/2002 1200	0.31	<1.05
9/2/2002	1115	20	9/1–5/2002	10.16	237	0.4458	9/2/2002 0900	20.0	2.00
11/6/2002	1139	6.32	11/6–8/2002	5.25	34.2	0.0643	11/6/2002 1800	7.22	<1.05
11/18/2002	1515	15.7	11/16–20/2002	11.12	252	0.0024	11/18/2002 0400	16.2	1.40
Summed sediment load					**531.62**				

[1] Eastern Standard Time

[2] Samples on 8/29/2002 and 8/30/2002 were collected during the same runoff event.

Table 5b. Tracer properties of fluvial sediment samples in the Pocomoke River near Willards, Maryland.

[Bq/g, becquerels per gram; w, mass fraction by weight; C_T, total carbon; N, nitrogen; P, phosphorus; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; ---, not reported; %, percent; ‰, per mil]

Sample date	Sample time[1]	Unsupported lead-210 (Bq/g)	Error in unsupported lead-210 (Bq/g)	$w(C_T)$ (%)	$w(N)$ (%)	$w(C_T) : w(N)$	$w(P)$ (%)	$\delta^{13}C_T$ (‰)	$\delta^{15}N$ (‰)
7/19/2001	1000	0.0001	---	11.72	1.02	11.49	0.601	-27.29	10.99
3/21/2002	0945	0.0001	---	11.4	0.93	12.258	0.343	-27.88	8.64
[2]8/29/2002	1400	0.47	0.113	12.6	1.36	9.265	0.627	-27.41	8.72
[2]8/30/2002	0900	0.0001	0.151	8.17	1.1	7.427	0.577	-26.65	8.37
9/2/2002	1115	0.098	0.031	11.4	1.37	8.321	0.937	-25.48	7.6
11/6/2002	1130	0.116	0.011	11.3	1.55	7.29	0.62	-27.4	11.85
11/18/2002	1515	0.041	0.011	8.48	0.89	9.528	0.651	-26.1	9.08

[1] Eastern Standard Time

[2] Samples on 8/29/2002 and 8/30/2002 were collected during the same runoff event.

Table 6. Tracer properties of upland source sediment samples collected in the Pocomoke River Watershed, water years 2001–03.

[Site locations are shown in figure 18. Sand is defined as sediment that has a diameter greater than 0.062 millimeters. Unsupported lead-210 analyses were determined at Case Western University, unless indicated by "*," where samples were run at the U.S. Geological Survey Denver facilities; Bq/g, becquerels per gram; *w*, mass fraction; C_T , total carbon; N, nitrogen; P, phosphorus; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent; ‰, per mil]

Site identifier	Sand % (%, dry weight)	Unsupported lead-210 (Bq/g)	Error in unsupported lead-210 (Bq/g)	$w(C_T)$ (%)	$w(N)$ (%)	$w(C_T) : w(N)$	$w(P)$ (%)	$\delta^{13}C_T$ (‰)	$\delta^{15}N$ (‰)
Ditch Bank									
B2	29.3	0.045*	0.2	6.67	0.50	13.34	0.10	-27.59	6.02
B1	89.2	0.062	0.0088	9.72	0.75	12.96	0.09	-26.78	5.56
B9	80.3	0.082*	0.2	8.76	0.63	13.90	0.20	-27.76	6.92
B3	57.3	0.012*	0.2	5.19	0.54	9.61	0.11	-27.08	5.50
B7	93.9	0.085	0.0112	11.80	1.09	10.83	0.38	-27.65	10.58
B6	93.6	0.030	0.0078	7.45	0.59	12.63	0.20	-27.67	6.47
B8	94.7	0.034	0.0051	7.86	0.66	11.91	0.13	-26.79	8.11
B4	96.8	0.035	0.0064	7.78	0.55	14.15	0.26	-27.61	6.80
B5	95.8	0.014	0.0063	4.99	0.30	16.63	0.07	-27.49	4.57
Average	**81.2**	**0.044**		**7.80**	**0.62**	**12.88**	**0.17**	**-27.38**	**6.73**
Standard error	**7.71**	**0.0089**		**0.71**	**0.07**	**0.68**	**0.03**	**0.13**	**0.59**
Ditch Bed									
D3	52.3	0.027	0.0091	5.76	0.44	13.09	0.10	-28.64	8.28
D4	99.4	0.011	0.0107	5.96	0.35	17.03	0.09	-29.02	7.24
D2	86.3	0.018	0.0016	3.91	0.28	13.96	0.09	-29.05	6.63
D5	92.9	0.003*	0.2	1.08	0.08	13.50	0.03	-25.95	9.80
D8	98.6	0.0001	NA	4.71	0.36	13.08	0.15	-28.46	8.74
D6	99.2	0.049	0.0052	9.67	0.91	10.63	0.20	-26.71	8.37
D1	87.5	0.022	0.0038	7.80	0.71	10.99	0.21	-27.23	9.83
D7	96.0	0.008	0.0085	11.00	0.91	12.09	0.49	-26.40	9.22
Average	**89.0**	**0.017**		**6.24**	**0.51**	**13.05**	**0.17**	**-27.68**	**8.51**
Standard error	**5.23**	**0.0056**		**1.13**	**0.11**	**0.71**	**0.05**	**0.44**	**0.40**
Crop Area									
C8	91.1	0.104*	0.2	6.84	0.67	10.21	0.54	-22.44	10.26
C11	77.2	0.067*	0.2	4.99	0.36	13.86	0.15	-24.20	8.81
C3	80.9	0.021*	0.2	2.90	0.25	11.60	0.17	-22.67	11.54
C10	90.6	0.034*	0.2	10.20	0.75	13.60	0.36	-24.49	8.54
C4	87.8	0.135*	0.2	6.95	0.52	13.37	0.21	-24.21	6.44
C6	76.5	0.041*	0.2	14.20	0.76	18.68	0.12	-26.60	4.85
C5	87.7	0.032	0.0067	6.94	0.56	12.39	0.24	-24.88	7.05
C9	77.3	0.022*	0.2	3.31	0.30	11.03	0.14	-24.72	9.57
C7	85.2	0.030*	0.2	6.03	0.39	15.46	0.17	-24.21	7.51
C2	89.6	0.087*	0.2	6.12	0.58	10.55	0.39	-23.51	8.70
C2	92.4	0.142*	0.2	7.17	0.65	11.03	0.36	-23.74	8.31
C2	91.4	0.087	0.0054	6.60	0.61	10.82	0.35	-23.38	7.92
C16	81.9	0.066*	0.2	8.36	0.63	13.27	0.49	-24.08	10.11

Table 6. Tracer properties of upland source sediment samples collected in the Pocomoke River Watershed, water years 2001–03.—Continued

[Site locations are shown in figure 18. Sand is defined as sediment that has a diameter greater than 0.062 millimeters. Unsupported lead-210 analyses were determined at Case Western University, unless indicated by "*," where samples were run at the U.S. Geological Survey Denver facilities; Bq/g, becquerels per gram; *w*, mass fraction; $\mathrm{C_T}$, total carbon; N, nitrogen; P, phosphorus; $\delta^{13}\mathrm{C_T}$, stable isotopic total carbon-13; $\delta^{15}\mathrm{N}$, stable isotopic nitrogen-15; %, percent; ‰, per mil]

Site identifier	Sand % (%, dry weight)	Unsupported lead-210 (Bq/g)	Error in unsupported lead-210 (Bq/g)	$w(\mathrm{C_T})$ (%)	$w(\mathrm{N})$ (%)	$w(\mathrm{C_T}) : w(\mathrm{N})$	$w(\mathrm{P})$ (%)	$\delta^{13}\mathrm{C_T}$ (‰)	$\delta^{15}\mathrm{N}$ (‰)
C12	82.4	0.057*	0.2	8.22	0.58	14.17	0.37	-25.23	10.64
C14	89.9	0.078	0.0094	6.67	0.55	12.13	0.17	-23.40	7.52
C15	93.4	0.143*	0.2	7.34	0.65	11.29	0.38	-22.71	8.30
C13	86.6	0.029*	0.2	7.46	0.61	12.23	0.26	-24.92	10.66
C17	89.2	0.056*	0.2	6.69	0.65	10.29	0.46	-22.82	11.06
C18	84.5	0.053*	0.2	8.74	0.55	15.89	0.23	-25.11	6.94
C20	90.3	0.045*	0.2	8.28	0.67	12.36	0.51	-23.22	10.55
C19	91.7	0.048*	0.2	7.13	0.71	10.04	0.53	-23.30	11.32
C1	95.8	0.113	0.0077	10.20	0.79	12.91	0.38	-24.28	7.40
Average	**87.0**	**0.068**		**7.33**	**0.58**	**12.60**	**0.32**	**-24.01**	**8.82**
Standard error	**1.18**	**0.0083**		**0.50**	**0.03**	**0.45**	**0.03**	**0.22**	**0.38**
				Forest Area					
F1	93.5	0.123	0.0056	17.10	1.14	15.00	0.04	-27.62	-0.75
F3	91.6	0.149	0.0118	22.60	1.20	18.83	0.03	-27.51	-2.06
F4	96.3	0.146	0.0143	24.80	1.38	17.97	0.07	-26.15	-0.47
F2	94.3	0.184	0.0077	22.80	1.72	13.26	0.06	-27.79	-1.67
Average	**93.9**	**0.150**		**21.83**	**1.36**	**16.27**	**0.05**	**-27.27**	**-1.24**
Standard error	**0.97**	**0.0126**		**1.65**	**0.13**	**1.30**	**0.01**	**0.38**	**0.38**

Table 7. Summary of samples collected in the Pocomoke River Watershed of mass fraction (*w*) and isotope (δ) analyses for total carbon ($\mathrm{C_T}$), organic carbon ($\mathrm{C_O}$) and inorganic carbon ($\mathrm{C_I}$).

[Site locations are shown in figure 18. The value of $w(\mathrm{C_I})$ is calculated as $w(\mathrm{C_I}) = [w(\mathrm{C_T}) - w(\mathrm{C_O})]$, but the calculated value $w(\mathrm{C_I})$ is set equal to 0.0 when $[w(\mathrm{C_I}) / w(\mathrm{C_T})] \leq 0.05$ because there is a ±5% uncertainty in the value of $w(\mathrm{C_O})$. *w*, mass fraction by weight; $\mathrm{C_T}$, total carbon; $\delta^{13}\mathrm{C_T}$, stable isotopic total carbon-13; $\mathrm{C_O}$, organic carbon; $\delta^{13}\mathrm{C_O}$, stable isotopic organic carbon-13; $\mathrm{C_I}$, organic carbon; %, percent; ‰, per mil]

Sample identifier	Sample location	$w(\mathrm{C_T})$ (%)	$\delta^{13}\mathrm{C_T}$ (‰)	$w(\mathrm{C_O})$ (%)	$\delta^{13}\mathrm{C_O}$ (‰)	$w(\mathrm{C_I}) / w(\mathrm{C_T})$	$w(\mathrm{C_I})$ (%)
B8	Ditch bank	9.28	-26.75	9.37	-26.60	-0.01	0.0
C1	Crop	10.59	-24.24	10.71	-25.04	-0.01	0.0
F4	Forest	34.14	-26.11	35.31	-25.84	-0.03	0.0
11122004	Fluvial	8.41	-27.33	8.19	-27.59	0.03	0.0

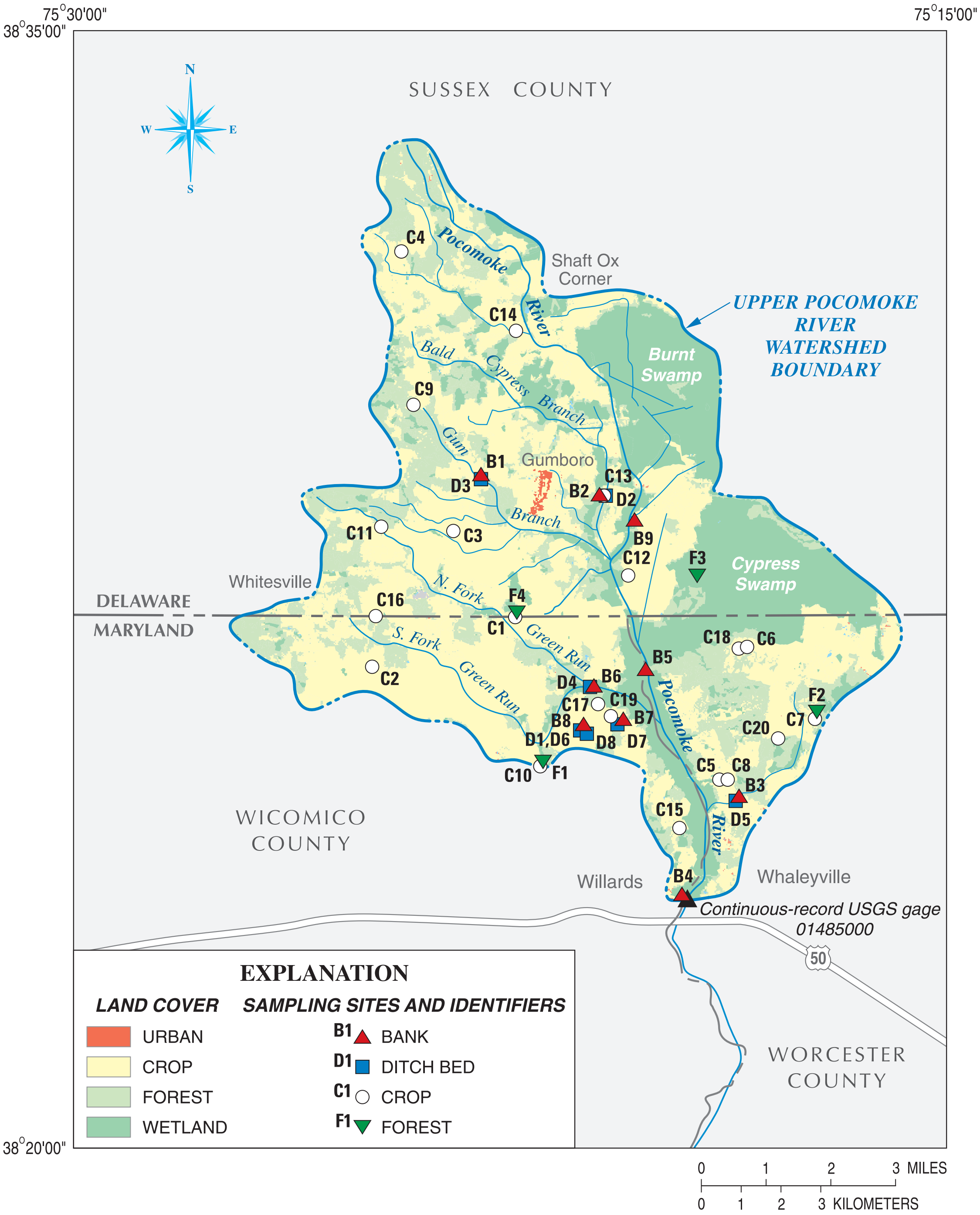

Figure 18. Location of sediment source sampling sites in the Pocomoke River Watershed above Willards, Maryland. [Samples were collected between May 14, 2001 and November 12, 2004. Land cover from U.S. Geological Survey National Land Cover Database (NLCD)].

Table 8. Median values within source areas in the Pocomoke River Watershed and test statistics for tracers for which the Kruskal-Wallis test for equality of medians among source areas was rejected.

[Bq/g, becquerels per gram; *w*, mass fraction by weight; C_T , total carbon; N, nitrogen; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent; ‰, per mil]

Sample location	Number of samples	Unsupported lead-210 (Bq/g)	$w(C_T)$ (%)	w(N) (%)	$\delta^{13}C_T$ (‰)	$\delta^{15}N$ (‰)
			Median Values			
Ditch bank	9	0.035	7.78	0.59	-27.59	6.47
Ditch bed	8	0.014	5.86	0.40	-27.85	8.56
Crop	22	0.056	7.04	0.61	-24.14	8.62
Forest	4	0.148	22.70	1.29	-27.57	-1.21
			Test Statistics			
H value		21.4	12.2	11.3	30.7	18.0
Critical value		7.81	7.81	7.81	7.81	7.81
ρ-value		8.82E-05	6.81E-03	1.02E-02	9.72E-07	4.33E-04
Reject or accept the null hypothesis of equality of medians		Reject	Reject	Reject	Reject	Reject

Table 9. Results (probability values) of Tukey test performed between source areas within the Pocomoke Watershed for those tracers which passed the Kruskal-Wallis test screening.

[*w*, mass fraction by weight; C_T , total carbon; N, nitrogen; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; <, less than; %, percent; ‰, per mil]

Tracer compared between source areas	Ditch bed	Crop	Forest
	Unsupported lead-210		
Bank	0.073	0.308	<0.01
Ditch bed		<0.01	<0.01
Crop			0.016
	$w(C_T)$ (%)		
Bank	0.505	0.917	0.039
Ditch bed		0.730	<0.01
Crop			<0.01
	w(N) (%)		
Bank	0.874	1.000	0.019
Ditch bed		0.810	<0.01
Crop			<0.01
	$\delta^{13}C_T$ (‰)		
Bank	0.992	<0.01	1.000
Ditch bed		<0.01	0.990
Crop			<0.01
	$\delta^{15}N$ (‰)		
Bank	0.093	<0.01	0.220
Ditch bed		0.969	<0.01
Crop			<0.01

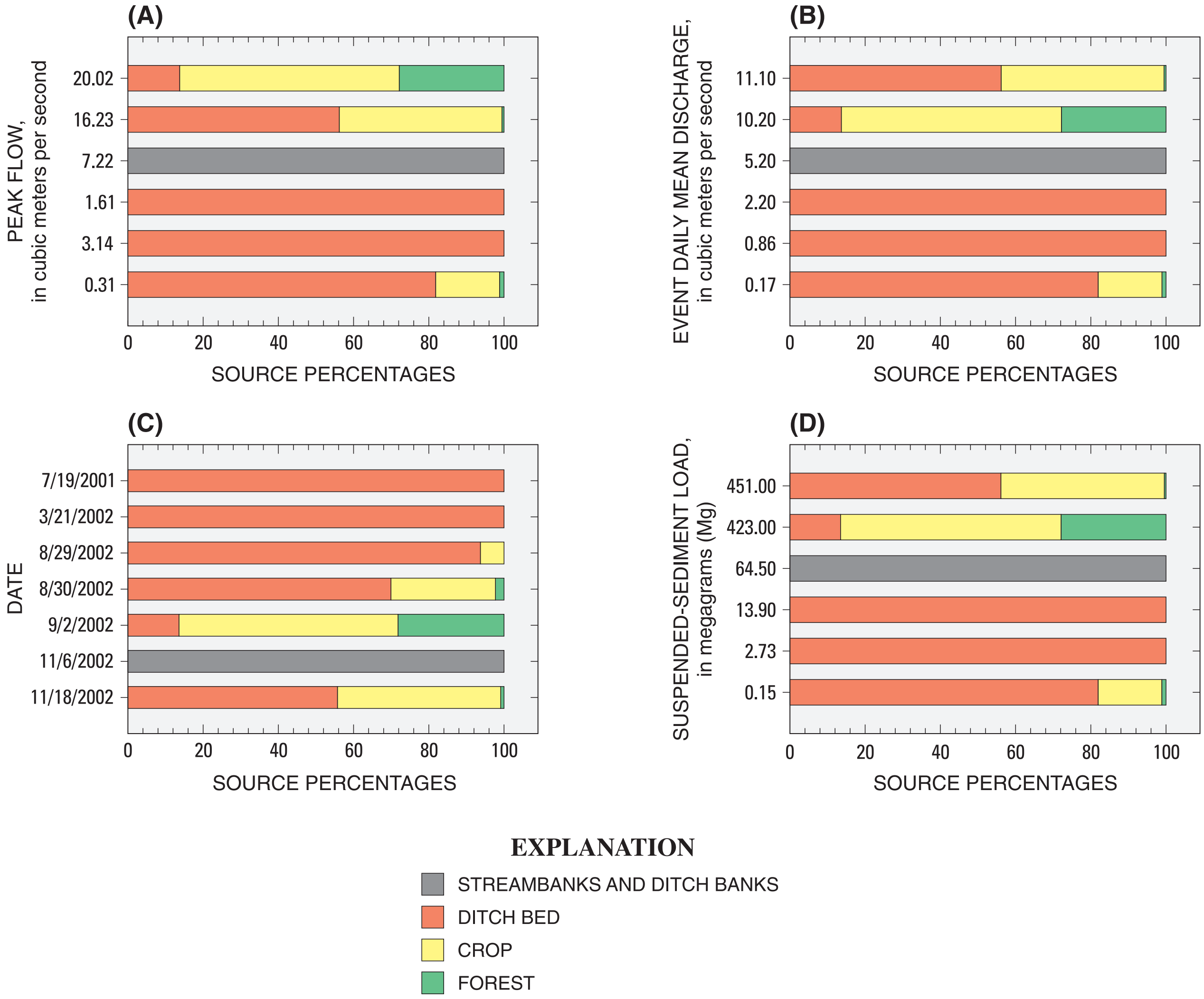

Figure 19. Sediment sources for the Pocomoke River showing sediment sources by (A) peak flow of sampled event, (B) daily mean discharge for sampled event, (C) ascending order of day and month sampled, and (D) suspended-sediment load for sampled runoff event. [For plots A, B, and D, samples on August 29 and 30, 2002 were collected for the same runoff event and the sediment sources were averaged.]

Table 10. Unmixing model results for the Pocomoke River Watershed showing sediment sources (in percent) for sampled storms using four tracers: unsupported lead-210, $w(C_T)$, $\delta^{13}C_T$, and $\delta^{15}N$.

[w, mass fraction by weight; C_T, total carbon; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent]

Sample date	Banks (%)	Bed (%)	Crop (%)	Forest (%)	Error
7/19/2001	0	100	0	0	3.72
3/21/2002	0	100	0	0	2.09
[1]8/29/2002	0	94	6	0	2.18
[1]8/30/2002	0	70	28	2	0.59
9/2/2002	0	14	58.5	27.5	2.37
11/6/2002	100	0	0	0	5.46
11/18/2002	0	56	44	0	1.14
Average	**14**	**62**	**20**	**4**	**2.51**
Sediment weighted average	**7**	**34**	**46**	**13**	

[1] Source analysis for this date did not include unsupported lead-210.

highest peak-flow event, which had a weighted average of 13 percent (fig. 19; table 10). Ditch banks and streambanks were an important source of sediment for the third highest peak flow, third highest event daily mean discharge, and third highest sediment load, and contributed a weighted average of 7 percent (fig. 19).

Sediment is detached through intense rainfall events and transported by overland flow (runoff) (Toy and others, 2002). Periods of significant overland flow are rare in the upper Pocomoke River Watershed, occurring only 20 percent of the time when flows exceed 2.83 m^3/s (Ator and others, 2005). Analysis of storm-generated hydrographs by Ator and others (2005) indicated that over 70 percent of the streamflow in the Pocomoke River is from ground-water discharge. Infrequent periods of overland flow in the Pocomoke River Watershed limit upland areas (cropland and forest) as significant sources of sediment, except during periods of high rainfall intensity or under saturated-soil conditions when overland flow may occur. Examination of the sampled events showed that four of the events had a peak flow greater than 2.83 m^3/s (table 5a), but only two of these events (September 2, 2002 and November 18, 2002) showed upland areas (cropland and forest) as a sediment source (fig. 19; table 10). The two other events, March 21, 2002 and November 6, 2002, showed the ditch bed and banks, respectively, as important sources.

Suspended-sediment concentrations change across the storm hydrograph in many rivers. This is thought to reflect changes in sediment sources and sediment exhaustion (Walling and Webb, 1982; Carter and others, 2003). In the Pocomoke River, only one sample was collected before the peak, on November 6, 2002, and showed banks (main stem and ditch banks) as the most important sediment source (table 10). Lawler (2005) examined the timing of streambank erosion for two events in the River Wharfe, United Kingdom. Erosion for one event in November 1996, occurred on the rising limb around the peak flow. The other event occurred in February 1997 and resulted in bank erosion on the recessional limb. Differences in the timing of bank erosion are related to a variety of factors including flow conditions, bank material composition, and antecedent soil moisture conditions (Knighton, 1984). The contribution of streambank sources in the Pocomoke River before the peak flow may reflect their shorter travel distances.

Seasonality may also be an important factor contributing sediment for the two highest discharge events. Corn and soy, which are grown in the Pocomoke River Watershed, are harvested starting in late summer. The reduced vegetative cover and increase in bare ground after harvesting combined with a large rainfall event would make this a likely sediment source. The highest peak flows of the seven sampled events occurred in early September (September 2, 2002) during this harvesting period, and the second highest peak flow occurred in November (November 6, 2002), when the ground may have been bare (table 5a). The availability of sediment combined with a large runoff event is the likely reason why cropland is an important sediment source for the two highest runoff events.

