Prepared in cooperation with the
Johnson County Stormwater Management Program

Transport and Sources of Suspended Sediment in the Mill Creek Watershed, Johnson County, Northeast Kansas, 2006–07

Scientific Investigations Report 2009–5001

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

Cover photographs. Background photograph shows stormflow at Clear Creek upstream from 79th Street, Johnson County, Kansas (photograph taken by Casey Lee, U.S. Geological Survey, May 2006). Inset photograph shows stormflow at Mill Creek upstream from 87th Street Lane, Johnson County, Kansas (photograph by Casey Lee, U.S. Geological Survey, August 2006).

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Contents

Figures

Tables

Conversion Factors and Abbreviations

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
micrometer (µm)	0.00003937	inch (in.)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter ($m^{3)}$
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per second (ft^3/s)	1.9835	acre-feet per day (acre-ft/d)
foot per mile (ft/mi)	0.1894	meter per kilometer (m/km)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m^3/s)
	Rate	
acre-foot per square mile (acre-ft/mi^2)	476.1	cubic meter per square kilometer (m^3/km^2)
inch per hour (in/hr)	25.40	millimeter per hour (mm/hr)
	Weight	
gram (g)	0.03527	ounce (oz)
pound per second (lb/s)	43.2	ton per day (ton/d)
ton	2,000	pound (lb)
	Yield	
ton per square mile (ton/mi^2)	0.3503	tonne per square kilometer (tonne/km^2)

Temperature can be converted to degrees Celsius (°C) or degrees Fahrenheit (°F) by the equations:

$$°C = 5/9\ (°F-32)$$

$$°F = 9/5\ (°C) + 32$$

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

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

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

Suspended-sediment concentrations are report in milligrams per liter (mg/L).

Sediment loads are reported in tons.

Transport and Sources of Suspended Sediment in the Mill Creek Watershed, Johnson County, Northeast Kansas, 2006–07

By Casey J. Lee, Patrick P. Rasmussen, Andrew C. Ziegler, and Christopher C. Fuller

Abstract

The U.S. Geological Survey, in cooperation with the Johnson County Stormwater Management Program, evaluated suspended-sediment transport and sources in the urbanizing, 57.4 mi^2 Mill Creek watershed from February 2006 through June 2007. Sediment transport and sources were assessed spatially by continuous monitoring of streamflow and turbidity as well as sampling of suspended sediment at nine sites in the watershed.

Within Mill Creek subwatersheds (2.8–16.9 mi^2), sediment loads at sites downstream from increased construction activity were substantially larger (per unit area) than those at sites downstream from mature urban areas or less-developed watersheds. Sediment transport downstream from construction sites primarily was limited by transport capacity (streamflow), whereas availability of sediment supplies primarily influenced transport downstream from mature urban areas. Downstream sampling sites typically had smaller sediment loads (per unit area) than headwater sites, likely because of sediment deposition in larger, less sloping stream channels. Among similarly sized storms, those with increased precipitation intensity transported more sediment at eight of the nine monitoring sites. Storms following periods of increased sediment loading transported less sediment at two of the nine monitoring sites.

In addition to monitoring performed in the Mill Creek watershed, sediment loads were computed for the four other largest watersheds (48.6–65.7 mi^2) in Johnson County (Blue River, Cedar, Indian, and Kill Creeks) during the study period. In contrast with results from smaller watersheds in Mill Creek, sediment load (per unit area) from the most urbanized watershed in Johnson County (Indian Creek) was more than double that of other large watersheds. Potential sources of this sediment include legacy sediment from earlier urban construction, accelerated stream-channel erosion, or erosion from specific construction sites, such as stream-channel disturbance during bridge renovation. The implication of this finding is that sediment yields from larger watersheds may remain elevated after the majority of urban development is complete.

Surface soil, channel-bank, suspended-sediment, and streambed-sediment samples were analyzed for grain size, nutrients, trace elements, and radionuclides in the Mill Creek watershed to characterize suspended sediment between surface or channel-bank sources. Although concentrations and activities of cobalt, nitrogen, selenium, total organic carbon, cesium-137, and excess lead-210 had significant differences between surface and channel-bank samples, biases resulting from urban construction, additional sorption of constituents during sediment transport, and inability to accurately represent erosion from rills and gullies precluded accurate characterization of suspended-sediment source.

Introduction

Sediment is the most frequently reported cause of impairment to streams and rivers (U.S. Environmental Protection Agency, 2002) and is known to transport pathogens, metals, and nutrients (the second-, fourth-, and fifth-most reported impairments) (Horowitz, 1991; Christensen and others, 2000; Rasmussen and Ziegler, 2003). Accelerated erosion and transport of fluvial sediment can reduce soil fertility, increase water-treatment costs, impair aquatic habitat, and decrease storage capacity in impoundments and lakes (Osterkamp and others, 1998). Combined annual damages from these and other detrimental effects of sediment erosion in North America have been estimated at 16 billion dollars (Osterkamp and others, 1998).

Johnson County, northeast Kansas, is the most populous and fastest growing county in the State. Population in the county is estimated to have increased from 451,100 to 516,700 people from 2000 to 2006 (U.S. Census Bureau, 2007). Rapid population growth in Johnson County has resulted in the construction of new homes, roads, and businesses in the Mill Creek watershed, located to the west of the most populated northeastern part of the county (fig. 1; Mid-America Regional Council, 2008). The removal of vegetation and disturbance of soils during construction increase the potential for soil erosion. Streams in urbanizing watersheds have shown as much as a 100-fold increase in sediment production compared to agricultural or undeveloped watersheds (Walling and Gregory, 1970). Following the completion of construction, the collection and routing of stormwater over impervious surfaces generally result in decreased sediment transport from surface soils and increased channel-bank erosion (Wolman, 1967, Leopold and others, 2005). Sediments in urban streams have larger concentrations of selected metals (Van Metre and Mahler, 2003; Mahler and others, 2006), indicator bacteria (Rasmussen and others, 2008), and a variety of organic contaminants (Lee and others, 2005). The Kansas Department of Health and Environment (KDHE) has identified suspended sediment as a cause of impairment to biological communities in Mill Creek (fig. 1) (Kansas Department of Health and Environment, 2007).

Information on the sources and transport of suspended-sediment is necessary to achieve maximum impact from management practices designed to reduce soil erosion and transport. Improved understanding of sediment transport processes can help managers predict if, when, and how potential changes in land-use or management practice will affect sediment transport downstream. To address this need, the U.S. Geological Survey (USGS) in cooperation with the Johnson County Stormwater Management Program, conducted a study to characterize suspended-sediment transport and sources in the urbanizing Mill Creek watershed

Purpose and Scope

The purpose of this report is to characterize transport and sources of suspended sediment in the Mill Creek watershed from February 2006 through June 2007. Sediment sources and transport are described spatially and with respect to variations in land-use and storm characteristics. This report describes data collected using continuously recording stage and water-quality sensors at nine sites throughout the Mill Creek watershed and analysis of soil and sediment samples for particle size, selected trace elements, nutrients, carbon, and radionuclides. Results from the Mill Creek watershed are compared with sediment transport observed in other watersheds throughout Johnson County during the same study period.

Data collected from this study can be used by local officials to help identify causes of increased sediment transport and to apply best management practices (BMPs) where they will be most effective. These results support Federal, State, and local efforts to improve water quality and identify processes affecting the transport of fluvial sediment.

Description of Study Area

Mill Creek drains 62.7 mi^2 of land in north-central Johnson County, Kansas (fig. 1), and includes a large percentage of the cities of Lenexa, Olathe, and Shawnee (fig. 2). Streamflow and sediment data were collected at nine sampling sites throughout the watershed (fig. 2, table 1). One municipal wastewater-treatment facility discharges to Mill Creek, directly upstream from sampling site MI3 (fig. 2).

The Mill Creek watershed is located partly within the Attenuated Drift Border of the Dissected Till Plains physiographic section and partly within the Osage Cuestas of the Osage Plains physiographic section (fig. 1; Schoewe, 1949). Topography consists of gently rolling uplands with hilly areas along streams. Because percolation of precipitation to ground water is largely limited because of impermeable limestone and shale bedrock (O'Connor, 1971), the majority of stormflow likely originates from overland or shallow subsurface flow. The majority of Mill Creek and its tributaries flow over alternating layers of limestone and shale; streambeds are composed primarily of cobble, rock, and bedrock. Entrainment of streambed material is not considered a substantial part of the stream-sediment load. Soils within the Mill Creek watershed generally consist of erosive to moderately erosive silt and silty clay loams (Evans, 2003). Channel banks are composed primarily of silt and silty clay loams, with occasional limestone and shale outcrops.

Channel slope was determined upstream from each monitoring site by subtracting the stream elevation (in feet) at the gage location from the stream elevation 10 percent of the total stream length downstream from the most headwater stream location (streams were defined from County produced drainage lines; Johnson County Automated Information Mapping System, written commun., 2006), and by dividing the elevation change by stream length (in miles). Channel slope between headwater and downstream sampling sites was determined by subtracting the stream elevation at the downstream location by that of the upstream location (and dividing by stream length). Channel slope was steepest at headwater sampling sites (CO1, 43.1 ft/mi; LM1, 29.2 ft/mi; CL1, 28.3 ft/mi; table 2) and decreased downstream. Channel slopes were smallest between sites MI4 and MI5 (13.1 ft/mi), sites MI5 and MI7 (5.9 ft/mi), and sites CL1 and CL2 (17.6 ft/mi).

The mean annual temperature (1931–2006) in Olathe, Kansas (fig. 1), is 56.7 °F, with a mean monthly range of 29.5 °F in January to 78.8 °F in July (National Oceanic and Atmospheric Administration, 2007). Mean annual precipitation (1931–2006) is 38.2 in., with 69 percent of the precipitation occurring during the growing season from April through September (National Oceanic and Atmospheric Administration, 2007). Storms with more than 1 in. of rainfall occur an average of 10.6 days per year (1948–2006).

The largest percentage of urban development in the Mill Creek watershed has occurred in the eastern and southern sections of the watershed (figs. 1, 3; table 2) in and near the most populated part of Lenexa (upstream from site LM1), Shawnee (upstream from sites LM1 and LM2), and Olathe (upstream from site MI3). Watersheds upstream from these sites have the largest percentage of residential land and impervious surface (defined as rooftops and pavement), and the smallest percentage of undeveloped and agricultural land (table 2). Undeveloped areas (such as agricultural land, forests, and grassland) are the primary land use in the central and western parts of the watershed, between sites MI4 and MI5 (57.4 percent) and upstream from site CL1 (56.8 percent; table 2).

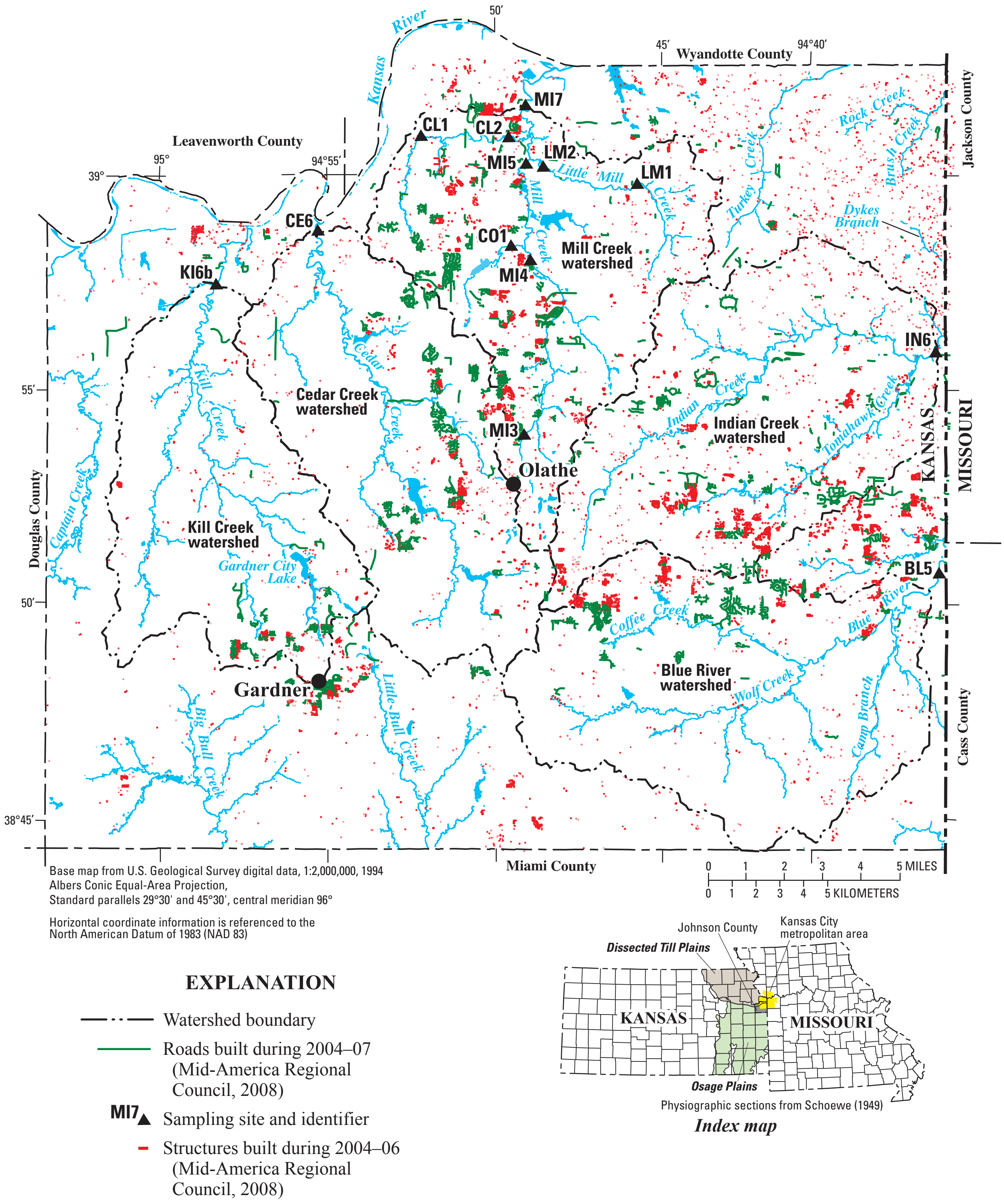


Figure 1. Location of sampling sites, watershed boundaries, road additions (from 2004–07), and building construction (from 2004–06), in Johnson County, northeast Kansas, February 2006–June 2007.

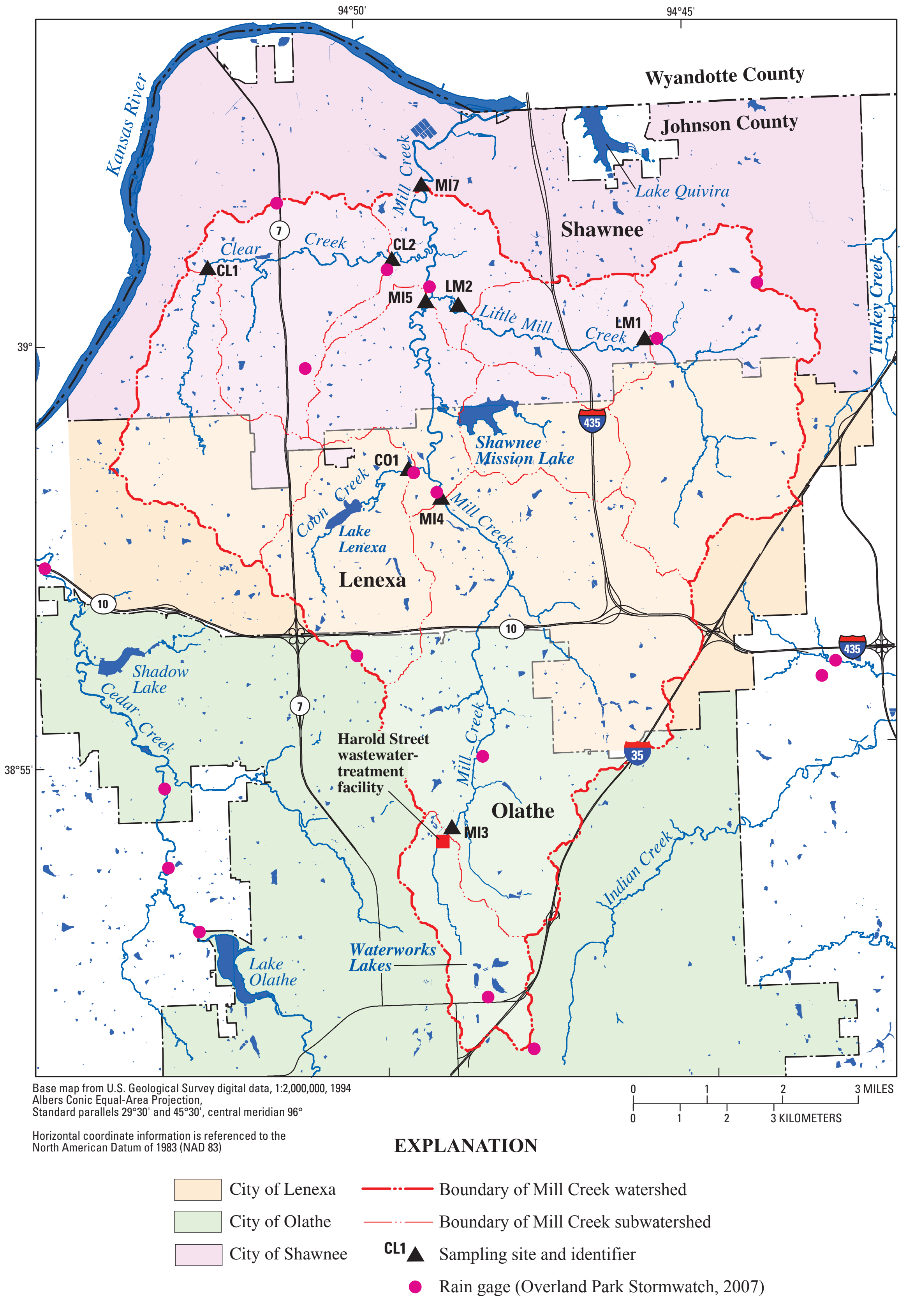


Figure 2. Location of watershed boundaries, sampling sites, and municipalities in the Mill Creek watershed, February 2006–June 2007.

Table 1. Location and contributing drainage area for sampling sites in Johnson County, northeast Kansas, February 2006–June 2007.

[mi², square miles]

Sampling-site identifier (fig. 1)	U.S. Geological Survey identification number	Site name	Contributing drainage area (mi²)	Latitude (degrees, minutes, seconds)	Longitude (degrees, minutes, seconds)
		Mill Creek sampling sites			
CL1	390051094522200	Clear Creek at Clare Road	5.5	39°00'51"	94°52'22"
CL2	390056094493200	Clear Creek at Woodland Road	10.9	39°00'56"	94°49'32"
CO1	385826094491700	Coon Creek at Woodland Road	5.1	38°58'26"	94°49'17"
LM1	385952094454000	Little Mill Creek at Lackman Road	8.8	38°59'52"	94°45'40"
LM2	390010094482100	Little Mill Creek at Warwick Lane	12.1	39°00'10"	94°48'21"
MI3	385404094485800	Mill Creek at Woodland Road	2.8	38°54'04"	94°48'58"
MI4	385800094485300	Mill Creek at 87th Street Lane	19.7	38°58'00"	94°48'53"
MI5	390026094485800	Mill Creek upstream of Shawnee Mission Parkway	31.7	39°00'26"	94°48'58"
MI7	06892513	Mill Creek at Johnson Drive	57.4	39°01'46"	94°49'03"
		Additional Johnson County sites sampled during study period (fig. 1)			
BL5	06893100	Blue River at Kenneth Road	65.7	38°50'32"	94°36'44"
CE6	06892495	Cedar Creek near DeSoto	58.5	38°58'41"	94°55'20"
IN6	06893390	Indian Creek at State Line Road	63.1	38°56'15"	94°36'30"
KI6b	06892360	Kill Creek at 95th Street	48.6	38°57'28"	94°58'30"

Shawnee Mission Park occupies 28 percent of the land area (classified as undeveloped) between sites MI4 and MI5 and is composed primarily of grass and forest land. Although only 2 percent of the land between sites MI4 and MI5 is cultivated, approximately 15 percent of the land upstream from site CL1 is cropland (K. Skridulis, Johnson County Appraiser's Office, written commun., 2008).

Three relatively large (more than 30-acre) surface-water impoundments are present within the Mill Creek watershed. The largest impoundment is Shawnee Mission Lake, which has an estimated contributing drainage area of approximately 2.9 mi² and impounds 42 percent of the watershed between sampling sites MI4 and MI5 (fig. 2). Lake Lenexa is a 550 acre-foot impoundment constructed from 2005–06 which has an estimated contributing drainage area of 2.0 mi², and impounds 40 percent of the watershed upstream from site CO1 (R. Beilfuss, City of Lenexa, written commun., 2007). Waterworks Lakes have an estimated contributing drainage area of 1.0 mi² and impound 36 percent of the watershed upstream from site MI3 (fig. 2; table 2). Impoundments with the most storage capacity generally trap more suspended sediment (depending upon upstream watershed area), decreasing sediment loads at downstream sampling sites. Smaller farm ponds and erosion-control structures present in the Mill Creek watershed also likely remove suspended sediment from fluvial transport (fig. 2; Renwick and others, 2005).

Areas of urban development are defined in this investigation by increases in land occupied by buildings and roads from 2004 through the most recent data collected (2006 for buildings, 2007 for roads) upstream from sampling sites (fig. 1; table 3). Subwatersheds upstream from sampling sites LM1, LM2, and MI3 had among the smallest increase in building area and road length (table 3), indicating that the extent of urban development is largely unchanged (fig. 1). The largest increase in roads and buildings occurred upstream from sites CL1, CL2, and MI4, indicating that recent urban development is occurring primarily in the central and western parts of the Mill Creek watershed.

Previous Investigations

USGS has collected streamflow and water-quality data in the Mill Creek watershed since 2002 as part of three countywide studies. Lee and others (2005) found that discharge from the Harold Street wastewater-treatment facility (fig. 2) was the largest source of streamflow to Mill Creek during base-flow conditions. This facility also was the largest point source of nutrients, indicator bacteria, and organic wastewater compounds to the stream during base-flow conditions. However, concentrations of suspended-sediment, nutrients, and indicator bacteria generally were largest during stormflow conditions, suggesting that nonpoint sources contribute most of the water-quality-contaminant load to the stream.

Rasmussen and others (2008) used continuous water-quality monitoring to estimate constituent concentrations and loads in the five largest Johnson County streams, including Mill Creek. This study determined that most streamflow and sediment were transported from the most urbanized watershed (Indian Creek; Rasmussen and others, 2008). Suspended-

Table 2. Sampling sites, estimated contributing drainage area, impoundments and percentage of impounded drainage area, channel slope, and percentage of land use and impervious surface in Mill Creek subwatersheds and four other monitored watersheds in Johnson County, northeast Kansas, 2006.

[Data from Johnson County Automated Information Mapping System, written commun., 2006; mi^2, square miles; ft/mi, feet per mile; --, not applicable]

Sampling site (fig. 1)	Sampling site(s) immediately upstream (fig. 1)	Estimated drainage area (mi^2)	Percentage of impounded drainage area (impoundment name; fig. 2)	Channel slope (ft/mi)	Percentage land use								Percentage impervious surface
					Residential	Business	Industrial	Rights of way	Parks	Surface water	Undeveloped and agricultural[1]	No data[2]	
Subwatersheds upstream from sampling sites													
CL1	--	5.5	--	28.3	18.9	8.5	0.4	1.3	1.1	0.7	56.8	12.3	4.2
CL2	CL1	10.9	--	20.0	22.4	7.7	.7	2.2	3.7	1.0	48.1	14.2	6.3
CO1	--	5.1	40 (Lake Lenexa)	43.1	25.9	3.3	.4	5.3	3.8	1.3	40.4	19.6	5.8
LM1	--	8.8	--	29.2	54.1	12.9	3.3	1.8	.4	.7	6.1	20.7	23.6
LM2	LM1	12.1	--	22.8	50.0	12.0	2.5	3.0	2.2	.9	10.3	19.1	20.9
MI3	--	2.8	36 (Waterworks Lakes)	22.9	38.5	14.4	5.4	6.0	.1	2.1	9.9	23.6	22.2
MI4	MI3	19.7	5	21.6	27.3	16.8	3.3	5.6	1.6	1.4	26.7	17.3	14.5
MI5	CO1, MI4	31.7	19	18.2	24.9	12.1	2.7	4.4	1.8	2.2	35.6	16.3	11.9
MI7	CL2, LM2, MI5	57.4	10	14.6	30.0	11.0	2.6	3.6	2.6	1.7	32.7	16.0	12.8
Subwatersheds between sampling sites													
CL2	CL1	5.4	--	17.6	26.0	6.9	1.0	3.1	6.3	1.2	39.2	16.3	8.4
LM2	LM1	3.3	--	23.1	38.9	9.5	.3	6.3	7.2	1.4	21.5	14.9	13.8
MI4	MI3	16.9	--	24.0	25.5	17.2	2.9	5.6	1.8	1.2	29.5	16.3	13.2
MI5	CO1, MI4	6.9	42 (Shawnee Mission Lake)	13.1	17.0	5.4	2.6	.1	.9	5.3	57.4	11.3	8.7
MI7	CL2, LM2, MI5	2.7	--	5.9	30.7	6.1	9.1	2.0	10.3	2.4	36.3	3.1	13.7
Other monitored watersheds in Johnson County (Rasmussen and others, 2008)													
BL5	--	65.7	--	9.6	15.1	2.5	1.0	.6	1.6	2.2	69.3	7.7	3.0
CE6	--	58.5	18 (Lake Olathe)	14.6	12.4	4.9	3.8	2.5	2.8	2.3	64.5	6.8	3.9
IN6	--	63.1	--	11.8	68.1	8.9	.3	1.9	2.2	0.6	6.4	11.6	23.5
KI6b	--	48.6	11 (Gardner City Lake)	17.1	6.4	.9	1.3	.8	.5	1.9	61.7	26.5	2.9

[1] "Undeveloped" land use includes agricultural land use and land not under production.

[2] "No data" land use includes untaxed land uses (such as government property and public roads).

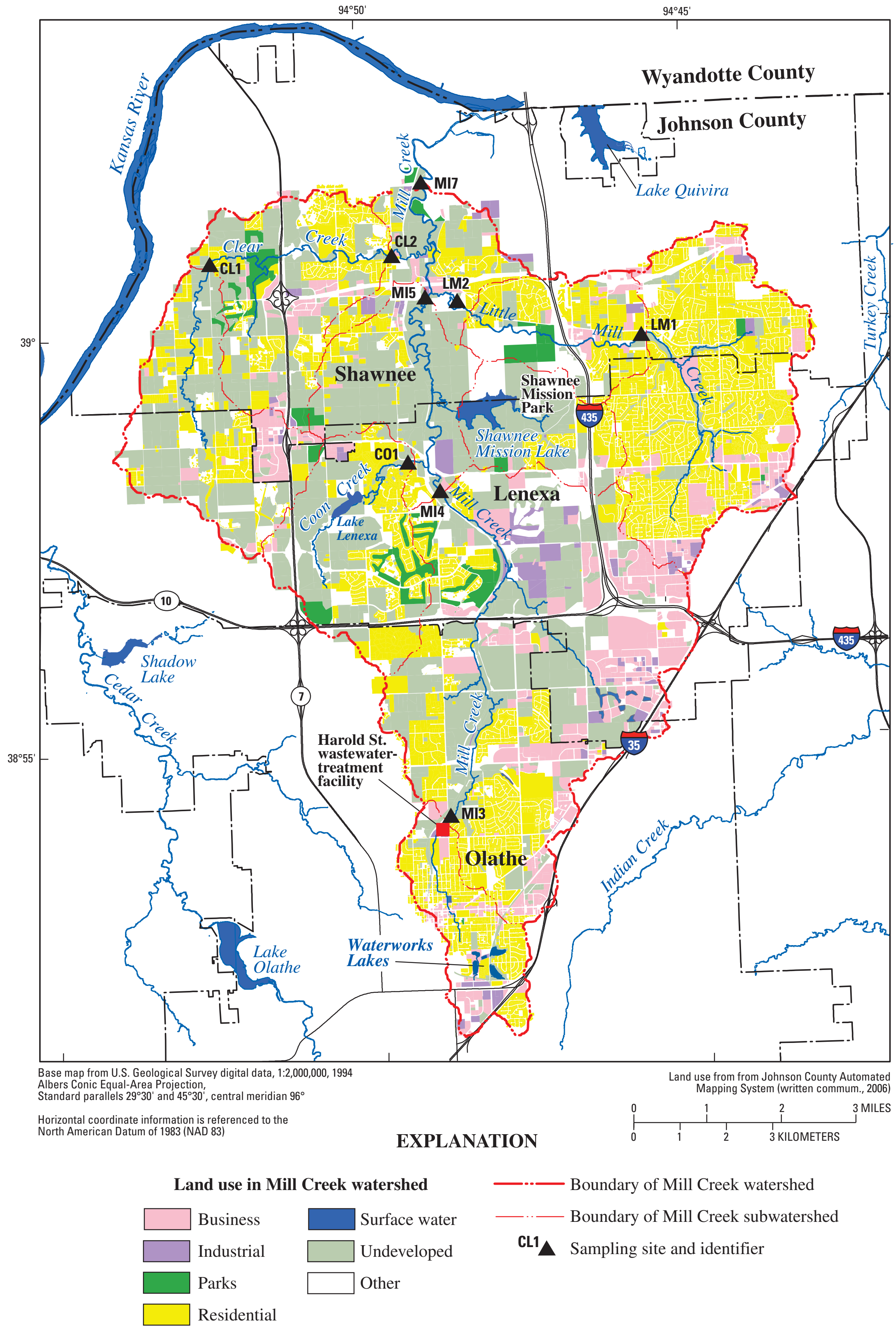


Figure 3. Land use in the Mill Creek watershed, 2006.

Table 3. Changes in building area and road length in Johnson County watersheds, northeast Kansas, 2004–07.

[Data from Johnson County Automated Information Mapping System, written commun., 2007; mi, miles; mi/mi², miles per square mile]

Sampling site (fig. 1)	Sampling site(s) immediately upstream (fig. 1)	Drainage area (mi²)	Building area		Road length	
			Increase in building area, 2004–06 (mi²)	Percentage of watershed with new building construction, 2004–06	Increase in road length, 2004–07 (mi)	Increase in road length, 2004–07 normalized by watershed area (mi/mi²)
Subwatersheds upstream from sampling sites						
CL1	--	5.5	0.03	0.5	12.6	2.3
CL2	CL1	10.9	.09	.8	17.9	1.6
CO1	--	5.1	.04	.8	2.6	.5
LM1	--	8.8	.04	.5	.6	.1
LM2	--	12.1	.05	.4	.6	.1
MI3	--	2.8	.01	.4	1.5	.5
MI4	MI3	19.7	.08	.4	13.7	.7
MI5	CO1, MI4	31.7	.14	.4	18.6	.6
MI7	CL2, LM2, MI5	57.4	.28	.5	37.1	.6
Subwatersheds between sampling sites						
CL2	CL1	5.4	.06	1.2	5.3	1.0
LM2	LM1	3.3	.01	.2	.03	.01
MI4	MI3	16.9	.07	.4	12.2	.7
MI5	CO1, MI4	6.9	.02	.3	2.3	.3
MI7	CL2, LM2, MI5	2.7	.01	.3	1.4	.5
Other monitored watersheds in Johnson County (Rasmussen and others, 2008)						
BL5	--	65.7	.1	.2	19.5	.3
CE6	--	58.5	.1	.2	30.8	.5
IN6	--	63.1	.4	.6	29.9	.5
KI6b	--	48.6	.1	.1	12.7	.3

sediment yields from Mill Creek were smaller than yields from Indian Creek but larger than those from the more rural Cedar and Kill Creeks (fig. 1).

A study of the geomorphology of Little Mill Creek (fig. 1) was commissioned by the City of Lenexa (Intuition Logic, 2002). The study found channel adjustment was the result of both indirect and direct effects of urban development. Direct channel adjustments such as piping, straightening, bank armoring, and widening at bridge crossings are cited as the primary causes of channel instability in Little Mill Creek. Although localized disturbances were linked to channel incision, the limestone channel bed generally limited streambed incision. Previous widening of the Little Mill Creek channel was observed in many locations, but observation of internal flood-plain formation, well-imbricated knick points, and a lack of obvious bank-toe erosion led the authors to conclude that the majority of the creek is in a depositional phase, reaching equilibrium with historic changes in the watershed and stream channel.

Typically, suspended-sediment loads have been estimated at USGS stream-gaging stations using rating curves that approximate a relation between instantaneous streamflow and measured sediment concentration or load. The rating-curve slope and intercept are applied to a continuous (often hourly or daily) record of streamflow to estimate sediment loads over time (Porterfield, 1972; Walling, 1977; Glysson, 1987). Errors in sediment-load estimates using streamflow-rating curves are most pronounced in small- to medium-sized watersheds and over less than annual time periods (Walling, 1977). In contrast, computation of suspended-sediment concentration using continuously recording turbidity sensors can substantially reduce errors in sediment-load estimates in small watersheds and over less than annual time scales (Walling, 1977; Lewis, 1996; Rasmussen and others, 2008). In Kansas streams, continuous turbidity measurement has been shown to improve the accuracy of suspended-sediment concentration estimates compared to those derived from continuous streamflow data (Christensen and others, 2000; Rasmussen and others, 2005, 2008)

Characterization of suspended-sediment sources has proven valuable to the design of management strategies to reduce sediment transport in streams and lakes (Walling, 2005). Many studies have used sediment-associated concentrations of radionuclides, nutrients, and trace elements to ascribe suspended-sediments to surface-soils, channel-banks, and (or) areas of varying land use (Walling and Woodward, 1995; Walling and others, 1999; Brigham and others, 2001; Russell and others, 2001; Walling, 2005; Juracek and Ziegler, 2007). Numerous studies, including those by Walling and Woodward (1995), Brigham and others (2001), Russell and others (2001), and Walling (2005), have found statistically significant differences in constituent concentrations and radionuclide activities between various sources of suspended sediment. Based on results of these studies, nutrients, trace elements, beryllium-7 (^{7}Be), lead-210 (^{210}Pb), radium-226 (^{226}Ra), and cesium-137 (^{137}Cs) were analyzed in surface soils, channel-banks, streambed sediment, and suspended-sediment in Mill Creek for this study in an attempt to estimate predominant sources (channel-bank or surface-soil) of suspended sediment.

Because radionuclides are entrained on surface soils by atmospheric fallout, they have been used in many studies to characterize differences between surface- and channel-bank soils. Radionuclides are predominantly deposited by precipitation, thus activities in soils are dependent on the extent of precipitation over a given area (Ritchie and McHenry, 1990, Walling and others, 1999). After deposition, radionuclides decay at rates dependent on their respective half-lives (53.3 days for ^{7}Be, 22.3 years for ^{210}Pb, and 30.3 years for ^{137}Cs) (Holmes, 1998). Radionuclides generally are considered conservative in soils; the dominant mechanism for loss being radioactive decay. Because decay of radionuclides is rapid with respect to geologic time, concentrations typically are larger in surface soils, and are absent deeper in the soil profile.

^{7}Be is produced in the upper atmosphere by cosmic ray interaction with nitrogen (Lal and others, 1958). Because of its short half life (53.3 days); detection in suspended-sediment is an indication of recently eroded sediment as well as recent contributions from precipitation. ^{210}Pb is a naturally occurring radioisotope in the ^{238}U decay series. Emanation of radon (^{222}Rn) gas from continental land masses and subsequent decay to ^{210}Pb results in atmospheric deposition of ^{210}Pb that can be decoupled from the production of ^{210}Pb in soils produced by decay of its long-lived parent radium (^{226}Ra). This ^{210}Pb deposited by atmospheric fallout is termed “excess” ^{210}Pb and is typically concentrated in the upper layers of the soil profile (Appleby and Oldfield, 1992). ^{137}Cs was artificially produced as a byproduct of nuclear fission; global release to the environment occurred from above-ground nuclear weapons testing. Measurable fallout of ^{137}Cs began in 1952. Maximum deposition occurred in 1963–64; but because of the nuclear test ban treaty of 1963, deposition is essentially nonexistent today (Ritchie and McHenry, 1990).

Methods

Sample Collection

Eight monitoring sites were installed in the Mill Creek watershed in February 2006 (in addition to site MI7; operated since October 2002). YSI water-quality monitors equipped with specific conductance, water temperature, and model 6136 turbidity sensors were operated at each site (table 2; fig. 2). Sensors recorded values measured in the stream, and were housed in polyvinyl chloride pipes drilled with holes to allow flow through the installation. Monitors were installed near the stream edge, approximately 1–2 feet from the streambed. Site locations were chosen to divide the study area into equally sized subwatersheds while accounting for site suitability and attempting to avoid backwater conditions. Data considered in this report were collected from February 15, 2006, through June 20, 2007. Monitors collected data every 5 minutes, and data are available on the USGS Kansas Water Science Center Web page (*http://ks.water.usgs.gov/Kansas/rtqw/*). Monitor maintenance and data reporting generally followed procedures described in Wagner and others (2006) with the exception of increased length between calibration checks (approximately 2–3 months). Length between calibration checks was extended beyond the recommended monthly frequency because of the absence of pH and dissolved oxygen sensors which are most prone to calibration drift. Turbidity records generally were rated good (error of 5–10 percent) and occasionally fair (10–15 percent) on the basis of guidelines developed by Wagner and others (2006).

Solinst Levellogger (Ontario, Canada) sensors and (or) radar gage sensors were installed to monitor gage height. Streamflow was measured and calculated using methods described in Kennedy (1983, 1984). Rating curves comparing gage height and streamflow were developed using streamflow measurements and the slope-conveyance method (Kennedy, 1984). Streamflow records were developed without regular streamflow measurements during low-flow conditions (which have a negligible effect on sediment loads). Nonstandard development of streamflow record required a “poor” rating, implying that 95 percent of daily flows could be in error by more than 15 percent. With the exception of site MI7, streamflow and water-quality data were not collected from November 30 to December 18, 2006, and from January 10 to February 20, 2007, due to freezing conditions. Because precipitation during these periods generally consisted of snow, streamflow and sediment concentrations observed at site MI7 were at (or near) base-flow conditions. Because aggregate measures of streamflow were similar between sites LM1 and LM2, the flow volume of two small storms missing at site LM1 from April 6–16, 2007, were estimated using data from site LM2.

Suspended-sediment-concentration samples were collected at a minimum of five locations equally distributed across the stream-cross section according to methods described in Nolan and others (2005). Precipitation data were obtained from tipping-bucket rain gages maintained by the Overland Park Stormwatch Network (fig. 2; Overland Park Stormwatch, 2007). Base flow (defined as wastewater discharge and ground-water flow) and stormflow (defined as overland flow and interflow) parts of the streamflow record were separated using the base-flow index program (BFI; Wahl and Wahl, 2006).

Individual storms were delineated on the basis of observed precipitation and streamflow conditions. Storms in which more than 0.5 in. of rain fell on the Mill Creek watershed were assigned a whole number starting at the beginning of the study period. Storms in which streamflow increased relative to base-flow conditions in response to less than 0.5 in. of rainfall in the watershed were assigned a decimal dependent upon which whole-numbered storm they fell between. The beginning and end of stormflow periods were assigned from the first few values prior to an observed rise in streamflow after a period of precipitation, until streamflow values were not consistently decreasing as a result of the prior storm (or beginning of the next storm).

Stormflow volumes were determined by subtracting the volume of base flow from the volume of streamflow transported during the storm. A consistent numeric criterion was not used to determine the beginning and end times of storms because (1) back-to-back precipitation periods occasionally increased streamflows prior to a complete return to base-flow conditions, (2) multiple storms at headwater sampling sites often could not be isolated at downstream sites (and thus were combined into one storm), and (3) data analysis indicated that a very small percentage of stormflow volume and sediment loads occurs during the beginning and end of stormflow periods and that minor changes in storm beginning and end times have a negligible effect on the computed cumulative stormflow volume and sediment load.

Surface-soil and channel-bank samples were composited from five locations in each subwatershed in the study area. Surface-soil samples were collected within the top 1 in. of soil with a stainless-steel or plastic scoop, generally at sites with observed soil disturbance. Channel-bank samples were collected using a stainless-steel scoop from approximately 1 ft from the top of the channel bank to 1.5 ft from the channel bottom. The surface of the bank was removed to ensure channel-bank samples consisted exclusively of channel material (and not surface soils trickling down the bank). The length of the sampling zone varied dependent on the depth of the surface-soil horizon (estimated visually) and the height of any sediment recently deposited at the foot of the bank. Samples were dried at 113°F, disaggregated, and homogenized into one sample (for each type and subwatershed) on the basis of equal weights.

Trace elements, nutrients, carbon, and radionuclides were analyzed in suspended-sediment samples collected during four storms in 2006 at sampling sites CL2, LM2, MI5, and MI7 (fig. 1). Three samples were collected per storm, per site, to characterize potential differences in sediment sources throughout the stormflow hydrograph. Samples were collected using 2- and 5-gal plastic carboys that were dipped in flowing water near the stream edge. Samples were collected by dip-sampling methods because of the large amount of water necessary to collect sufficient suspended sediment (10 g) for laboratory analysis.

Streambed sediment was collected on March 6, 2007, at sites CL2, LM2, MI5, and MI7 using a plastic spoon. At each site, samples were collected from the top 1 in. of fine-grained-sediment deposits and composited from 10 to 15 sampling locations along the streambed. Surface-soil, channel-bank, suspended-sediment, and streambed-sediment samples were stored at room temperature and shipped to the USGS Sediment Trace Element Partitioning Laboratory in Atlanta, Georgia, for analysis.

Sample Analysis

Suspended-Sediment Concentration and Particle Size

Suspended-sediment concentration and the percentages of sediment greater and less than 63 µm in diameter were determined at the USGS Sediment Laboratory in Iowa City, Iowa, using methods from Guy (1969). Particle size was determined for sediment-source samples using a Beckman-Coulter LS Particle Size Analyzer at the USGS Sediment Laboratory in Menlo Park, California.

Chemical Constituent Analyses

Samples were analyzed for trace elements, nutrients, and carbon at the USGS Trace Element Laboratory in Atlanta, Georgia, using methods described by Arbogast (1996), Briggs and Meier (1999), Fishman and Friedman (1989), and Horowitz and others (2001). Samples were analyzed for beryllium-7 (^{7}Be), lead-210 (^{210}Pb), radium-226 (^{226}Ra), and cesium-137 (^{137}Cs) at the USGS Sediment Radioisotope Laboratory in Menlo Park, California, using a high-resolution gamma spectrometer with an intrinsic germanium detector following methods similar to Robbins and Edgington (1975) and Fuller and others (1999). Measured activities of ^{7}Be were corrected for radioactive decay from the period of sample collection to the date of analysis. Excess ^{210}Pb is defined as the difference between the measured total ^{210}Pb and its long-lived parent, radium-226.

Quality Assurance

Specific conductance, water temperature, and turbidity measurements were collected across the width of the stream during the collection of suspended-sediment samples using the YSI water-quality monitor. Median values of cross-sectional turbidity measurements were used to compute suspended-sediment concentration (SSC) using regression analysis. To ensure that the values of the cross-sectional turbidity readings represent those recorded by in-stream continuous water-quality sensors, comparisons of turbidity values were made between in-stream sensors and the median of cross-sectional measurements. Relations between turbidity readings were accurate ($R^2 = 0.98$) and had a near 1:1 relation (slope = 1.03; fig. 4). These data verify that continuous water-quality-sensor readings were representative of stream-water quality across the width of the stream-cross section under a variety of streamflow conditions (3.4 to 1,190 cubic feet per second) and that in-stream sensor values were reproducible by an independently calibrated sensor. Replicate samples were not collected for suspended-sediment concentration samples because random errors in these analyses are accounted for within regression analyses with turbidity (see 'Regression Models' section).

Replicate and duplicate samples were collected in conjunction with approximately 10 percent of surface-soil, channel-bank, and suspended-sediment samples analyzed for nutrients, trace elements, and radionuclides. Mean relative percentage differences (RPDs) between replicates and samples are presented in table 4 for trace elements, nutrients, total organic carbon, and radionuclides. RPDs were calculated for each constituent by dividing the absolute value of the difference between original and replicate values by the mean of those values and multiplying by 100. Replicate samples were generally within 10 percent of the original samples; larger differences in cadmium, selenium, tin, and excess ^{210}Pb replicates were reported because sample values were near laboratory reporting levels (table 4).

Regression Models

Regression analysis was used to develop statistical models relating suspended-sediment concentration (SSC) and the median of turbidity values collected across the stream cross section. SSC and turbidity values were log-transformed to better approximate normality and homoscedasticity in the data distribution. After development of the regression relation, variables were retransformed back to a linear scale. Because this retransformation can cause bias when adding load estimates over time, a bias-correction factor (Duan's smearing estimator; Duan, 1983) was used to correct for potential bias (Helsel and Hirsch, 2002). Uncertainty of regression estimates were determined by the 95-percent prediction intervals (Helsel and Hirsch, 2002). Regression methods used in this study are described in more detail in Helsel and Hirsch (2002) and

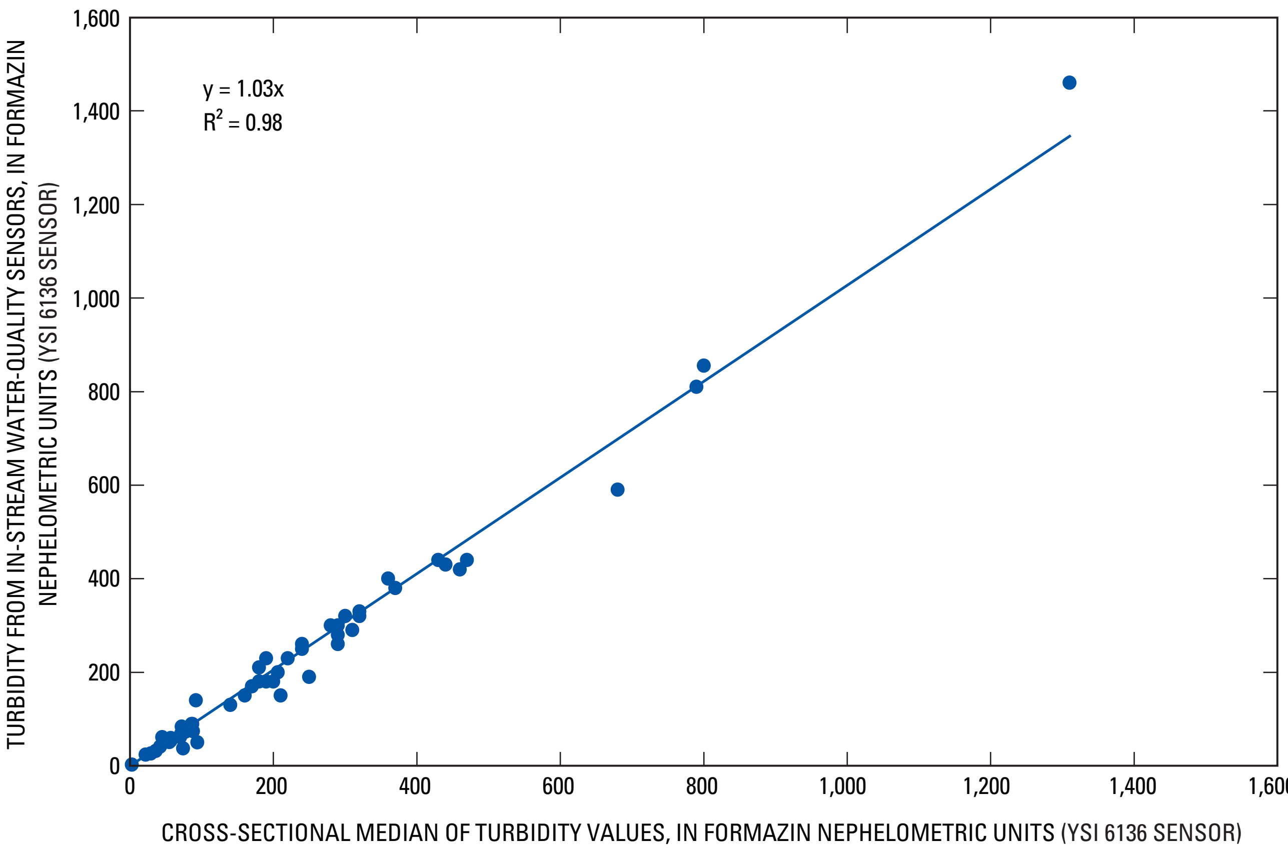


Figure 4. Linear fit between cross-sectional median and in-stream sensor turbidity readings in the Mill Creek watershed, Johnson County, northeast Kansas, February 2006–June 2007.