Ditches extend over a large area of the Pocomoke River Watershed. A GIS coverage of ditches was obtained for the Pocomoke River Watershed from the Wicomico County, Maryland, Department of Planning, Zoning, and Community Development, and the Sussex County, Delaware, Division of Soil and Water Conservation (fig. 20). For Wicomico County, the ditch coverage was based on 2006 digital orthophotograph quarter quadrangles (DOQQs) at a scale of 1:1,200. For Sussex County, the ditch coverage was based on 2006 DOQQs at a scale of 1:4,800. Ditches that occur in the part of the Pocomoke River that drains within Worcester County, Maryland (29.3 km^2, 19 percent of the watershed area) were digitized

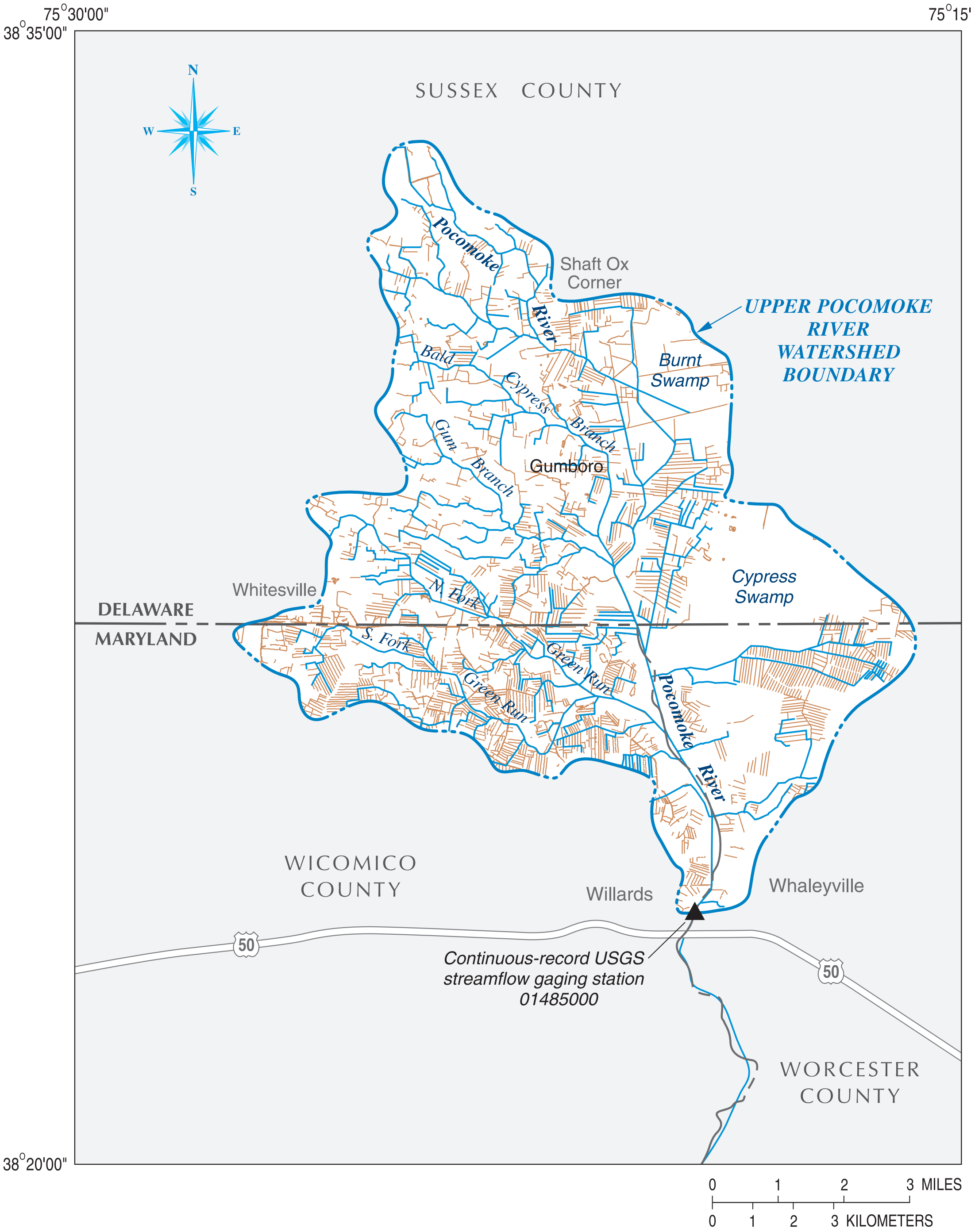

Figure 20. Extent of ditches (shown as brown lines) in the Pocomoke River Watershed above Willards, Maryland. [Ditches were obtained from 2005 Geographic Information System coverages for Wicomico County, Maryland (obtained from Wicomico County, Maryland, Department of Planning, Zoning and Community Development) and Sussex County, Delaware (obtained from Sussex County, Delaware, Division of Soil and Water Conservation). For parts of the Pocomoke River that drain within Worcester County, Maryland, ditches were digitized onto a Geographic Information System from interpretations of 2006 digital orthophotograph quarter quadrangles for Worcester County. Blue lines are streams that appear on 1:24,000 U.S. Geological Survey Topographic Quadrangles.]

in the USGS Maryland-Delaware-D.C. Water-Science Center from 2005 DOQQs at a 1-m resolution onto a GIS (fig. 20). Although the ditches can be observed clearly in the 2005 DOQQs, some of the older ditches are harder to discern if they are not maintained. The ditch coverages presented in figure 20 were not ground-truthed, thus, some error may exist in the accuracy of this coverage. In addition, new ditches may have been added since the DOQQs were taken.

Ditches in the Pocomoke River Watershed exist at several scales, from small ditches excavated in farm fields that may only have flowing water when it rains, to larger ditch systems that are perennial (fig. 20). A coverage of streams (blue lines) that appear on 1:24,000 USGS Topographic Quadrangles was obtained for the Pocomoke River Watershed (fig. 20). In the Pocomoke River Watershed, streams are 247 km in length, whereas ditches extend over 593 km in the watershed (fig. 20). Therefore, there are 346 km more ditches or more than twice (2.4 times) the amount of ditches than streams in the Pocomoke River Watershed. Many of the streams (blue lines in figure 20) and ditches have been channelized and are straight (fig. 20). Straight reaches of channels have higher slopes and higher total streampower available for erosion (Schumm and others, 1984). The tendency of straight channels to meander increases bank erosion (Schumm and others, 1984).

Ditches in the Pocomoke Watershed, at all scales, are initially dug and periodically maintained. Bell and Favero (2000) reported that sediment loads increase during the 10 to 20 years following ditch construction. In established (older) ditches, 90 percent of the sediment loss is attributed to significant rainfall events (Bell and Favero, 2000). Newell and Clark (2008) indicated that ditches in the Nassawango Creek Watershed, a tributary to the Pocomoke River, are initially excavated to a depth of 2 m, with steep banks. After excavation, the ditches respond by meandering and developing braided patterns, resulting in ditch widening and bank erosion (Newell and Clark, 2008). Sediment deposition can also occur in ditches. In North Carolina Coastal Plain ditches, deposition of sediment was observed in 75 percent of surveyed ditch cross sections (Lecce and others, 2006b). Erosion that did occur in the ditches was observed during the winter, during the dormant growing season, and after vegetation is removed for maintenance. Over time, the ditches may choke with vegetation and fill with sediment (Lecce and others, 2006b; Newell and Clark, 2008). At this stage, the ditch is re-excavated, and the cycle of erosion and sedimentation starts again. In North Carolina, re-excavation occurs every 10–15 years (Lecce and others, 2006b). Ditches as a source of sediment in the Pocomoke River Watershed may reflect this cycle of periodic excavation and bank erosion.

Forests contributed 28 percent for the highest peak flow event and 13 percent of the weighted average of all sources (table 10). Forests comprise almost 50 percent of the Pocomoke River Watershed. Timber harvesting activities were observed in the Pocomoke River Watershed during the study period. Estimates of timber harvesting area specifically for the Pocomoke River Watershed are not available, but estimates for the counties draining the Pocomoke River are available. In Wicomico County, Maryland an estimated 564 ha (hectares) were harvested annually between 1992–99, which represent 0.5 percent of the area of the county (Maryland Department of Natural Resources, 2007). In Sussex County, Delaware an estimated 683 ha were harvested annually between 1998 and 2005 or 0.2 percent of the county area (Maryland Department of Natural Resources, 2007). Timber harvesting operations in both counties consist of clear cutting and select harvesting. Although the area under timber harvesting in both counties is small, erosion and sediment problems associated with timber harvesting activities include dirt roads, stream crossings, and gullying, rilling, and sheetwash erosion on cleared slopes (Ryder and Edwards, 2005). It is possible that some of the sediment supplied from forests to the Pocomoke River may be related to timber harvesting activities or to overland flow and erosion of the forest floor, but additional studies are needed to confirm this.

Mattawoman Creek Watershed

Sediment transport and sediment source analysis results in Mattawoman Creek Watershed for water year 2004 are presented in this section.

Mattawoman Creek Sediment Transport

The average water-year discharge at the Mattawoman Creek near Pomonkey, Maryland for the period of study (2004) was 2.53 m^3/s, which was 57 percent higher than the historical average water-year discharge (1956–72 and 2002–06) of 1.61 m^3/s (USGS-NWIS Database, *http://waterdata.usgs.gov/nwis/sw*; last accessed on March 10, 2008). Therefore, streamflow conditions during the period of study were higher compared to historical averages. The transport curve for Mattawoman Creek shows that the majority of suspended-sediment concentrations (94 percent) are below 100 mg/L (fig. 21). The transport curve indicates that the relation of discharge to suspended-sediment concentration is poor for Mattawoman Creek. The scatter of data in figure 21 may be related to a tributary, Old Woman Creek, entering the channel just upstream of the sediment sampling station. Old Woman Creek drains a smaller area (14.9 km^2) than the main stem Mattawoman Creek above Old Woman Creek (134.5 km^2). The timing of the hydrograph at Old Woman Creek may be different than the timing of the hydrograph at Mattawoman Creek, which may deliver suspended sediment at different concentrations at different times compared to the main stem Mattawoman Creek, causing the scatter in the sediment-transport curve (fig. 21).

Turbidity measurements were correlated to suspended-sediment concentrations. Using the equation of the line of best fit developed from the regression, they were converted from NTU to mg/L (fig. 22). The converted values of turbidity were imported into GCLAS as a background curve to help construct

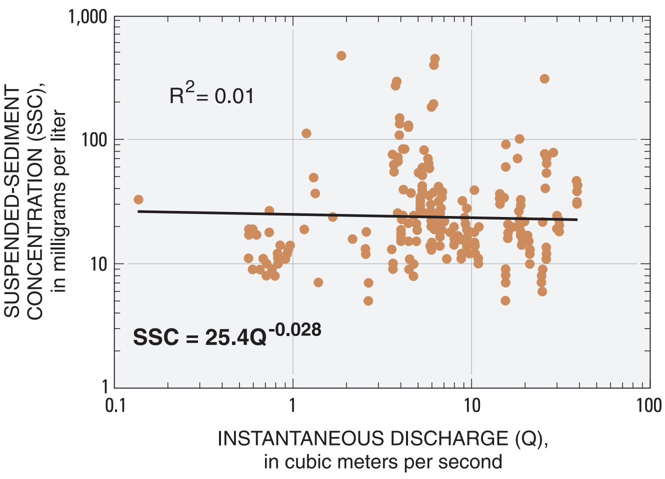

Figure 21. Sediment-transport curve for Mattawoman Creek near Pomonkey, Maryland, during water year 2004.

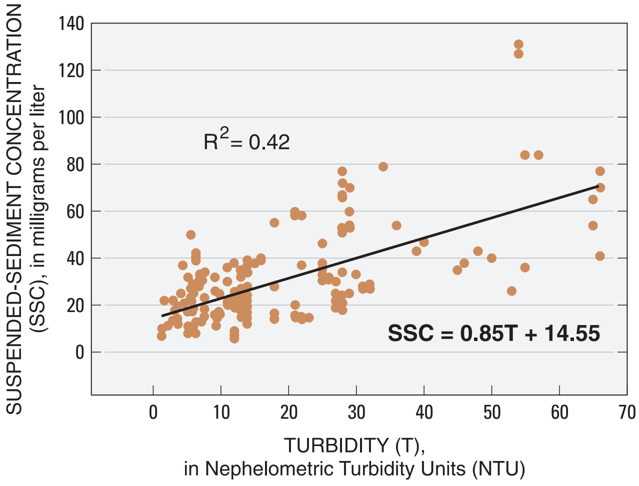

Figure 22. Suspended-sediment concentration plotted against turbidity for Mattawoman Creek near Pomonkey, Maryland, during water year 2004.

a continual trace of suspended-sediment concentration. The suspended-sediment load for water year 2004 at Mattawoman Creek near Pomonkey, Maryland, was 2,669 Mg and the annual sediment yield was 17.9 Mg/km^2/yr (Appendix A2). Comparison of the Mattawoman Creek Watershed sediment yield of 17.9 Mg/km^2/yr to the average sediment yield for other Coastal Plain streams (average = 11.9 Mg/km^2/yr; table 1), indicates that it is a high sediment-yielding stream relative to other Coastal Plain streams (table 1).

Sediment Source Assessment Using Sediment Fingerprints at Mattawoman Creek

At Mattawoman Creek near Pomonkey, Maryland, six storm suspended-sediment samples were collected for sediment source analysis in water year 2004 (tables 11a, b). Two of the samples were collected 25 hours and 15 minutes, 14 hours and 19 minutes, and 45 minutes before peak flow, and three samples were collected 4 hours and 56 minutes, 9 hours and 45 minutes, and 18 hours and 30 minutes after the peak flow (table 11a). To determine the sediment sources for these 6 events, 33 samples from 5 source areas (main stem Mattawoman Creek and tributary banks, construction sites, cropland, and forest) were taken at n = 8, 10, 8, and 4 sites, respectively (fig. 23; table 12). The amount of sand in the sources was high, averaging 79 percent for banks, 84 percent for construction sites, 67 percent for cropland, and 87 percent for forest (table 12). The high sand content in the source samples reflects the high sand composition in the Coastal Plain sediments.

Suspended-sediment concentrations in Mattawoman Creek during high-flow events seldom were above 100 mg/L (fig. 21). Only 22 of the 367 (6 percent) suspended-sediment samples were above 100 mg/L. The low suspended-sediment concentrations provided low amounts of mass for chemical analyses. All of the six fluvial samples had mass below 3 g and therefore, ^{137}Cs was not used as a tracer in Mattawoman Creek. For five of the source samples, unsupported ^{210}Pb activity was not detected and a value of 0.0001 was assigned to these samples. Since there was no unsupported ^{210}Pb activity detected, it was not possible to report error terms for these samples (table 12). RSIL analysis for a subset of Mattawoman Creek samples showed that $w(C_T)$ was not significantly different than $w(C_O)$ for a majority of the samples (7 out of 10), as shown in table 13, and the appropriate tracers to be used in this watershed were $w(C_T)$ and $\delta^{13}C_T$.

Examination of the fluvial tracer, unsupported ^{210}Pb, showed that five samples [two banks (B3, B8) and three construction (D3, D7, D9)] (table 12) had error terms that were equal to or greater than the unsupported ^{210}Pb activity for that sample. The high errors may be related to mass, counting time, and activity (see equation 3). Since five samples showed high errors in unsupported ^{210}Pb, this tracer was removed from the source analysis for Mattawoman Creek.

Examination of the fluvial-tracer values compared to the source samples showed that the measured values for the tracer, $w(P)$ were outside the range of measured source values in six cases. This tracer was deemed not conservative and was not used. One fluvial sample collected on June 6, 2004 had a $\delta^{15}N$ value that was outside the range of the source $\delta^{15}N$ values, but it was within the range of measurement error and was retained. One fluvial sample collected on August 18, 2004 had a N value that was outside the range of the source $w(N)$ values, but it was within measurement error and was retained. A Kruskal-Wallis test performed for each of the remaining five potential tracers ($w(C_T)$, $w(N)$, $w(C_T) : w(N)$, $\delta^{13}C_T$, and $\delta^{15}N$) for the four sources (banks, crop, construction, and forest) confirmed

Table 11a. Hydrologic characteristics for sampled flow events in the Mattawoman Creek near Pomonkey, Maryland.

[m^3/s, cubic meters per second; Mg, megagrams]

Sample date	Sample time[1]	Discharge at time of sample (m^3/s)	Dates of runoff event	Daily mean discharge of event period (m^3/s)	Total sediment load for event period (Mg)	Weighted value = event sediment load divided by cumulative load of all events	Peak flow (date and time[1])	Peak flow, (m^3/s)	Peak flow recurrence interval (years)
12/5/2003	1200	4.70	12/05–08/2003	6.0	30.2	0.039	12/6/2003 1315	9.49	1.1
2/5/2004	1000	3.68	2/3–5/2004	3.5	15.0	0.019	2/4/2004 1530	5.58	1.0
4/2/2004	1245	6.83	4/1–4/2004	5.0	59.9	0.077	4/2/2004 0300	7.11	1.0
06/06/04	0826	6.23	6/5–7/2004	3.5	263	0.340	6/6/2004 0330	6.32	1.0
07/27/04	1241	6.29	7/27–29/2004	4.5	368	0.476	7/28/2004 0300	8.92	1.1
8/13/2004	1415	6.54	8/12–16/2004	3.2	37.0	0.048	8/13/2004 1500	6.66	1.0
Summed sediment load					**773.1**				

[1] Eastern Standard Time

Table 11b. Tracer properties of fluvial sediment samples in the Mattawoman Creek near Pomonkey, Maryland.

[Bq/g, becquerels per gram; *w*, mass fraction by weight; C_T, total carbon; N, nitrogen; P, phosphorus; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent; ‰, per mil]

Sample date	Sample time[1]	Unsupported lead-210 (Bq/g)	Error in unsupported lead-210 (Bq/g)	$w(C_T)$ (%)	$w(N)$ (%)	$w(C_T) : w(N)$	$w(P)$ (%)	$\delta^{13}C_T$ (‰)	$\delta^{15}N$ (‰)
12/5/2003	1200	0.031	0.044	5.39	0.55	9.80	0.1495	-27.2	6.05
2/5/2004	1000	0.170	0.059	4.41	0.45	9.80	0.0887	-26.74	6.01
4/2/2004	1245	0.058	0.017	4.34	0.41	10.59	0.1545	-26.75	7.68
06/06/04	0826	0.106	0.014	4.62	0.53	8.72	0.1969	-28.03	7.97
07/27/04	1241	0.051	0.014	3.77	0.37	10.19	0.1075	-27.56	5.75
8/13/2004	1415	0.014	0.021	5.95	0.63	9.44	0.1912	-27.46	5.04

[1] Eastern Standard Time

Table 12. Tracer properties of upland source sediment samples collected in the Mattawoman Creek Watershed.

[Site locations are shown in figure 23. Sand is defined as sediment that has a diameter greater than 0.062 mm. Unsupported lead-210 analyses were determined at Case Western University, unless indicated by "*," where samples were run at the U.S. Geological Survey Denver facilities. Bq/g, becquerels per gram; *w*, mass fraction; C_T , total carbon; N, nitrogen; P, phosphorus; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent; ---, not determined; ‰, per mil]

Site identifier	Sand % (% dry weight)	Unsupported lead-210 (Bq/g)	Error in unsupported lead-210 (Bq/g)	$w(C_T)$ (%)	w(N) (%)	$w(C_T) : w(N)$	w(P) (%)	$\delta^{13}C_T$ (‰)	$\delta^{15}N$ (‰)
Streambank									
B1	74	0.0001	---	1.99	0.18	11.06	0.04	-26.92	5.92
B2	89	0.0239	0.0065	2.56	0.21	12.19	0.03	-27.86	3.84
B3	83	0.0024	0.0045	1.68	0.15	11.20	0.04	-26.68	6.88
B4	66	0.0001	---	1.96	0.14	14.00	0.02	-27.06	4.87
B5	77	0.0094	0.0048	2.87	0.24	11.96	0.05	-27.26	6.40
B6	80	0.0046	0.0049	2.51	0.20	12.55	0.04	-27.68	5.00
B7	86	0.0067	0.0048	2.23	0.20	11.15	0.06	-26.9	6.96
B8	80	0.0028	0.0065	1.84	0.14	13.14	0.03	-27.44	5.48
Average	**79**	**0.0063**		**2.21**	**0.18**	**12.16**	**0.04**	**-27.23**	**5.67**
Standard error	**2.5**	**0.0028**		**0.14**	**0.01**	**0.37**	**0.00**	**0.15**	**0.38**
Crop Area									
C1	59	0.0312*	0.2	1.26	0.12	10.50	0.05	-23.65	5.90
C2	77	0.0395*	0.2	2.58	0.24	10.75	0.08	-22.87	2.84
C3	60	0.0143*	0.2	1.87	0.16	11.69	0.04	-25.10	2.46
C4	73	0.0530*	0.2	2.52	0.23	10.96	0.06	-22.44	7.84
C5	80	0.0137*	0.2	1.26	0.13	9.69	0.04	-24.46	5.54
C6	74	0.0610*	0.2	2.42	0.21	11.52	0.07	-24.59	2.79
C7	43	0.0045*	0.2	1.13	0.10	11.30	0.04	-24.85	6.99
C8	63	0.0288*	0.2	1.88	0.18	10.44	0.03	-24.92	6.72
Average	**67**	**0.0308**		**1.87**	**0.17**	**10.86**	**0.05**	**-24.11**	**5.14**
Standard error	**4.3**	**0.0070**		**0.21**	**0.02**	**0.23**	**0.01**	**0.36**	**0.76**
Construction Area									
D1 Site	79	0.0046	0.0040	0.39	0.04	9.75	0.02	-26.73	5.51
D2 Site	91	0.0067	0.0063	1.59	0.15	10.60	0.07	-27.53	5.89
D3 Site	76	0.0002	0.0055	0.84	0.10	8.40	0.07	-24.74	5.88
D4 sediment pond	85	0.0126	0.0060	0.43	0.04	10.75	0.01	-30.09	5.01
D5 sediment pond	88	0.0108	0.0043	0.84	0.07	12.00	0.02	-29.06	5.83
D6 drainage area	89	0.0001	---	0.28	0.04	7.00	0.01	-25.61	5.42
D7 drainage ditch	89	0.0001	0.0061	0.49	0.06	8.17	0.03	-25.24	6.32
D8 sediment pond	84	0.0184	0.0042	1.13	0.10	11.30	0.02	-26.19	4.7
D9 sediment pond	82	0.0008	0.0038	1.05	0.07	15.00	0.01	-28.78	4.88
D10 Site	76	0.0099	0.0056	0.40	0.05	8.00	0.00	-32.65	4.81
Average	**84**	**0.0064**		**0.74**	**0.07**	**10.10**	**0.03**	**-27.66**	**5.43**
Standard error	**1.7**	**0.0020**		**0.13**	**0.01**	**0.75**	**0.01**	**0.79**	**0.18**
Forest Area									
F1	76	0.0596	0.00506	7.52	0.47	16.00	0.05	-27.57	2.29
F2	95	0.1370*	0.20	11.60	0.60	19.33	0.06	-27.02	1.74
F3	76	0.0553*	0.20	4.57	0.36	12.69	0.06	-27.57	2.82
F4	89	0.1090*	0.20	7.00	0.40	17.50	0.04	-27.37	2.42
Average	**87**	**0.0902**		**7.67**	**0.46**	**16.38**	**0.05**	**-27.38**	**2.32**
Standard error	**4.8**	**0.0198**		**1.46**	**0.05**	**1.41**	**0.00**	**0.13**	**0.22**

Table 13. Summary of samples collected in Mattawoman Creek Watershed of mass fraction (*w*) and isotope (δ) analyses for total carbon (C_T), organic carbon (C_0), and inorganic carbon (C_I).