Table 4. Mean relative percentage differences between replicate and environmental samples for analysis of trace elements, nutrients, total organic carbon, and radionuclides in the Mill Creek watershed, Johnson County, northeast Kansas, February 2006–June 2007.

[mg/kg, milligram per kilogram; dpm/g, disintegrations per minute per gram; n, number of samples; --, not applicable]

Constituent	Laboratory reporting level	Mean relative percentage differences			
		Laboratory split samples		Replicate samples	
		Surface-soil and channel-bank soil samples (n = 2)	Suspended-sediment samples (n = 6)	Surface-soil and channel-bank soil samples (n = 2)	Suspended-sediment samples (n = 3)
Trace elements					
Aluminum	1 mg/kg	1.1	2.0	1.6	5.8
Antimony	0.1 mg/kg	3.9	4.9	0	3.9
Arsenic	0.1 mg/kg	3.6	2.6	5.4	9.0
Barium	1 mg/kg	10.0	3.1	1.4	1.5
Berlyllium	0.1 mg/kg	4.2	1.7	0	6.3
Cadmium	0.1 mg/kg	13.0	17.4	17.9	28.5
Chromium	1 mg/kg	2.0	3.6	1.8	4.3
Cobalt	1 mg/kg	3.9	4.0	1.3	7.1
Copper	1 mg/kg	2.0	2.8	2.9	1.3
Iron	1,000 mg/kg	3.2	2.8	3.8	5.3
Lead	1 mg/kg	3.0	3.1	5.4	12.8
Lithium	1 mg/kg	0	2.1	3.4	8.9
Manganese	10 mg/kg	4.7	3.8	8.5	4.4
Molybdenum	1 mg/kg	3.5	9.6	2.9	18.5
Nickel	1 mg/kg	3.8	3.0	.3	1.8
Selenium	0.1 mg/kg	17.0	7.1	31.0	9.0
Silver	0.5 mg/kg	--	--	--	--
Strontium	1 mg/kg	5.3	3.1	0	6.8
Sulfur	1,000 mg/kg	4.8	5.2	4.0	--
Thallium	50 mg/kg	--	--	--	--
Tin	0.1 mg/kg	21.0	16.6	0	23.9
Titanium	50 mg/kg	2.6	3.7	1.3	2.3
Uranium	0.05 mg/kg	--	--	--	--
Vanadium	1 mg/kg	2.7	2.9	1.9	9.2
Zinc	1 mg/kg	3.6	4.3	2.6	5.7
Nutrients					
Nitrogen	100 mg/kg	0	7.8	6.7	4.3
Phosphorus	100 mg/kg	2.0	2.1	2.2	2.7
Carbon					
Total carbon	1,000 mg/kg	0	2.1	0	
Total organic carbon	1,000 mg/kg	3.9	6.0	0	1.6
Radionuclides					
^{7}Beryllium	0.04 dpm/g	--	--	--	1.2
^{137}Cesium	0.07 dpm/g	--	--	1.0	--
“Excess” ^{210}Lead	0.07 dpm/g	--	--	76.0	6.3

Rasmussen and Ziegler (2003). Continuous suspended-sediment concentration and load computations, uncertainty, and duration curves are available on the World Wide Web at URL *http://ks.water.usgs.gov/Kansas/rtqw*.

Five to 10 samples were collected at newly installed monitoring sites (excluding site MI7) from February 2006 through June 2007 in an attempt to cover the range of turbidity values observed at each site (table 5). The range and distribution of SSC values in samples reflect differences in sediment-transport conditions among sites. Maximum suspended-sediment concentrations ranged from 410 mg/L at sampling site MI5 to 1,920 mg/L at site CL1 (table 5). Site CO1 had smaller maximum and mean SSC values likely because of sediment trapping by Lake Lenexa and several additional small impoundments within the watershed (fig. 2, table 5). SSC values were smaller at site MI5 because the site was not located at a bridge, and samples could not be collected during high-flow conditions. Sediment concentrations at sites CL1 and CL2 were often increased for prolonged periods during stormflow conditions, resulting in larger maximum and median SSC values than other monitoring sites.

In addition to the distribution of SSC values, the grain size and color of suspended sediment are the primary factors that affect the turbidity-SSC regression (Downing, 2006). Turbidity has been shown to accurately estimate SSC in northeast Kansas streams with a preponderance of silt- and clay-sized sediment (Christensen and others, 2000; Rasmussen and others, 2005, 2008). Silt- and clay-sized sediment composed the vast majority of suspended-sediment samples at all Mill Creek sites, as only 2 of 62 samples (at sites CL2 and MI4) had less than 89 percent silt/clay particles. Particle-sizes were often the most fine during high-flow conditions, indicating a general lack of sand-sized sediment transported within stream channels. Of the two samples with less than 89 percent silt/clay particles, both had relatively small sediment concentrations and were biased by insect parts (at site MI4) and sand-sized precipitate (at site CL2). Twelve samples were collected during high-flow conditions at sites CL2, LM2, and MI5, sieved to less than 63 µm in diameter, and analyzed for particle-size distribution. Samples were collected using 2- and 5 gallon carboys dipped at the stream edge for purposes of attributing suspended sediment to surface-soil or channel-bank sources. Although these samples were not collected using depth- and width-integrated isokinetic methods (and thus were not included with SSC analyses), they do give an indication of the silt and clay distribution of suspended sediment in the Mill Creek watershed, already determined (using isokinetic methods) to be composed primarily of silt- and clay-sized particles at high flow. The mean diameter of silt and clay particle sizes ranged from 9.5 to 12.8 µm, indicating that suspended sediment in the watershed consisted primarily of fine silt and clay-sized particles (table 5).

A single regression relation (as opposed to multiple, site-specific relations) was developed between turbidity and SSC data for the eight sampling sites installed in February 2006 (fig. 5). Turbidity explained 93 percent of the variability in SSC values at the eight Mill Creek sites (based on the coefficient of determination), and the relation had a root mean squared error of 0.106. Regression diagnostics were similar to values observed for other Johnson County streams (Rasmussen and others, 2008) and for three sites on the nearby Kansas River (Rasmussen and others, 2005). Residuals from the regression relation generally were evenly distributed around zero; individual sampling sites did exhibit consistent bias in relation to the regression line (fig. 5).

A single relation was chosen for several reasons. The turbidity-SSC relation (affected primarily by particle size and color) is expected to be similar among sampling sites because soils in the Mill Creek watershed are similar in terms of particle size, mineralogy, and organic content (Evans, 2003). Also, because relatively few samples were collected at each site, site-specific relations could bias comparisons between sites. The turbidity-SSC relation developed at eight Mill Creek sampling sites was compared to relations established by Rasmussen and others (2008) at site MI7 (log(SSC) = 1.02 log(turbidity) + 0.144; coefficient of determination (R^2) = 0.96; root mean squared error = 0.216; Duan's bias correction = 1.11). Using the equation from Rasmussen and others (2008), 34,700 tons of sediment were estimated to have been transported past site MI7 during the study period. Using the equation developed in this study, 34,100 tons of sediment were estimated to have been transported past site MI7. Additionally, samples from Clear Creek sites (CL1 and CL2), Little Mill Creek sites (LM1 and LM2), and main-stem Mill Creek sites (MI3, MI4, MI5) were aggregated and compared by analysis of covariance (ANCOVA; Helsel and Hirsch, 2002). Neither the slope nor the y-intercept of turbidity-SSC relations was significantly different (p-value less than 0.05) between tributary and main-stem sampling sites. Similar results using different calibration data sets indicate similar turbidity-SSC relations among sampling sites were similar, and a single regression relation is likely representative of turbidity-SSC relations throughout the watershed.

Estimating Periods of Turbidity Truncation

YSI model 6136 turbidity sensors can record values from 0 to 1,200–2,000 formazin nephelometric units—the maximum recordable value varying among sensors (YSI Inc., 2007). When in-stream turbidity values are larger than maximum sensor values, sensors record the maximum value, resulting in underestimation of actual in-stream turbidity (fig. 6). Truncation of turbidity measurements for only minutes can bias results as these occur when sediment loads are largest. Varying degrees of truncation among sampling sites also bias comparisons of sediment loads and yield between sites.

Three methods were evaluated to estimate turbidity values during periods of sensor truncation. Method 1 interpolates the slope of turbidity measurements before and after sensor truncation (similar to methods described in Bragg and others, 2007). The assumption of this method is that turbidity

Table 5. Suspended-sediment concentration and percentage of silt-clay for equal-width increment samples collected at all Mill Creek sampling sites, and mean suspended-sediment diameter from dip samples collected at selected Mill Creek sampling sites, Johnson County, northeast Kansas, February 2006–June 2007.

[mg/L, milligrams per liter; µm, micrometers; --, not determined]

Sampling site (fig. 1)	Number of samples	Suspended-sediment concentrations (mg/L)				Percentage of sediment less than 63 µm			Mean diameter of suspended sediment (µm)[1]
		Maximum	Minimum	Mean	Standard deviation	Maximum	Minimum	Mean	
CL1	10	1,920	49	730	630	100	91	98	--
CL2	10	1,400	110	550	410	100	69	96	9.5
CO1	7	510	110	260	140	99	93	97	--
LM1	6	760	55	410	300	99	96	97	--
LM2	9	1,530	50	530	530	100	96	98	12.5
MI3	7	910	130	340	280	97	89	94	--
MI4	8	1,150	94	480	370	100	73	92	--
MI5	5	410	130	200	120	99	97	98	12.8

[1]Determined from dip samples analyzed for trace elements and radionuclides.

values increase and decrease at a constant rate during sensor truncation. Method 2 identifies the turbidity-streamflow ratio of the measurement before and after sensor truncation and multiplies that ratio by continuous streamflow data during the period of sensor truncation to obtain a time-series estimate of turbidity. The assumption of method 2 is that turbidity values increase and decrease corresponding with streamflow during sensor truncation. Method 3 is similar to method 2, except that the turbidity-streamflow ratio is interpolated over the period of truncation and then multiplied by continuous streamflow data to obtain an estimate of turbidity. Method 3 assumes that the slope of the turbidity-streamflow ratio will stay relatively constant over the period of truncation. Any turbidity estimates that are less than the truncation value are set equal to the original truncation value. Truncation methods were evaluated by artificially truncating values at varying turbidity thresholds for storms in the Mill Creek at 87th Street Lane subwatershed (site MI4, table 6, fig. 7). Storms selected for analysis resulted in peak turbidity values larger than 800 FNU and did not result in any truncated turbidity values.

Evaluation of the three methods indicated that the static turbidity/streamflow ratio method (method 2) had the least bias over multiple storms and truncation levels (table 6). Interpolation of turbidity values (method 1) and turbidity-streamflow ratios prior to and after truncation (method 3) tended to overestimate turbidity values during small (10–35 minutes) and medium (45–110 minutes) periods of truncation. Extended periods of truncation generally caused large variability in estimated sediment loads for all methods used to estimate truncated values. Use of the static turbidity-streamflow ratio (method 2) before and after truncation allowed turbidity levels to rise and fall coincident with time-series streamflow values. Although the accuracy of individual turbidity estimates is unknown, load calculations for the entire period of truncation were only 1.2 percent larger than observed values during small periods of truncation and -0.1 percent less than actual values during medium periods of truncation (table 6). Method 2 exhibited consistent bias only when turbidity values varied independently of streamflow (storm 7; table 6, fig. 7). Method 1 was more accurate for stormflow periods in which streamflow was observed to vary independently of turbidity (fig. 7; table 6). Estimation method 2 was used if turbidity and streamflow values co-varied prior to truncation of turbidity values; method 1 was used if turbidity and streamflow varied independently prior to truncation.

Estimation of data during periods of truncation increased sediment loads at monitoring sites from 0 to 23 percent. Turbidity sensors truncated most frequently at sampling sites CL1 (11.3 hours) and MI4 (10.5 hours) and had the largest percentage increase in sediment load (23 and 15 percent, respectively) at these sites (table 7).

Transport of Suspended Sediment

Precipitation

Precipitation data were collected and analyzed from 18 tipping-bucket rain gages located in and around the Mill Creek watershed from February 2006 through June 2007 (fig. 2, Overland Park Stormwatch, 2007). Data from the rain gages were combined and weighted using Thiessen polygons (Thiessen and Alter, 1911) to estimate precipitation characteristics for watersheds upstream from sampling sites. Individual storms with rainfall more than 0.5 in. throughout the watershed were summarized and assigned whole numbers

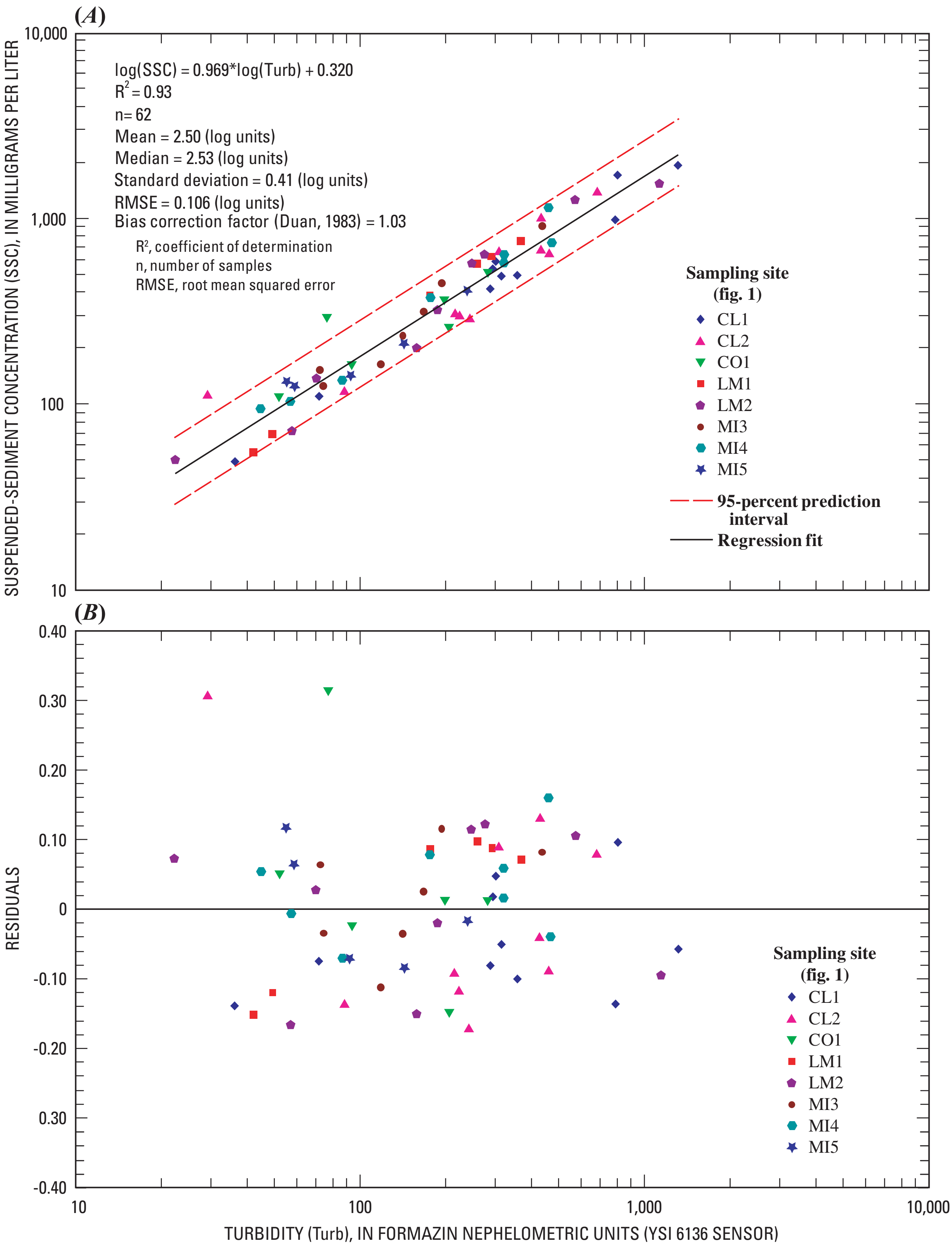


Figure 5. *(A)* Regression relation and *(B)* relation residuals between turbidity and suspended-sediment concentration for Mill Creek sampling sites, February 2006–June 2007.

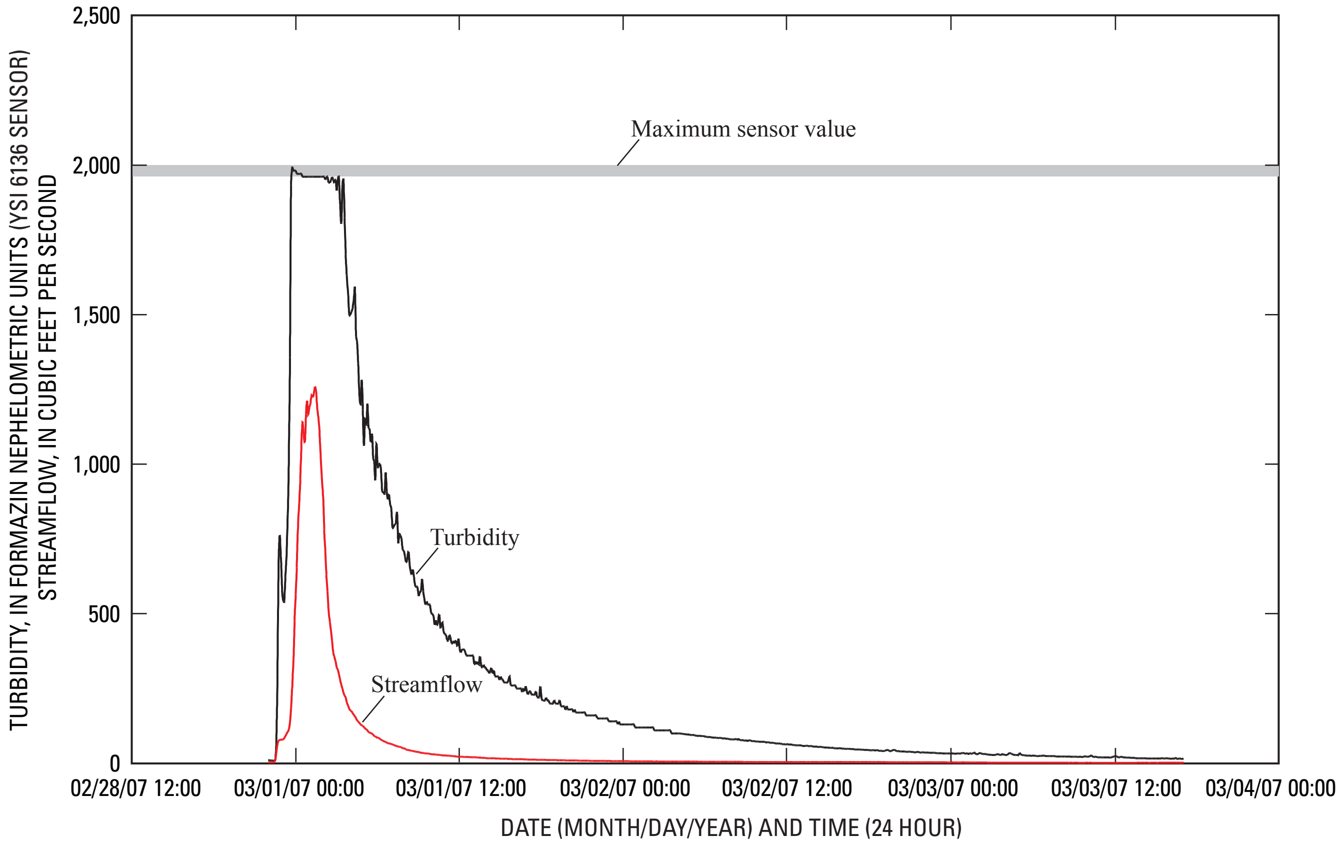


Figure 6. Example of turbidity sensor truncation at sampling site CL1, Mill Creek watershed, February 28–March 3, 2007.

(1 through 20; fig. 8) additional storms with less than 0.5 in. that resulted in stormflow at one or more sampling sites were summarized and assigned decimal numbers depending on the whole numbered storms they fell between (fig. 8). Daily rainfall displayed on figure 8 is occasionally greater than the rainfall observed for individual storms.

Rainfall recorded during the period of record is considered normal compared to historic conditions. Annual average rainfall for 1960–2006 in Olathe, Kansas, over a similar period of study (17 months) totaled 58.2 in. compared with 59.4 in. observed over the study period, February 2006 through June 2007 (National Oceanic and Atmospheric Administration, 2007). Additionally, the study period had similar days of intense rain (39 days with 0.5 in. or more; 16 days with 1 in. or more) compared to historical annual averages (38 days with 0.5 in. or more; 16 days with 1 in. or more). The maximum observed rainfall from February 2006 through June 2007 for a single day was 2.9 in. on August 27, 2006, which is less than the 1-year daily recurrence interval estimated for the Mill Creek watershed (3.5 in.; U.S. Department of Commerce, 1961). Streamflow and suspended-sediment loads and yield observed during this 17-month study should approximate those expected during an average period of precipitation.

Streamflow and Stormflows

The Harold Street wastewater-treatment facility upstream from sampling site MI3 (fig. 2) is the only known point source of streamflow in the watershed, contributing 2,800 acre-ft of water during the study period (City of Olathe, written commun., 2008; table 8). The Harold Street facility contributed approximately 44 percent of the total streamflow at site MI3. The facility contributed slightly more than the total base flow at site MI3 estimated using flow-separation techniques (2,600 acre-ft; Wahl and Wahl, 2006). Increased wastewater discharge may be related to comparing monthly mean wastewater discharge data to daily base-flow estimates and error in the low flow portion of the gage-height/streamflow rating. Downstream from site MI3, streamflow from the Harold Street facility comprised approximately 44 percent (site MI4), 35 percent (site MI5), and 30 percent (site MI7) of the base-flow volume estimated during the study period. Downstream sites have larger drainage areas and lower stream elevations, which potentially increase ground-water contributions to base flow. Because fewer (approximately two) base-flow measurements were made at each sampling site in the Mill Creek watershed compared to conventional USGS stream gages (approximately eight over a similar period of record), interpretations of base-flow volumes in this report are more prone to error.