[The value of $w(C_I)$ is calculated as $w(C_I) = [w(C_T) – w(C_O)]$, but the calculated value $w(C_I)$ is set equal to 0.0 when $[w(C_I) / w(C_T)] \leq 0.05$ because there is a ±5% uncertainty in the value of $w(C_O)$. *w*, mass fraction by weight; C_T, total carbon; $\delta^{13}C_T$, stable isotopic total carbon-13; C_O, organic carbon; $\delta^{13}C_O$, stable isotopic organic carbon-13; C_I, organic carbon; %, percent; ‰, per mil]

Sample identifier	Sample location	$w(C_T)$ (%)	$\delta^{13}C_T$ (‰)	$w(C_0)$ (%)	$\delta^{13}C_0$ (‰)	$w(C_I) / w(C_T)$	$w(C_I)$ (%)
B5	Bank	2.89	-27.26	2.83	-27.75	0.02	0.0
B6	Bank	2.5	-27.68	2.56	-27.9	-0.02	0.0
C5	Crop	2.50	-24.46	1.25	-25.12	0.50	1.25
C8	Crop	1.85	-24.92	1.89	-25.68	-0.02	0.0
D5	Construction	0.82	-29.06	0.85	-29.06	-0.04	0.0
D10	Construction	0.47	-32.65	0.41	-30.74	0.13	0.06
F1	Forest	7.45	-27.57	7.7	-27.41	-0.03	0.0
4022004	Fluvial	4.63	-26.75	4.27	-27.4	0.08	0.36
6062004	Fluvial	6.46	-28.03	6.16	-27.54	0.05	0.0
8132004	Fluvial	5.7	-27.46	5.75	-27.68	-0.01	0.0

Table 14. Median values for tracers within source areas in the Mattawoman Creek Watershed and test statistics for tracers for which the Kruskal-Wallis test for equality of medians among source areas was rejected.

[*w*, mass fraction by weight; C_T , total carbon; N, nitrogen; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent; ‰, per mil]

Sample location	Number of samples	$w(C_T)$ (%)	$w(N)$ (%)	$w(C_T) : w(N)$	$\delta^{13}C_T$ (‰)	$\delta^{15}N$ (‰)
Median Values						
Bank	8	2.11	0.19	12.07	-27.16	5.70
Construction	10	0.67	0.065	10.18	-27.13	5.46
Crop	8	1.87	0.17	10.85	-24.52	5.72
Forest	4	7.26	0.44	16.75	-27.47	2.36
Test Statistics						
H value		22.78	21.48	14.78	16.06	9.75
Critical value		7.8	7.8	7.8	7.8	7.8
ρ-value		4.49E-05	8.36E-05	0.002	0.001	0.020
Reject or accept the null hypothesis of equality of medians		Reject	Reject	Reject	Reject	Reject

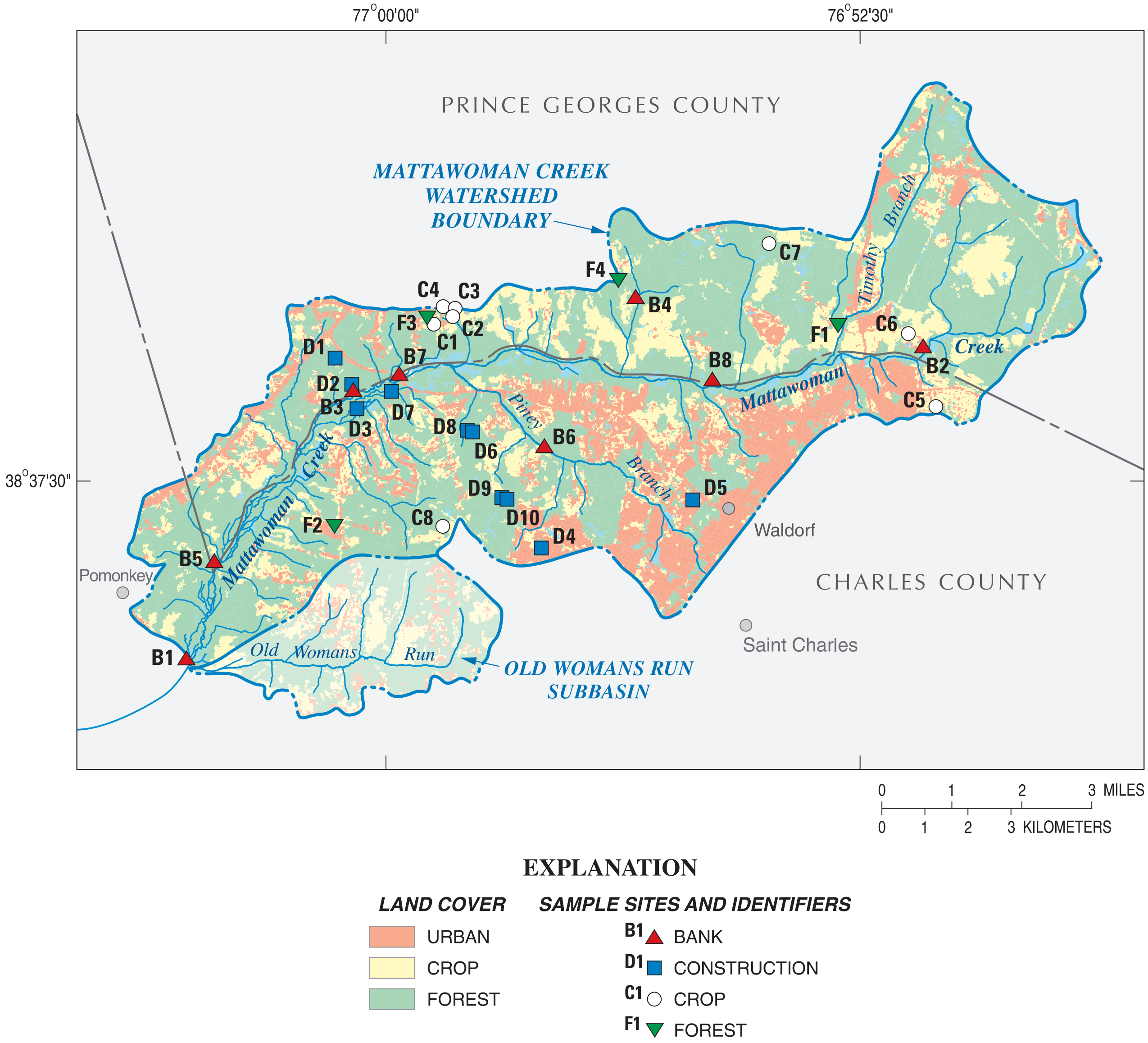

Figure 23. Location of sediment source sample sites in the Mattawoman Creek Watershed near Pomonkey, Maryland. (Samples were collected between August 17, 2004 and December 20, 2005. The lighter shaded subbasin is Old Womans Run.) [Land cover from U.S. Geological Survey National Land Cover Database (NLCD).]

that there were statistically significant differences between the medians of the measured tracer values in the four source areas (table 14).

Results of the Tukey test confirmed that the remaining five tracers could distinguish between the four sources in Mattawoman Creek (table 15). Both $w(\mathrm{N})$ and $w(\mathrm{C_T})$ identified the same sources, so use of both tracers was redundant. $w(\mathrm{C_T})$ has greater precision and accuracy; therefore, $w(\mathrm{N})$ was removed. The number of tracers remaining after the Tukey test was T = 4 ($w(\mathrm{C_T})$, $w(\mathrm{C_T}) : w(\mathrm{N})$, $\delta^{13}\mathrm{C_T}$, and $\delta^{15}\mathrm{N}$).

Results of the unmixing model for the four tracers showed variations in sediment sources with respect to flow, timing of the hydrograph, sediment loads, and time of year. Averaging sediment sources for the seven events indicated that all sources were important, with forest showing the highest percentage, followed by streambanks, construction, and cropland (table 16). Weighting the sediment sources by the sediment transported for each event, indicated that streambanks were the most important source of sediment (30 percent), followed by forest (29 percent), construction (25 percent), and cropland (17 percent) (table 16). The sediment load used to weight the sediment sources in Mattawoman Creek included flow and sediment contributions from Old Woman Creek (14.9 km^2), which drains 10 percent of the area to the streamflow-gaging station at Mattawoman Creek near Pomonkey, Maryland.

Streambanks were a source of sediment for a range of flow conditions, including the two highest peak flows

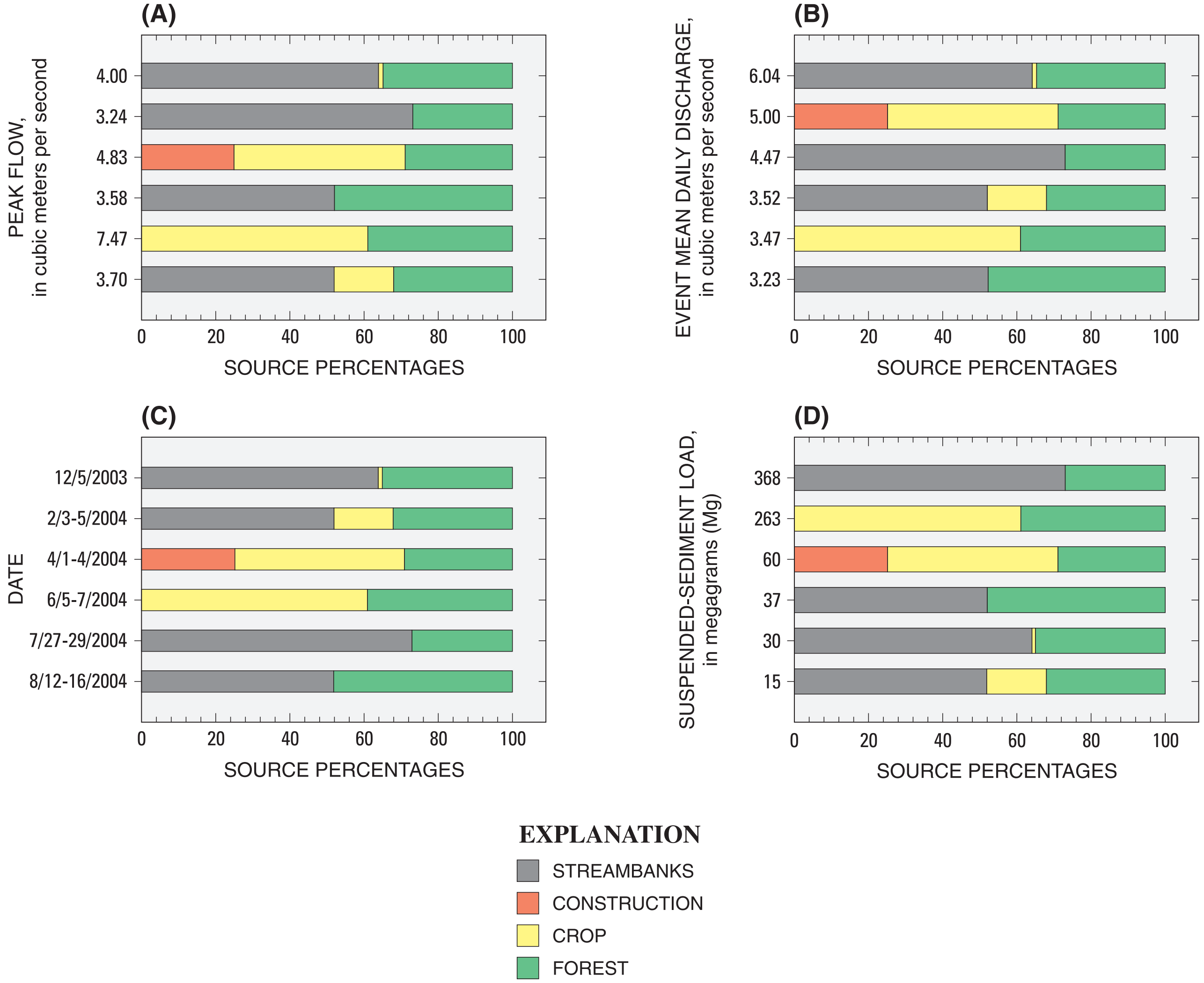

Figure 24. Sediment sources for Mattawoman Creek showing sediment sources by (A) peak flow of sampled event, (B) mean daily discharge for sampled event period, (C) ascending order of day and month sampled, and (D) suspended-sediment load for sampled runoff event period.

(9.49 m^3/s on December 6, 2004, 64 percent streambanks and 8.92 m^3/s on July 28, 2004, 52 percent streambanks) (fig. 24). For the highest sediment-loading event (368 Mg on 7/27–29/2004), streambanks were an important source of sediment. However, this event does not correspond to the highest sampled peak flow event.

Examining sediment sources by time of year shows that for storms that occurred between February and June 2004, cropland was a major source of sediment. Cropland as a source of sediment may reflect bare-ground conditions and tilling and planting operations that occur during this time of year.

Construction as a source of sediment ranged from 0 to 34 percent (table 16) over a range of peak flows, throughout most of the year, and for a range of sediment loading events (fig. 24). Construction sites can be important sediment contributors to streams (Wolman and Schick, 1967; Yorke and Herb, 1976; Harbor, 1999). Yorke and Herb (1976) monitored the effects of urbanization in eight watersheds (drainage areas of 0.91 to 25.2 km^2) draining the Washington, D.C. metropolitan area in Maryland between 1963 and 1974. Sediment yields estimated from construction sites ranged from 1,600 to 22,600 $Mg/km^2/yr$. Factors such as slope, distance to the stream, and erosion-control practice explained the range in sediment yields. In some watersheds, a 60- to 80-percent decrease in sediment yields occurred over time and was attributed to implementation of sediment-control measures (Yorke and Herb, 1976).

To determine the area that was in construction during the study period at Mattawoman Creek, DOQQs at 0.30-m resolution were obtained from the Charles County, Maryland, Planning Division (2004; scale 1:1500) and Prince Georges County, Maryland, Planning Division (2005; scale 1:1000).

The DOQQs were imported into a GIS and the areas under construction were delineated and tabulated. The construction sites were not ground-truthed. Some of the bare ground in cropland sites could be mistaken for construction sites. For selected construction sites, 2007 road maps were analyzed to verify that the areas interpreted as construction sites were not farm fields. The total area under construction in Mattawoman Creek, during 2004–2005, was 182 ha, which is 1.26 percent of the watershed area.

In 1970, a statewide sediment-control program was established in Maryland that mandated an erosion-control plan for land disturbance of 0.0465 ha or more; there are exemptions for agricultural use (Maryland Department of the Environment, 2007). In the Mattawoman Creek Watershed, engineering solutions to control sediment from construction sites were observed to be silt fences and sediment ponds (Maryland Department of the Environment, 1994). Several studies have reviewed the effectiveness of silt fences and sediment ponds. Although designed to trap sediment, silt fences and sediment ponds may not have a 100-percent trap efficiency. Harbor (1999) noted that in many cases, incorrect installation and maintenance of erosion-control measures limits their effectiveness. In an assessment made of silt fences in active highway construction sites in Austin, Texas, Barrett and others (1995) assessed the trap efficiency by measuring total suspended solids (TSS) upstream and downstream of the construction site. Results indicated that the trap efficiency of silt fences was 0 percent, with a range of negative 61 percent to +54 percent. Negative values indicated an increase in TSS downstream of the silt fence. In the case of sediment ponds, poor trapping efficiency of fine sediment, poor design that did not account for the amount of runoff delivered to the pond, and the design of the outlet and spillway, are common problems (Bidelspach and others, 2004; Harbor, 1999). Barrett and others (1995) compiled evaluations of sediment ponds and cite Schueler and Lugbill's (1990) work in suburban Maryland, where in spite of significant sediment removal, sediment levels in outflows

Table 15. Results (probability values) of Tukey test performed between source areas within the Mattawoman Creek Watershed for those tracers that passed the Kruskal-Wallis test screening.

[*w*, mass fraction by weight; C_T , total carbon; N, nitrogen; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; <, less than; %, percent; ‰, per mil]

Tracer compared between source areas	Bank	Forest	Construction
	$w(C_T)$ (%)		
Forest	0.013		
Construction	<0.01	<0.01	
Crop	0.531	<0.01	<0.01
	$w(N)$ (%)		
Bank			
Forest	0.011		
Construction	<0.01	<0.01	
Crop	0.943	<0.01	<0.01
	$w(C_T) : w(N)$		
Forest	0.211		
Construction	0.020	<0.01	
Crop	0.106	<0.01	0.915
	$\delta^{13}C_T$ (‰)		
Forest	0.96		
Construction	1.0	0.94	
Crop	<0.01	<0.01	<0.01

Table 16. Unmixing model results for the Mattawoman Creek Watershed, Maryland showing sediment sources (in percent) for sampled storms using four tracers: $w(C_T)$, $w(C_T) / w(N)$, $\delta^{15}N$, and $\delta^{13}C_T$.

[*w*, mass fraction by weight; C_T , total carbon; N, nitrogen; $\delta^{13}C_T$, stable isotopic total carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent]

Sampling Date	Bank (%)	Construction (%)	Crop (%)	Forest (%)	Error
12/5/2003	64	0	1	35	4.00
2/5/2004	0	34	31	35	3.63
4/2/2004	0	25	43	32	4.61
6/6/2004	0	34	37	29	7.12
7/27/2004	52	22	0	26	3.22
8/13/2004	52	0	0	48	3.58
Average	**28**	**19**	**19**	**34**	**4.36**
Sediment weighted average[1]	**30**	**25**	**17**	**29**	

[1] Percentage values add up to 101 percent because of rounding.

remained elevated with a median TSS of 283 mg/L. In Austin, Texas, the efficiency of a dry sediment pond and a wet sediment pond in controlling sediment from highway construction were evaluated (Barrett and others, 1995). The dry pond is designed to be dry between storms and had a trap efficiency of 16 percent. The wet pond is designed to maintain a permanent pool of water and had a trap efficiency of 46 percent (Barrett and others, 1995). Reed (1980) collected 7 years of sediment data to determine the effectiveness of various erosion-control measures in Harrisburg, Pennsylvania. During construction, annual sediment loads increased 100 to 300 percent. Sediment ponds were found to be the most effective measure, trapping from 70 to 80 percent of sediment (Reed, 1980).

Based on the literature, depending on the design, implementation, and maintenance of the erosion-control measure, the effectiveness of reducing sediment delivery from construction sites will vary. For this study, a thorough investigation of the effectiveness of various erosion-control measures in Mattawoman Creek was not undertaken. Results from this study using the sediment-fingerprinting approach indicate that for some storms, sediment is derived from construction sites.

Forest appears to be a source of sediment for all events, ranging from 26 to 48 percent (fig. 24; table 16). Due to vegetation canopy, organic litter, and root strength, forests are not usually considered an important source of sediment (Patric and others, 1984). In an analysis of sediment yields in 812 forested watersheds (with greater than 75 percent forested cover) throughout the United States, 75 percent of the sediment yields were between 4.5 and 56 Mg/km^2/yr (Patric and others, 1984). Forest cover is 60 percent of the Mattawoman Creek Watershed and the sediment yield of Mattawoman Creek (17.9 Mg/km^2/yr) was within the range of sediment yields reported by Patric and others (1984). Therefore, although forest is a source of sediment in Mattawoman Creek, it must be emphasized that this is a low sediment-yielding environment. Forest as a source of sediment in the Mattawoman Creek Watershed may indicate some sort of disturbance leading to erosion. Smith and Wilcock (2006) observed enlargement of first-order gully channels in forested areas of the upper Patuxent River Watershed, which drains the Maryland Piedmont. The gullying was thought to be due to disturbance of the forested areas from increased stormflow runoff from roads.

Sediment sources may also be related to the timing of the samples relative to the flood hydrograph (Lawler, 2005). Two of the samples at Mattawoman Creek were collected before the peak flow (December 5, 2003 and July 27, 2004), two after the peak flow (February 5, 2004 and April 2, 2004), and one sample at peak flow (within 45 minutes of peak flow on August 13, 2004) (table 11a). Samples collected before the peak flow had higher bank sources (69 percent), on average, than samples collected after the peak flow (17 percent). The contribution of streambank sources before the peak flow may reflect their shorter travel distances. For samples obtained after the peak flow, cropland sources (41 percent) were higher than samples obtained before the peak flow (1 percent). Cropland as a source of sediment may reflect the longer travel distance of upland sources that reach the stream after the peak flow. For the sample collected at peak flow (August 13, 2004), the streambanks were the highest source of sediment (52 percent). Forest as a source of sediment was similar in samples collected before the peak flow (31 percent), and after the peak flow (33 percent). Since forest covers much of the Mattawoman Creek Watershed, distances of forest to the stream channel may vary from being close to the channel to farther away.

Little Conestoga Creek Watershed

Soil erosion results are presented in this section using ^{137}Cs inventories. Sediment transport and sediment source analysis in the Little Conestoga Creek Watershed are also presented in this section.

Erosion Rates Using Cesium-137

The ^{137}Cs technique was applied to one reference site and five cropland sites in the Little Conestoga Creek Watershed (fig. 25; table 17). Three samples were taken in the reference pasture site. For each cropland site, ^{137}Cs was sampled in two transects running parallel to slope. Sample cores extended down to 25 cm, the approximate till depth in the area. Three cores collected in the reference pasture site, each to a depth of 25 cm, had ^{137}Cs activity ranging from 2,324 to 2,576 Bq/kg, averaging 2,432 Bq/kg, (table 17). Detailed activity of ^{137}Cs with depth was not obtained for the reference site, which may affect interpretation of the appropriateness of this pasture site as a reference site. The owner said that it had been in pasture for many years. Unlike the ^{137}Cs sampling in the Pocomoke River Watershed, the sampling scheme in the Little Conestoga Creek Watershed did address the spatial variability of ^{137}Cs activity.

The Mass Balance 2 model predicted erosion at all sites, ranging from 14.0 to 28.1 Mg/ha/yr, averaging 19.4 Mg/ha/yr (table 17). For the Mass Balance 2 model, the value used for γ was 0.5, a value which was used in a ^{137}Cs-based erosion study for a Maryland Piedmont site (Ritchie and McCarty, 2003; Jerry Ritchie, USDA-ARS, oral commun., 2007).

If the average value of erosion from all sites (19.4 Mg/ha/yr) (table 17) is extrapolated to the 13 percent of the Little Conestoga Creek Watershed that is in cropland (1,423.5 ha), then 27,600 Mg/yr of sediment could be generated. The average annual sediment load computed at the Little Conestoga Creek near Millersville, Pennsylvania streamflow-gaging station for water years 2003–04 was 7,130 Mg/yr (Appendix A3). Therefore, cropland could contribute almost four times (387 percent) of the average annual sediment load transported out of the Little Conestoga Creek. Over 20,000 Mg of sediment is deposited annually in the watershed, possibly on hillslopes, or in the stream corridor before it reaches the sampling point of the watershed. This assumes that all the sediment at the gage (7,130 Mg) is coming from

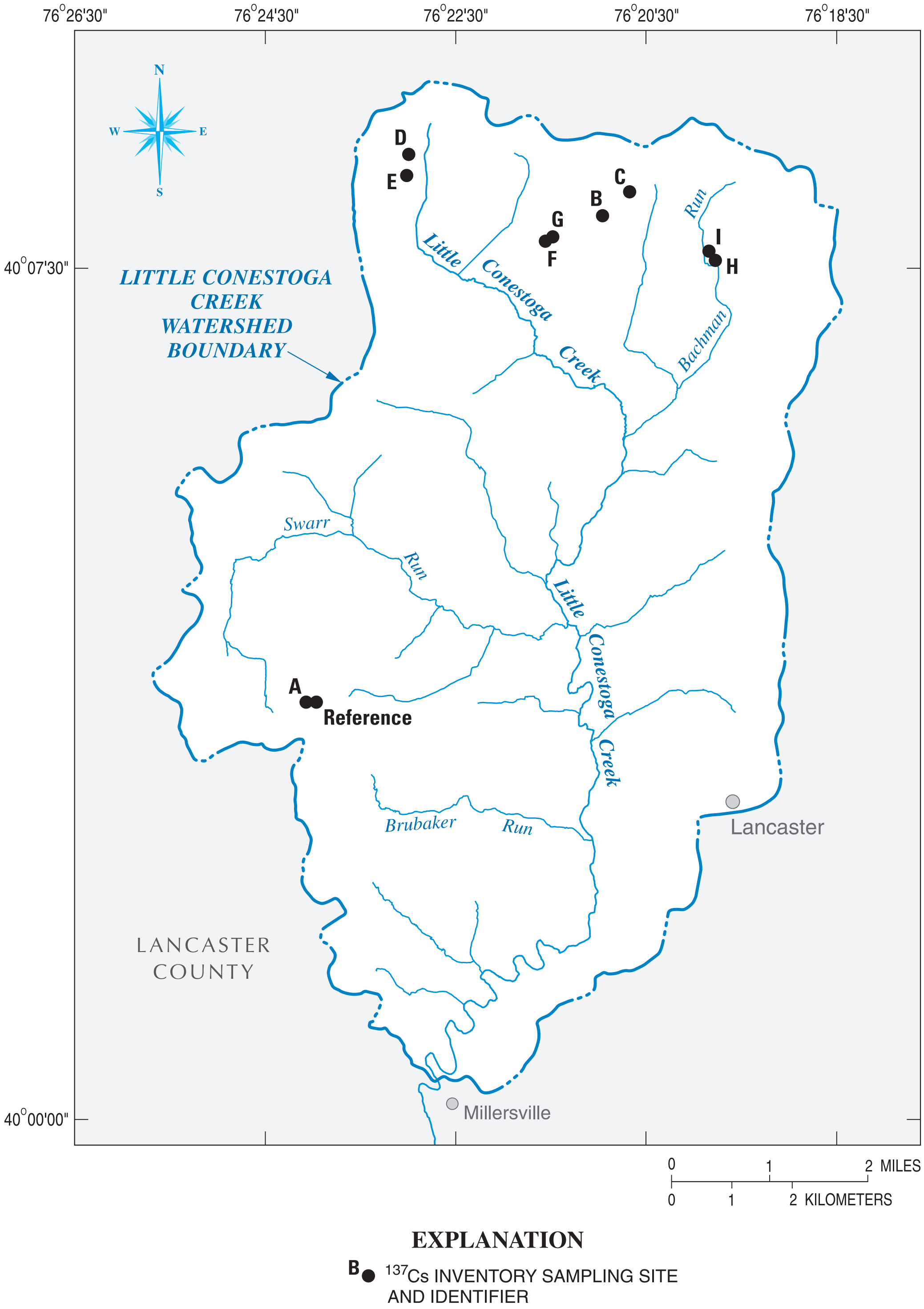

Figure 25. Location of cesium-137 inventory sampling sites in the Little Conestoga Creek Watershed draining above Millersville, Pennsylvania. [Sites were sampled on November 23, 2004.]