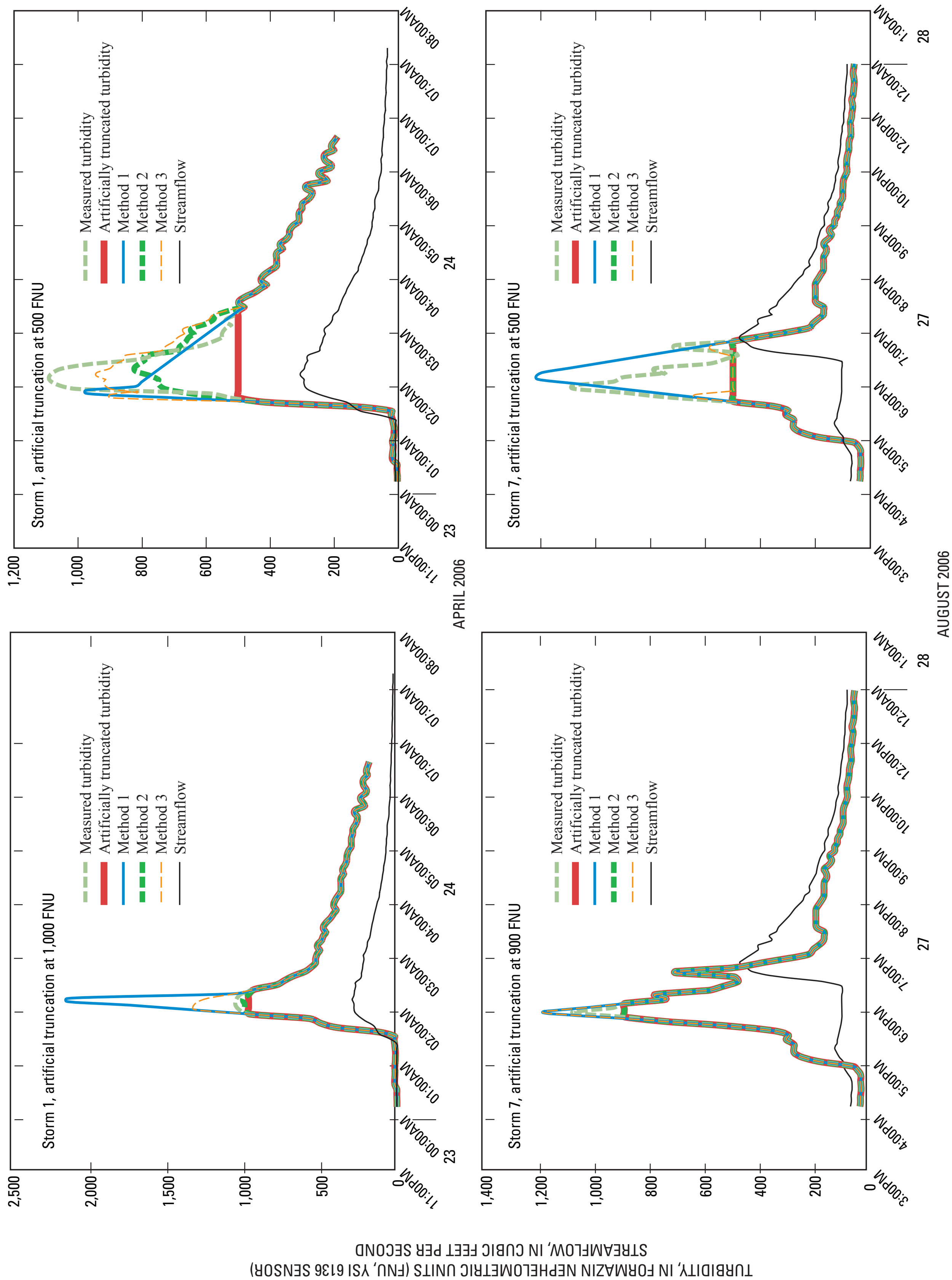


Figure 7. Example of methods used to estimate periods of turbidity truncation for sampling site MI4, Mill Creek watershed (fig. 1).

Table 6. Evaluation of sediment loads for selected storms using three methods of estimating turbidity values during periods of sensor truncation at sampling site MI4, Mill Creek watershed, Johnson County, northeast Kansas, February 2006–June 2007.

[FNU, formazin nephelometric units]

Storm evaluated	Sediment load observed from storm (tons)	Peak turbidity for storm (FNU)	Artifically imposed truncation value (FNU)	Number of minutes truncated	Observed sediment load with artifically truncated turbidity values (tons)	Estimated sediment loads during truncation periods			Percentage difference from original storm (truncated load)	Percentage difference from original storm		
						Method 1—load calculated by interpolation of truncated turbidity values (tons)	Method 2—load calculated using streamflow/turbidity ratio prior to truncation (tons)	Method 3—load calculated using slope of streamflow/turbidity ratio for last two values prior to and after truncation (tons)		Method 1	Method 2	Method 3
1	99	1,090	1,000	25	97	100	98	100	-1.5	1.0	-1.1	1.0
1	99	1,090	500	110	78	110	92	110	-27	10	-7.8	10.0
1	99	1,090	200	295	43	93	100	120	-129	-6.4	.6	18
2	93	823	700	10	93	93	93	93	-.7	-.2	-.6	-.4
2	93	823	500	50	87	93	89	91	-7.5	-.7	-5.1	-2.1
2	93	823	200	260	54	110	98	190	-71	15	4.4	51
3	412	1,520	1,100	35	400	450	410	410	-3.0	8.5	-.5	-.5
3	412	1,520	1,000	45	390	450	400	460	-5.6	8.4	-3.0	10
3	412	1,520	400	240	290	350	390	490	-42	-18	-5.6	16
5	231	957	900	25	230	230	230	230	-.3	-.3	-.2	-.3
5	231	957	800	55	220	250	230	230	-4.8	7.8	-.3	-.3
5	231	957	600	120	180	210	280	260	-28	-9.8	18	11
6	561	1,140	1,100	35	560	560	620	910	-.2	-.2	9.5	38
6	561	1,140	800	80	500	670	660	500	-12	16	15	-12
6	561	1,140	400	215	350	670	670	640	-60	16	16	12
[1]7.1	66	1,090	900	25	66	67	66	67	-.6	.7	-.5	.2
[1]7.1	66	1,090	500	50	60	62	61	63	-9.9	-7.9	-9.7	-5.6
[1]7.1	66	1,090	200	170	45	61	46	47	-47	-9.0	-45	-42

[1]Turbidity rises and falls independent of streamflow; percentage differences not included in final tabulation.

Table 7. Sediment-load estimates without estimation during turbidity truncation and with truncated periods estimated for sampling sites in the Mill Creek watershed, Johnson County, northeast Kansas, February 2006–June 2007.

Sampling site (fig. 1)	Hours of truncated data	Sediment load without estimation during turbidity truncation (tons)	Sediment load with truncated periods estimated (tons)
CL1	11.3	6,400	7,900
CL2	5.3	5,500	5,600
CO1	5.8	1,000	1,100
LM1	2.8	3,200	3,700
LM2	3.1	4,300	4,600
MI3	2.8	1,400	1,400
MI4	10.5	13,000	14,900
MI5	6.3	11,900	13,100
MI7	2.0	34,100	34,700

Base flow and stormflow were divided by total streamflow to approximate the magnitude of wastewater/ground water and stormflow (composed of overland flow and interflow contributions) relative to precipitation volume. Base- and stormflow separation indicate that stormflow comprised the majority of flow at Mill Creek sampling sites (59–96 percent), especially at sites without upstream wastewater discharge (78–96 percent). Site CL1 was the only stream sampling site in which zero flow was observed during prolonged dry periods and had the largest percentage (96 percent) of streamflow estimated to originate as stormflow. With the exception of site MI3 (49 percent), the percentage of total precipitation as stormflow was similar among sites (23–31 percent). Increased routing of precipitation as streamflow at site MI3 may be because of large upstream impervious surface area (22.2 percent) and additional streamflow contributed by stormwater overflows from the Harold Street wastewater facility.

Stormflow yields were compared between sampling sites by subtracting base-flow volume from total streamflow and dividing this volume by upstream drainage area. The two sites with the most impervious surface (site LM1, 23.6 percent, and site MI3, 22.2 percent) had the largest stormflow yields (820 and 1,360 acre-ft/mi^2, respectively). Other than at these two sites, impervious surface did not have an identifiable relation with streamflow yields. Watershed regulation, increased interactions with ground water at downstream sites, variations in watershed slope and soil permeability, and uncertainty in streamflow ratings likely contributed to variability in relations between stormflow and impervious surface among sampling sites. Although the potential for backwater exists at monitoring sites during large flows, it was not apparent in time-series records, and stormflow yields did not exhibit bias during the study period.

Streamflow-duration curves were calculated at the nine Mill Creek sampling sites to evaluate and compare the distribution of continuous streamflow data (figs. 9 and 10). Duration plots display how frequently a given streamflow is exceeded during the period of study. Streamflow durations were created for equivalent study periods (February 15 through June 20 of the following year) for site MI7 for the 4 years of streamflow record (fig. 9). Streamflow conditions during the study period for this investigation (2006–07) are in between the wettest (2004–05) and driest (2003–04) periods of record for site MI7.

Because the number of sampling sites inhibit the display of duration curves at all nine sites, statistics derived from the flow-duration curves (streamflow values at 1-, 5-, 10-, 25-, 50-, 75-, 90-, 95-, and 99-percent exceedance) are compared among sites (fig. 10). Sites with increased drainage area had larger streamflows for more prolonged periods of time relative to headwater sites. Wastewater discharge increased base-flow values at sites MI3, MI4, MI5, and MI7, decreasing the range of streamflow conditions relative to sites without wastewater discharge (fig. 10). To better distinguish potential effects of land use on streamflow distribution, streamflow statistics were normalized by upstream watershed area (fig. 10). After normalization, sites MI3, MI4 and LM1 had the largest 99-percent exceedance values, likely because upstream impervious surfaces route precipitation directly to the stream.

The three largest storms at the most downstream site (MI7) occurred during February through May 2007. The largest stormflows occurred May 6–10, 2007 (storm 17; 4,500 acre-ft at site MI7), February 28 through March 4, 2007 (storm 12; 3,500 acre-ft at site MI7), and March 29 to April 2, 2007 (storm 13; 2,400 acre-ft at site MI7) (table 9). During individual storms, stormflow volume was typically a small percentage of the total rainfall. Stormflows generally increased relative to the amount of rainfall during larger storms and when storms occurred in rapid succession. Peak streamflow values observed at sites CL2, LM2, and MI7 were less than the 2-year peak streamflow recurrence interval estimated by Perry and others (2004).

Suspended Sediment

Continuous turbidity data were multiplied by the turbidity-SSC regression relation (fig. 5) to obtain a continuous, 5-minute estimate of SSC at each sampling site. Duration statistics for SSC values are displayed on a log-10 scale to compare the frequency of SSC values observed among sampling sites (fig. 11). One-percent (900 mg/L, site CL1; 650 mg/L, site CL2), 5-percent (220 mg/L, site CL1; 190 mg/L, site CL2) and 10-percent (90 mg/L, site CL1; 88 mg/L, site CL2) exceedance values were largest at sites CL1 and CL2, indicating that these sites had the largest SSC values for the longest period of time. Watersheds upstream from these sites had the largest percentage of land area under construction without the presence of large watershed impoundments. One-, 5-, and 10-percent exceedance intervals were smallest at sites CO1, LM1, LM2, and MI3. Impervious surfaces and relatively

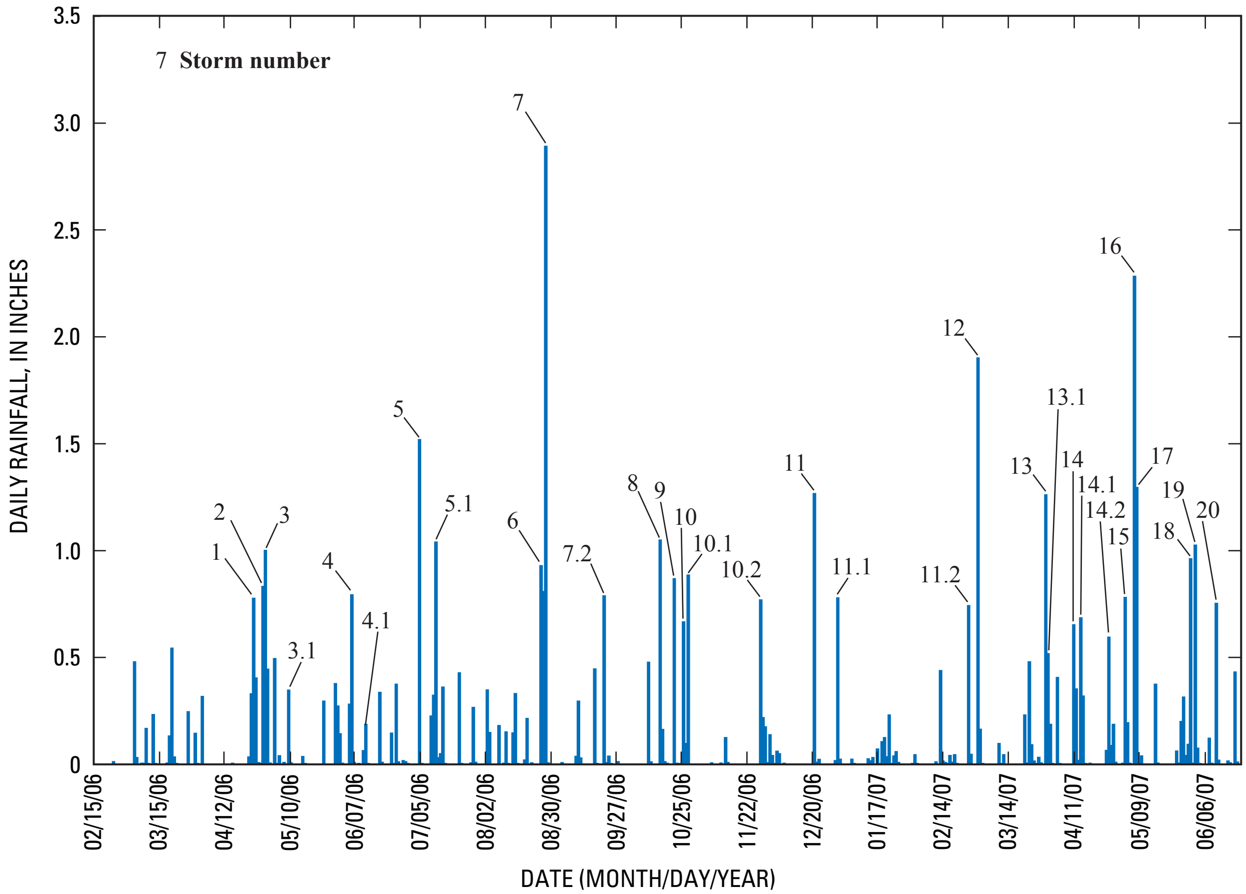


Figure 8. Daily rainfall in the Mill Creek watershed upstream from sampling site MI7 (fig. 1) and numbers used to identify storms, February 2006–June 2007.

stable vegetation in urban watersheds (sites LM1, LM2, and MI3) decrease the potential for surface-soil erosion, thus limiting the concentration of sediment at these sites. Lake Lenexa (upstream from site CO1) and Waterworks Lakes (upstream from site MI3) likely slow water velocities and trap suspended sediment upstream from their respective dams. Increased SSC values at less-frequent exceedance intervals at sites MI4, MI5, and MI7 may be related to larger upstream watersheds (and thus, less flashy streamflow) as well as increased urban construction between sites MI3 and MI4 (table 3).

Time-series streamflow and turbidity data are displayed during three average-sized storms at sampling sites CL1, CL2, and LM1 to compare sediment-transport dynamics among sites affected by urban construction (sites CL1 and CL2) and relatively stable urban-land use (site LM1; fig. 12). Peak-turbidity values were the largest at site CL1 during the three storms, frequently occurred after peak streamflow, and remained elevated well after streamflow had returned to base-flow conditions. Larger turbidity values on the falling limb of the hydrograph at site CL1 (fig. 12) indicate that primary sediment-source areas are distant from the sampling site, likely in the headwaters of the watershed (where the majority of urban construction is ongoing; fig. 1). Although peak streamflow was larger during each storm at site CL2, peak-turbidity values were smaller, and turbidity values returned to pre-storm values prior to those at site CL1. Part of the sediment transported past site CL1 during the falling limb of storm hydrographs appears to be deposited in the channel upstream from site CL2. Increased deposition in the downstream Clear Creek channel during averaged-sized storms is likely related to decreasing stream-channel slope and increased stream size. Stream segments with less-sloping gradients have smaller stream-water velocities (for a given streamflow), allowing more time for suspended-sediment fall to the streambed.

Site LM1 generally had larger peak streamflow values than sites CL1 and CL2 for a given storm, but streamflow values remained elevated for a shorter duration of time. Turbidity values at site LM1 typically returned to pre-storm levels before streamflow returned to base-flow conditions (fig. 12). Because less sediment is available for transport in mature urban areas than those with construction activity, equivalent increases in streamflow result in smaller, less prolonged increases in sediment concentration.

Table 8. Total rainfall, streamflow volume, and streamflow yield at Mill Creek sampling sites, Johnson County, northeast Kansas, February 2006–June 2007.

[mi^2, square miles; ft^3/s, cubic feet per second; acre-ft/mi^2, acre-feet per square mile; --, not applicable]

Sampling site (fig. 1)	Contributing drainage area (mi^2)	Total rainfall (acre-feet)	Total streamflow volume (acre-feet)	Total estimated base flow (acre-feet)	Total streamflow from Harold Street waste-water-treatment facility (upstream from site MI3) (acre-feet)	Percentage of streamflow as stormflow	Percentage of precipitation as stormflow	Percentage of streamflow from Harold Street waste-water-treatment facility (assuming no loss downstream)	Stormflow yield (acre-ft/mi^2)	5-minute peak streamflow (ft^3/s)	Percentage impervious surface	Percentage of watershed regulation
CL1	5.5	14,400	3,600	150	--	96	24	--	630	1,400	4.2	--
CL2	10.9	28,600	8,900	1,800	--	80	25	--	650	1,250	6.3	--
CO1	5.1	13,200	5,000	1,100	--	78	30	--	770	430	5.8	40
LM1	8.8	23,500	8,800	1,600	--	82	31	--	820	1,810	23.6	--
LM2	12.1	32,300	9,000	1,500	--	83	23	--	620	1,910	20.9	--
MI3	2.8	7,700	6,400	2,600	2,800	59	49	44	1,360	470	22.2	36
MI4	19.7	51,400	22,400	6,400	2,800	71	31	13	810	3,460	14.5	5.1
MI5	31.7	83,300	27,200	7,900	2,800	71	23	10	610	3,490	11.9	19
MI7	57.4	152,300	44,300	9,200	2,800	79	23	6	610	4,850	12.8	10

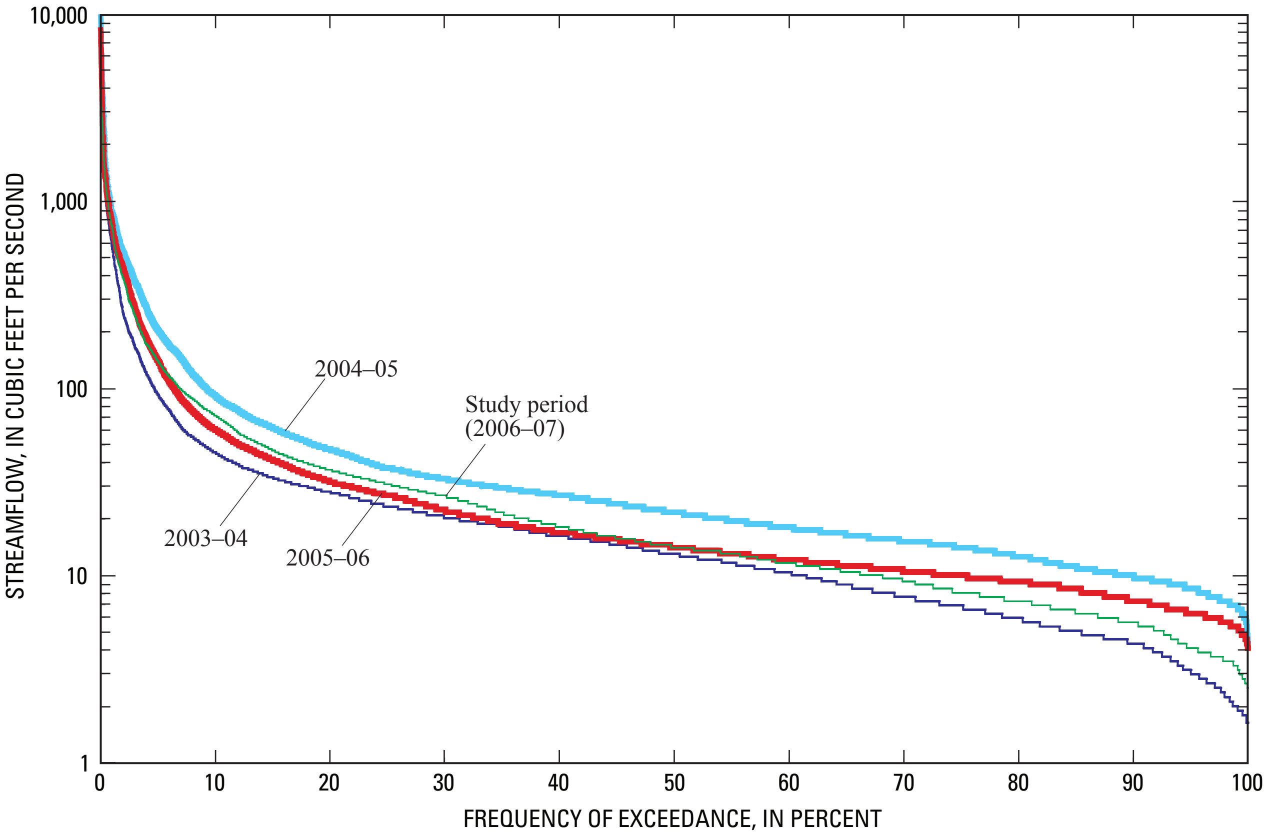


Figure 9. Duration plot showing streamflow exceedance for Mill Creek at Johnson Drive (sampling site MI7, fig. 1) during equivalent study periods (February through June of the following year) since gage installation in 2002.

Sediment Loads During Storms

Time-series (5-minute) streamflow values were multiplied by 5-minute computations of SSC and by a unit-conversion factor (6.243 x 10^{-5}) to compute time-series suspended-sediment loads (SSL) in pounds per second. Five-minute sediment-load computations are summed and multiplied by a unit conversion factor (0.15) to compute sediment loads (in tons) for time periods of interest.

Unlike traditional approaches that use continuous streamflow to estimate SSC (or SSL), continuous-turbidity measurement results in a computation of SSC independent of streamflow, allowing evaluation of sediment transport among varied streamflow conditions. Total stormflow volume and sediment load transported as a result of individual storms were compared by linear regression (on log-transformed values) to evaluate sediment transport among storms and sampling sites (figs. 13 and 14). The largest storms were labeled to enable comparison of sediment transported for the same storms among sampling sites (figs. 13 and 14; table 9). Analysis of covariance (ANCOVA) was used to assess differences in sediment loads between sampling sites after accounting for covariance with stormflow volume. Significant differences between sites are indicated if there is greater than 95-percent probability (p-value less than 0.05) that the mass of sediment transported is different between sites across the range of stormflow conditions. Because sediment concentration and streamflow are computed by relations to measured turbidity and gage height, errors in these relations are compounded.

Sites CL1 and CL2 had the best linear correlation (R^2 of 0.94) between sediment load and stormflow volume compared to other Mill Creek sampling sites (fig. 13, table 10). Improved correlation between stormflow volume and sediment load implies that consistent increases in stormflow will result in more consistent increases in sediment transport among observed storms. Less correlation between stormflow volume and sediment load at other Mill Creek sites (R^2 from 0.78 to 0.86; fig. 13) imply that variation in sediment loading is more influenced by availability of sediment supplies. These differences are especially evident when examining the largest storms (7, 12, 13, 16, 17; table 9). Although the largest storms at sites CL1 and CL2 had relatively similar sediment loads, larger differences in sediment load were observed among large storms at the other sites. Differences in fit indicate that soil disturbance from urban construction likely increases sediment supply at sites CL1 and CL2, resulting in a more transport- (streamflow-) limited system. Sites with relatively less soil disturbance have less sediment available for erosion and transport, which results in a more supply-limited system.

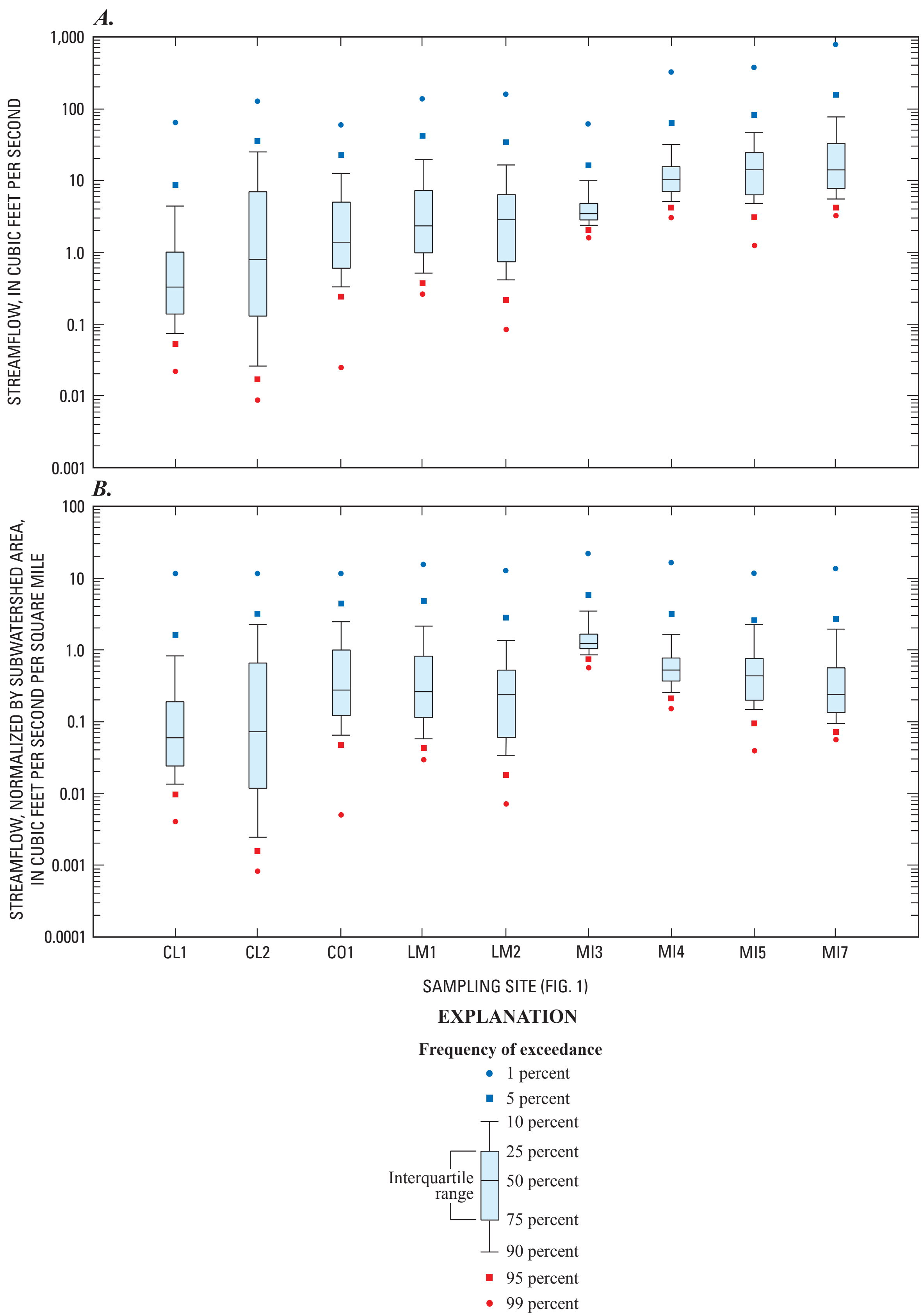


Figure 10. Duration statistics for streamflow and streamflow normalized by subwatershed area for Mill Creek sampling sites, February 2006–June 2007.

Table 9. Total stormflow and precipitation volumes for storms at Mill Creek sampling sites, Johnson County, northeast Kansas, February 2006–June 2007.

[Sampling sites located in figure 1. --, not applicable]

Storm number	Storm dates and times (month/day/year, 24-hour time)	Total stormflow volume, in acre–feet (precipitation volume, in acre–feet)								
		CL1	CL2	CO1	LM1	LM2	MI3	MI4	MI5	MI7
0.1	3/4/2006 9:25 – 3/4/2006 16:50	--	--	--	--	--	--	120 (470)	--	--
1	4/23/2006 21:50 – 4/28/2006 9:30	42 (330)	71 (650)	25 (150)	88 (460)	10 (240)	21 (140)	67 (1,000)	250 (2,000)	440 (1,900)
2	4/28/2006 11:00 – 4/29/2006 23:15	49 (210)	52 (410)	28 (180)	78 (310)	130 (410)	39 (100)	160 (660)	230 (1,100)	410 (2,000)
3	4/29/2006 18:15 – 5/3/2006 7:45	240 (430)	550 (860)	94 (330)	170 (600)	240 (810)	110 (180)	450 (1,300)	740 (2,100)	1,500 (4,000)
3.1	5/3/2006 6:30 – 5/10/2006 21:35	54 (130)	170 (260)	26 (130)	77 (260)	100 (350)	7 (53)	20 (450)	160 (770)	540 (1,100)
3.2	5/9/2006 1:10 – 5/10/2006 21:40	--	42 (220)	--	37 (120)	--	11 (60)	95 (400)	--	--
3.3	5/24/2006 2:55 – 5/24/2006 23:50	--	4 (180)	--	14 (200)	13 (280)	--	--	--	--
3.4	5/30/2006 9:15 – 5/31/2006 6:55	--	3 (390)	--	--	--	7 (80)	--	--	--
3.5	6/4/2006 6:50 – 6/4/2006 21:25	--	3 (160)	--	20 (160)	--	--	--	--	--
4	6/5/2006 18:30 – 6/11/2006 0:15	7 (130)	37 (270)	25 (200)	90 (470)	89 (600)	37 (100)	190 (800)	160 (1,300)	410 (2,200)
4.1	6/10/2006 23:40 – 6/11/2006 20:40	--	7 (99)	--	21 (170)	12 (590)	2 (29)	--	--	68 (1,100)
4.2	6/17/2006 22:05 – 6/18/2006 13:30	--	--	--	--	--	5 (28)	10 (130)	--	--
4.3	6/24/2006 21:00 – 6/26/2006 14:30	--	--	--	--	--	--	--	--	--
5	7/3/2006 20:30 – 7/6/2006 20:30	3 (320)	59 (670)	1 (360)	120 (980)	140 (1,300)	41 (190)	160 (1,500)	170 (2,500)	480 (4,500)
5.1	7/11/2006 20:30 – 7/13/2006 22:45	--	--	60 (460)	82 (700)	74 (800)	55 (340)	580 (1,500)	440 (2,300)	670 (2,900)
5.2	7/14/2006 8:20 – 7/16/2006 21:05	3 (69)	--	--	--	9 (190)	7 (43)	--	--	--
5.3	8/2/2006 20:40 – 8/3/2006 20:05	--	2 (300)	--	--	--	5 (67)	49 (450)	46 (750)	--
5.4	8/7/2006 6:30 – 8/8/2006 7:05	--	--	--	--	--	12 (68)	34 (290)	--	--
5.5	8/14/2006 1:35 – 8/14/2006 16:20	--	3 (170)	--	17 (280)	--	4 (40)	23 (370)	--	--
6	8/25/2006 3:20 – 8/27/2006 4:40	14 (320)	60 (640)	24 (440)	140 (500)	120 (710)	86 (270)	420 (1,800)	420 (2,900)	640 (4,500)
7	8/27/2006 0:00 – 8/30/2006 11:40	95 (290)	300 (630)	210 (270)	430 (1600)	450 (2,000)	240 (470)	1,200 (2,100)	1,500 (2,700)	2,200 (5,000)
7.1	9/17/2006 5:15 – 9/18/2006 12:05	--	--	5 (140)	29 (200)	21 (290)	1 (54)	--	--	--
7.2	9/21/2006 18:15 – 9/25/2006 18:45	20 (67)	51 (130)	35 (61)	75 (370)	76 (530)	25 (130)	140 (850)	190 (1,400)	310 (2,400)
7.3	10/10/2006 19:25 – 10/11/2006 23:45	--	--	--	--	--	9 (77)	--	--	--
8	10/15/2006 4:00 – 10/18/2006 1:45	26 (290)	80 (580)	14 (270)	130 (640)	110 (840)	15 (130)	150 (1,000)	200 (1,700)	420 (3,300)
9	10/21/2006 9:15 – 10/24/2006 22:55	16 (250)	73 (500)	24 (230)	95 (420)	81 (550)	19 (130)	160 (920)	240 (1,500)	380 (2,600)
10	10/25/2006 20:45 – 10/30/2006 14:15	92 (230)	240 (460)	41 (200)	120 (350)	83 (490)	6 (88)	90 (630)	150 (1,100)	320 (2,200)

Table 9. Total stormflow and precipitation volumes for storms at Mill Creek sampling sites, Johnson County, northeast Kansas, February 2006–June 2007.—Continued

[Sampling sites located in figure 1. --, not applicable]

Storm number	Storm dates and times (month/day/year, 24-hour time)	Total stormflow volume, in acre–feet (precipitation volume, in acre–feet)								
		CL1	CL2	CO1	LM1	LM2	MI3	MI4	MI5	MI7
10.1	10/27/2006 1:00 – 10/29/2006 1:05	--	--	50 (150)	160 (390)	140 (470)	49 (72)	330 (450)	460 (660)	800 (1,200)
10.2	11/27/2006 0:05 – 11/30/2006 10:25	28 (250)	59 (460)	25 (170)	66 (320)	--	--	120 (110)	170 (1,300)	380 (2,500)
11	12/20/2006 4:00 – 12/24/2006 6:15	62 (360)	140 (720)	64 (320)	160 (600)	170 (780)	59 (110)	350 (1,100)	370 (2,000)	810 (3,700)
11.1	12/30/2006 15:20 – 1/2/2007 20:10	20 (190)	--	5 (130)	--	--	39 (32)	--	--	--
11.2	2/24/2007 4:20 – 2/27/2007 11:25	--	--	--	--	--	--	--	--	660 (1,300)
12	2/28/2007 17:45 – 3/4/2007 18:15	330 (550)	460 (1,100)	320 (550)	620 (1,200)	740 (1,500)	210 (300)	1,700 (1,800)	2,200 (3,400)	3,500 (6,300)
12.1	3/22/2007 1:45 – 3/23/2007 21:40	--	82 (340)	--	17 (94)	--	15 (96)	--	--	--
13	3/29/2007 19:30 – 4/2/2007 22:00	490 (640)	770 (1,200)	370 (710)	80 (400)	210 (600)	130 (290)	810 (1,400)	1,300 (2,300)	2,400 (4,100)
13.1	4/3/2007 1:45 – 4/5/2007 22:45	12 (110)	52 (230)	34 (76)	130 (210)	76 (270)	10 (57)	160 (300)	190 (630)	430 (1,200)
14	4/9/2007 11:15 – 4/13/2007 17:15	43 (220)	140 (450)	45 (190)	160 (500)	160 (670)	40 (160)	250 (750)	460 (1,500)	810 (2,800)
14.1	4/13/2007 17:45 – 4/17/2007 5:15	140 (240)	280 (490)	100 (170)	250 (460)	250 (610)	120 (190)	610 (1,000)	810 (1,300)	1,600 (2,700)
14.2	4/24/2007 18:25 – 4/28/2007 7:35	6 (220)	13 (430)	--	110 (630)	100 (830)	18 (110)	94 (880)	110 (1,300)	200 (2,800)
15	5/2/2007 0:45 – 5/4/2007 21:45	20 (140)	38 (280)	19 (250)	130 (510)	100 (540)	30 (40)	220 (440)	220 (900)	490 (1,900)
16	5/6/2007 2:00 – 5/6/2007 22:45	290 (450)	390 (910)	120 (360)	240 (760)	380 (980)	130 (270)	850 (1,600)	770 (2,700)	1,800 (5,200)
17	5/6/2007 18:30 – 5/10/2007 13:30	810 (640)	1,000 (1,300)	500 (510)	380 (890)	680 (1,100)	280 (240)	1,700 (1,900)	1,700 (2,900)	4,500 (5,600)
17.1	5/15/2007 5:50 – 5/16/2007 19:55	8 (120)	46 (350)	--	60 (190)	61 (230)	11 (46)	77 (340)	53 (550)	--
17.2	5/27/2007 4:40 – 5/30/2007 14:30	--	--	--	--	34 (110)	7 (13)	18 (130)	--	--
18	5/30/2007 10:30 – 6/1/2007 8:25	35 (140)	72 (290)	38 (290)	150 (420)	120 (570)	92 (260)	510 (620)	470 (1,200)	740 (2,000)
19	6/1/2007 2:40 – 6/3/2007 2:30	62 (290)	130 (570)	65 (250)	100 (420)	160 (540)	47 (83)	360 (770)	430 (1,500)	790 (2,800)
20	6/10/2007 1:45 – 6/13/2007 7:00	28 (230)	57 (450)	2 (180)	80 (410)	73 (570)	10 (59)	30 (490)	55 (1,100)	180 (2,300)

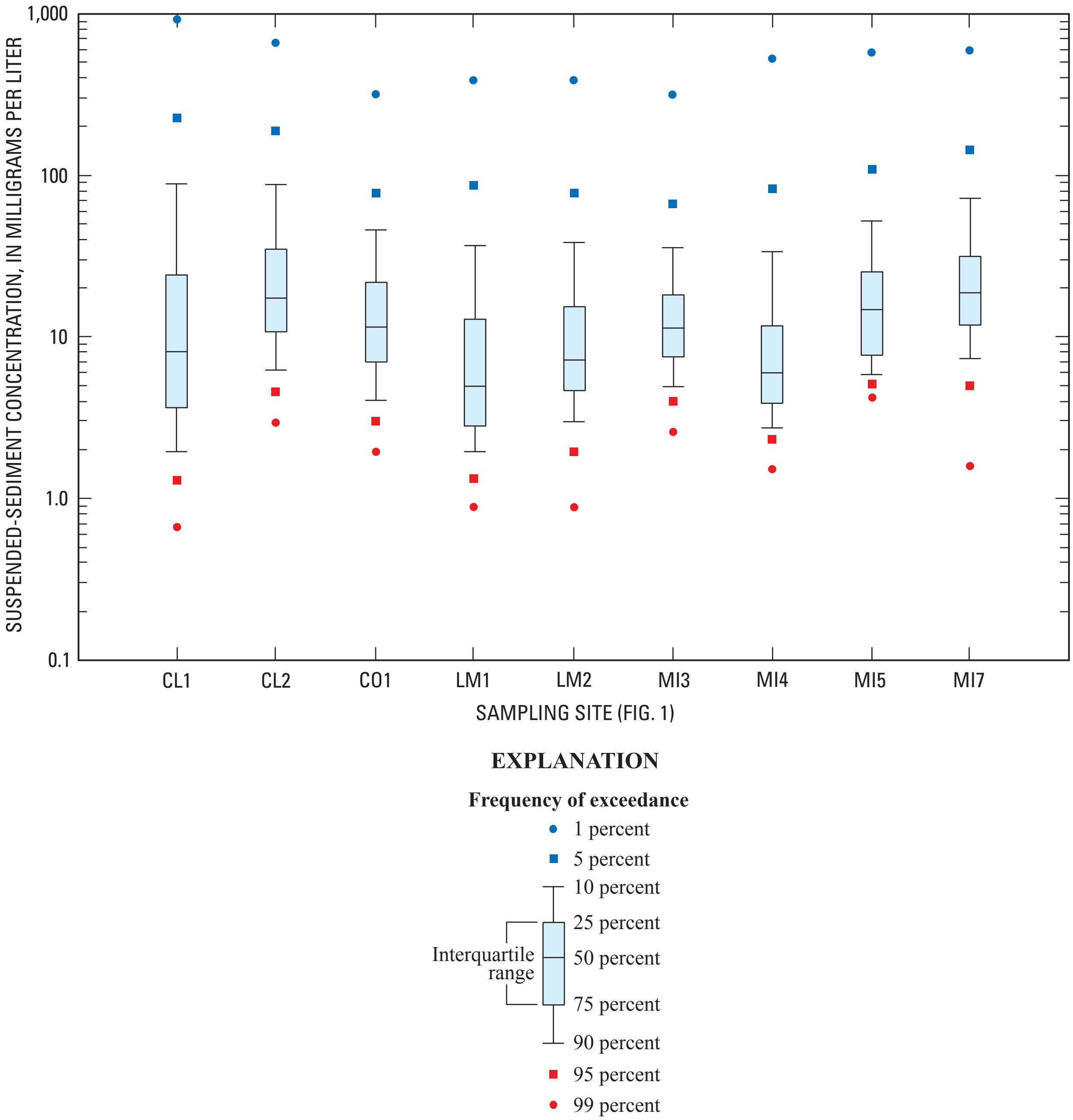


Figure 11. Duration statistics for suspended-sediment concentrations at Mill Creek sampling sites, February 2006–June 2007.

Storms generally increased in flow volume between sites CL1 and CL2 but had less than equivalent increases (and occasionally decreased) in sediment loading, resulting in a significant difference in sediment load per flow volume between the two sites (p-value less than 0.01; fig. 13). Fine sediments were observed deposited on and in the streambed between sites CL1 and CL2 more than at other stream segments in the study area (fig. 15). The sediment load increased more between sites CL1 and CL2 for storm 17 (for a given flow volume) than for smaller storms, possibly indicating that ratios of sediment load/stormflow volume are more similar between sites CL1 and CL2 during storms larger than those observed during the study period (data for storms 12 and 13 were missing for site CL2 because of sensor malfunction).

Stormflow-weighted suspended-sediment concentrations (SWSCs) were computed for storms at site CL1 and from stormflow volumes and sediment loads originating between sites CL1 and CL2 to better characterize sediment transport during storms of different magnitude (fig. 16). SWSCs were calculated for each storm by dividing the storm-sediment load by the volume of stormflow and multiplying by a unit

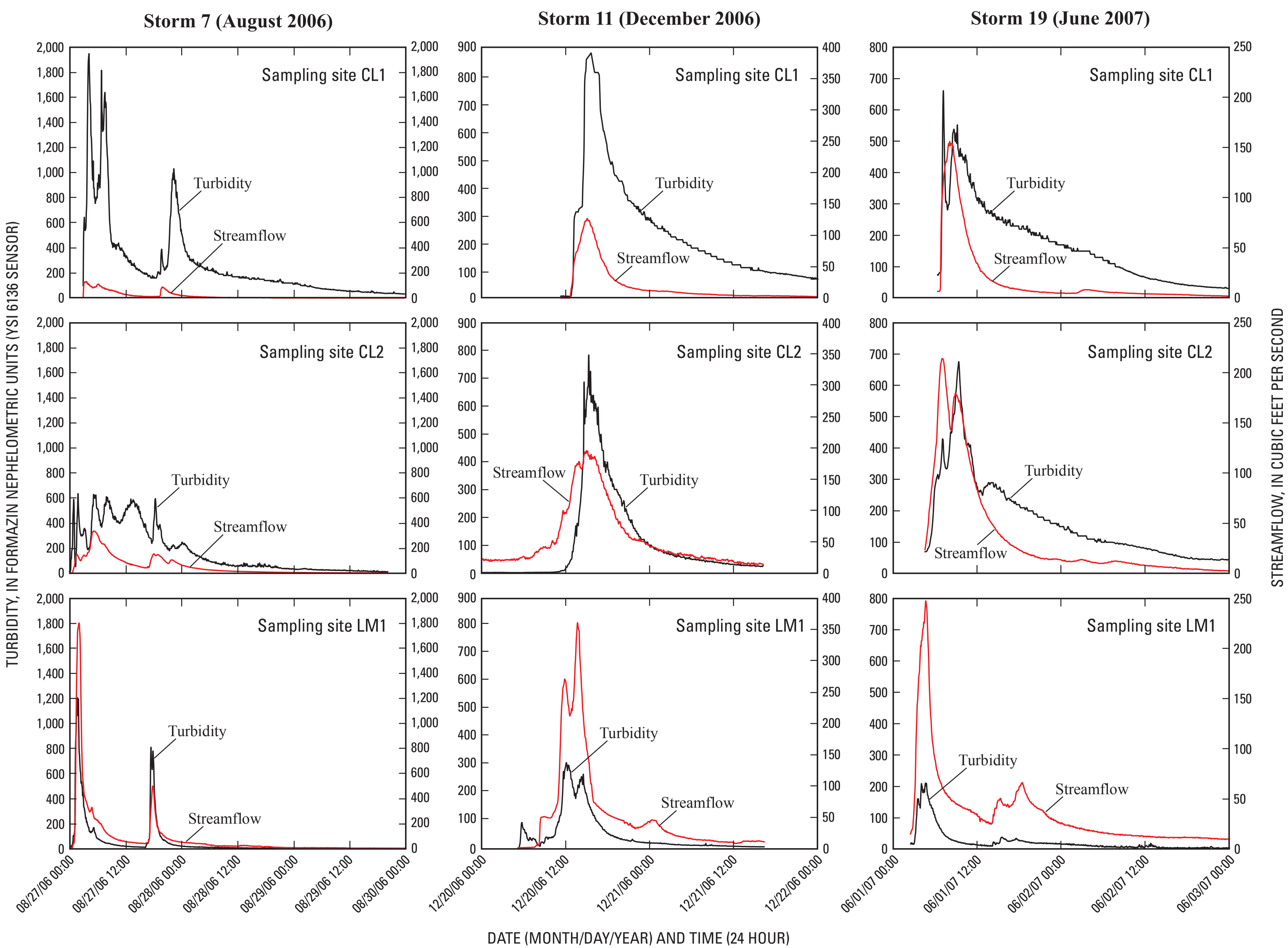
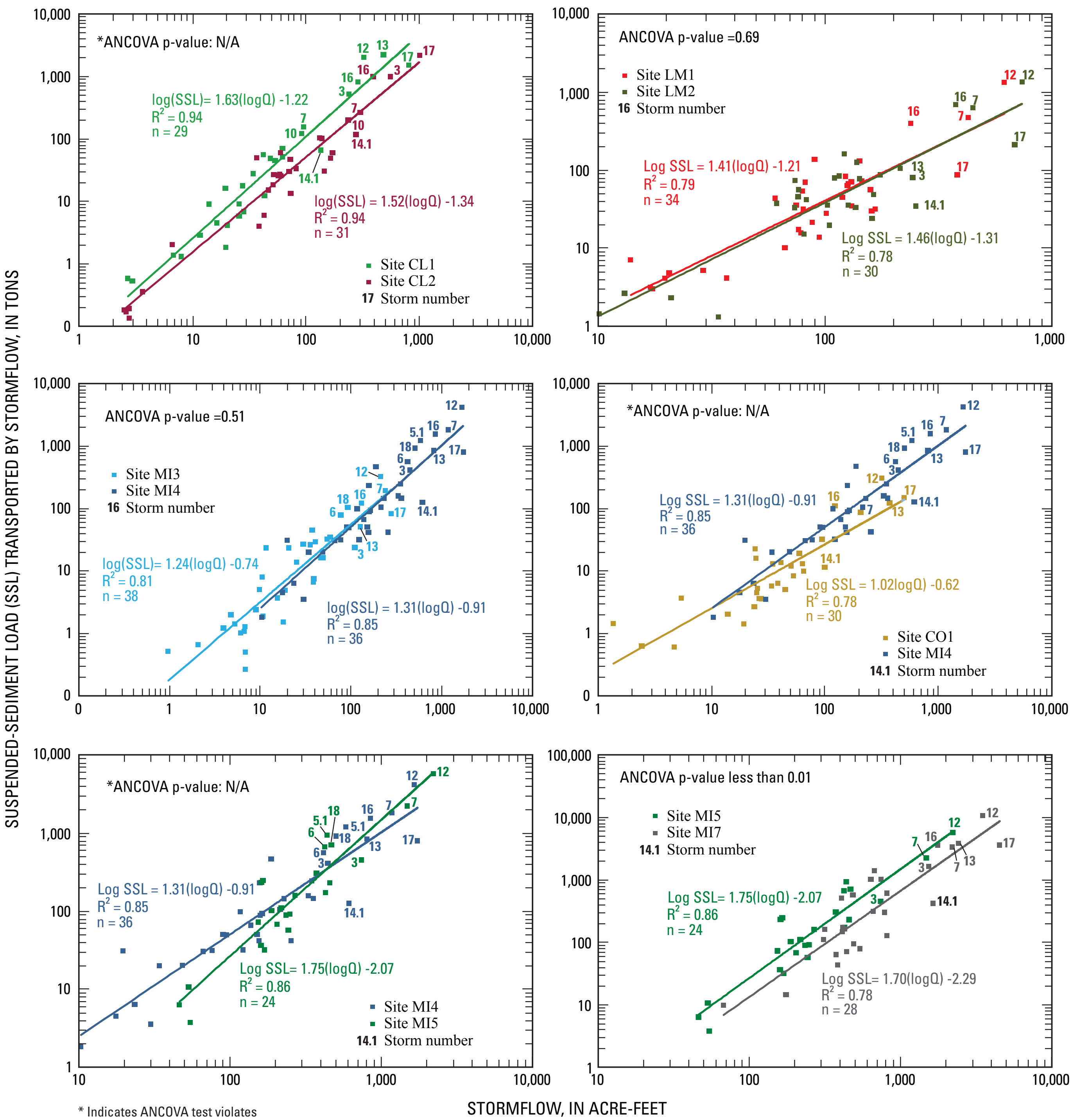