Table 17. Results of cesium-137 technique for selected cropland sites in the Little Conestoga Creek Watershed.

[Site locations are shown in figure 25. Samples collected November 23, 2004. g/cm^3, grams per cubic centimeter; kg/m, kilograms per meter; Bq/kg, becquerels per kilogram; ^{137}Cs, cesium-137; Bq/m^2, becquerels per square meter; Mg/ha/yr, megagrams per hectare per year; cm, centimeter]

Site Identifier	Slope position	Bulk density (g/cm^3)	Mass depth[1,2] (kg/m)	Transect 1 ^{137}Cs activity (Bq/kg)	Transect 2 ^{137}Cs activity (Bq/kg)	Average ^{137}Cs activity of transects (Bq/m^2)	Mass Balance Model II results erosion/deposition[2,3] (Mg/ha/yr) (+ = aggradation)	Site average erosion /deposition (Mg/ha/yr) (+ = aggradation)
REF-pasture reference		1.18		7.39	7.21	2,576		
		1.10		7.26	7.27	2,395		
		1.14		6.85	6.74	2,324		
						2,432		
A-corn, small grains	Top	1.34	1,336	3.55	3.51	1,414	-23.6	
		1.16	1,157	3.91	3.39	1,267	-26.5	
		1.25	1,252	4.47	4.51	1,686	-15.0	
		1.11	1,110	3.63	4.35	1,329	-23.8	
		1.21	1,213	3.24	3.44	1,215	-29.2	
		1.34	1,339	4.33	4.18	1,709	-15.0	
	Bottom	1.09	1,094	7.11	7.06	2,326	-1.6	-19.2
B-corn, small grains	Top	1.35	1,350	4.46	4.69	1,853	-11.4	
	Mid slope	1.43	1,435	3.72	3.94	1,648	-17.2	
	Bottom	1.06	1,056	5.88	6.08	1,894	-9.1	
	Bottom	1.18	1,175	6.39	6.06	2,195	-3.9	
	Bottom	1.34	1,340	3.74	3.65	1,485	-21.3	
	Mid slope	1.42	1,416	2.06	2.31	928	-46.8	
	Mid slope	1.30	1,305	5.81	5.42	2,198	-4.1	
	Top	1.37	1,367	3.12	3.07	1,270	-29.2	-17.9
C- corn	Top	1.37	1,373	3.60	3.70	1,503	-21.1	
	Mid slope	1.31	1,307	3.05	3.20	1,227	-30.1	
	Mid slope	1.25	1,253	5.92	5.93	2,225	-3.5	
	Bottom	1.27	1,267	5.56	5.89	2,178	-4.4	
	Bottom	1.38	1,381	3.02	2.93	1,232	-30.9	
	Bottom	1.47	1,469	3.64	4.73	1,844	-12.2	-17.0
D-corn, soy	Bottom	1.26	1,261	4.75	4.93	1,830	-11.6	
	Low slope	1.27	1,269	3.48	3.64	1,355	-24.9	
	Low slope	1.19	1,189	4.70	4.86	1,706	-14.1	
	Low slope	1.30	1,303	4.25	4.36	1,684	-15.4	
	Low slope	1.17	1,168	4.15	4.21	1,464	-20.3	
	Top	1.24	1,243	3.49	4.00	1,397	-23.2	-18.2

Table 17. Results of cesium-137 technique for selected cropland sites in the Little Conestoga Creek Watershed.—Continued

[Site locations are shown in figure 25. Samples collected November 23, 2004. g/cm^3, grams per cubic centimeter; kg/m, kilograms per meter; Bq/kg, becquerels per kilogram; ^{137}Cs, cesium-137; Bq/m^2, becquerels per square meter; Mg/ha/yr, megagrams per hectare per year; cm, centimeter]

Site Identifier	Slope position	Bulk density (g/cm^3)	Mass depth[1,2] (kg/m)	Transect 1 ^{137}Cs activity (Bq/kg)	Transect 2 ^{137}Cs activity (Bq/kg)	Average ^{137}Cs activity of transects (Bq/m^2)	Mass Balance Model II results erosion/deposition[2,3] (Mg/ha/yr) (+ = aggradation)	Site average erosion /deposition (Mg/ha/yr) (+ = aggradation)
E-corn, plowed	Top	1.33	1,326	4.83	5.16	1,987	-8.4	
	Low slope	1.25	1,250	4.08	4.38	1,586	-17.6	
	Low slope	1.35	1,354	4.19	4.15	1,694	-15.4	
	Low slope	1.33	1,334	4.12	4.09	1,642	-16.7	
	Low slope	1.17	1,166	6.94	7.08	2,453	0.4	
	Top	1.12	1,119	4.60	4.65	1,552	-17.4	
	Top	1.04	1,036	2.79	3.04	907	-38.9	-16.3
F-corn	Bottom	1.23	1,233	3.58	3.46	1,301	-26.3	
		1.30	1,302	5.70	5.19	2,127	-5.4	
		1.47	1,468	3.62	3.45	1,555	-20.2	
	Top	1.48	1,481	3.34	3.15	1,442	-24.1	-19.0
G-corn, soy	Top	1.44	1,438	2.89	3.06	1,282	-29.6	
		1.39	1,393	5.06	4.80	2,060	-7.0	
		1.29	1,293	5.69	5.38	2,149	-5.0	
		1.34	1,342	4.33	4.30	1,737	-14.2	
	Bottom	1.27	1,272	4.60	4.40	1,716	-14.4	-14.0
H- corn	Top	1.32	1,321	3.72	3.83	1,495	-20.9	
		1.29	1,290	2.36	2.59	959	-42.2	
		1.18	1,183	4.28	4.46	1,551	-18.0	
	Bottom	1.36	1,361	2.96	3.00	1,216	-31.2	-28.1
I-corn	Bottom	1.42	1,420	2.25	2.34	977	-43.9	
		1.40	1,398	3.57	3.84	1,552	-19.8	
		1.37	1,370	3.60	3.69	1,497	-21.2	
	Top	1.40	1,402	4.15	4.18	1,751	-14.2	-24.8
Average of all cores								**-19.4**

[1] Based on a tillage depth of 25 centimeters.

[2] Relaxation mass depth, *H* in equation (8) is 4.0, based on experimental work by He and Walling (1997).

[3] γ, the proportion of the annual ^{137}Cs input susceptible to removal by erosion is estimated as 0.5 (Ritchie and McCarty, 2003).

cropland. If lesser percentages of sediment are attributed to cropland, the amount of sediment deposited on the landscape from cropland would increase.

Little Conestoga Creek Sediment Transport

Suspended-sediment loads for the Little Conestoga Creek near Millersville were computed for water years 2003 and 2004 by developing a continual trace of suspended-sediment concentrations and computing loads with the program GCLAS (Appendix A3). For water year 2003, the station began recording river stage on February 1, 2003, so only a partial sediment record is shown for that water year. The sediment-transport curve for Little Conestoga Creek, a Piedmont stream, shows suspended-sediment concentrations reaching 1,000 mg/L and higher, with 318 suspended-sediment samples out of 543 (59 percent) containing concentrations greater than 100 mg/L (fig. 26). Turbidity measurements were correlated to suspended-sediment concentrations, and using the equation of the line of best fit developed from the regression, converted from NTU to mg/L (fig. 27). The converted values of turbidity were imported into GCLAS as a background curve to help construct a continual trace of suspended-sediment concentration. The suspended-sediment load for part of water year 2003 (February 1, 2003–September 30, 2003) was 4,720 Mg and for water year 2004 was 7,732 Mg (Appendix A3). Averaging the suspended-sediment load by months and summing produced an average sediment load of 7,130 Mg/yr. Using this value, the average annual sediment yield for Little Conestoga Creek is 65.1 Mg/km^2/yr, which is lower than the annual sediment yield of Piedmont streams (103.7 Mg/km^2/yr; table 1).

Sediment Source Assessment Using Sediment Fingerprints at Little Conestoga Creek

In the Little Conestoga Creek near Millersville, Pennsylvania, 12 storm suspended-sediment samples were collected from March 2, 2003 through June 5, 2004 (tables 18a, b). The source dataset consisted of a total of 35 samples from the 3 source areas (n = 12 channel banks, 10 construction sites, and 13 crop) (fig. 28). The amount of sand in the source areas averaged 71 percent for banks, 75 percent for construction sites, and 67 percent at cropland sites (table 19).

RSIL analysis showed that for two fluvial sediment samples, $w(\mathrm{C_T})$ was significantly different than $w(\mathrm{C_O})$, as shown in table 20, so that the appropriate tracers to be used in this watershed were $w(\mathrm{C_O})$ and $\delta^{13}\mathrm{C_O}$. The bedrock geology of the Little Conestoga Creek Watershed is the Conestoga Limestone and could explain the source of inorganic C. Examination of the fluvial-tracer values compared to the source samples showed that the measured values for the tracers ^{137}Cs, unsupported ^{210}Pb, and $w(\mathrm{N})$ were outside the range of measured source values. These tracers were not representative of the source areas in the Little Conestoga Creek Watershed and were not used. A Kruskal-Wallis test performed for each of the remaining five potential tracers ($w(\mathrm{P})$, $w(\mathrm{C_O})$, $w(\mathrm{C_O}) : w(\mathrm{N})$, $\delta^{13}\mathrm{C_O}$, and $\delta^{15}\mathrm{N}$) for the three sources indicated that all tracers, with the exception of $w(\mathrm{C_O}) : w(\mathrm{N})$, had statistically significant differences between the medians of the measured tracer values in the three source areas (table 21). As a result, $w(\mathrm{C_O}) : w(\mathrm{N})$ was removed from the analysis.

Results of the Tukey test indicated that the remaining four tracers could distinguish between some of the three sources in the Little Conestoga Creek Watershed (table 22).

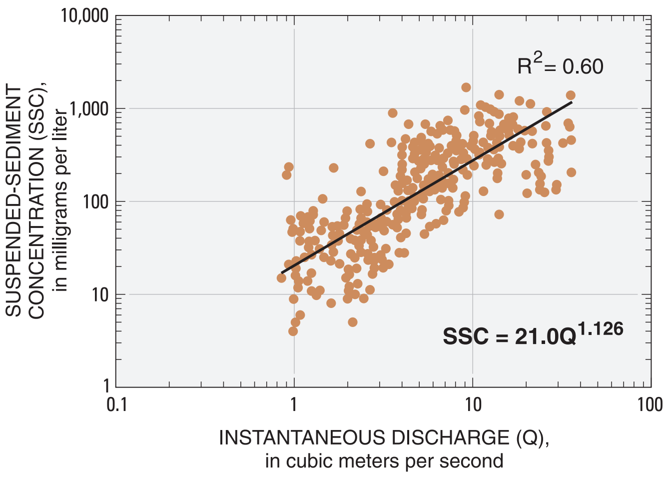

Figure 26. Sediment-transport curve for U.S. Geological Survey streamflow-gaging station 01576712 in the Little Conestoga Creek near Millersville, Pennsylvania using suspended-sediment concentrations collected during water years 2003 and 2004.

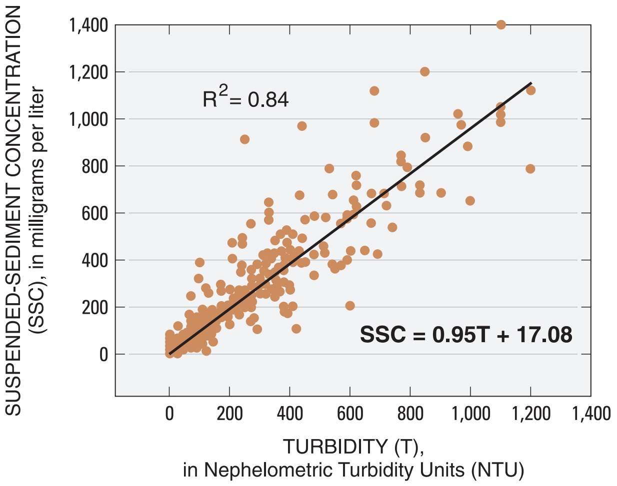

Figure 27. Suspended-sediment concentration plotted against turbidity for U.S. Geological Survey streamflow-gaging station 01576712 in the Little Conestoga Creek near Millersville, Pennsylvania during water years 2003 and 2004.

Table 18a. Hydrologic characteristics for sampled flow events in the Little Conestoga Creek near Millersville, Pennsylvania.

[m^3/s, cubic meters per second; Mg, megagrams]

Sample starting date and time[1]		Sample ending date and time[1]		Dates of period of runoff event	Daily mean discharge of event period (m^3/s)	Total sediment load of event period (Mg)	Peak flow date and time[1]		Peak flow, (m^3/s)
3/2/2003	1730	3/2/2003	2145	3/2–3/2003	3.5	53	3/3/2003	0015	5.4
3/9/2003	1508	3/9/2003	2238	3/9–10/2003	4.84	134	3/9/2003	2000	10.3
3/20/2003	1745	3/21/2003	0138	3/20–21/2003	6.83	432	3/21/2003	0000	17.3
4/11/2003	1037	4/11/2003	1732	4/11–12/2003	4.18	125	4/11/2003	1300	10.5
5/26/2003	0202	5/26/2003	1118	5/26/–27/2003	3.57	121	5/26/2003	1000	8.6
6/4/2003	0246	6/5/2003	0134	6/3–5/2003	4.63	236	6/4/2003	0915	16.3
6/7/2003	0931	6/8/2003	0646	6/7–8/2003	5.20	159	6/7/2003	1630	14.2
9/1/2003	2332	9/2/2003	0432	9/1–2/2003	2.69	73	9/2/2003	0200	9.3
9/19/2003	0050	9/20/2003	0340	9/18–20/2003	2.55	78	9/19/2003	0915	6.3
10/14/2003	1738	10/16/2003	0553	10/14–16/2003	3.23	145	10/15/2003	0245	17.2
2/6/2004	1822	2/7/2004	0922	2/6–8/2004	10.2	1,029	2/6/2004	2130	28.9
6/5/2004	1705	6/5/2004	2205	6/5–6/2004	2.49	77	6/5/2004	1915	6.6

[1] Eastern Standard Time

Table 18b. Tracer properties for sampled flow events in the Little Conestoga Creek near Millersville, Pennsylvania.

[Bq/g, becquerels per gram; ^{137}Cs, cesium-137; *w*, mass fraction by weight; C_O, organic carbon; N, nitrogen; P, phosphorus; $\delta^{13}C_O$, stable isotopic organic carbon-13; δ^{13}N, stable isotopic nitrogen-15; %, percent; ‰, per mil]

Sample starting date and time[1]		Sample ending date and time[1]		^{137}Cs (Bq/g)	Error ^{137}Cs (Bq/g)	Unsupported lead-210 (Bq/g)	Error in unsupported lead-210 (Bq/g)	$w(C_0)$ (%)	w(N) (%)	$w(C_0)$: w(N)	w(P) (%)	$\delta^{13}C_0$ (‰)	δ^{15}N (‰)
3/2/2003	1730	3/2/2003	2145	0.0001	0.0046	0.059	0.017	3.51	0.48	7.31	0.09	-26.74	6.14
3/9/2003	1508	3/9/2003	2238	0.0160	0.0035	0.019	0.010	2.88	0.32	9.00	0.11	-26.31	6.69
3/20/2003	1745	3/21/2003	0138	0.0001	0.0023	0.021	0.015	2.67	0.30	8.90	0.09	-26.47	5.87
4/11/2003	1037	4/11/2003	1732	0.0050	0.0040	0.032	0.011	3.41	0.32	10.7	0.10	-26.48	6.41
5/26/2003	0202	5/26/2003	1118	0.0055	0.0040	0.024	0.012	3.99	0.29	13.8	0.10	-25.95	6.53
6/4/2003	0246	6/5/2003	0134	0.0001	0.0023	0.061	0.012	3.26	0.31	10.5	0.11	-26.92	6.46
6/7/2003	0931	6/8/2003	0646	0.0004	0.0064	0.000	0.016	3.09	0.32	9.66	0.10	-26.62	6.47
9/1/2003	2332	9/2/2003	0432	0.0001	0.0043	0.000	0.014	3.22	0.29	11.1	0.11	-27.17	5.97
9/19/2003	0050	9/20/2003	0340	0.0001	0.0044	0.050	0.018	3.46	0.32	10.8	0.11	-26.76	6.09
10/14/2003	1738	10/16/2003	0553	0.0001	0.0078	0.013	0.020	3.62	0.34	10.6	0.11	-26.70	6.31
2/6/2004	1822	2/7/2004	0922	0.0001	0.0025	0.041	0.012	2.87	0.29	9.90	0.12	-26.33	7.78
6/5/2004	1705	6/5/2004	2205	0.0058	0.0062	0.041	0.018	2.96	0.35	8.44	0.10	-26.83	6.42

[1] Eastern Standard Time

Table 19. Summary of upland source information collected in the Little Conestoga Creek Watershed.

[Site locations are shown in Figure 28. Sand is defined as sediment that has a diameter greater than 0.062 millimeters. Unsupported lead-210 analyses were determined at Case Western University. Bq/g, becquerels per gram; *w*, mass fraction; C_O, organic carbon; N, nitrogen; P, phosphorus; $\delta^{13}C_O$, stable isotopic organic carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent; ---, not determined; ‰, per mil]

Site identifier	Sand % (% dry weight)	Unsupported lead-210 (Bq/g)	Error in unsupported lead-210 (Bq/g)	$w(C_O)$ (%)	$w(N)$ (%)	$w(C_O)$: $w(N)$	$w(P)$ (%)	$\delta^{13}C_O$ (‰)	$\delta^{15}N$ (‰)
				Bank					
B1	72	0.0108	0.0100	2.18	0.20	10.9	0.08	-26.54	5.29
B2	65	0.0102	0.0050	1.77	0.19	9.32	0.08	-26.55	5.54
B3	74	0.0059	0.0044	1.79	0.19	9.44	0.10	-25.80	6.26
B4	84	0.0113	0.0047	1.48	0.15	9.87	0.06	-25.99	6.46
B5	---	0.0078	0.0070	1.67	0.13	12.8	0.04	-27.40	3.11
B6	74	0.0177	0.0067	2.20	0.23	9.54	0.06	-27.23	5.72
B7	65	0.0001	0.0048	2.00	0.20	10.0	0.08	-27.34	5.44
B8	70	0.0001	0.0049	1.57	0.17	9.24	0.06	-26.10	6.15
B9	78	0.0043	0.0049	2.23	0.20	11.1	0.09	-26.14	6.04
B10	71	0.0151	0.0050	2.14	0.20	10.7	0.09	-26.76	5.97
B11	61	0.0113	0.0076	2.42	0.22	11.0	0.09	-26.96	5.36
B12	63	0.0001	0.0060	1.30	0.18	7.41	0.06	-25.90	4.78
Average	**71**	**0.0079**		**1.89**	**0.19**	**10.11**	**0.07**	**-26.56**	**5.51**
Standard error	**2.0**	**0.0017**		**0.10**	**0.01**	**0.39**	**0.01**	**0.17**	**0.26**
				Crop Area					
C1	49	0.0094	0.0070	1.48	0.15	9.87	0.09	-20.46	6.75
C2	66	0.0002	0.0064	1.66	0.17	9.75	0.09	-21.51	6.40
C3	70	0.0259	0.0089	1.82	0.19	9.41	0.09	-23.86	6.02
C4	59	0.0058	0.0049	1.54	0.17	9.03	0.10	-23.03	7.03
C5	78	0.0023	0.0072	1.63	0.14	11.64	0.11	-23.22	7.92
C6	56	0.0001	---	1.58	0.16	9.88	0.10	-22.29	7.92
C7	64	0.0020	0.0055	4.39	0.35	12.42	0.28	-23.84	6.67
C8	---	0.0056	0.0031	1.54	0.23	6.65	0.10	-22.58	4.62
C9	77	0.0046	0.0066	1.07	0.12	8.92	0.09	-21.98	6.52
C10	72	0.0044	0.0030	1.52	0.18	8.66	0.15	-21.79	9.58
C11	77	0.0001	---	1.39	0.15	9.27	0.05	-24.96	5.14
C12	---	0.0001	0.0060	1.56	0.17	9.18	0.10	-21.15	6.67
C13	70	0.0165	0.0072	2.85	0.36	7.97	0.22	-21.77	7.66
Average	**67**	**0.0059**	**0.0060**	**1.85**	**0.20**	**9.43**	**0.12**	**-22.50**	**6.84**
Standard error	**2.6**	**0.0021**	**0.0005**	**0.24**	**0.02**	**0.40**	**0.02**	**0.35**	**0.35**
				Construction Area					
D1	79	0.0001	---	0.52	0.04	13.00	0.03	-25.75	5.92
D2	84	0.0001	---	0.38	0.03	12.67	0.03	-26.00	6.66
D3	71	0.0160	0.0082	0.82	0.10	8.20	0.05	-23.16	5.50
D4	69	0.0001	---	0.46	0.05	9.20	0.07	-21.57	7.51
D5	---	0.0001	---	0.45	0.05	9.00	0.07	-21.63	7.60
D6	62	0.0069	0.0070	0.89	0.09	9.87	0.09	-22.95	7.58
D7	---	0.0009	0.0035	0.98	0.11	9.33	0.04	-23.91	4.85
D8	---	0.0001	---	0.78	0.09	8.58	0.05	-24.00	5.83
D9	83	0.0019	0.0051	0.77	0.08	9.63	0.06	-25.06	5.02
D10	77	0.0063	0.0083	0.45	0.05	9.00	0.06	-25.07	5.95
Average	**75**	**0.0032**	**0.0064**	**0.65**	**0.07**	**9.85**	**0.06**	**-23.91**	**6.24**
Standard Error	**2.6**	**0.0016**	**0.0007**	**0.07**	**0.01**	**0.52**	**0.01**	**0.50**	**0.33**

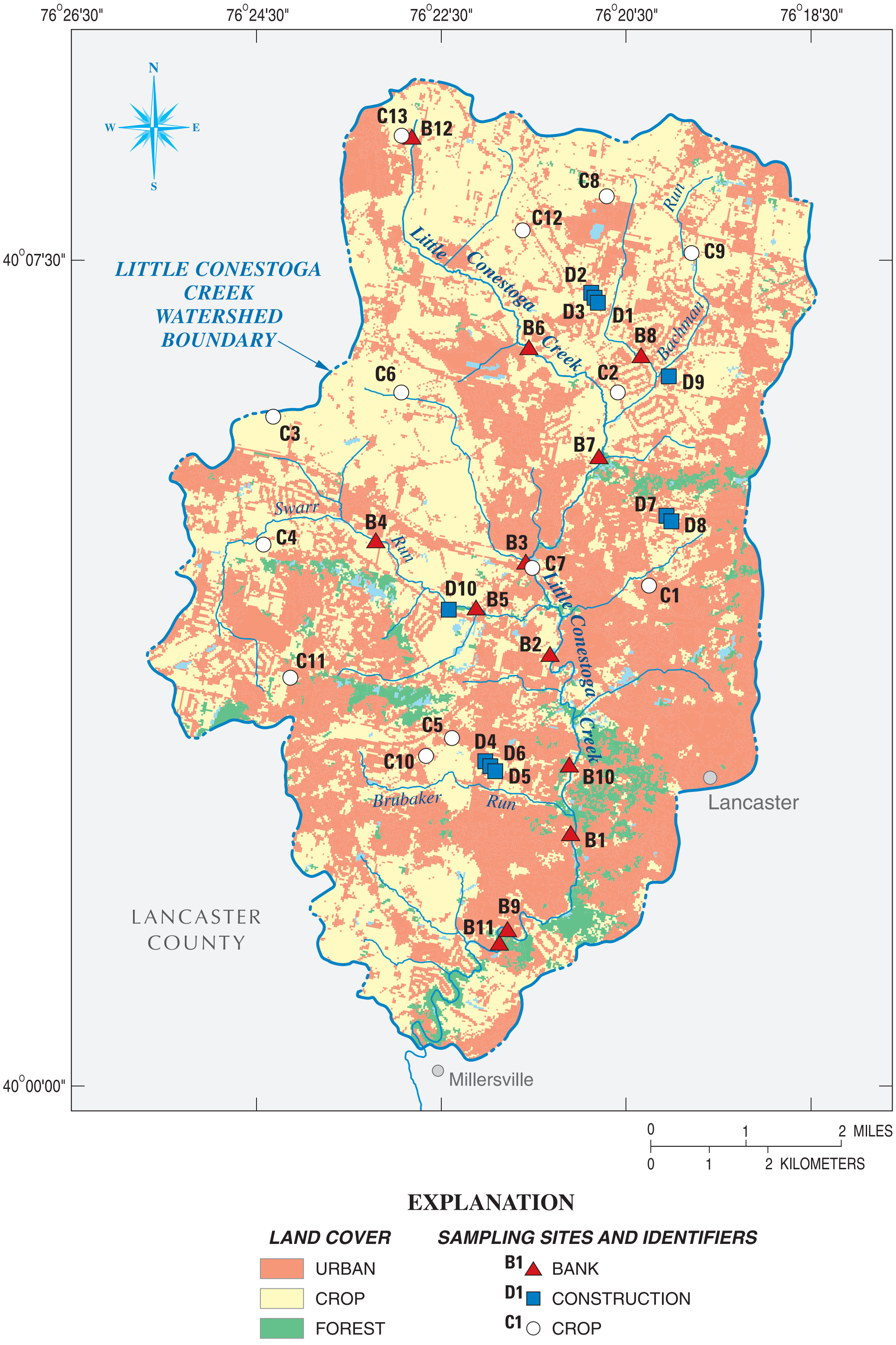

Figure 28. Location of sediment source sampling sites in the Little Conestoga Creek Watershed near Millersville, Pennsylvania, collected from August 2003 to July 2005. [Land cover from U.S. Geological Survey National Land Cover Database (NLCD)].