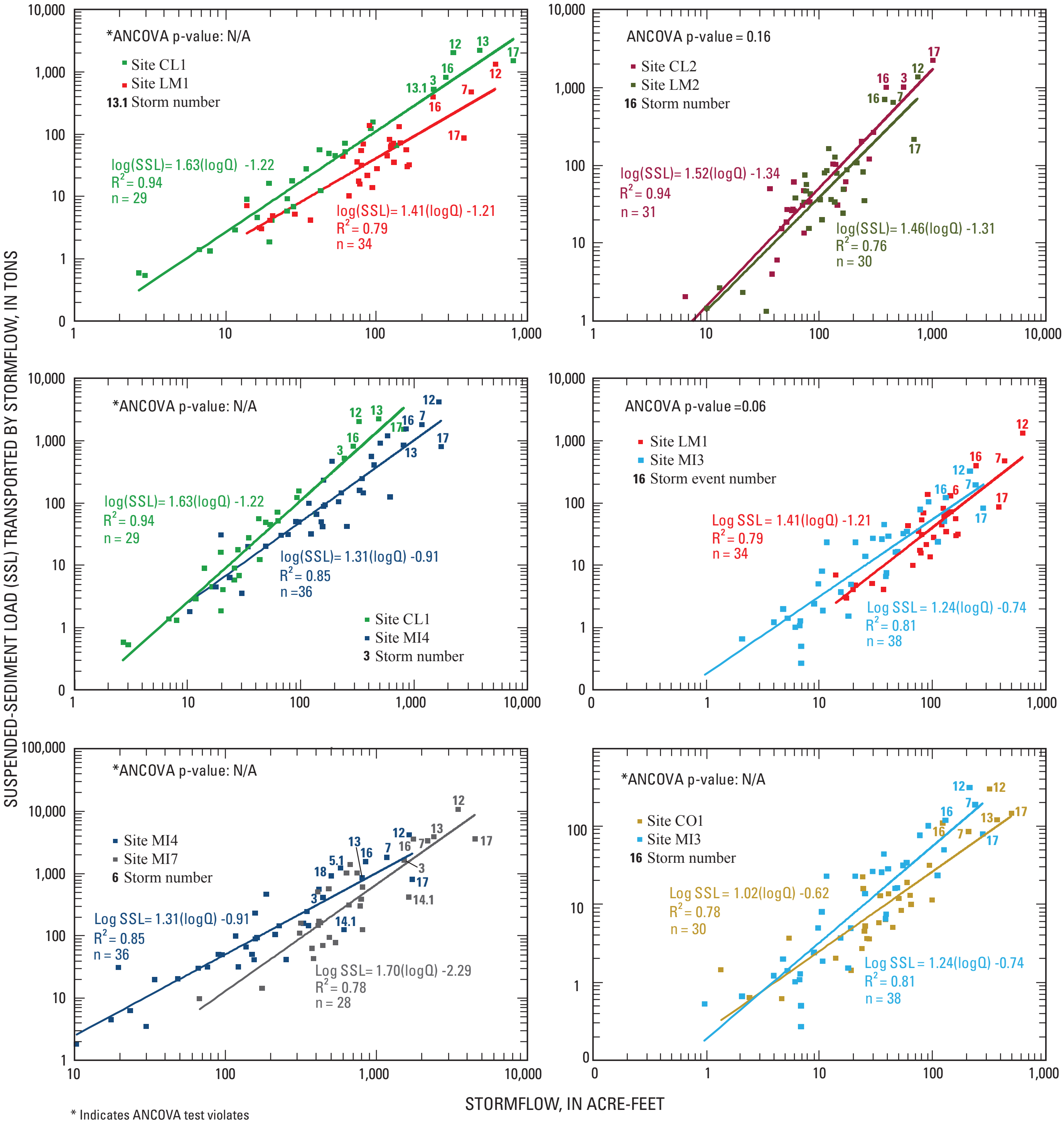
Figure 12. Comparison of time-series turbidity and streamflow data for sampling sites downstream from urban construction (sites CL1 and CL2) and urban land use (site LM1) during three storms in the Mill Creek watershed, August 2006, December 2006, and June 2007.



* Indicates ANCOVA test violates the assumption of homogeneity of regressions

N/A, not applicable; Q, streamflow, in cubic feet per second; R^2, coefficent of determination; n, number of storms

Figure 13. Suspended-sediment load (SSL) transported by stormflows for sampling sites immediately up or downstream, Mill Creek watershed, February 2006–June 2007.



* Indicates ANCOVA test violates the assumption of homogeneity of regressions

N/A, not applicable; Q, streamflow, in cubic feet per second; R^2, coefficent of determination; n, number of storms

Figure 14. Suspended-sediment load (SSL) transported by stormflows among different sampling sites, Mill Creek watershed, February 2006–June 2007.

Figure 15. Example of fine sediment deposition in the streambed between sites CL1 and CL2.

conversion (0.3677). SWSCs represent the average amount of sediment transported for a given volume of stormflow. SWSCs were larger at site CL1 compared to stormflow and sediment loads transported from between sites CL1 and CL2 for 17 of the 23 concurrently observed storms (fig. 16). Small (less than 100 acre-ft) storms in which more than 60 percent of the stormflow at site CL2 originated upstream from site CL1 resulted in negative SWSCs from the CL1–CL2 subwatershed, indicating possible net sediment deposition in the stream channel between the monitoring sites. Four of the storms (storms 4, 5, 10.2, and 17.1) with larger SWSCs between sites CL1 and CL2 were small (less than 100 acre-ft) and occurred when stormflow at site CL1 was less than half of that at site CL2. The other two storms with larger SWSCs between sites CL1 and CL2 occurred during the second smallest storm (15), in which SWSCs were similar between sites, and the largest storm (17), in which SWSCs were much larger between sites CL1 and CL2 despite more than 80 percent of the streamflow originating upstream from site CL1 (fig. 16). A larger SWSC from the watershed between CL1 and CL2 during storm 17 indicates that larger storms may transport sediment previously deposited in the streambed between sites CL1 and CL2.

Among sites within the same subwatershed, small storms at headwater sites (CL1, MI3, MI4, MI5) often had smaller stormflow volumes but similar sediment loads compared to sites immediately downstream (CL2, MI4, MI5, MI7; fig. 13). SWSCs were compared for storms at site MI4 and from the subwatershed between sites MI4 and MI7 to further examine flow conditions leading to sediment deposition between these sites (fig. 16). SWSCs were larger at site MI4 than from the subwatershed between sites MI4 and MI7 for 12 of the 17 smallest storms (less than 800 acre-ft), but were smaller than from the subwatershed between sites MI4 and MI7 for eight of the nine largest storms (more than 800 acre-ft). Small storms likely have small sediment delivery ratios, meaning that they erode sediment but lack the capacity for transport throughout larger, less sloping downstream channels. The sediment from these small storms is deposited in the stream channel and is likely available for transport during subsequent, larger storms with increased transport capacity. The only consecutive large

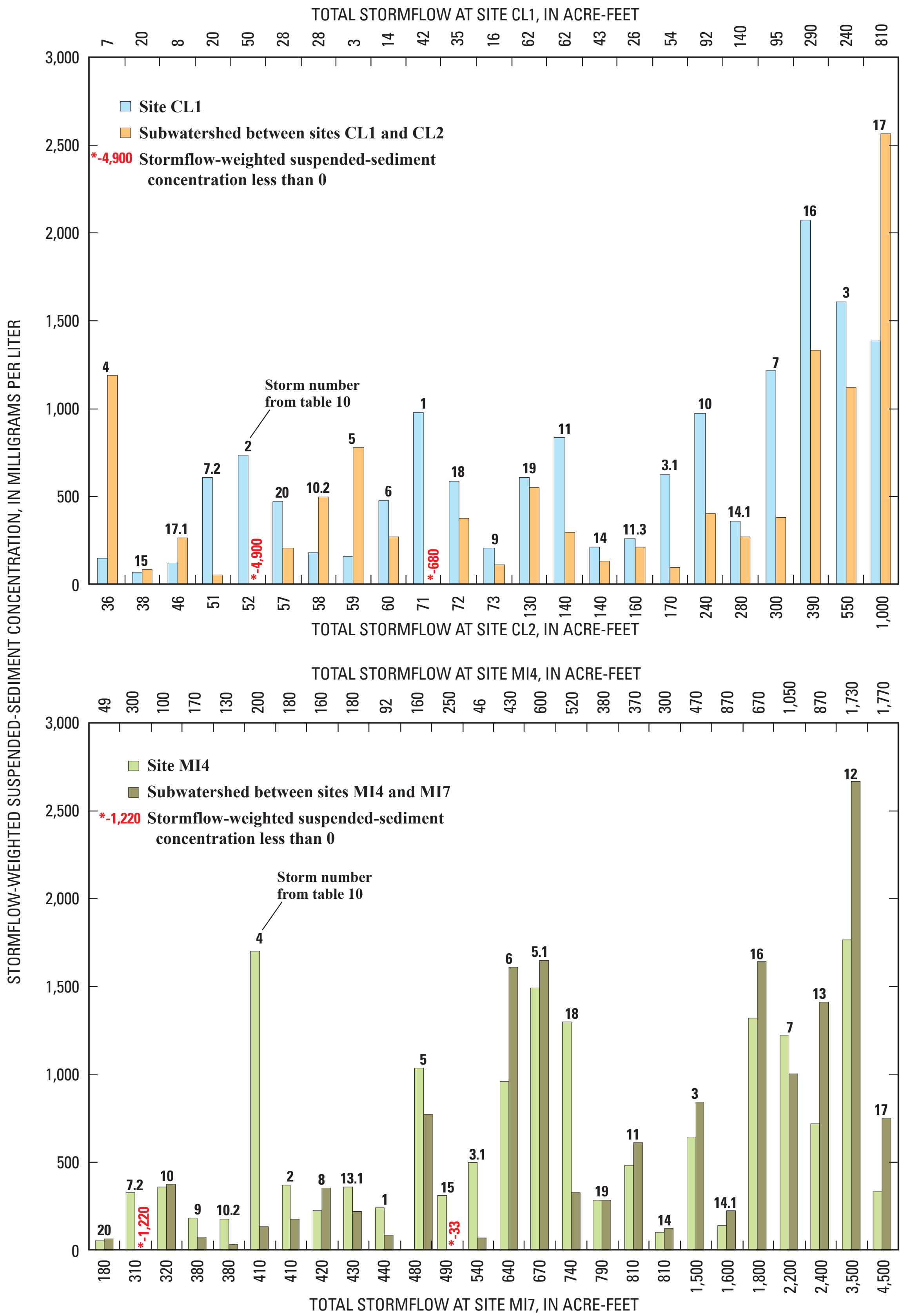


Figure 16. Stormflow-weighted suspended-sediment concentrations and stormflow volumes for storms observed at sampling sites CL1, MI4, between sites CL1 and CL2, and between sites MI4 and MI7, Mill Creek watershed, February 2006–June 2007.

storms (storms 16 and 17, table 9) observed during the study period generally had decreasing SWSCs (except at site CL2), likely because storm 16 transported easily movable, previously eroded (by small storms or anthropogenic activity) sediments deposited within watersheds and stream channels, decreasing the sediment available for transport by storm 17 (fig. 13).

Sediment loading/stormflow volume relations at site CL1 either had a statistically larger slopes (violating the ANCOVA assumption of homogeneity of regressions), or statistically larger y-intercept values for a given stormflow than other monitoring sites (p-value less than 0.05; figs. 13 and 14), likely because upstream construction increased the amount of sediment available for transport. Sediment loads transported at site MI3 had a larger slope for a given storm volume than at site CO1, despite similar magnitudes of watershed regulation (table 2). Decreased trapping efficiency at the older (established 1886–1914) Waterworks Lakes (upstream from site MI3) relative to Lake Lenexa (upstream from site CO1) likely resulted in larger sediment loads at site MI3, especially during larger storms (fig. 14).

Storms 12 and 17 were the largest in terms of total stormflow at all nine sampling sites but were different in terms of sediment transport. Storm 12 was the first large storm in 2007 (beginning February 28, 2007) and was the largest storm (in terms of stormflow volume) during the study period at three of the nine sites. Storm 17 began on May 6, 2007, and was the largest (in terms of stormflow volume) at six of the nine sampling sites. Although storm 17 generally transported more water, storm 12 transported more sediment at all sites (data for storm 12 were missing at site CL2, and data for storm 17 were missing at site MI5 because of sensor failure). Storm 12 was the first substantial rainfall after the winter and had among the most intense rainfall of storms at all sampling sites. Storm 17 was less intense than storm 12, occurred immediately after another large storm (16), and plotted beneath the stormflow/sediment load regression fit at all sites except site CL2 (fig. 13). Sediment deposited in the intermediate stream channel between sites CL1 and CL2 likely provided additional sediment sources for storm 17. Overbank sediment deposition did not affect comparisons of large storms between sites because peak-flow storms rarely exceeded bank-full height during the study period. Differences in sediment transport between storms 12 and 17 indicate that processes other than storm size play a substantial role in sediment transport.

Stormflow magnitude, storm intensity, and antecedent precipitation can affect sediment transport (Smith and others, 2003). Multiple-regression analysis was performed between sediment load, stormflow volume, and characteristics of precipitation intensity and antecedent conditions for storms at Mill Creek sites. Characteristics of storm intensity include maximum precipitation intensity over 5, 15, 30, and 60 minutes, and the total kinetic energy of rainfall (indicator of storm erodibility; Brown and Foster, 1987). Measures of antecedent conditions include the amount of precipitation in the prior 7 and 14 days, and the total sediment load transported in the past 15, 30, 60, and 90 days. Two to three of the storms at each site had no precipitation over the prior 3 days, and 0.001 in. was substituted for these storms. Antecedent conditions are not completely evaluated using discrete measurements of precipitation and sediment load as they do not account for the time-integrated nature of these processes.

All regression variables were log-transformed to approximate homoscedasticity in regression residuals. An example plot of partial residuals from site CL1 (fig. 17) indicates that residuals of stormflow volume, sediment transported in the past 60 days, and maximum 5-minute intensity generally were evenly distributed around the regression fit. Independent variables were added to regression equations if they significantly improved (p-value less than 0.05) the regression relation and if the resulting equation decreased the PRESS statistic, an indication that the independent variables added to the regression equation had the smallest amount of error when making new predictions (Helsel and Hirsch, 2002). Because of multicollinearity among measures of precipitation intensity and antecedent conditions, only one variable from each category that most improved the fit of the regression equation was included in the analysis; thus, a maximum of three independent variables (total flow, a measure of precipitation intensity, and measures of antecedent precipitation or sediment-load conditions) were included in the regression equations (table 10). Variance inflation factors among independent variables in regression relations were all less than 1.5, indicating that they generally were uncorrelated (Helsel and Hirsch, 2002).

Measures of precipitation intensity significantly improved relations between stormflow volume and sediment load among storms at eight of the nine sampling sites. Intense precipitation increases erosion from land surfaces, volume of overland flow, and the velocity of flow in rills, gullies, and stream channels. Multiple regression analysis indicated that increased recent sediment transport (in the past 60 days) significantly decreased sediment loads at two of nine sites; both sites with increased urban construction in the upstream watershed (sites CL1 and MI4). This finding indicates that large storms can diminish the amount of sediment available for transport by subsequent storms and that longer periods between large storms allow time for the regeneration of sediment supplies. Several natural processes likely regenerate sediment supplies between large storms. Sediments may be regenerated by small storms that erode sediment, but lack the capacity for downstream transport. Sediment deposited by these storms is subsequently transported by large storms with increased transport capacity. Sediment also may be regenerated by the destabilization of surface soils from freezing and thawing during winter months. Small storms and freeze/thaw processes likely affect sediment transport more at sites with less stable surface soils (such as construction sites). Redistribution of surface soils by construction activities also likely increase the mobility of surface sediments.

Measures of antecedent precipitation and sediment loading did not significantly affect sediment transport at site CL2 (which had the second-most amount of upstream construction) possibly because enough sediment has been deposited in the

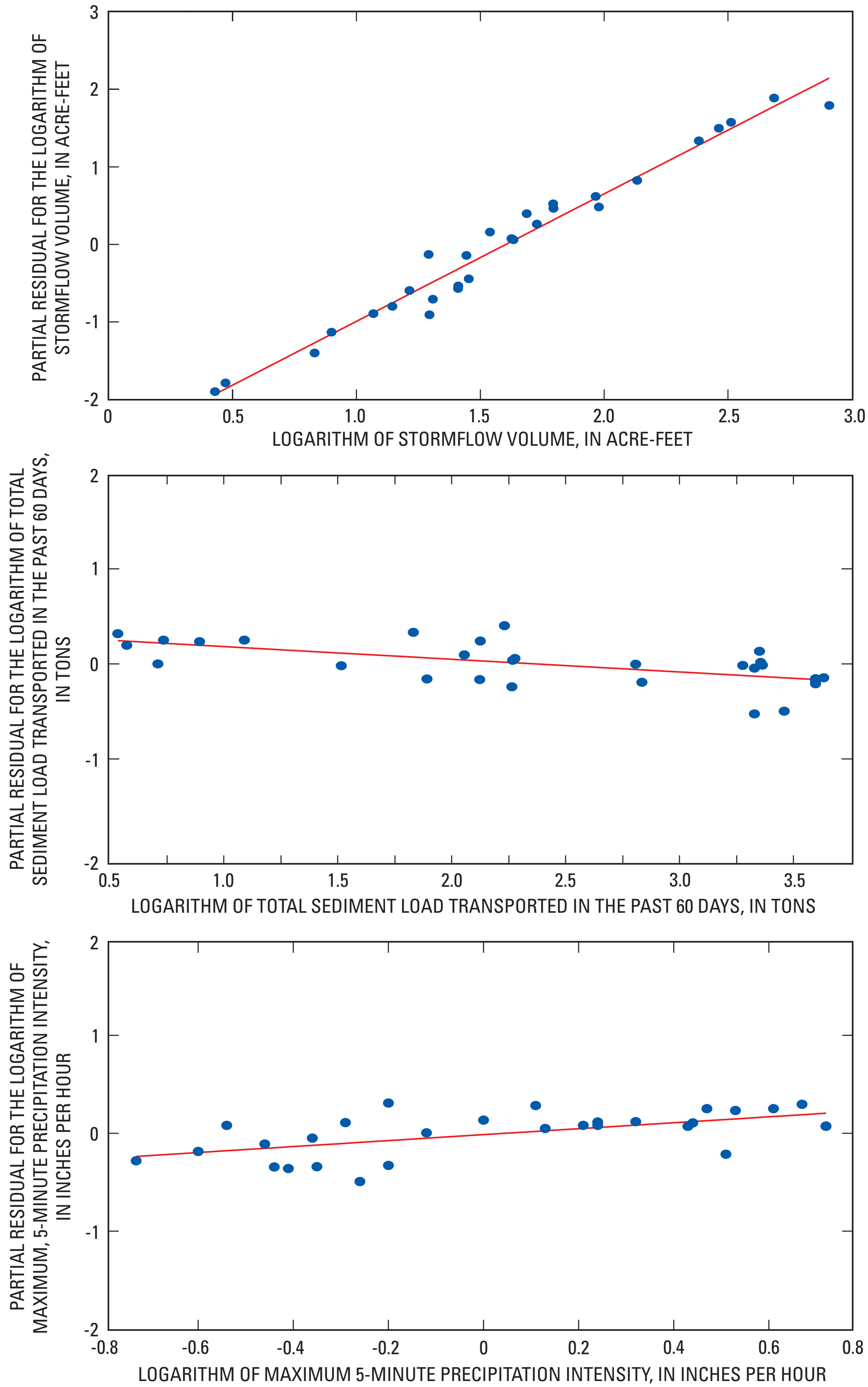


Figure 17. Partial residual plots of streamflow volume, precipitation intensity, and antecedent precipitation and sediment-load conditions for sampling site CL1, Mill Creek watershed, February 2006–June 2007.

Table 10. Multiple-regression relations between suspended-sediment load and stormflow magnitude, precipitation intensity, and antecedent precipitation and sediment-load conditions for Mill Creek sampling sites, Johnson County, northeast Kansas, February 2006–June 2007.

[Bold regression relations were used to estimate loads for storms at a site when storms were not observed at nearby sites to estimate missing record. SSL, suspended-sediment load transported by storm event, in tons; Qtotal, total stormflow, in acre-feet; P5, maximum precipitation intensity over 5 minutes, in inches per hour; P15, maximum precipitation intensity over 15 minutes, in inches per hour; P60 maximum precipitation intensity over 60 minutes, in inches per hour; Sed60, sediment load transported 60 days prior to storm, in tons; n, number of storms; R^2, coefficient of determination; RMSE, root mean squared error; PRESS, predicted residual sum of squares; VIF, variance inflation factor; <, less than]

Sampling site (fig. 1)	Regression relation	Number of independent variables	n	R^2	RMSE	PRESS statistic	p-value (significance level) of new independent variable	VIF between independent variables
CL1	**Log(SSL) = 1.63log(Qtotal) - 1.22**	1	29	0.94	0.27	2.26	<0.01	--
	Log(SSL) = 1.70log(Qtotal) - 0.14log(Sed60) - 1.00	2		.95	.23	1.72	<.01	1.12
	Log(SSL) = 1.64log(Qtotal) -0.13log(Sed60) + 0.30log(P5) -0.94	3		.97	.19	1.19	<.01	1.06 (Qtotal, P5); 1.00 (P5, Sed60)
CL2	Log(SSL) = 1.52log(Qtotal) - 1.34	1	31	.94	.27	2.33	<.01	--
	Log(SSL) = 1.50log(Qtotal) + 0.38log(P5) - 1.32	2		.96	.23	1.75	<.01	1.01
CO1	**Log(SSL) = 1.02log(Qtotal) - 0.62**	1	30	.78	.33	3.60	<.01	--
	Log(SSL) = 0.96log(Qtotal) + 0.51log(P15) - 0.48	2		.87	.26	2.23	<.01	1.03
LM1	Log(SSL) = 1.41log(Qtotal) - 1.21	1	34	.79	.30	3.15	<.01	--
	Log(SSL) = 1.26log(Qtotal) + 0.54log(P5) - 0.98	2		.89	.22	1.76	<.01	1.10
LM2	Log(SSL) = 1.46log(Qtotal) - 1.31	1	30	.78	.34	3.76	<.01	--
	Log(SSL) = 1.43log(Qtotal) + 0.52log(P5) - 1.31	2		.86	.27	2.59	<.01	1.00
MI3	Log(SSL) = 1.24log(Qtotal) - 0.74	1	38	.81	.36	5.13	<.01	--
MI4	**Log(SSL) = 1.31log(Qtotal) - 0.91**	1	36	.85	.31	3.69	<.01	--
	Log(SSL) = 1.18log(Qtotal) + 0.54log(P30) - 0.45	2		.90	.25	2.57	<.01	1.21
	Log(SSL) = 1.27log(Qtotal) + 0.55log(P15) - 0.19log(Sed60) - 0.10	3		.92	.23	2.22	<.01	1.10 (Qtotal, P15); 1.00 (Qtotal, Sed60); 1.00 (P15, Sed60)
MI5	**Log(SSL) = 1.75log(Qtotal) - 2.07**	1	24	.86	.28	2.03	<.01	--
	Log(SSL) = 1.71log(Qtotal) + 0.33log(P15) - 2.13	2		.89	.26	1.93	.04	1.03
MI7	**Log(SSL) = 1.70log(Qtotal) - 2.29**	1	28	.78	.36	3.85	<.01	--
	Log(SSL) = 1.50log(Qtotal) + 0.81log(P60) - 1.47	2		.88	.27	2.45	<.01	1.11

channel downstream from site CL1 so that sediment transport was never limited by available supply. Also, missing data at site CL2 during storms 12 and 13 may have obscured potential relations. Antecedent conditions did not have a significant effect on regression relations at the most urban sites (LM1, LM2, MI3) likely because impervious surfaces and stable surface vegetation limit erosion and because increased runoff and stream velocities efficiently transport sediment that reaches the stream. Thus, urban sites likely have decreased deposition of fine sediment in stream channels and decreased potential effects of antecedent conditions on sediment loads.

Total Sediment Load and Yield Among Subwatersheds

Estimation of Missing Values

Gaps occasionally occur in the continuous turbidity record because of environmental fouling or turbidity-sensor malfunction. When sensors malfunction during storms, sediment transport is unaccounted for, biasing computations of sediment load. Sediment loads are estimated for missing periods of record using stormflow/sediment-load relations from nearby sampling sites.

Although sediment loads varied among similar-sized storms, SWSCs were relatively consistent for the same storms at nearby sampling sites (fig. 18). Relations between SWSCs of nearby sites were constructed after omitting storms in which precipitation and streamflow were not evenly distributed throughout the watershed. Regression relations (after log transformation) between sites and bias correction factors were used to estimate SWSCs for missing storms (fig. 18, table 11). Estimated SWSCs (in mg/L) were multiplied by the total stormflow (in acre-ft) observed during the missing storm (and a unit conversion, 0.00136) to derive an estimate of suspended-sediment load (in tons). Because estimated sediment loads were calculated using the same storm from the upstream/downstream site, they should incorporate the individual characteristics (such as precipitation intensity and antecedent conditions) that affect storm sediment loads. SWSC data were generally evenly distributed around the log-linear fit, with the exception of SWSCs between sampling sites CL1 and CL2. As shown earlier, site CL1 generally had larger SWSCs than site CL2 during medium-sized storms but had more similar SWSCs to site CL2 during the largest storms (figs. 13 and 16). Although the relation between sites CL1 and CL2 underestimated the largest SWSC values, this underestimate inflated the bias correction upon retransformation, resulting in estimates of sediment load that appear reasonable compared to values observed at site CL1 (fig. 19). If storms were not observed at nearby sampling sites because of too little streamflow or malfunctioning sensors, stormflow/sediment loading relations were used to estimate sediment loading (table 10, 11).

The only sampling sites missing data for large enough storms to substantially bias computation of total sediment loads were sites CL2 (storms 12 and 13) and site MI5 (storms 13, 16, and 17, fig. 19). Sites CO1, MI4, and MI7 had complete turbidity data during all storms; estimated loads at sites CL1, LM1, LM2, and MI3 were less than 5 percent of the total sediment load. Because of the magnitude of storms missing from the turbidity record, 54 percent of the total sediment load at site CL2 and 21 percent of the sediment load at site MI5 were estimated (table 11). Because of missing data, total sediment loads computed for sites CL2 and MI5 have unknown uncertainty.

Comparisons of Total Sediment Load Among Sampling Sites

Sediment yield represents the total load normalized by upstream watershed area and is calculated by dividing sediment load (in tons) by subwatershed contributing drainage area (in square miles; table 12). Sediment loads and yields from February 2006 through June 2007 were calculated for each sampling site (table 12, fig. 20) and for subwatersheds between sampling sites by subtracting the total load of the downstream site from that observed at the upstream site (table 13, fig. 20). Because sediment is not transported conservatively through stream channels, loads and yields estimated from subwatersheds between monitoring sites do not represent the actual amount of sediment contributed from soils within that subwatershed. Loads and yields are calculated for intermediate subwatersheds only for comparison to those expected given subwatershed land-use practices and loads observed at up- and downstream sites. Smaller (or larger) than expected loads and yields from intermediate subwatersheds indicate sediment deposition (or resuspension) within a given subwatershed.

Figure 20 shows increases in sediment loads corresponding to increasing drainage area from the headwaters (near Olathe) to the farthest downstream (site MI7) site in the Mill Creek watershed. Because sediment load divided by watershed area is sediment yield, the slope of lines between sampling site is equal to the sediment yield from each subwatershed. The width of the line between each sampling site is set equivalent to the amount of new road construction during 2004–07 normalized by contributing drainage area (fig. 20). A line of organic correlation (LOC) is used to characterize the relation between road construction and sediment yield from watersheds upstream from Mill Creek sampling sites (fig. 21). LOC is used (as opposed to linear regression) in this instance because although linear regression produces the most accurate estimate of a particular dependent (y-axis) variable, LOC is the most appropriate method to characterize the relation between two variables (Hirsch and Gilroy, 1984).

Sediment yields generally decreased from headwater to downstream sites, corresponding to decreasing stream channel slopes (table 12; fig. 20). Sites downstream from urban construction generally had larger sediment yields (sites CL1, CL2, MI4; figs. 20 and 21). Site CL1 had the largest (1,440 ton/mi^2) yield of suspended sediment compared to other subwatersheds, corresponding to the largest increase in road

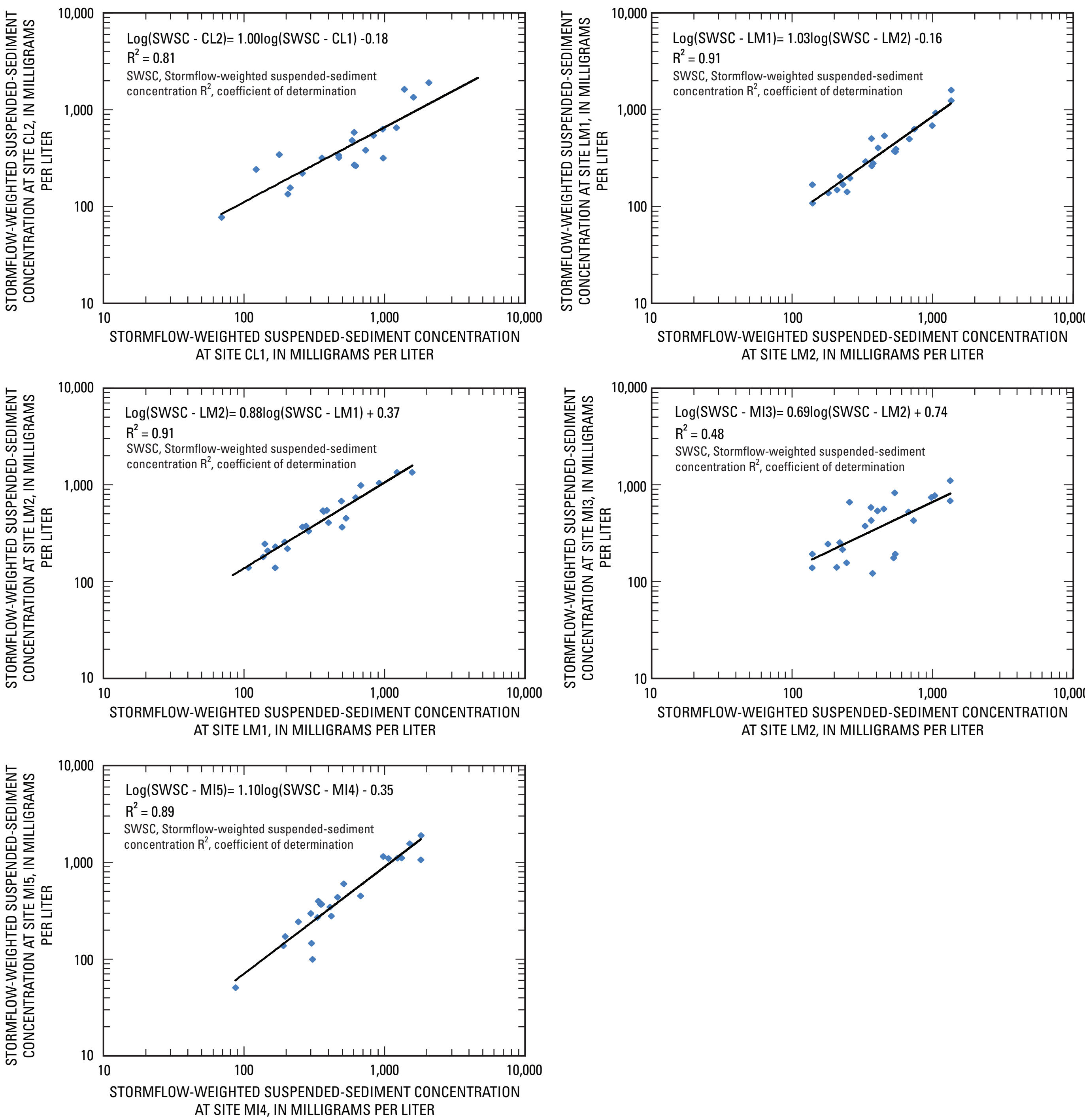


Figure 18. Relations between stormflow-weighted sediment concentrations for storms at up and downstream sampling sites, Mill Creek watershed, February 2006–June 2007.

Table 11. Periods of missing turbidity record, regressions used to estimate stormflow-weighted sediment concentration between sites, and the total estimated suspended-sediment load for Mill Creek sampling sites, Johnson County, northeast Kansas, February 2006–June 2007.

[*SWSC* stormflow-weighted sediment concentration in milligrams per liter; R^2, coefficient of determination; RMSE, root-mean squared error; Qtotal, total stormflow in acre-feet; SSL, suspended-sediment loading in tons; --, not applicable]

Sampling site identifier (fig. 1)	Water-shed drainage area (mi²)	Q/SSL regression relation/R^2	Duan's bias correction[1]	RMSE	Missing turbidity record for numbered storms (table 10)	Total estimated suspended-sediment load (tons)	Suspended-sediment load at up/downstream sampling site during same period (tons)	Suspended-sediment load with missing values (tons)	Total suspended-sediment load with estimated values (tons)	Percentage of load estimated
CL1	5.5	[2]Log (SSL) = 1.63log(Qtotal)-1.22 (0.94)	[2]1.18	[2]0.27	[2]14.2	[2]1.3	-- (CL2)	7,900	7,900	0
CL2	10.9	Log(*SWSC-CL2*) = 1.00log*SWSC-CL1* - .18 (.81)	1.49	.17	8 12 13 13.1	18 2,900 3,600 13	6.1 (CL1) 1,300 (CL1) 1,600 (CL1) 3.0 (CL1)	5,600	12,100	54
CO1	5.1	--	--	--	--	--	--	1,100	1,100	0
LM1	8.8	Log(*SWSC-LM1*) = 1.03log*SWSC-LM2* - 0.16 (.91)	1.02	.09	14.0 14.1	18 27	24 (LM2) 35 (LM2)	3,700	3,800	2.6
		[2]Log (SSL) = 1.41log(Qtotal)-1.21 (.79)	[2]1.26	[2].30	[2]14.2	[2]59	--			
LM2		Log(*SWSC-LM2*) = 0.88log*SWSC-LM1* + .37 (.91)	1.02	.09	4.0 4.1	140 3.7	140 (LM1) 4.9 (LM1)	4,600	4,800	4.2
	12.1	[2]Log (SSL) = 1.46log(Qtotal)-1.31 (.78)	[2]1.38	[2].34	[2]14.2	[2]50	--			
		Log(*SWSC-MI3*) = 0.69log*SWSC-LM2* +.74 (.48)	1.10	.21	14.0 14.1	8.2 24	42 (MI4) 130 (MI4)	1,400	1,400	0
MI3	2.8	[2]Log (SSL) = 1.24log(Qtotal)-.74 (.81)	[2]1.35	[2].36	[2]12.1 [2]14.2	[2]7.2 [2]9.1	-- --			
MI4	19.7	--	--		--	--	--	14,900	14,900	0
MI5	31.7	Log(*SWSC-MI5*) = 1.10log*SWSC-MI4* - .35 (.89)	1.04	.13	13 13.1 14 14.1 16 17	1,200 90 57 140 1,300 650	850 (MI4) 89 (MI4) 42 (MI4) 130 (MI4) 1,600 (MI4) 800 (MI4)	13,100	16,500	21
MI7	57.4	--	--		--	--	--	34,700	34,700	0

[1](Duan, 1983).

[2](Estimated from total streamflow/sediment load relation from table 10 if sensor malfunction or no storm observed at nearby site).

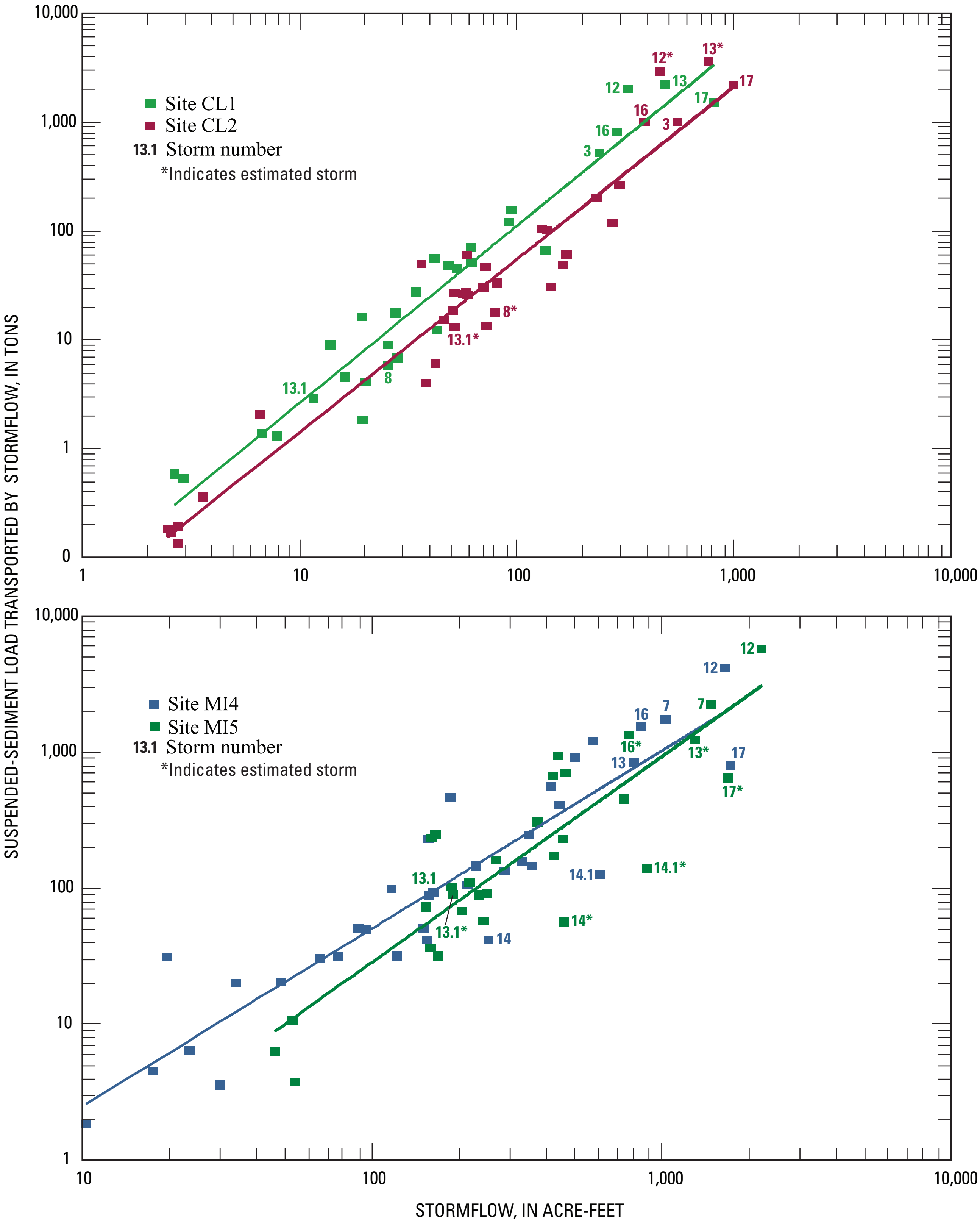


Figure 19. Estimated suspended-sediment loads for storms at sampling sites CL1, CL2, MI4, and MI5, Mill Creek watershed, February 2006–June 2007.

Table 12. Total stormflow and median annual suspended-sediment load and yield observed at Mill Creek sampling sites, Johnson County, northeast Kansas, February 2006–June 2007.

[mi^2, square miles; acre-ft, acre-feet; mg/L, milligrams per liter; ton/yr, tons per year; ton/mi^2/yr, tons per square miles per year]

Sampling site (fig. 1)	Contributing drainage area (mi^2)	Total stormflow (acre-ft)	Total suspended-sediment load (tons)	Stormflow-weighted suspended-sediment concentration (mg/L)	Total suspended-sediment yield (ton/mi^2)	Median annual suspended-sediment load (tons/yr)	Median annual suspended-sediment yield (tons/mi^2/yr)
CL1	5.5	3,500	7,900	1,660	1,440	5,500	1,000
CL2	10.9	7,100	12,100	1,250	1,110	8,700	780
CO1	5.1	3,900	1,100	210	220	770	150
LM1	8.8	7,200	3,800	390	430	3,000	340
LM2	12.1	7,500	4,800	470	400	3,600	300
MI3	2.8	3,800	1,400	270	500	1,100	390
MI4	19.7	16,000	14,900	680	760	11,200	570
MI5	31.7	19,300	16,500	630	520	13,500	430
MI7	57.4	35,100	34,700	730	600	25,900	450

Table 13. Subwatershed total stormflow and suspended-sediment load and yield calculated upstream from and between Mill Creek sampling sites, Johnson County, northeast Kansas, February 2006–June 2007.

[mi^2, square miles; () indicates value is negative]

Site(s) immediately upstream (fig. 1)	Downstream site	Drainage area between sampling sites (mi^2)	Subwatershed stormflow (acre-feet)	Subwatershed suspended-sediment load (tons)	Subwatershed suspended-sediment yield (tons/mi^2)
--	CL1	5.5	3,500	7,900	1,440
CL1	CL2	5.4	3,600	4,200	780
--	CO1	5.1	3,900	1,100	220
--	LM1	8.8	7,200	3,800	430
LM1	LM2	3.3	300	1,000	300
--	MI3	2.8	3,800	1,400	500
MI3	MI4	16.9	12,200	13,500	800
CO1, MI3, MI4	MI5	6.9	(600)	500	70
CL2, LM2, MI5	MI7	2.7	1,200	1,300	480

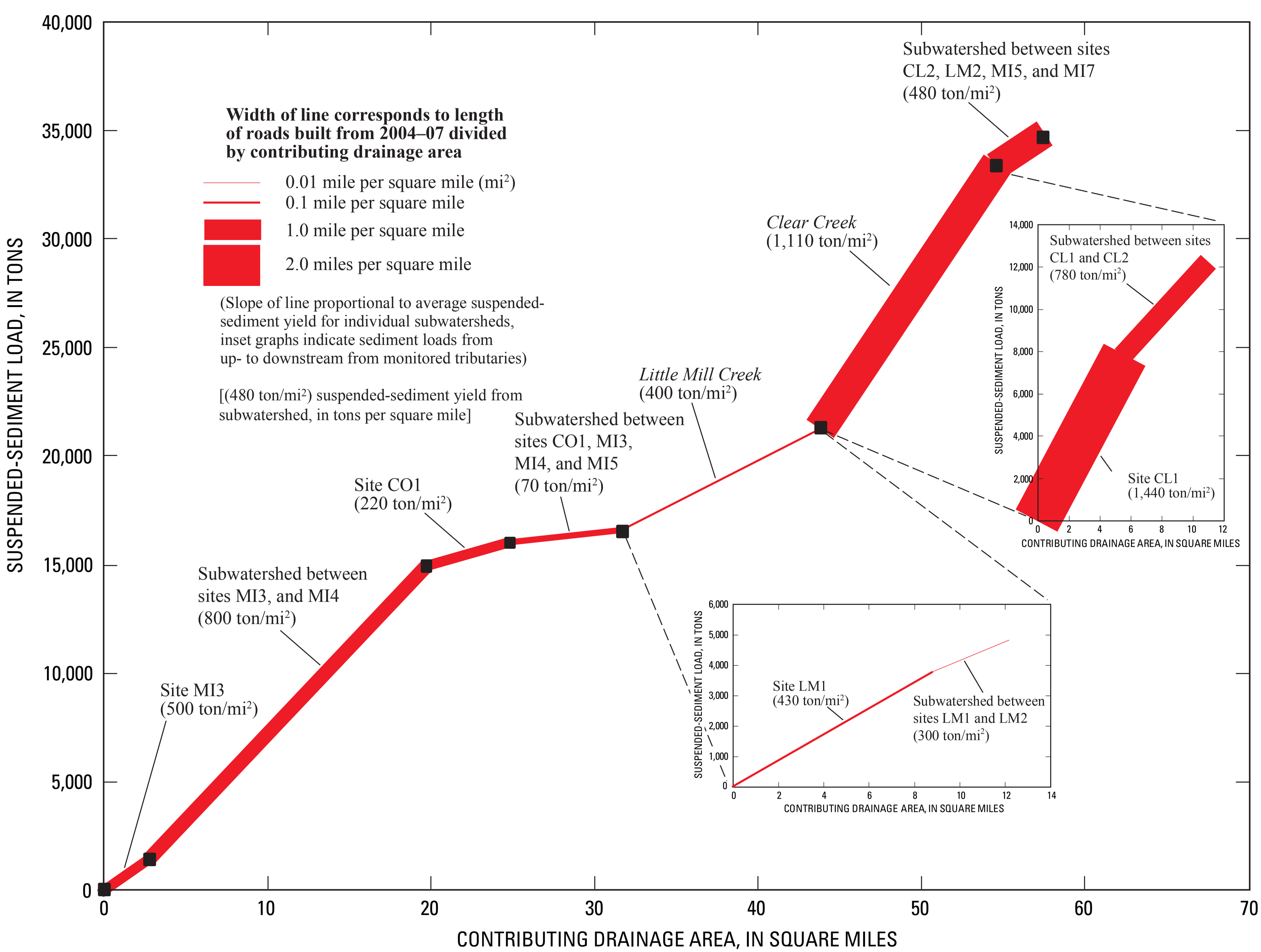


Figure 20. Sediment loads, yields, and road construction from individual subwatersheds, up- to downstream, in the Mill Creek watershed, February 2006–June 2007.