Table 20. Summary of samples collected in the Little Conestoga Creek Watershed of mass fraction (*w*) and isotope (*δ)* analyses for total carbon (C_T), organic carbon (C_O), and inorganic carbon (C_I).

[The value of $w(C_I)$ is calculated as $w(C_I) = [w(C_T) – w(C_O)]$, but the calculated value $w(C_I)$ is set equal to 0.0 when $[w(C_I) / w(C_T)] \leq 0.05$ because there is a ±5% uncertainty in the value of $w(C_O)$. *w*, mass fraction by weight; C_T, total carbon; $\delta^{13}C_T$, stable isotopic total carbon-13; C_O, organic carbon; $\delta^{13}C_O$, stable isotopic organic carbon-13; C_I, organic carbon; %, percent; ‰, per mil]

Sample identifier	Sample location	$w(C_T)$ (%)	$\delta^{13}C_T$ (‰)	$w(C_O)$ (%)	$\delta^{13}C_O$ (‰)	$w(C_I) / w(C_T)$	$w(C_I)$ (%)
LC060703H	Fluvial	4.20	-21.38	3.80	-26.40	0.10	0.4
LCC0426AB	Fluvial	3.95	-19.36	3.40	-26.41	0.14	0.55

Table 21. Median values within source areas in the Little Conestoga Creek Watershed and test statistics for tracers for which the Kruskal-Wallis test for equality of medians among source areas was rejected.

[*w*, mass fraction by weight; C_O, organic carbon; N, nitrogen; P, phosphorus; $\delta^{13}C_O$, stable isotopic organic carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; %, percent; ‰, per mil]

Sample location	Number of samples	$w(C_O)$ (%)	$w(C_O) : w(N)$	$w(P)$ (%)	$\delta^{13}C_O$ (‰)	$\delta^{15}N$ (‰)
			Median Values			
Bank	12	0.1898	9.93	0.0765	-26.55	5.63
Construction	10	0.6450	8.95	0.0564	-23.54	5.935
Crop	13	1.5600	9.27	0.1008	-22.29	6.68
			Test Statistics			
H value		22.07	2.80	14.08	24.20	8.03
Critical value		6.0	6.0	6.0	6.0	6.0
P-Value		22.07	0.25	0.0009	5.68E-06	0.018
Reject or accept the null hypothesis of equality of medians		Reject	Accept	Reject	Reject	Reject

Table 22. Probability values of Tukey test performed between source areas within the Little Conestoga Creek Watershed for those tracers which passed the Kruskal-Wallis test screening.

[*w*, mass fraction by weight; C_O, organic carbon; P, phosphorus; $\delta^{13}C_O$, stable isotopic organic carbon-13; $\delta^{15}N$, stable isotopic nitrogen-15; <, less than; ‰, per mil]

Tracer compared between source areas	Bank	Construction
	$w(C_O)$ (%)	
Construction	<0.01	
Crop	0.178	<0.01
	w(P) (%)	
Construction	0.209	
Crop	<0.01	<0.01
	$\delta^{13}C_O$ (‰)	
Construction	<0.01	
Crop	<0.01	0.033
	$\delta^{15}N$ (‰)	
Construction	0.379	
Crop	0.01	0.254

$\delta^{15}N$ only distinguished between two sources, cropland and banks, the same sources that were distinguished by *w*(P) and $\delta^{13}C_O$. A Spearman's Rho correlation test performed on $\delta^{15}N$, *w*(P), and $\delta^{13}C_O$, indicated that $\delta^{15}N$ was correlated to $\delta^{13}C_O$ (correlation coefficient = 0.57; ρ = less than 0.0001) and to P (correlation coefficient = 0.62; ρ = 0.0004). Since $\delta^{15}N$ did not provide any additional information to help identify sediment sources, it was removed. The final three tracers used in the unmixing model were *w*(P), $\delta^{13}C_O$, and $w(C_O)$.

Averaging the sediment sources from the unmixing model results for the 12 sampled events showed that cropland was the most important sediment source (61 percent), followed by streambanks (39 percent) (table 23). Weighting the sampled events by sediment load indicated that streambanks were the most important source of sediment (63 percent), followed by cropland (37 percent) (table 23). Construction-derived sediment did not appear as a sediment source for any of the sampled events (table 23). For Little Conestoga Creek, the area under construction was obtained from the Lancaster County, Pennsylvania, GIS Service Section and was based on 2002 1:2400 orthophotographs with a 0.61-m resolution. The area under construction in 2002 was 56 ha, which is only a small area of the watershed (0.51 percent). The lack of construction sites as a source of sediment in Little Conestoga Creek Watershed may reflect the small spatial area of this sediment source or the effectiveness of erosion-control strategies at these construction sites. Additional studies would be necessary to determine the effectiveness of erosion-control strategies on sediment yields in Lancaster County, Pennsylvania.

Streambanks were an important source of sediment for the two highest peak flows, the four highest daily mean discharges, and for the two events that transported the most sediment (fig. 29). Fifty-five percent of the total sediment load during the period of study was transported by the two highest peak flows, 28.9 m^3/s on February 6, 2004 and 17.3 m^3/s on March 21, 2003. Cropland was an important source for the lower flows and throughout the year (figs. 29a, b).

Thirty-seven percent of the sediment is attributed to cropland (table 23). Applying this value of 37 percent to the annual suspended-sediment load computed for the Little Conestoga Creek near Millersville, Pennsylvania (7,130 Mg) indicates that 2,638 Mg would be from cropland. Results from the ^{137}Cs mass balance for the Little Conestoga Creek indicated that 27,600 Mg/yr of sediment was eroded from cropland. The difference in sediment eroded from croplands (27,600 Mg/yr) and sediment reaching the station from cropland (2,638 Mg/yr) is 24,962 Mg/yr, which is the amount of sediment deposited on slopes or in the stream corridor annually. The delivery ratio of sediment from cropland sources to the sediment station is 0.096 (2,638 Mg/yr / 27,600/Mg/yr), indicating that around 10 percent of eroded cropland reaches the sampling point of the watershed, annually.

Using the bare ground information for the Little Conestoga Creek Watershed that was previously presented, estimates were made of bare ground for the days when fluvial samples were collected for sediment source analysis (fig. 29c). The estimates of bare ground for the sampled events were made by assuming a linear trend of bare ground between the different dates of the satellite imagery (fig. 13). Using these estimates, the bare ground percentages for the sampled events are plotted with the sediment source estimates (fig. 29c). Examination of figure 29c does not indicate that cropland is a more important source of sediment when more bare ground is present. Examination of figures 29a and b also indicates that sediment sources in the Little Conestoga Creek Watershed are related to flow conditions. During the highest flows and peak flows, the streambanks are the major source of sediment.

Table 23. Unmixing model results for the Little Conestoga Creek Watershed showing sediment sources (in percent) for sampled storms using the three tracers: $w(C_0)$, $w(P)$, and $\delta^{13}C_0$.

[*w*, mass fraction by weight; C_O, organic carbon; P, phosphorus; $\delta^{13}C_O$, stable isotopic organic carbon-13; %, percent]

Sample date	Banks (%)	Construction (%)	Crop (%)	Error
3/2/2003	0	0	100	6.45
3/9/2003	92	0	8	4.47
3/20–21/2003	95	0	5	3.60
4/11/2003	0	0	100	6.06
5/26/2003	0	0	100	6.34
6/4–5/2003	0	0	100	6.25
6/7–7/2003	95	0	5	5.54
9/1–2/2003	0	0	100	6.44
9/19–20/2003	0	0	100	6.37
10/14–16/2003	0	0	100	6.53
2/6–7/2004	91	0	9	4.81
6/5/2004	93	0	7	5.73
Average	**39**	**0**	**61**	**5.72**
Sediment weighted average	**63**	**0**	**37**	

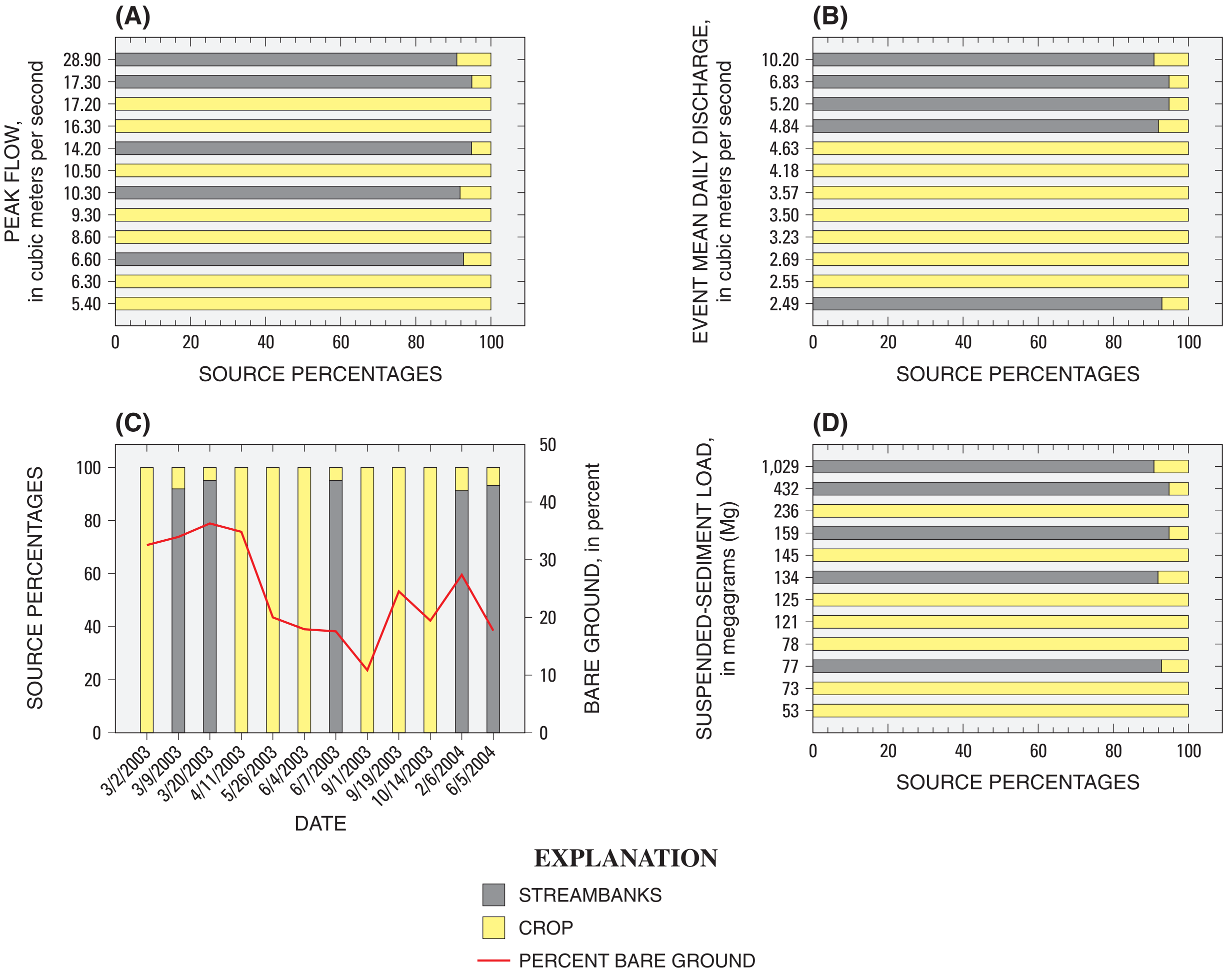

Figure 29. Sediment sources for the Little Conestoga Creek Watershed by (A) peak flow of sampled event, (B) mean daily discharge for sampled event period, (C) ascending order of day and month sampled, and (D) suspended-sediment load for sampled runoff event period. [Bare ground percent, based on satellite interpretations, is presented in C.]

Sediment Trapping on Chesapeake Bay Flood Plains

Initial flood-plain deposition measurements in selected rivers of the Chesapeake Bay Watershed began in late 1996, and included the establishment of feldspar clay pads and dendrogeomorphic (tree-ring) analysis of sediment deposition above lateral roots. Most study sites along selected rivers were fully established in 1997, except for intensive investigations along the Pocomoke River, which began in 1998. The Little Conestoga Creek and Mattawoman Creek were investigated more recently, beginning in 2004. Clay pads at most sites were measured for deposition during late 2006. Thus, most sites were monitored for sediment deposition over a period of at least 8 years. In all, 350 pads were established on 54 transects along the 10 selected streams (fig. 2).

Dendrogeomorphic analyses cover various periods of time, depending on the age of the tree at the time of sampling, and are considered long-term (relative to clay pads) estimates of sedimentation for the purposes of this report. Tree ages ranged from about 10 to 250 years old; most were between 30 and 90 years old. At least 525 trees were dendrogeomorphically sampled for long-term sedimentation-rate estimation. Intensive dendrogeomorphic sampling occurred along transects at sites along each of the selected streams except for the Little Conestoga Creek, Popes Creek, and Mattawoman Creek.

Vertical Accretion

The average annual sedimentation rate (vertical accretion) by stream and site is listed in tables 24 and 25 and are shown spatially for the entire Chesapeake Bay (fig. 30). Annual sedimentation rates vary among sites (fig. 31), and range from 0.55 mm/yr along channelized parts of the Pocomoke River to 8.05 mm/yr at a site on the Little Conestoga Creek. An anomalously high rate of 9.67 mm/yr occurred on Dragon Run at a site severely impacted by beaver dams (Big Island Site; table 24). Vertical accretion averaged for each river ranged from 1.05 to 7.44 mm/yr (fig. 32). Individual clay-pad values (not shown in tables 24 and 25) ranged from zero in erosional environments such as on some levees near crevasses or along channelized reaches to about 20 mm/yr in highly depositional backswamps. Atypical maximum rates near 45 mm/yr for Dragon Run are a result of beaver activity.

All sites except those along the Little Conestoga Creek (entirely on the Piedmont) are located on Coastal Plain reaches. In general, alluvial rivers that originate above the Fall Line and flow across the Coastal Plain (fig. 31) had generally higher sedimentation rates (mean, 4.0 mm/yr) than those that head on the Coastal Plain (mean, 2.3 mm/yr), reflecting the higher sediment yields of these rivers (table 1). Mean river sedimentation rates fall within the range of most alluvial systems in the southeastern United States (1.5 to 5.4 mm/yr, Hupp, 2000), except for the Big Island site on Dragon Run (table 24, fig. 32), which has been impacted by beaver. Sedimentation measurements on Popes Creek were limited to upstream sites, and the Mattawoman Creek site was located along a reach with relatively high velocities associated with a narrowing in the valley bottom. Both of these topographic conditions limit flood-plain sediment deposition (Hupp, 2000).

Sedimentation rates determined from dendrogeomorphic (long-term) analyses were determined for all streams except the Little Conestoga Creek, Mattawoman Creek, and Popes Creek, and ranged from 3.0 mm/yr on the urbanizing Chickahominy River to 1.2 mm/yr on the forested Pamunkey River (fig. 32). Dendrogeomorphic sedimentation rates are lower at most sampling locations than short-term vertical accretion rates, except for the Patuxent River (fig. 32). Lower long-term rates indicate a trend that was confirmed by Ross and others (2004) that can be partly attributed to soil compaction and organic oxidation over long time frames. Shifts in sedimentation rates over time can also affect differences (sometimes large) between short- and long-term rates, however. For the Patuxent River, the higher sedimentation over the longer time period relative to the clay-pad measurements may be due to the urbanization that occurred in the watershed prior to clay-pad placement. Urbanization can lead to higher rates of erosion and sediment yields.

In relation to land use in the watershed, sedimentation rates are highest in watersheds with urban areas (Chickahominy River, Little Conestoga Creek, and Patuxent River). Sedimentation rates were lowest in the agricultural watersheds (Choptank and Pocomoke Rivers) and forested watersheds (Mattawoman, Pamunkey, and Mattaponi River Watersheds). The lowest short-term sedimentation rate was in forested Mattawoman Creek and the highest short-term sedimentation rate occurred on the flood plain of Dragon Run, which has been severely affected by beaver dams that can increase sedimentation rates many times over the background rate. The forested Pamunkey and Mattaponi River Watersheds, particularly the Pamunkey, are also somewhat affected by recent increased residential development that may increase flood-plain deposition rates. Both rivers historically had significantly larger areas in agricultural land use that may have substantially increased the sediment volume now in quasi storage (legacy sediment) along Coastal Plain reaches. Legacy sedimentation was shown to be important in present-day sediment dynamics along the Chickahominy River just to the south of the study area (Hupp and others, 1993). The agricultural and forested watersheds (Choptank and Pocomoke River Watersheds) are both entirely on the Coastal Plain, where sediment transport is inherently low (Hupp, 2000).

Sedimentation rates at individual sites along study streams reflect both downvalley trends and local influences. The locations of sites, shown by river and sediment-deposition trends, are presented in figure 30. Flood-plain deposition increases downstream on the Pamunkey, Mattaponi, Patuxent, and Pocomoke Rivers (figs. 30, 31). Flood-plain deposition on the Coastal Plain typically increases downstream (Hupp, 2000) up to the area where tides substantially affect flow (Kroes and

Table 24. Flood-plain sedimentation rates for selected locations in the Chesapeake Bay Watershed.

[Sites shown with an asterisk are not used in the present analyses but were part of earlier studies and became inaccessible. Tree-ring data are not available for all sites. gm/cm^3, gram per cubic centimeter; mm/yr, millimeters per year; N/A, not available]

River / Stream	Site	Bulk density (gm/cm^3)	Clay pad deposition rate (mm/yr)	Tree rings (mm/yr)
Chickahominy River	Average	0.67	4.78	3.03
	Upham Brook	0.67	6.48	5.70
	Bottom’s Bridge	0.67	3.80	2.10
	Providence Forge	0.67	4.05	1.30
Pamunkey River	Average	0.42	3.50	1.16
	Engel Farm	0.47	1.72	1.08
	Pampatike	0.38	5.28	1.23
Mattaponi River	Average	0.65	3.46	1.92
	Burke’s Bridge	0.66	2.63	1.29
	Aylett	0.65	4.28	2.55
Dragon Run	Average	0.68	7.44	1.68
	Big Island	0.56	9.67	N/A
	Mascot	0.68	5.22	1.68
Popes Creek	Average	0.67	1.20	0.69
	G.W. Birthplace	0.67	1.20	0.69
	Gage	0.67	1.05	N/A
Patuxent River	Average	0.73	2.10	2.95
	Brock Bridge	0.79	1.29	1.66
	Hardesty	0.60	2.90	4.24
Choptank River	Average	0.39	3.36	1.71
	Holiday Park	0.35	4.12	1.73
	Red Bridges	0.43	1.43	1.32
	Gravely Branch*	0.67	4.52	2.09
Pocomoke River	Average	0.18	2.71	1.50
	Delaware Crossing	0.12	0.55	N/A
	Cypress Swamp	0.10	1.17	1.22
	Willards	0.16	1.07	1.85
	Whiton Crossing	0.25	4.80	1.43
	Porters Crossing	0.33	3.56	1.73
	Blades Road	0.10	3.10	1.27
	Milburn Landing*		1.03	N/A
	Dividing Creek*		2.89	N/A
	Nassawango Creek*		1.29	N/A
	Beverly (marsh)*		7.67	N/A
Little Conestoga	Average		4.36	N/A
	Pump Station	0.67	4.11	N/A
	Mennonite home	0.67	8.05	N/A
	Stone House	0.67	1.31	N/A
	gage house	0.67	5.90	N/A
	Walnut Branch	0.67	4.98	N/A
	West Branch	0.67	1.81	N/A

Table 25. Flood-plain sedimentation rates and trapping efficiencies summarized for selected locations in the Chesapeake Bay Watershed.

[mm/yr, millimeters per year; gm/cm^3, gram per cubic centimeter; Kg/m^2/yr, kilograms per square meter per year; %, percent; Mg/yr, megagram per year]

River	Clay pad deposition rate (mm/yr)	Long term tree-ring deposition rate (mm/yr)	Clay pad trapping, (Kg/m^2/yr)	Tree-ring trapping (Kg/m^2/yr)	Bulk density (gm/cm^3)	Organics, loss on ignition (%)	Average annual sediment load (Mg/yr)	River trapping (Mg/yr)	Potential sediment load trapped (%)
Chickahominy River	4.78	3.03	2.31	1.55	0.67		[1]3,782	35,190	930
Pamunkey River	3.50	1.16	1.10	0.34	0.42	15.1	35,740	9,130	25.5
Mattaponi River	3.46	1.92	1.62	0.94	0.65		4,560	16,270	356
Dragon Run	7.44	1.68	3.86	0.88	0.62	10.9		34,720	
Mattawoman Creek	1.05		0.13		0.67	8.78	2,666	2,330	87.4
Patuxent River	2.10	2.95	0.34	0.49	0.70	10.3	20,870	4,358	20.9
Choptank River	3.36	1.71	0.88	0.41	0.48		2,096	876.1	41.8
Pocomoke River	2.71	1.50	0.39	0.15	0.19	55.1	3,222	2,739	85.0
Little Conestoga	4.36		-0.87		0.67	3.89	7,125	-904.9	-12.7

[1] The suspended-sediment load estimate for the Chickahominy River is based on a limited dataset and may be an outlier.

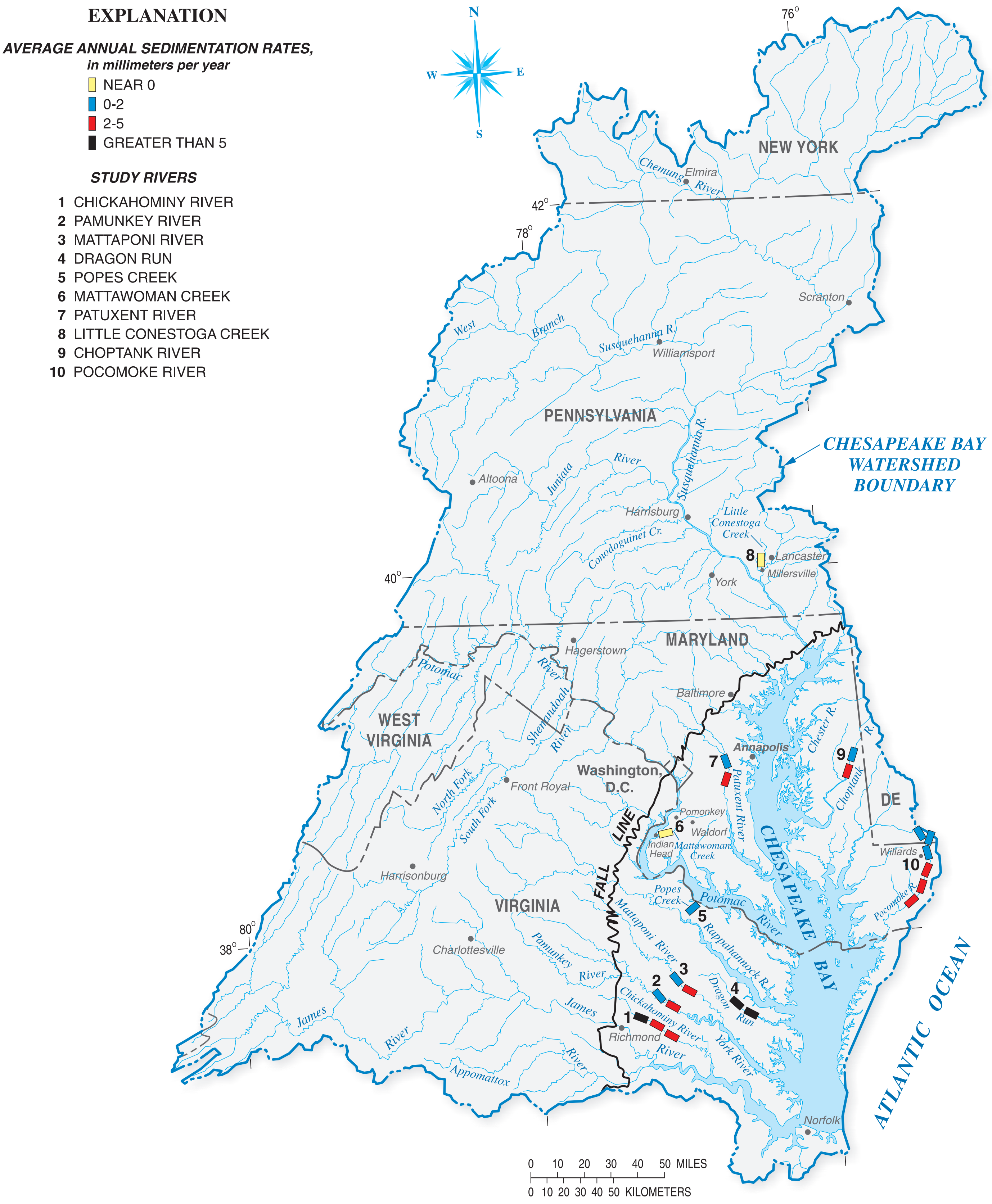

Figure 30. Average annual sedimentation rates for sites in the Chesapeake Bay Watershed, 1996–2006.

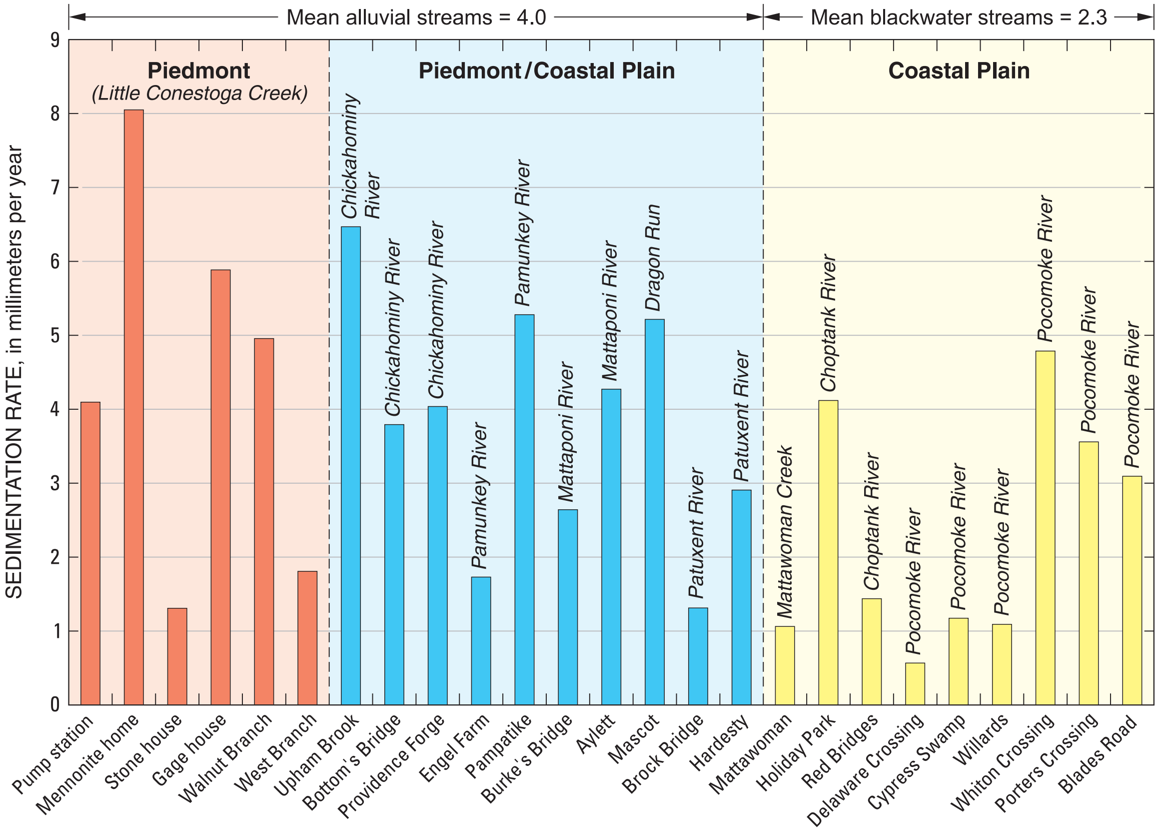

Figure 31. Sedimentation rates (vertical accretion in millimeters per year) on flood plains of selected Chesapeake Bay tributaries, 1996–2006. [Mean values for alluvial and blackwater sites are shown. (Sites are arranged by location of headwaters and specific location of sampling stations. The Piedmont stream in red, Little Conestoga Creek, has both its headwaters and sampling stations located in the Piedmont. Sites shown in blue derive at least some sediment from Piedmont sources, and sampling stations are located on the Coastal Plain. Sites shown in yellow are entirely within and affected by the Coastal Plain. Sites are listed from upstream to downstream where streams have more than one study site). The Big Island site is not shown in this figure because it was completely flooded during parts of the study and suffered from heavy sedimentation mostly related to beaver activity].

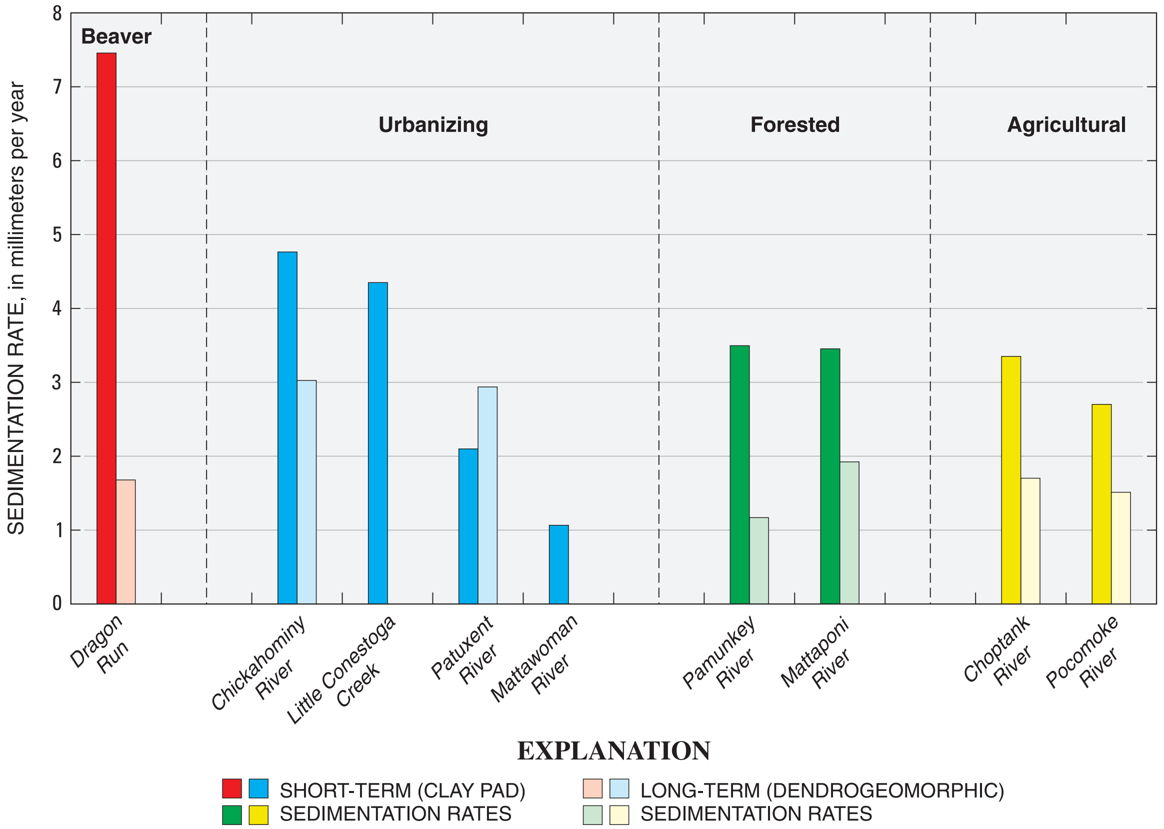

Figure 32. Short- and long-term sedimentation rates (in millimeters per year) by river and land use for the Chesapeake Bay Watershed. [Measurements were made from 1996–2006. (Streams affected by beaver are shown in red, by urbanizing land use in blue, by forested land use in green, and by agricultural land use in yellow.)]

others, 2007). The Little Conestoga Creek is represented by a single box because of the close proximity of sites (fig. 30). This river and the Pocomoke River will be discussed in more detail in the following section.

The highest deposition rates occur on the Virginia Western Shore of the Chesapeake Bay (fig. 30). The Upham Brook site on the Chickahominy River is within the City of Richmond, Virginia, and is affected by recent urbanization (figs. 30, 31). Pampatike, on the Pamunkey River (fig. 31), is located along a reach where initial widening of the flood plain and a decrease in stream gradient occur below the Fall Line, which are conducive to high sedimentation rates (Hupp and others, 1993; Hupp, 2000). Mascot on Dragon Run (fig. 31) is affected by beaver activity. The lowest deposition rates occur for streams that drain entirely on the Coastal Plain (fig. 31). Three out of four of the lowest deposition rates occur on channelized reaches of the Pocomoke River at three upstream sites (Delaware Crossing, Cypress Swamp, and Willards; fig. 31). The majority of the Pocomoke River drainage basin was ditched (drainage created where no drainage previously occurred) and channelized (natural drainage modified to facilitate efficient drainage). The channelization of the main stem of the Pocomoke began in 1939 and was completed in 1946 (Bell and Favero, 2000). This channelization left only the lower 60 km of the Pocomoke River main stem and a few small tributaries unchannelized. Channelization and subsequent incision dramatically reduces contact between sediment-laden streamflow and the flood plain (Hupp, 1999). The effect of channelization is clearly demonstrated by the two- to three-fold increase in flood-plain deposition on the Pocomoke River between the channelized Willards site and the largely unchannelized sites downstream (fig. 31).

Rivers that head in either the Piedmont or Appalachian Mountains characteristically transport large amounts of suspended sediment and bedload (Hupp, 2000). Blackwater rivers (those that head on the Coastal Plain) have a considerably smaller sediment load than rivers originating in the Piedmont (table 1). The sediment in suspension in Coastal Plain streams has a relatively high organic content, whereas alluvial rivers principally transport mineral sediment. This condition is reflected in the flood-plain sediment of the Little Conestoga Creek, a Piedmont stream, which has an average

LOI of 3.89 percent (table 25). Western Shore streams have only a slightly higher mean LOI at 9.87 percent (table 25). The Western Shore Streams are located on the Coastal Plain, but originate in the Piedmont, except for Mattawoman Creek. The Eastern Shore Pocomoke River, which drains entirely on the Coastal Plain, had flood-plain averages of 55.10 percent LOI (table 25). Thus, in terms of mineral sedimentation patterns on the Coastal Plain, the Western Shore streams generally have higher deposition rates than the Eastern Shore streams (fig. 32).

Sediment Trapping

Conversion of sedimentation rates in millimeters per year (mm/yr) to mass of sediment trapped in kilograms (kg) allows for comparison with suspended-sediment loads transported out of the watershed. An estimation of flood-plain area and the bulk density of the sample is required for this conversion and is presented in table 25. Topographic maps (USGS, scale 1:24,000) and digital mapping software (Garmin Mapsource, Garmin Ltd.) were used to estimate the flood-plain area for each of the study rivers between the Fall Line and head of tides. Each river was divided into flood-plain segments delineated by the midpoint between study sites and bounded by the upstream Fall Line and the downstream head of tides. The width of each flood-plain segment was estimated by averaging approximately 10 width measurements from topographic maps (USGS, 1:24,000). The length of each segment was determined as the river length through the segment. The flood-plain area was then adjusted to reflect the active flood plain by dividing out the proportion of each segment that had deposition rates below 2 mm/yr, which was assumed to indicate areas not influenced by river sedimentation.

Positive sediment-trapping rates ranged from 0.13 to 3.86 kg/m^2/yr (fig. 33; table 25). The rates for the Little Conestoga are unusual because overall trapping rates along this river have had measured bank erosion rates subtracted, indicating net erosion where sediment in storage is being eroded (fig. 33). The use of sediment-trapping amounts rather than vertical accretion rates accentuates the difference among most sites (fig. 33). The recent (last decade) trapping rates estimated on the basis of clay pads are generally greater than the long-term rates, which are based on dendrogeomorphic evidence. Differences between most Western Shore streams and the Southern Maryland and Eastern Shore streams (fig. 33) are distinct where the latter distinctly trap less sediment. This is likely due, in part, to the blackwater nature of Eastern Shore streams

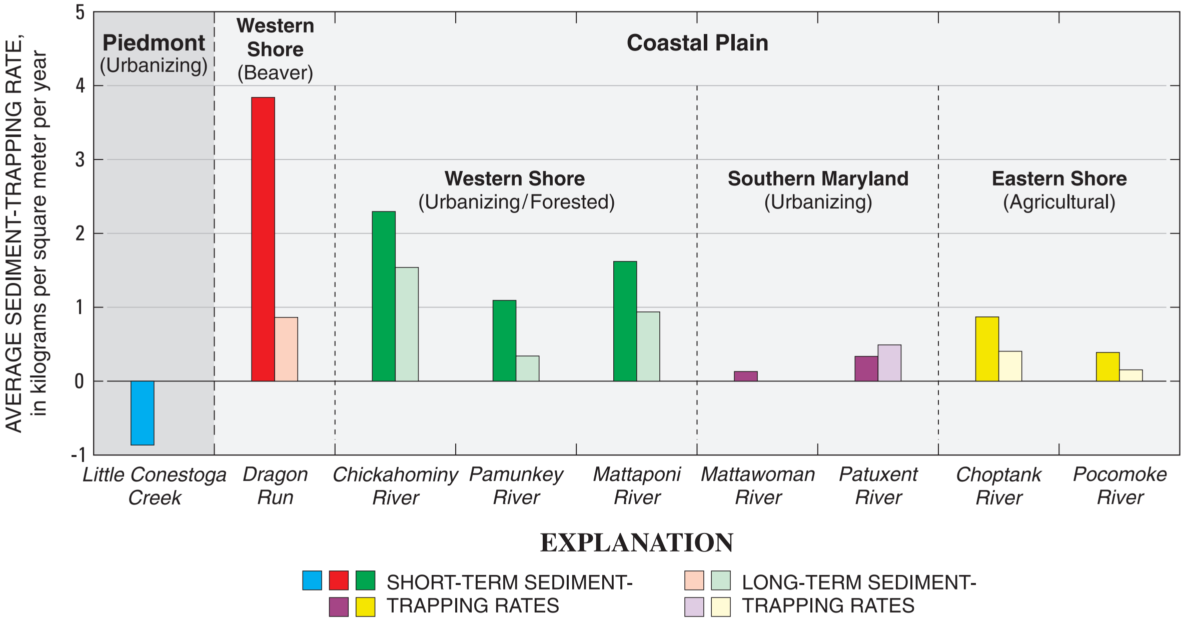

Figure 33. Average sediment-trapping rates for flood-plain study sites in the Chesapeake Bay Watershed derived from short- and long-term estimates. [Measurements were made from 1996–2006.]

with limited watershed area, lower suspended-sediment loads, and organic-rich flood-plain sediment (table 25). The Southern Maryland streams, Patuxent River and Mattawoman Creek, have sediment-trapping rates more similar to Eastern Shore streams than other streams (fig. 33); however, the Patuxent River has several upstream reservoirs that may be trapping sediment before it reaches the downstream sampling sites, and Mattawoman Creek originates on the Coastal Plain and therefore, has low suspended-sediment concentrations (fig. 21).

Determination of the role flood-plain sediment trapping plays in sediment delivery to the Chesapeake Bay is facilitated by extrapolating site trapping results to large reaches of the flood plain in tributary streams. Annual trapping amounts ranged over two orders of magnitude from 35,190 Mg/yr on the Chickahominy River down to 876 Mg/yr on the Choptank River (table 25). Annual suspended-sediment loads from upstream streamflow-gaging stations ranged from 35,740 Mg/yr on the Pamunkey River down to 2,096 Mg/yr on the Choptank River (table 25). Both annual sediment loads and the aerial extent of the flood plain between the Fall Line and the head of tides exert a strong influence on these trapping efficiencies. A quasi-mass balance (sediment budget) may be developed by subtracting trapping amounts from upstream river loads and determining the percent difference, which is an indication of the potential amount of sediment load trapped (fig. 34).

Streams that head in the Coastal Plain (blackwater systems; Hupp, 2000) consistently transport and trap less sediment than alluvial streams such as Piedmont streams (fig. 34). Sediment-trapping amounts exceeded sediment loads on the Chickahominy and Mattaponi Rivers (fig. 34), where extensive flood plains have developed in underfit valleys (valleys too large to have developed under present-day discharges) (Hupp, 2000) and likely provide a distinct overestimate of trapping potential. Part of the overestimation is due to the assumption that all parts of the flood plain have similar deposition rates and resuspension of existing flood plain sediment is not taken into account. Additionally, both the Chickahominy and Mattaponi Rivers have significant tributary inputs of suspended sediment downstream of the gaging station and upstream of the flood-plain monitoring sites. Other factors that contribute uncertainty to the sediment-trapping estimates relate to the permanency of the storage of accumulated sediment on flood plains (Noe and Hupp, 2005). The remaining rivers in the analysis are generally not underfit and do not have significant tributary inputs below gages and therefore provide more realistic trapping estimates that range from 21 to 87 percent of the sediment load (fig. 34), amounting to about 106 million Mg/yr. Based on this analysis, Coastal Plain flood plains trap large amounts of sediment that otherwise would be delivered to the Bay and provide for relatively long-term storage where important biogeochemical activity may ameliorate associated nutrients and other contaminants (Noe and Hupp, 2005).

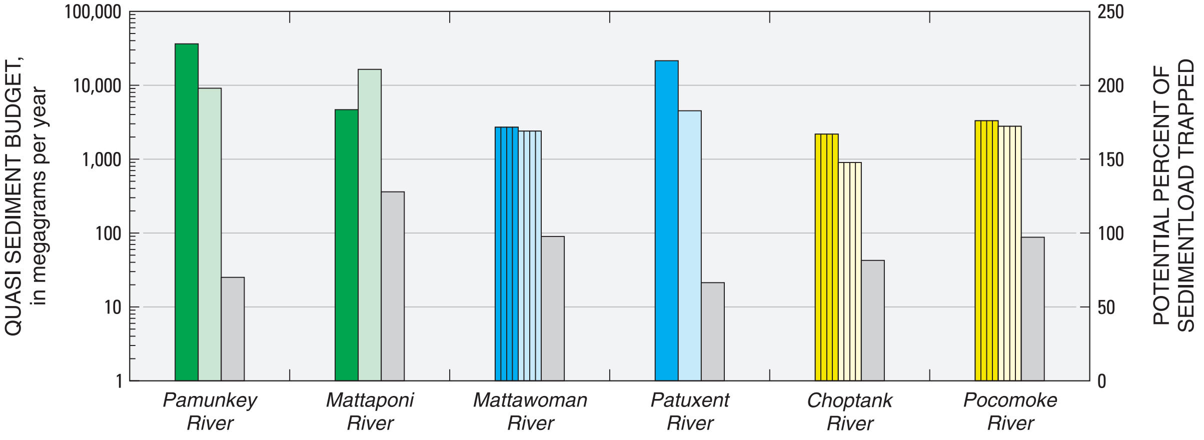

Figure 34. Quasi sediment budget for selected study streams in megagrams per year for annual sediment load (dark green, dark blue, and dark yellow bars), megagrams per year for potential annual amount trapped on flood plains (light green, light blue, and light yellow bars), and potential percent of sediment load trapped (gray bars). [Alluvial streams (heading Piedmont) are indicated with solid bars and blackwater (Coastal Plain) streams are vertically striped.]

Summary and Conclusions

Sediment is an important pollutant in the Chesapeake Bay and its receiving waters. The U.S. Geological Survey is engaged in several studies for which the objectives are to understand the sources, transport, storage, and delivery of sediment to the Bay and its watershed. This report summarizes findings from several U.S. Geological Survey studies designed to understand the sources, transport, and storage of sediment in selected sites of the Chesapeake Bay Watershed.

Erosion, sediment transport, and deposition were assessed at several scales and in a variety of environments in the Chesapeake Bay Watershed. For the entire Chesapeake Bay Watershed, modern sediment yields (20th Century) were highest in the Piedmont Physiographic Province and lowest in the Coastal Plain. Beryllium-10 data also show that the Piedmont has been most impacted by soil disturbance. Erosion indices based on meteoric beryllium-10, showed the highest rates of soil erosion from the Piedmont part of the Susquehanna River Watershed, specifically in the Conestoga River Watershed. The Conestoga River Watershed also had the highest modern sediment yields for the entire Chesapeake Bay Watershed. Geologic rates of erosion (between 10,000 years and 100,000 years) measured with *in situ* beryllium-10 were lowest in the Piedmont Province compared to other physiographic provinces in the Susquehanna River Watershed. By contrast, recent land-use disturbance and high rates of erosion in the Piedmont Province are shown by meteoric beryllium-10 indices and by modern sediment yields based on sediment gaging.

An analysis of bare ground over time in the Little Conestoga Creek Watershed from April 9, 2000 to September 30, 2005 was conducted using Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) satellite imagery. Although the percentages of bare cropland and bare pasture change over time, the majority of land in bare ground is pasture, averaging 67 to 69 percent. Taking averages of bare ground by month shows a correlation of bare ground to the growing season, with the highest percentage of bare ground present in the early spring “plow season,” and after “the fall harvest.” The lowest percentage of bare ground occurs in August, when most fields are in full cover and on average, only 10 percent of the watershed is in bare ground. Results of the bare ground satellite imagery showed that nearly one-third of the Little Conestoga Creek Watershed is in bare ground for 6 months out of the year.

Sediment-source analysis using geochemical fingerprints was performed for three watersheds draining the Chesapeake Bay Watershed—two in the Coastal Plain (Pocomoke River and Mattawoman Creek) and one in the Piedmont (Little Conestoga Creek). Important sediment sources in the agricultural Pocomoke River Watershed, which were weighted to the sediment transported by each event, were cropland (46 percent), ditch beds (34 percent), streambanks (7 percent), and forest (13 percent). Cropland was an important source of sediment for the two highest peak flows. Results from the cesium-137 inventories of cropland in the Pocomoke River Watershed indicate that erosion and deposition are both occurring on cropland fields. The two highest peak flows occurred during and after the harvesting period, when large areas of bare ground in the watershed were present and may have been a factor in characterizing cropland as an important sediment source. Ditch beds, ditch banks, and streambanks also were important sources of sediment. Many parts of the Pocomoke River Watershed are ditched, and channelization of the Pocomoke River extends back to the late 19th century and up to the late 20th century. Ditching and straightening (channelization) of the main stem Pocomoke River, and continual dredging have created conditions favorable for channel-corridor erosion in the Pocomoke River.

Important sediment sources for the mixed land use (forest, agricultural, and urbanizing) Mattawoman Creek Watershed on the Coastal Plain Western Shore were streambanks (30 percent), followed by forest (29 percent), construction (25 percent), and cropland (17 percent). Disturbance in the forest from centuries of agriculture and more recent urbanization may explain forest as a source of sediment. The importance of construction sites as a sediment source indicates that further work is needed to examine the design, implementation, and maintenance of the various erosion-control measures used in the Mattawoman Creek Watershed.

Important sediment sources for the agricultural and urbanizing Little Conestoga Creek Watershed were streambanks (63 percent), followed by cropland (37 percent). Results of the sediment-fingerprinting analysis showed that in the Little Conestoga Creek Watershed, flow may be a more important factor than seasonality in determining sediment sources. Cesium-137 inventories of cropland in the Little Conestoga Creek Watershed show high erosion rates averaged over the last 40 years (19.4 megagrams per hectare). With 13 percent of the watershed in cropland, 27,600 megagrams per year of sediment could be generated, which represents 387 percent of the average annual sediment load transported out of the Little Conestoga Creek for water years 2003–04 (7,130 megagrams per year), indicating significant sediment storage on hillslopes or in the stream corridor.

Centuries of agriculture in the Piedmont region have led to the high rates of modern erosion and storage of sediment on flood plains and behind mill dams. Recent land-use disturbance in the Piedmont Province may explain the higher modern sediment yields compared to geologic rates of erosion, and highlights the Piedmont as an important regional source of sediment in the Chesapeake Bay Watershed. The removal of sediment from storage is currently occurring today and is observed as streambank erosion. In addition, cropland still remains an important source of sediment.

Long-term and short-term flood-plain deposition rates were measured using tree rings and clay pads. Streams that drain within some or all of the Piedmont had generally higher sedimentation rates than streams that drain entirely on the Coastal Plain. Three out of four of the lowest deposition rates occurred in the channelized reaches of the Pocomoke River. Channelization and subsequent incision dramatically reduces contact between sediment-laden streamflow and the flood plain. Extrapolating flood-plain deposition rates from each site to larger parts of the flood plains drained by each river show that annual trapping amounts ranged over two orders of magnitude from 876 to 35,190 megagrams per year. Except for the Chickahominy and Mattaponi Rivers, the remaining rivers analyzed in this study have sediment-trapping estimates ranging from 21 to 87 percent of the river's sediment load. Based on this analysis, Coastal Plain flood plains trap large amounts of sediment that otherwise would be delivered to the Bay.

To reduce sediment to the Bay, the Chesapeake Bay Program is committed to developing strategies and management plans that may decrease erosion and sediment transport and improve water quality. Information described in this report on the sources, transport, storage, and delivery of sediment is helpful in targeting management actions to reduce sediment loadings to the Bay and its watershed.

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Appendix

Records of mean daily discharge and daily suspended-sediment loads for:

A1. The Pocomoke River near Willards, Maryland,
water year October 1, 2000 through September 30, 2003;

A2. Mattawoman Creek near Pomonkey, Maryland,
water year October 1, 2003 through September 30, 2004;

A3. Little Conestoga Creek near Millersville, Pennsylvania,
water year February 1, 2003 through September 30, 2004.

A1. The Pocomoke River near Willards, Maryland, water year October 1, 2000 through September 30, 2003.

[m^3/s, cubic meters per second; Mg, megagrams; ---, not applicable]

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	October 2000		November 2000		December 2000		January 2001		February 2001		March 2001	
1	2.12	4.14	0.51	0.31	0.79	0.70	0.71	0.57	2.32	4.87	2.41	5.19
2	1.84	3.20	0.48	0.28	0.74	0.61	0.68	0.53	2.10	4.04	2.18	4.34
3	1.64	2.60	0.48	0.28	0.68	0.53	0.62	0.45	1.98	3.66	1.98	3.66
4	1.44	2.06	0.48	0.28	0.65	0.49	0.62	0.45	1.81	3.11	1.81	3.11
5	1.27	1.65	0.48	0.28	0.71	0.57	0.68	0.53	3.57	10.57	2.41	5.19
6	1.19	1.45	0.48	0.28	0.65	0.49	0.59	0.42	6.03	27.28	2.78	6.71
7	1.10	1.27	0.48	0.28	0.62	0.45	0.59	0.42	4.45	15.73	2.46	5.41
8	0.99	1.05	0.48	0.28	0.62	0.45	0.59	0.42	3.60	10.72	2.15	4.24
9	0.91	0.89	0.48	0.28	0.59	0.42	0.59	0.42	3.17	8.54	1.98	3.66
10	0.85	0.79	0.57	0.38	0.57	0.38	0.57	0.38	2.95	7.47	1.84	3.20
11	0.82	0.74	0.57	0.38	0.59	0.42	0.54	0.35	2.55	5.76	1.67	2.69
12	0.76	0.65	0.54	0.35	0.59	0.42	0.54	0.35	2.24	4.55	1.50	2.21
13	0.71	0.57	0.57	0.38	0.57	0.38	0.54	0.35	2.38	5.08	2.55	5.76
14	0.65	0.49	0.62	0.45	0.68	0.53	0.54	0.35	2.66	6.23	3.26	8.96
15	0.65	0.49	0.62	0.45	0.99	1.05	0.65	0.49	2.66	6.23	2.80	6.84
16	0.59	0.42	0.57	0.38	1.10	1.27	0.76	0.65	2.46	5.41	5.78	25.24
17	0.59	0.42	0.57	0.38	1.67	2.69	0.76	0.65	3.12	8.27	4.84	18.35
18	0.59	0.42	0.57	0.38	2.55	5.76	0.74	0.61	3.20	8.68	3.99	12.95
19	0.62	0.45	0.54	0.35	1.95	3.56	1.56	2.37	2.69	6.35	3.26	8.96
20	0.59	0.42	0.54	0.35	1.70	2.77	6.60	32.08	2.44	5.30	2.78	6.71
21	0.57	0.38	0.54	0.35	1.36	1.85	8.21	47.63	2.27	4.65	8.72	53.11
22	0.57	0.38	0.51	0.31	1.25	1.58	5.81	25.46	2.07	3.94	18.00	197.00
23	0.54	0.35	0.48	0.28	1.13	1.33	4.42	15.55	2.07	3.94	14.00	126.00
24	0.54	0.35	0.48	0.28	0.99	1.05	3.79	11.81	2.10	4.04	9.35	60.15
25	0.54	0.35	0.48	0.28	0.96	0.99	3.34	9.39	2.41	5.19	6.66	32.58
26	0.54	0.35	0.79	0.70	0.88	0.84	2.92	7.35	3.57	10.57	5.30	21.57
27	0.54	0.35	1.16	1.39	0.82	0.74	2.72	6.47	3.12	8.27	4.73	17.58
28	0.54	0.35	0.99	1.05	0.82	0.74	2.49	5.53	2.72	6.47	4.13	13.79
29	0.54	0.35	0.88	0.84	0.79	0.70	2.27	4.65	---	---	3.77	11.65
30	0.51	0.31	0.82	0.74	0.76	0.65	2.29	4.76	---	---	9.03	56.58
31	0.51	0.31	---	---	0.74	0.61	2.55	5.76	---	---	9.40	60.81

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	April 2001		May 2001		June 2001		July 2001		August 2001		September 2001	
1	7.11	36.70	1.13	1.33	1.05	1.16	0.76	0.65	1.61	2.52	0.68	0.53
2	5.75	25.01	1.08	1.21	1.13	1.33	0.71	0.57	1.13	1.33	0.62	0.45
3	4.81	18.16	1.05	1.16	1.33	1.78	0.65	0.49	0.93	0.94	0.59	0.42
4	4.11	13.62	0.96	0.99	1.10	1.27	0.59	0.42	0.82	0.74	0.57	0.38
5	3.62	10.88	0.91	0.89	1.39	1.92	0.59	0.42	0.76	0.65	0.54	0.35
6	3.26	8.96	0.85	0.79	2.46	5.41	0.68	0.53	0.76	0.65	0.51	0.31
7	3.00	7.74	0.82	0.74	3.74	11.50	0.62	0.45	0.71	0.57	0.48	0.28
8	2.72	6.47	0.79	0.70	4.70	17.39	0.54	0.35	0.62	0.45	0.48	0.28
9	2.75	6.59	0.76	0.65	2.95	7.47	0.54	0.35	0.54	0.35	0.45	0.25
10	2.89	7.22	0.74	0.61	2.15	4.24	0.48	0.28	0.51	0.31	0.45	0.25
11	3.17	8.54	0.68	0.53	1.64	2.60	0.45	0.25	0.51	0.31	0.42	0.23
12	5.10	20.13	0.65	0.49	1.36	1.85	0.42	0.23	0.82	0.74	0.40	0.20
13	4.73	17.58	0.62	0.45	1.19	1.45	0.40	0.20	4.59	16.64	0.40	0.20
14	4.67	17.20	0.59	0.42	1.05	1.16	0.40	0.20	12.30	99.07	0.40	0.20
15	3.79	11.81	0.57	0.38	0.93	0.94	0.37	0.17	8.64	52.17	0.40	0.20
16	3.48	10.12	0.57	0.38	0.88	0.84	0.34	0.15	4.87	18.54	0.40	0.20
17	3.40	9.68	0.54	0.35	3.20	8.68	0.34	0.15	3.34	9.39	0.37	0.17
18	3.34	9.39	0.54	0.35	3.65	11.03	0.42	0.23	2.58	5.87	0.37	0.17
19	2.92	7.35	0.68	0.53	2.21	4.45	1.30	1.71	2.35	4.97	0.34	0.15
20	2.58	5.87	0.68	0.53	1.61	2.52	0.85	0.79	2.15	4.24	0.34	0.15
21	2.32	4.87	0.71	0.57	1.33	1.78	0.62	0.45	1.76	2.94	0.37	0.17
22	2.15	4.24	0.82	0.74	1.25	1.58	0.54	0.35	1.47	2.14	0.37	0.17
23	1.95	3.56	3.31	9.25	1.44	2.06	0.48	0.28	1.25	1.58	0.34	0.15
24	1.78	3.02	2.04	3.85	2.58	5.87	0.45	0.25	1.25	1.58	0.34	0.15
25	1.70	2.77	1.50	2.21	1.95	3.56	0.42	0.23	1.16	1.39	0.40	0.20
26	1.59	2.44	1.61	2.52	1.42	1.99	0.40	0.20	1.02	1.10	0.37	0.17
27	1.47	2.14	2.27	4.65	1.13	1.33	0.65	0.49	0.93	0.94	0.34	0.15
28	1.36	1.85	1.93	3.47	0.99	1.05	0.62	0.45	0.88	0.84	0.34	0.15
29	1.25	1.58	1.73	2.85	0.88	0.84	0.62	0.45	0.82	0.74	0.34	0.15
30	1.16	1.39	1.47	2.14	0.82	0.74	2.75	6.59	0.74	0.61	0.34	0.15
31	---	---	1.19	1.45	---	---	2.72	6.47	0.71	0.57	---	---

A1. The Pocomoke River near Willards, Maryland, water year October 1, 2000 through September 30, 2003.—Continued

[m^3/s, cubic meters per second; Mg, megagrams; ---, not applicable]

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	October 2001		November 2001		December 2001		January 2002		February 2002		March 2002	
1	0.34	0.15	0.28	0.11	0.19	0.05	0.24	0.08	0.56	0.37	0.39	0.20
2	0.35	0.16	0.26	0.09	0.18	0.05	0.21	0.06	0.55	0.36	0.39	0.20
3	0.33	0.15	0.25	0.08	0.18	0.05	0.21	0.06	0.51	0.32	0.58	0.40
4	0.32	0.14	0.24	0.08	0.18	0.05	0.23	0.08	0.52	0.32	0.62	0.44
5	0.32	0.13	0.23	0.07	0.18	0.05	0.23	0.07	0.50	0.30	0.55	0.36
6	0.34	0.15	0.21	0.06	0.18	0.05	0.25	0.08	0.53	0.34	0.55	0.36
7	0.36	0.17	0.22	0.07	0.18	0.05	0.55	0.36	0.58	0.40	0.54	0.35
8	0.34	0.15	0.22	0.07	0.19	0.05	0.40	0.21	0.77	0.66	0.52	0.33
9	0.33	0.14	0.20	0.06	0.19	0.05	0.36	0.17	0.72	0.59	0.51	0.31
10	0.33	0.14	0.21	0.06	0.19	0.05	0.36	0.17	0.68	0.53	0.50	0.31
11	0.34	0.15	0.19	0.05	0.22	0.07	0.36	0.17	0.71	0.57	0.47	0.28
12	0.33	0.14	0.17	0.04	0.23	0.08	0.35	0.16	0.64	0.48	0.48	0.28
13	0.33	0.14	0.18	0.05	0.21	0.07	0.39	0.19	0.61	0.44	0.57	0.39
14	0.34	0.15	0.18	0.05	0.21	0.06	0.40	0.20	0.57	0.38	0.80	0.71
15	0.39	0.20	0.19	0.05	0.20	0.06	0.39	0.20	0.55	0.36	0.77	0.67
16	0.38	0.19	0.19	0.06	0.19	0.05	0.41	0.21	0.54	0.35	0.75	0.63
17	0.36	0.17	0.18	0.05	0.18	0.05	0.43	0.24	0.53	0.34	0.68	0.53
18	0.35	0.16	0.18	0.05	0.23	0.07	0.36	0.17	0.50	0.30	0.99	1.05
19	0.34	0.15	0.19	0.05	0.23	0.07	0.38	0.19	0.51	0.31	1.54	2.32
20	0.33	0.15	0.21	0.06	0.21	0.06	0.67	0.51	0.51	0.31	1.61	2.52
21	0.32	0.14	0.21	0.07	0.20	0.06	0.77	0.67	0.49	0.29	2.87	7.11
22	0.32	0.14	0.19	0.05	0.19	0.05	0.68	0.53	0.47	0.27	2.16	4.26
23	0.32	0.13	0.21	0.06	0.18	0.05	0.62	0.45	0.45	0.25	1.77	2.97
24	0.32	0.13	0.26	0.09	0.24	0.08	0.66	0.51	0.43	0.23	1.58	2.42
25	0.32	0.13	0.18	0.05	0.24	0.08	0.72	0.59	0.43	0.23	1.43	2.02
26	0.34	0.15	0.19	0.05	0.22	0.07	0.69	0.54	0.44	0.24	1.33	1.79
27	0.32	0.14	0.19	0.05	0.21	0.06	0.66	0.50	0.43	0.23	2.01	3.75
28	0.32	0.14	0.20	0.06	0.21	0.07	0.63	0.47	0.41	0.21	2.08	3.98
29	0.31	0.13	0.20	0.06	0.22	0.07	0.61	0.43	---	---	1.79	3.03
30	0.30	0.12	0.22	0.07	0.21	0.06	0.59	0.41	---	---	1.63	2.57
31	0.29	0.11	---	---	0.20	0.06	0.57	0.38	---	---	2.12	4.14

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	April 2002		May 2002		June 2002		July 2002		August 2002		September 2002	
1	4.66	17.13	2.11	4.09	0.49	0.30	0.21	0.06	0.09	0.01	7.02	35.89
2	3.50	10.19	2.20	4.41	0.46	0.26	0.20	0.06	0.09	0.01	19.30	223.00
3	2.73	6.53	2.63	6.08	0.42	0.22	0.20	0.06	0.10	0.02	13.20	113.00
4	2.40	5.15	1.95	3.54	0.40	0.21	0.25	0.09	0.10	0.02	7.25	38.02
5	2.07	3.96	1.87	3.29	0.39	0.20	0.22	0.07	0.09	0.01	4.00	12.98
6	1.87	3.29	1.77	2.97	0.39	0.20	0.19	0.05	0.09	0.01	2.76	6.63
7	1.69	2.75	1.60	2.49	0.51	0.32	0.17	0.04	0.09	0.01	2.05	3.87
8	1.57	2.39	1.45	2.09	0.45	0.25	0.16	0.04	0.08	0.01	1.67	2.68
9	1.49	2.17	1.33	1.77	0.40	0.21	0.16	0.04	0.07	0.01	1.43	2.03
10	1.52	2.27	1.28	1.65	0.39	0.19	0.16	0.04	0.07	0.01	1.28	1.65
11	1.46	2.12	1.13	1.33	0.36	0.17	0.15	0.04	0.07	0.01	1.20	1.47
12	1.41	1.97	1.03	1.11	0.34	0.15	0.14	0.03	0.06	0.01	1.04	1.14
13	1.42	2.01	1.02	1.11	0.33	0.14	0.14	0.03	0.06	0.01	0.87	0.83
14	1.37	1.88	1.81	3.11	0.38	0.19	0.15	0.03	0.06	0.01	0.77	0.67
15	1.33	1.78	1.51	2.22	0.43	0.23	0.16	0.04	0.05	0.01	0.75	0.64
16	1.27	1.64	1.25	1.58	0.71	0.57	0.14	0.03	0.05	0.01	0.82	0.74
17	1.20	1.47	1.13	1.32	0.54	0.35	0.13	0.03	0.05	0.01	1.07	1.20
18	1.17	1.40	1.17	1.41	0.44	0.24	0.12	0.02	0.05	0.01	0.97	1.01
19	1.16	1.38	1.36	1.84	0.39	0.19	0.12	0.02	0.05	0.01	0.84	0.77
20	1.07	1.19	1.20	1.48	0.35	0.16	0.15	0.03	0.04	0.01	0.74	0.62
21	0.99	1.05	1.09	1.25	0.32	0.14	0.13	0.03	0.04	0.01	0.66	0.51
22	1.12	1.30	0.97	1.01	0.30	0.12	0.12	0.02	0.04	0.01	0.62	0.44
23	1.10	1.27	0.90	0.88	0.28	0.11	0.12	0.02	0.04	0.01	0.57	0.39
24	0.98	1.02	0.86	0.81	0.27	0.10	0.13	0.03	0.04	0.01	0.53	0.34
25	1.00	1.05	0.79	0.70	0.26	0.09	0.15	0.04	0.05	0.01	0.49	0.29
26	1.02	1.09	0.73	0.60	0.24	0.08	0.14	0.03	0.04	0.01	0.51	0.31
27	0.91	0.89	0.67	0.52	0.23	0.08	0.14	0.03	0.04	0.01	0.61	0.44
28	2.20	4.41	0.62	0.45	0.23	0.08	0.14	0.03	0.07	0.01	0.61	0.44
29	4.43	15.59	0.58	0.40	0.23	0.07	0.13	0.02	0.26	0.10	0.52	0.33
30	2.71	6.44	0.55	0.37	0.22	0.07	0.11	0.02	0.17	0.04	0.47	0.27
31	---	---	0.53	0.33	---	---	0.10	0.02	0.12	0.02	---	---

A1. The Pocomoke River near Willards, Maryland, water year October 1, 2000 through September 30, 2003.—Continued

[m^3/s, cubic meters per second; Mg, megagrams; ---, not applicable]

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	October 2002		November 2002		December 2002		January 2003		February 2003		March 2003	
1	0.46	0.26	7.72	42.57	2.98	7.63	3.08	8.09	1.83	3.16	8.90	55.12
2	0.45	0.25	5.20	20.88	2.71	6.42	3.76	11.60	2.61	6.02	8.73	53.14
3	0.42	0.22	3.94	12.67	2.55	5.77	3.82	11.95	2.56	5.80	9.65	63.79
4	0.41	0.22	3.39	9.62	2.35	4.95	3.99	12.93	2.65	6.18	7.22	37.77
5	0.41	0.21	3.02	7.84	2.60	5.95	3.50	10.21	2.93	7.39	7.93	44.69
6	0.38	0.19	5.66	24.30	3.63	10.90	3.13	8.33	2.61	6.00	9.01	56.27
7	0.37	0.18	5.86	25.85	3.53	10.34	2.90	7.29	2.71	6.43	8.24	47.94
8	0.36	0.17	4.23	14.36	3.32	9.30	2.75	6.60	3.12	8.27	6.53	31.47
9	0.36	0.17	3.52	10.31	3.09	8.13	2.62	6.05	2.88	7.18	5.48	22.91
10	0.39	0.19	3.18	8.57	2.86	7.07	2.37	5.06	2.88	7.20	4.68	17.27
11	0.79	0.69	3.09	8.17	3.97	12.84	2.16	4.27	3.13	8.32	4.20	14.18
12	2.98	7.62	4.36	15.19	9.09	57.26	1.97	3.61	3.05	7.95	4.00	13.01
13	3.20	8.70	9.78	65.29	6.96	35.32	1.85	3.22	2.83	6.96	3.70	11.26
14	2.24	4.56	8.35	49.12	7.87	44.13	1.78	3.02	2.66	6.22	3.40	9.71
15	1.81	3.10	5.93	26.44	6.51	31.34	1.67	2.70	3.04	7.90	3.13	8.35
16	2.76	6.63	4.79	18.00	5.10	20.13	1.58	2.43	3.59	10.68	3.03	7.88
17	4.24	14.41	14.50	133.00	4.22	14.31	1.58	2.43	7.26	38.12	7.57	41.09
18	3.04	7.93	15.70	153.00	3.72	11.41	1.48	2.16	12.50	102.00	7.19	37.49
19	2.40	5.17	12.20	96.74	3.46	9.99	1.43	2.03	11.00	81.22	5.34	21.90
20	2.10	4.06	8.45	50.10	3.73	11.46	1.39	1.94	11.50	86.88	4.57	16.51
21	1.86	3.25	5.44	22.62	5.02	19.55	1.40	1.94	11.80	91.76	6.80	33.86
22	1.69	2.74	12.10	96.61	4.25	14.47	1.32	1.75	15.20	145.00	5.93	26.46
23	1.55	2.34	10.30	72.30	3.72	11.41	1.25	1.60	22.60	297.00	4.72	17.49
24	1.46	2.11	7.28	38.36	3.41	9.76	1.28	1.67	21.60	274.00	4.01	13.07
25	1.40	1.94	5.51	23.14	4.73	17.58	1.11	1.29	15.00	142.00	3.53	10.36
26	3.18	8.58	4.57	16.54	5.54	23.36	1.12	1.30	10.20	70.59	3.22	8.77
27	3.84	12.07	4.02	13.10	4.23	14.39	1.18	1.44	8.19	47.40	3.00	7.73
28	2.90	7.26	3.61	10.82	3.72	11.41	1.18	1.43	9.30	59.60	2.79	6.78
29	2.78	6.72	3.40	9.68	3.41	9.72	1.22	1.52	---	---	2.72	6.47
30	6.78	33.73	3.24	8.89	3.07	8.08	1.23	1.54	---	---	12.10	96.26
31	10.50	73.62	---	---	2.90	7.27	1.38	1.91	---	---	12.60	103.00

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	April 2003		May 2003		June 2003		July 2003		August 2003		September 2003	
1	9.19	58.31	1.65	2.63	3.18	8.56	0.95	0.97	0.54	0.35	1.41	1.97
2	6.88	34.63	1.55	2.34	2.65	6.16	0.91	0.90	0.51	0.31	1.24	1.57
3	5.32	21.72	1.48	2.16	2.24	4.54	6.37	30.09	0.48	0.29	1.16	1.39
4	4.46	15.81	1.38	1.89	2.15	4.23	4.72	17.50	0.47	0.27	2.53	5.66
5	4.03	13.19	1.28	1.67	2.36	5.02	3.08	8.11	0.53	0.34	5.06	19.83
6	3.63	10.88	1.28	1.65	2.24	4.57	2.25	4.60	0.93	0.92	3.25	8.93
7	4.09	13.54	1.23	1.53	2.38	5.07	1.75	2.91	1.13	1.32	2.20	4.41
8	6.63	32.34	1.98	3.63	9.05	56.75	1.45	2.07	1.08	1.22	1.54	2.33
9	10.20	69.85	1.97	3.60	6.98	35.52	1.25	1.58	1.00	1.07	1.18	1.44
10	13.90	124.00	1.81	3.10	4.61	16.81	1.14	1.34	0.91	0.90	0.95	0.96
11	19.70	231.00	1.69	2.73	3.42	9.77	1.08	1.23	1.16	1.38	0.79	0.69
12	24.40	342.00	1.53	2.29	2.82	6.91	0.98	1.02	1.11	1.28	0.75	0.64
13	23.20	310.00	1.34	1.81	2.42	5.25	0.87	0.83	1.03	1.11	1.26	1.62
14	15.60	152.00	1.21	1.50	2.11	4.10	0.89	0.86	1.30	1.71	1.66	2.65
15	9.82	65.74	1.12	1.29	1.84	3.20	1.08	1.22	1.15	1.36	1.58	2.44
16	6.72	33.16	3.79	11.76	1.64	2.59	1.08	1.22	1.04	1.14	1.53	2.29
17	4.91	18.84	9.43	61.08	1.51	2.25	0.95	0.96	2.21	4.46	1.24	1.57
18	4.00	12.99	7.36	39.05	1.58	2.44	0.83	0.77	2.34	4.93	2.07	3.96
19	3.74	11.49	5.67	24.42	4.69	17.30	0.78	0.67	1.72	2.82	14.40	131.00
20	3.49	10.15	4.22	14.31	7.17	37.24	0.75	0.63	1.34	1.81	14.10	127.00
21	3.14	8.39	3.40	9.69	5.68	24.51	0.70	0.56	1.13	1.32	10.10	69.54
22	2.92	7.35	4.38	15.28	4.08	13.46	0.66	0.50	0.99	1.04	6.85	34.33
23	2.63	6.09	5.14	20.43	3.17	8.51	0.66	0.50	0.88	0.84	6.07	27.56
24	2.35	4.97	5.59	23.75	2.48	5.50	0.65	0.49	0.78	0.68	7.08	36.43
25	2.19	4.36	4.43	15.60	2.00	3.72	0.62	0.45	0.71	0.57	5.36	22.03
26	2.37	5.05	5.05	19.81	1.68	2.70	0.57	0.38	0.66	0.50	4.09	13.51
27	2.38	5.07	5.56	23.56	1.46	2.10	0.54	0.35	0.65	0.49	3.32	9.28
28	2.15	4.22	5.02	19.55	1.29	1.69	0.51	0.31	0.75	0.63	3.11	8.22
29	1.94	3.52	5.69	24.58	1.16	1.38	0.54	0.35	0.72	0.59	3.05	7.94
30	1.77	2.98	4.89	18.66	1.03	1.13	0.57	0.38	0.77	0.66	2.66	6.20
31	---	---	3.84	12.07	---	---	0.57	0.38	1.30	1.70	---	---

A2. Mattawoman Creek near Pomonkey, Maryland, water year October 1, 2003 through September 30, 2004.

[m^3/s, cubic meters per second; Mg, megagrams; e, estimated; ---, not applicable]

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	October 2003		November 2003		December 2003		January 2004		February 2004		March 2004	
1	0.68	0.41	2.56	1.63	2.38	1.00	1.69	2.36	0.81	0.84	0.89	1.18
2	0.63	0.38	1.73	1.09	1.82	0.77	1.75	2.45	0.77	0.15	0.98	1.27
3	0.55	0.34	1.45	0.82	1.54	0.66	1.80	2.45	1.78	1.54	1.03	1.36
4	0.51	0.31	1.32	0.73	1.47	0.63	1.65	2.27	4.75	6.98	1.00	1.27
5	0.45	0.27	1.31	0.82	4.58	7.17	1.83	2.81	4.02	6.44	0.97	1.27
6	0.39	0.24	9.27	11.79	8.93	11.79	2.74	4.54	9.05	110.00	1.76	4.17
7	0.36	0.22	18.59	12.70	6.67	7.62	1.96	3.17	32.17	204.00	2.35	5.99
8	0.34	0.21	12.41	6.53	3.98	3.63	1.57	2.54	24.63	38.09	1.68	3.36
9	0.33	0.20	4.66	2.27	3.07	2.36	1.56	2.63	9.11	18.14	1.34	2.36
10	0.30	0.18	2.70	1.27	2.80	1.81	1.24	2.00	5.30	10.88	1.06	1.63
11	0.30	0.18	2.13	1.00	13.04	29.02	1.45	2.27	3.97	2.54	0.94	1.36
12	0.28	0.17	2.23	1.45	19.21	29.02	1.24	1.72	3.22	1.81	0.86	1.09
13	0.24	0.15	8.18	7.80	8.05	10.88	1.41	1.90	2.68	1.27	0.74	0.90
14	0.31	0.31	7.59	5.17	7.14	13.61	1.35	1.90	2.32	1.18	0.67	0.81
15	3.19	3.36	3.61	1.81	15.82	25.40	1.25	1.72	2.02	1.09	0.67	0.75
16	2.20	1.81	2.40	1.09	13.76	15.42	0.91	1.27	1.67	0.87	0.90	0.86
17	0.98	0.70	2.04	0.84	15.79	24.49	1.01	1.36	1.49	0.90	1.56	1.45
18	0.65	0.44	1.76	0.73	24.53	29.93	1.84	10.88	1.49	1.00	1.36	0.88
19	0.50	0.34	2.14	1.27	13.50	19.05	3.26	46.26	1.45	1.00	1.61	1.18
20	0.40	0.27	8.37	5.90	5.52	4.99	1.75	4.90	1.43	1.00	1.51	1.18
21	0.39	0.27	8.73	5.17	3.77	4.08	1.73	4.72	1.37	1.00	1.26	1.00
22	0.36	0.24	4.28	1.90	3.03	3.72	1.27	3.81	1.22	1.00	0.98	0.72
23	0.30	0.21	2.72	1.09	2.57	3.17	1.05	2.63	1.14	1.00	0.86	0.60
24	0.26	0.17	2.20	0.91	4.47	6.98	0.91	2.18	1.12	1.27	0.82	0.57
25	0.25	0.16	2.95	1.27	10.16	15.42	1.06	2.90	1.11	1.27	0.80	0.55
26	0.27	0.18	2.59	1.09	8.27	7.98	0.75	0.84	1.01	1.27	0.81	0.56
27	1.99	2.54	1.99	0.84	3.91	3.54	1.02	2.18	0.98	1.27	0.88	0.61
28	7.84	6.71	2.01	1.00	2.84	2.81	1.13	2.63	0.92	1.27	0.88	0.61
29	10.67	10.88	5.18	2.90	2.37	2.63	1.06	2.45	0.89	1.18	0.76	0.53
30	11.41	10.88	3.65	1.63	2.15	2.90	1.09	2.54	---	---	0.72	0.50
31	5.77	3.81	---	---	1.87	2.63	0.91	2.09	---	---	0.75	0.54

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	April 2004		May 2004		June 2004		July 2004		August 2004		September 2004	
1	3.16	16.33	0.64	0.79	0.65	1.54	0.18	0.26	0.75	19.05	0.01	0.01
2	6.80	21.77	0.64	0.87	0.52	1.18	0.14	0.20	1.82	35.37	0.01	0.01
3	5.94	16.33	3.13	15.42	0.25	0.39	0.10	0.15	5.06	54.42	0.00	0.01
4	4.11	5.44	4.05	14.51	0.14	0.39	0.16	0.22	6.85	102.00	0.00	0.01
5	2.63	2.54	1.89	4.54	2.36	30.84	0.85	1.27	1.70	14.51	0.00	0.01
6	1.82	1.63	1.20	1.72	5.70	180.00	0.51	0.72	1.28	5.71	0.00	0.01
7	1.51	1.27	0.93	1.90	2.36	52.61	0.25	0.34	0.73	2.99	0.00	0.01
8	1.32	1.09	2.32	13.61	1.13	11.79	0.17	0.23	0.44	1.72	0.00	0.01
9	1.24	1.09	1.25	2.63	0.70	4.26	0.12	0.16	0.29	1.09	0.92	1.27
10	1.11	1.09	0.84	1.00	0.55	2.45	0.08	0.11	0.21	0.73	0.95	1.09
11	1.00	1.00	0.65	0.73	1.77	11.79	0.05	0.06	0.17	0.54	0.30	0.31
12	2.76	5.35	0.49	0.51	5.10	23.58	0.03	0.04	0.52	1.63	0.15	0.15
13	15.63	40.82	0.40	0.42	2.32	6.44	0.02	0.03	5.41	16.33	0.08	0.08
14	18.13	28.12	0.32	0.33	1.08	2.00	0.02	0.02	3.95	8.16	0.05	0.05
15	9.18	13.61	0.25	0.25	0.69	1.00	0.06	0.07	4.33	7.62	0.83	1.18
16	4.61	6.26	0.21	0.22	0.65	0.83	0.05	0.06	1.95	3.27	2.03	2.45
17	3.10	3.72	0.20	0.21	1.56e	7.26e	0.01	0.02	1.10	1.72	0.82	1.00
18	2.35	2.81	0.18	0.18	24.1e	203.00e	0.13	0.30	0.79	0.82	7.23	9.98
19	1.90	2.27	0.24	0.25	23.49	72.56	0.48	1.27	0.78	0.82	11.90	15.42
20	1.58	1.90	0.24	0.24	3.35	7.07	0.19	0.44	0.50	0.73	1.89	2.27
21	1.40	1.72	0.23	0.22	1.51	2.72	0.08	0.16	0.40	0.54	0.83	1.00
22	1.25	1.54	0.18	0.16	1.24	2.09	0.05	0.08	0.46	0.63	0.53	0.60
23	1.07	1.27	0.14	0.13	2.33	4.90	0.25	0.35	0.37	0.45	0.34	0.37
24	1.06	1.27	0.12	0.11	1.77	3.72	0.26	0.35	0.24	0.27	0.23	0.24
25	0.94	1.18	0.09	0.08	1.11	2.18	0.14	0.18	0.17	0.18	0.18	0.19
26	0.99	1.27	0.09	0.09	0.91	1.63	0.13	0.21	0.14	0.09	0.18	0.18
27	1.37	1.90	0.20	0.18	0.66	1.18	5.51	93.42	0.11	0.09	0.16	0.16
28	1.05	1.45	0.20	0.19	0.44	0.74	5.89	196.00	0.08	0.09	2.16	4.17
29	0.81	1.09	0.22	0.21	0.32	0.52	2.01	78.91	0.06	0.01	10.42	11.79
30	0.72	0.91	0.18	0.16	0.24	0.36	0.92	30.84	0.04	0.01	5.85	6.17
31	---	---	0.18	0.23	---	---	0.56	15.42	0.03	0.01	---	---

A3. Little Conestoga Creek near Millersville, Pennsylvania, water year February 1, 2003 through September 30, 2004.

[m^3/s, cubic meters per second; Mg, megagrams; ---, not applicable]

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	October 2002		November 2002		December 2002		January 2003		February 2003		March 2003	
1	---	---	---	---	---	---	---	---	1.44	4.63	2.01	7.26
2	---	---	---	---	---	---	---	---	1.44	4.81	3.06	25.40
3	---	---	---	---	---	---	---	---	1.42	4.81	3.91	27.21
4	---	---	---	---	---	---	---	---	1.98	7.44	2.66	6.89
5	---	---	---	---	---	---	---	---	1.53	4.08	2.92	9.98
6	---	---	---	---	---	---	---	---	1.33	3.36	7.22	147.00
7	---	---	---	---	---	---	---	---	1.33	3.36	4.13	44.44
8	---	---	---	---	---	---	---	---	1.19	2.72	3.43	19.05
9	---	---	---	---	---	---	---	---	1.13	2.36	5.44	91.61
10	---	---	---	---	---	---	---	---	1.10	2.27	4.25	42.63
11	---	---	---	---	---	---	---	---	1.16	2.36	3.14	19.05
12	---	---	---	---	---	---	---	---	1.13	2.45	3.03	12.70
13	---	---	---	---	---	---	---	---	0.99	1.81	3.82	23.58
14	---	---	---	---	---	---	---	---	0.96	1.63	3.77	21.77
15	---	---	---	---	---	---	---	---	1.02	1.90	3.54	18.14
16	---	---	---	---	---	---	---	---	0.79	1.09	3.48	12.70
17	---	---	---	---	---	---	---	---	1.47	4.35	3.40	6.62
18	---	---	---	---	---	---	---	---	1.67	5.71	2.89	6.98
19	---	---	---	---	---	---	---	---	1.53	4.72	2.58	9.98
20	---	---	---	---	---	---	---	---	1.13	2.36	6.15	266.00
21	---	---	---	---	---	---	---	---	1.16	2.45	7.50	166.00
22	---	---	---	---	---	---	---	---	6.63	184.00	4.13	69.84
23	---	---	---	---	---	---	---	---	6.26	91.61	3.48	10.88
24	---	---	---	---	---	---	---	---	4.30	41.72	3.00	12.70
25	---	---	---	---	---	---	---	---	3.17	21.77	2.78	11.79
26	---	---	---	---	---	---	---	---	2.55	13.61	3.12	16.33
27	---	---	---	---	---	---	---	---	2.21	9.98	2.95	14.51
28	---	---	---	---	---	---	---	---	2.10	8.34	2.72	7.80
29	---	---	---	---	---	---	---	---	---	---	2.72	5.90
30	---	---	---	---	---	---	---	---	---	---	3.68	9.98
31	---	---	---	---	---	---	---	---	---	---	3.00	5.90

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	April 2003		May 2003		June 2003		July 2003		August 2003		September 2003	
1	2.46	2.45	1.53	6.71	2.01	8.44	1.78	6.71	0.99	6.17	1.19	12.70
2	2.41	4.26	1.53	7.17	1.67	5.71	1.78	7.71	0.88	2.18	4.19	59.86
3	2.35	3.63	1.39	5.99	1.81	8.98	1.61	7.07	0.85	1.72	1.93	5.80
4	2.12	3.08	1.39	5.90	7.87	189.00	1.56	5.90	1.02	4.17	2.83	10.88
5	1.98	3.72	1.33	5.99	4.19	38.09	1.61	6.08	0.93	2.90	1.78	5.17
6	1.84	8.07	1.36	6.53	3.03	17.23	1.59	6.26	1.59	5.26	1.56	4.72
7	2.01	11.79	1.30	5.90	6.32	131.00	1.81	6.71	1.13	3.36	1.39	4.54
8	2.10	10.88	1.64	7.71	4.08	28.12	1.47	5.71	0.91	2.90	1.25	2.45
9	2.52	11.79	1.61	7.53	3.12	15.42	1.39	5.71	1.02	2.81	1.13	1.45
10	2.18	1.81	1.67	7.89	2.86	12.70	1.56	7.07	0.96	3.27	1.10	1.54
11	5.04	106.00	1.44	6.44	2.63	10.88	1.42	6.17	1.78	35.37	1.02	1.36
12	3.31	19.05	1.33	5.80	2.35	8.89	1.33	5.62	1.13	3.72	0.96	1.18
13	2.72	5.62	1.25	4.72	2.29	8.62	1.27	5.17	0.88	1.09	1.56	5.44
14	2.61	2.72	1.16	3.36	2.27	8.62	1.19	4.72	0.82	1.27	1.50	4.08
15	2.66	2.45	1.10	2.81	2.18	8.44	1.10	4.44	0.76	1.54	1.78	6.53
16	2.52	2.45	1.78	9.98	1.95	7.44	1.05	4.35	5.72	182.00	1.33	3.63
17	2.18	2.18	1.53	5.53	1.87	6.71	1.02	4.35	2.12	9.98	1.13	2.54
18	2.29	5.35	1.25	1.54	2.18	9.07	0.96	2.00	1.39	3.81	1.22	7.35
19	2.15	7.07	1.16	1.45	2.21	11.79	0.99	1.72	1.13	2.72	4.36	66.21
20	1.98	7.26	1.10	2.27	7.93	306.00	0.93	1.45	1.05	2.18	2.07	4.17
21	1.93	7.26	1.50	6.26	6.17	137.00	1.42	40.82	0.96	1.90	1.73	1.36
22	2.12	8.53	1.19	3.72	3.88	25.40	3.85	146.00	1.59	9.07	1.59	1.27
23	1.81	6.44	1.30	5.17	3.12	16.33	2.12	10.88	1.30	4.72	21.07	485.00
24	1.73	4.81	2.10	30.84	2.63	12.70	2.78	23.58	0.88	1.81	4.33	16.33
25	1.67	2.90	1.70	29.93	2.58	10.88	1.30	5.26	0.85	1.27	3.17	6.35
26	3.26	22.68	4.76	112.00	2.24	9.07	1.13	4.44	0.85	1.09	3.46	8.80
27	2.10	5.26	2.38	8.80	2.27	8.71	1.05	3.54	0.88	1.09	2.72	5.99
28	1.76	6.08	2.24	8.71	2.12	7.53	1.05	2.90	0.76	0.86	2.61	4.81
29	1.70	6.71	1.93	5.53	1.93	6.71	0.96	2.63	0.74	0.84	2.35	3.45
30	1.59	6.44	1.73	6.44	1.81	6.17	0.91	2.27	0.85	1.09	2.10	2.72
31	---	---	1.76	6.71	---	---	1.08	14.51	0.74	0.89	---	---

A3. Little Conestoga Creek near Millersville, Pennsylvania, water year February 1, 2003 through September 30, 2004.—Continued

[m^3/s, cubic meters per second; Mg, megagrams; ---, not applicable]

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	October 2003		November 2003		December 2003		January 2004		February 2004		March 2004	
1	1.98	7.71	2.52	16.33	2.46	10.88	2.10	5.71	1.10	2.72	1.47	3.63
2	1.84	6.71	2.29	13.61	2.32	9.98	2.15	6.44	0.99	2.36	1.53	3.81
3	1.76	6.35	2.15	10.88	2.15	8.89	2.10	5.17	2.61	25.40	1.47	3.63
4	1.95	7.62	2.04	7.80	2.01	8.44	2.10	4.90	2.27	15.42	1.61	3.99
5	1.70	6.35	3.06	19.05	2.27	10.88	2.66	7.44	1.53	4.44	1.53	3.81
6	1.59	5.08	2.72	10.88	2.01	9.07	2.24	2.27	14.13	754.00	2.52	12.70
7	1.47	4.63	2.41	5.17	2.18	9.98	1.84	1.63	12.49	260.00	1.87	7.80
8	1.44	4.54	2.24	4.35	1.84	7.80	1.93	2.27	3.85	14.51	1.84	6.71
9	1.42	4.08	2.12	4.08	1.78	8.62	1.78	2.45	2.80	9.98	1.67	5.53
10	1.36	3.45	1.81	3.81	2.35	14.51	0.85	1.36	3.23	25.40	1.59	5.44
11	1.33	2.45	1.78	5.35	12.94	310.00	1.19	2.81	3.17	15.42	1.53	5.08
12	1.25	2.54	2.07	4.54	4.16	20.86	1.61	4.08	2.69	9.98	1.47	4.99
13	1.13	2.00	1.95	5.53	3.31	8.71	1.64	3.99	2.69	10.88	1.36	4.44
14	1.44	11.79	1.59	2.18	4.59	29.93	1.56	3.90	2.63	10.88	1.42	4.63
15	6.32	132.00	1.70	2.54	4.98	25.40	1.53	3.81	2.44	8.53	1.30	4.17
16	1.93	2.09	1.53	2.81	3.65	11.79	1.22	2.90	2.12	6.62	1.44	4.81
17	1.78	1.45	1.44	2.63	6.32	44.44	1.67	3.99	1.95	5.71	1.50	4.90
18	1.78	1.81	1.44	4.44	4.33	13.61	1.81	4.44	1.78	4.72	1.53	4.99
19	1.53	1.45	5.10	90.70	3.57	8.25	1.44	3.17	1.84	5.08	2.66	13.61
20	1.42	1.36	4.67	44.44	3.29	7.44	0.71	1.36	1.93	5.35	2.21	9.07
21	1.36	1.27	2.52	10.88	3.12	6.53	0.54	1.00	2.04	5.53	1.87	6.44
22	1.30	1.27	2.35	7.53	2.83	5.08	0.96	2.00	1.87	5.26	1.61	5.53
23	1.25	1.18	2.10	6.89	2.78	4.72	1.25	2.72	1.76	4.90	1.64	5.35
24	1.16	1.27	2.07	7.89	4.11	22.68	1.22	2.63	1.93	5.35	1.53	4.44
25	1.47	1.81	2.35	12.70	3.12	14.51	1.08	2.36	1.78	4.54	1.53	4.90
26	1.47	1.54	1.98	7.98	2.78	11.79	1.08	2.45	1.64	3.99	1.53	5.08
27	4.50	58.05	1.93	7.62	2.75	10.88	1.05	2.45	1.53	3.72	1.50	4.81
28	2.75	11.79	4.05	49.89	2.63	12.70	1.05	2.45	1.56	3.81	1.39	3.08
29	7.56	179.00	4.90	82.54	2.29	7.89	1.02	3.54	1.50	3.72	1.36	3.63
30	3.40	43.54	2.83	15.42	2.29	9.98	1.19	3.08	---	---	1.33	4.08
31	2.78	19.95	---	---	2.18	11.79	1.33	3.45	---	---	1.30	4.35

Day	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)	Mean daily discharge (m^3/s)	Suspended-sediment load (Mg)
	April 2004		May 2004		June 2004		July 2004		August 2004		September 2004	
1	2.97	58.05	2.35	9.98	1.13	3.36	1.22	3.63	4.19	61.68	1.50	3.63
2	1.98	13.61	2.24	10.88	1.16	3.81	1.39	4.72	1.76	6.44	1.36	3.17
3	1.87	11.79	3.46	36.28	0.99	2.27	1.39	4.63	1.90	6.80	1.16	2.27
4	1.95	9.98	2.21	12.70	0.93	1.90	1.16	3.54	1.78	10.88	1.19	2.54
5	1.70	7.62	2.10	11.79	2.86	58.96	1.10	3.17	2.38	16.33	1.10	2.18
6	1.56	6.80	1.95	9.98	2.12	18.14	1.05	2.90	1.95	7.26	1.02	1.90
7	1.50	7.07	1.95	10.88	1.30	5.62	2.04	48.07	1.95	6.71	1.05	2.18
8	1.50	6.71	1.87	9.98	1.22	4.72	1.56	10.88	1.70	7.53	1.02	2.18
9	1.47	4.63	1.73	9.07	1.02	3.36	1.10	3.63	1.39	3.99	1.30	2.63
10	1.42	3.90	1.84	9.98	1.10	3.45	1.10	2.81	1.33	4.17	1.10	2.36
11	1.33	2.81	1.59	7.26	2.58	73.47	1.02	2.72	1.47	4.63	0.99	2.09
12	1.81	9.07	1.50	6.35	1.59	14.51	5.10	131.00	3.40	190.00	0.93	1.72
13	4.08	72.56	1.44	5.35	1.27	6.98	2.63	19.95	16.71	372.00	0.88	1.72
14	3.29	42.63	1.44	4.81	1.22	6.08	1.87	8.71	3.65	19.05	0.85	1.72
15	2.29	10.88	1.44	5.26	2.15	12.70	2.66	26.30	2.97	8.16	0.85	1.72
16	2.10	7.07	2.10	13.61	2.12	11.79	1.81	6.35	2.55	7.07	0.85	2.09
17	2.01	6.80	1.44	5.44	7.05	484.00	1.76	5.26	2.32	5.44	0.85	1.72
18	1.90	6.53	1.56	6.98	14.81	530.00	1.87	7.53	2.18	5.35	12.32	308.00
19	1.76	6.26	2.04	10.88	3.23	19.05	1.59	5.08	2.32	7.71	3.03	20.86
20	1.67	7.35	1.61	6.62	2.69	13.61	1.47	3.90	2.38	8.71	2.12	7.53
21	1.64	7.62	1.50	5.44	2.24	10.88	1.36	2.27	5.10	99.77	1.95	4.17
22	1.56	6.53	1.36	4.44	2.15	9.98	1.30	2.63	2.95	19.05	1.59	3.36
23	2.27	48.98	1.39	4.17	1.98	8.53	2.63	44.44	2.24	9.07	1.39	2.45
24	2.44	29.93	1.19	3.27	1.81	7.35	1.70	7.44	2.12	8.71	1.30	2.27
25	1.59	5.53	1.08	2.72	1.84	6.98	1.33	3.99	1.76	4.99	1.30	2.09
26	9.01	492.00	1.36	3.90	1.84	7.17	1.19	3.63	1.67	5.26	1.39	2.36
27	3.99	59.86	1.16	3.27	1.56	5.53	1.50	8.16	1.53	4.99	1.33	2.18
28	2.89	14.51	1.08	2.99	1.42	4.54	2.18	22.68	1.33	4.63	6.85	102.00
29	2.55	13.61	1.05	2.72	1.47	5.08	1.39	4.35	1.25	3.99	7.84	87.98
30	2.38	10.88	0.99	2.27	1.22	3.72	1.22	2.81	1.67	3.90	2.89	8.62
31	---	---	0.99	2.00	---	---	1.50	10.88	1.70	3.90	---	---

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