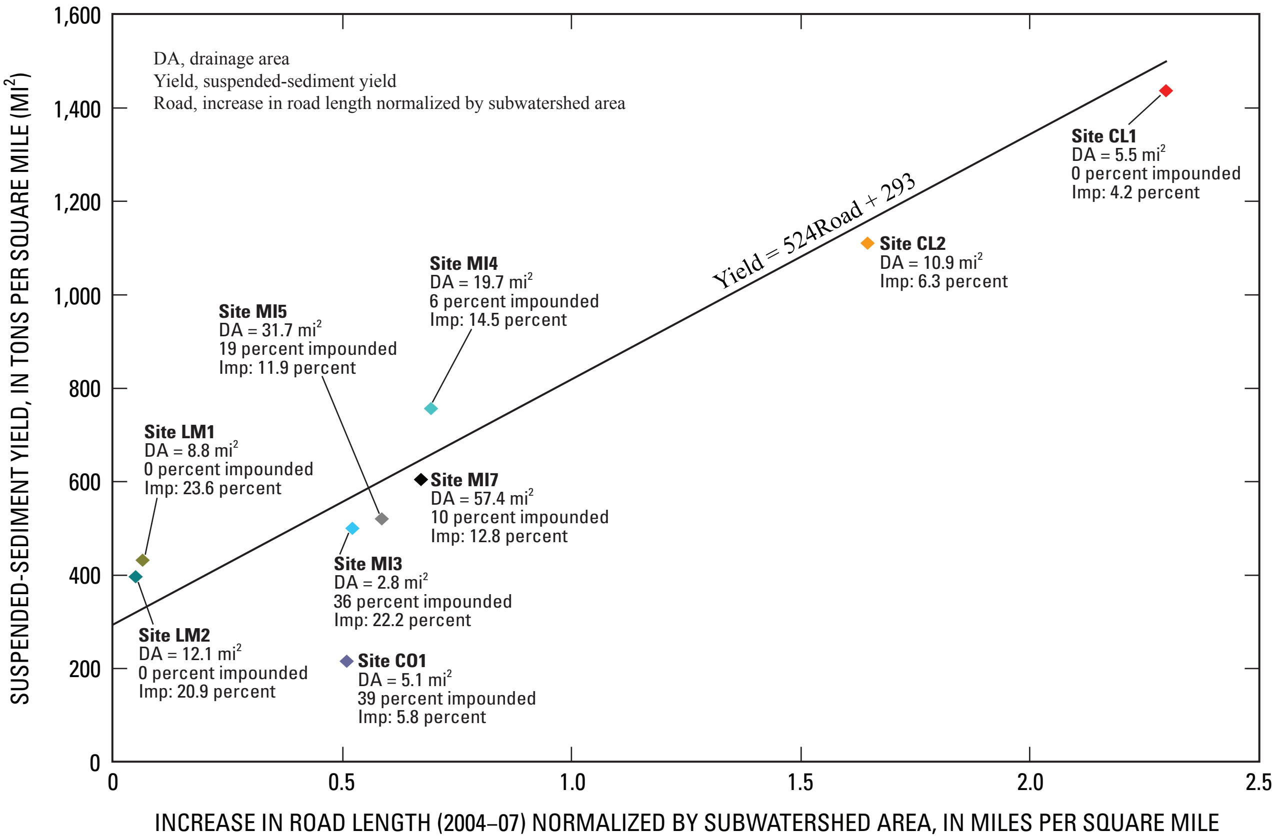


Figure 21. Relation between suspended-sediment yield and increase in new road length (2004–07) normalized by subwatershed area, Mill Creek sampling sites, February 2006–June 2007.

length per contributing drainage area (2.3 mi/mi^2; figs. 20 and 21) of sampling sites. Watersheds upstream from sites CL2 (including upstream from site CL1; 1,110 ton/mi^2; table 12) and MI4 (including upstream from site MI3; 760 tons/mi^2; table 12) had the second and third largest sediment yields and also underwent the most road building during 2004–07 (site CL2, 1.6 mi/mi^2; site MI4, 0.7 mi/mi^2; fig. 21, table 12). Watersheds upstream from urban sites LM1 (0.1 mi/mi^2) and LM2 (including upstream from site LM1; 0.1 mi/mi^2) had the smallest change in road length and the second (site LM2, 400 ton/mi^2; table 12) and third (LM1, 430 ton/mi^2; table 12) smallest sediment yields. Site CO1 had the smallest sediment yield of headwater sites (220 ton/mi^2) likely because of sediment deposition into Lake Lenexa. Downstream sites CL2, LM2, and MI5 had smaller sediment yields than sites immediately upstream (sites CL1, LM1, and MI4), likely because decreasing channel slopes encourage deposition of suspended sediment prior to transport past downstream sampling sites.

Because estimated storms accounted for 54 percent of the sediment load at site CL2, estimates of sediment load/deposition from the intermediate subwatershed are subject to increased error. Although analysis of individual storms indicated sediment deposition during smaller storms, sediment yield estimated from the subwatershed between sites CL1 and CL2 (780 ton/mi^2) and new road construction (1.0 mi/mi^2) are each approximately one-half of that observed at site CL1 (1,440 ton/mi^2; 2.3 mi/mi^2) (tables 3 and 13; fig. 21). Although the sediment yield estimated at site CL2 seems reasonable given the magnitude of construction, visual assessments underneath the bridge at site CL2 and just upstream indicated fine material deposited in channel pools after storms. Sediments deposited upstream from site CL2 are likely more efficiently transported during large storms. Because of this, sediment loads and yields at site CL2 may have increased relative to site CL1 if larger storms were observed during the study period.

The smallest subwatershed sediment yield was estimated between sites MI4 and MI5 (70 ton/mi^2) likely because: (1) 42 percent of the subwatershed is impounded by Shawnee Mission Lake, (2) large sediment loads from the upstream site (MI4) and decreased stream channel slopes between sites MI4 and MI5 encourage sediment deposition, and (3) negative stormflow volume computed from this subwatershed (table 13), which may be caused by lake evaporation, loss of stormflow to ground water, and (or) potential bias in comparisons of streamflow between site MI5 and upstream sites CO1 and MI4. Sediment yields were only slightly decreased from site LM1 (430 ton/mi^2) to the subwatershed between sites

LM1 and LM2 (300 ton/mi^2; table 13) likely because increased flow velocities (resulting from large areas of impervious surface) efficiently transport sediment reaching the stream and because small sediment loads decrease the potential for sediment deposition in the stream channel.

Comparison of Sediment Loads Across Johnson County

Total stormflow and suspended-sediment loads and yields from the Mill Creek sampling sites were compared to sampling sites operated in four other watersheds (Blue River at Kenneth Road, BL5; Cedar Creek near DeSoto, CE6; Indian Creek at State Line Road, IN6; and Kill Creek at 95th Street, KI6b) in Johnson County from February 2006 through June 2007 (Rasmussen and others, 2008). These sites were monitored for purposes of estimating constituent loads from the downstream-most location of the five largest watersheds (Blue River, Cedar Creek, Indian Creek, Kill Creek, and Mill Creek) in Johnson County. Regression relations between turbidity and suspended-sediment concentration were used from a previous study of these sites (Rasmussen and others, 2008), and any periods of missing record or turbidity truncation were estimated using methods described in “Estimating periods of turbidity truncation” and “Estimation of missing values” sections within this report. Sediment loads increased from 19.3 (Kill Creek) to 0.3 (Cedar Creek) percent after estimation of missing and truncated data (table 14). Land use is largely grass/cropland in the Kill Creek watershed, grass/crop/forestland in Cedar Creek (with urban construction ongoing in eastern parts of the watershed), and grass/cropland in the Blue River watershed (with urban construction in the northern part of the watershed) (Johnson County Automated Information Mapping System, written commun., 2006; K. Skridulis, Johnson County Appraiser’s Office, written commun., 2008). The majority of the Indian Creek watershed is urbanized, with older urban areas in the northern part of the watershed, and newer urban areas and urban construction in the southern part (fig. 1, tables 3 and 14; Lee and others, 2005; Rasmussen and others, 2008).

Because of increased impervious surface upstream from the Indian Creek site (IN6, 23.5 percent), stormflow volume was nearly double that of other large Johnson County sampling sites (table 14, fig. 22). Sediment yield from the Indian Creek watershed (site IN6; 1,310 ton/mi^2) was more than double that of the other large watersheds and was much larger than yields from smaller subwatersheds in Mill Creek with similar percentages of impervious surface (site LM1, 23.6 percent, 430 tons/mi^2; site MI3, 22.2 percent, 500 ton/mi^2) (tables 12 and 14). Sediment yield from the Blue River (monitoring site BL5; 620 ton/mi^2) was similar to that from Mill Creek (sampling site MI7; 600 ton/mi^2) despite less road construction per contributing drainage area. Stormflow and sediment yield was smaller from Cedar Creek (sampling site CE6; 470 ton/mi^2) compared to Indian and Mill Creek, despite similar levels of road construction. Sediment yield was the smallest from the primarily rural Kill Creek (sampling site K16b; 320 ton/mi^2).

Although additional stormflow increases the sediment-transport capacity of Indian Creek relative to other sampling sites in Johnson County (Rasmussen and others, 2008), observed loads originate from specific source areas. Road (and building) construction in the Indian Creek watershed is similar to that of the Mill Creek watershed, and thus current construction cannot account for the magnitude of sediment loading observed at the Indian Creek sampling site. Because the extent of urban development in the Indian Creek watershed (23.5 percent impervious upstream from sampling site IN6) is nearly double that of the Mill Creek watershed (12.8 percent impervious upstream from sampling site MI7), it may indicate that peak downstream sediment transport lags soil disturbance from urban construction by years or decades. Increased flow into the Indian Creek channel may increase channel-bank and streambed erosion and (or) more efficiently transport sediment from existing construction activities, such as channel disturbance during bridge renovation or residential and commercial construction in the headwater parts of the Tomahawk Creek (southern tributary of Indian Creek) watershed. The implication of this finding is that sediment loads in developing basins (such as Blue River, Cedar and Mill Creek) will likely continue to increase even after the majority of construction is complete. However, because Indian Creek has far fewer small (less than 30 acre) and no large surface-water impoundments that act to trap suspended sediment, sediment yields in developing basins may not reach that of Indian Creek (Lee and others, 2005; table 2).

Differences observed in sediment yields among Blue River, Cedar Creek, and Mill Creek likely are related to the timing and location of urban construction relative to sampling sites. In the smaller Mill Creek subwatersheds (0–10 mi^2), changes in sediment transport were observed in response to recent (2004–07) changes in land use. Soil disturbance near streams and sampling sites likely results in more immediate sediment transport, whereas construction far from stream channels and (or) sampling sites may not be observed for years or decades. Urban construction in the Cedar Creek watershed is concentrated in the southeastern part of the watershed, relatively distant from larger streams and the downstream sampling site (fig. 1). Construction in the Blue River watershed is concentrated along an unmonitored tributary in the northern part of the watershed and along the Coffee Creek tributary in the main watershed. Construction near a large tributary may allow for more rapid transport of sediment to site BL5 and thus larger sediment yields relative to Cedar Creek.

Table 14. Total stormflow and suspended-sediment load and yield at Mill Creek sampling sites and additional Johnson County sampling sites, northeast Kansas, February 2006–June 2007.

[mi², square miles; acre-ft, acre-feet; acre-ft/mi², acre-feet per square mile; ton/mi², ton per square mile]

Sampling site (fig. 1)	Estimated drainage area (mi²)	Total stormflow (acre-ft)	Stormflow yield (acre-ft/mi²)	Suspended-sediment load (tons)	Suspended-sediment yield (tons/mi²)	Stormflow-weighted sediment concentration (milligrams per liter)	Percentage of sediment load estimated during periods of sensor truncation or failure
Mill Creek sampling sites							
CL1	5.5	3,500	630	7,900	1,440	1,660	19.0
CL2	10.9	7,100	650	12,100	1,110	1,250	54.5
CO1	5.1	3,900	770	1,100	220	210	9.1
LM1	8.8	7,200	820	3,800	430	390	15.8
LM2	12.1	7,500	620	4,800	400	470	10.4
MI3	2.8	3,800	1,360	1,500	500	290	6.7
MI4	19.7	16,000	810	14,900	760	690	12.8
MI5	31.7	19,300	610	16,500	520	630	27.9
MI7	57.4	35,100	610	34,700	600	730	1.7
Additional Johnson County sites sampled during study period							
BL5	65.7	35,000	530	40,700	620	860	1.7
CE6	58.5	30,900	530	27,300	470	650	.3
IN6	63.1	65,200	1,040	82,700	1,310	930	6.1
KI6b	48.6	20,700	430	15,500	320	470	19.3

Characterization of Suspended-Sediment Sources

Surface soil, stream-channel banks, streambed sediments, and suspended sediment were analyzed for trace elements, nutrients, carbon, and radionuclides in an attempt to characterize predominant source areas of suspended sediment in the Mill Creek watershed (table 15). Results from surface-soil and channel-bank samples were compared to identify constituents with significant differences in concentration or radiochemical activity between the two source types. Constituents with significant differences between source types were then evaluated with the intention of attributing suspended sediments to surface soil or channel-bank sources (Walling, 2005).

Trace element concentrations in sediment samples were less than applicable probable-effect concentrations (PECs); concentrations above which a particular constituent shows a statistical relation to adverse biological effects (table 15; MacDonald and others, 2000). Measured concentrations of 25 of 31 constituents had larger median concentrations in suspended-sediment samples than in surface-soil or channel-bank samples (table 15). Because of increased-surface area available for adsorption, smaller grained sediments commonly have larger concentrations of constituents compared to larger-grained sediments (Horowitz, 1991). Median values of the mean grain-size distribution were smaller (11.7 µm) in suspended-sediment samples than surface soil (18.6 µm) or channel bank samples (18.7 µm) (table 15). Results of grain size and trace-element analyses indicate that the erosion, transport, and deposition of surface soil and channel-bank material result in smaller-grained suspended sediment. Streambed-sediment samples consisted of larger-sized sediment compared with suspended sediment, and typically had smaller concentrations and activities of analyzed constituents.

Non-parametric Mann-Whitney U tests were used to determine constituents with significant (p-value <0.05) differences between surface-soil and channel-bank samples. Cobalt, nitrogen, selenium, sulfur, total organic carbon, ^{137}Cs, and “excess” ^{210}Pb had statistically significant differences in median concentrations or activities between surface-soil and channel-bank sources (table 15, fig. 22). Values less than the laboratory reporting level were ranked as ties, and assigned the median rank of the number of nondetects (that is, if there were 6, all were ranked as 3.5) (Helsel, 2005). All of these constituents were larger in surface-soil than channel-bank samples except cobalt, which had slightly larger concentrations in channel banks. Although ^{7}Be is deposited on surface soils by atmospheric deposition, activities in surface soils were less than laboratory reporting levels.

Differences in grain-size between surface soils, channel-bank, and suspended-sediment samples were compared to

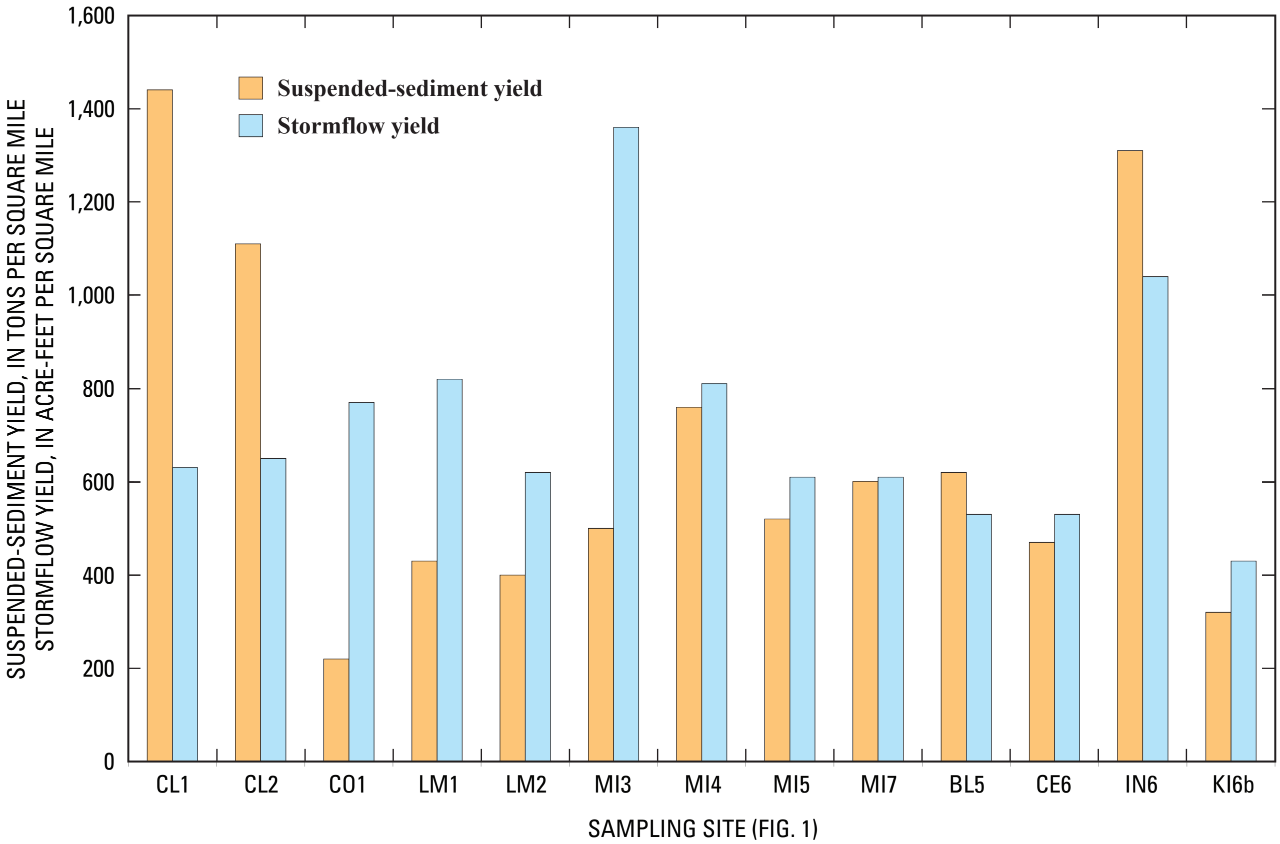


Figure 22. Stormflow and sediment yield compared for Mill Creek and other Johnson County sampling sites, February 2006–June 2007.

correct for bias created by the selection of smaller-sized sediments during erosion and transport processes. A grain-size correction factor was calculated for each suspended-sediment sample by dividing the mean grain-size diameter of the suspended-sediment sample by the mean grain-size of all surface-soil and channel-bank samples. Grain size corrections ranged from 1.14 to 0.29 that of the original constituent value, with a median of 0.63. These corrections were then multiplied by the concentration (or activity) of constituents in each suspended-sediment sample. After application of the grain-size correction, results from constituents with significant differences among source types were compared with results from suspended sediment samples (fig. 23).

Although statistically significant differences were observed in selected constituents among surface-soil and channel-bank samples, variability was observed among samples in different parts of the study area (fig. 23). Concentrations of constituents collected in the Clear Creek surface soils were typically less than those in Little Mill and Mill Creek samples, notably for nitrogen, total organic carbon, excess ^{210}Pb, and ^{137}Cs. Because of more recent urban construction in the Clear Creek watershed, surface soils in the Little Mill and Mill Creek have had more exposure to constituents contributed from atmospheric sources, and thus larger concentrations and activities of these constituents than soils redistributed by urban construction. Because of decreased constituent concentrations in Clear Creek surface soils, estimates of surface-soil contributions using data collected across the entire Mill Creek watershed would underestimate contributions from surface soils in the Clear Creek watershed.

Although concentrations of cobalt and selenium were significantly different among source types, differences in median concentrations were at, or near variability observed within duplicate and replicate analyses (tables 4, 15). In addition, substantial variability was observed within source types for all six constituents, particularly in analyses in surface soils (fig. 23). Variability in constituent concentrations among sites and source types precluded accurate characterization of suspended-sediment source.

Although constituent concentrations and activities were corrected for potential grain-size effects, concentrations and activities in suspended-sediment samples were often larger or smaller than those in surface-soil or channel-bank samples (fig. 23, table 15). This was particularly true for excess ^{210}Pb analyses, in which nearly all of the results from grain-size corrected samples were greater than either surface-soil or channel-bank samples. If excess ^{210}Pb is used exclusively to

Table 15. Statistical summary of particle size, trace element, nutrient, and carbon concentrations, and radionuclide activities in surface-soil, channel-bank, suspended-sediment, and streambed-sediment samples collected from the Mill Creek watershed, Johnson County, northeast Kansas, 2006–2007.

[mg/kg, milligrams per kilogram; dpm/g, disintegrations per minute per gram; n, number of samples collected; PEC, probable effect concentration; µm, micrometer; LRL, laboratory reporting level; <, less than; --, not applicable]

Constituent	Laboratory reporting level	Surface-soil samples (mg/kg) n = 9			Mann Whitney U[1]	Channel-bank samples (mg/kg) n = 9			Suspended-sediment samples (mg/kg) n = 48			Streambed-sediment samples (mg/kg) n = 4			PEC (MacDonald and others, 2000)
		Median	Maximum	Minimum		Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	
Particle-size diameter (µm)															
Average diameter of less than 63 µm sediment	--	18.6	22.0	16.7	--	18.7	21.3	16.2	11.7	21.22	5.39	16.43	18.74	12.04	--
Trace elements															
Aluminum	1 mg/kg	59,000	70,000	53,000	43	60,000	77,000	58,000	69,000	88,000	57,000	57,500	59,000	57,000	--
Antimony	.1 mg/kg	1.0	1.2	.9	29	.9	1.10	.9	1.10	1.7	.80	.9	.9	.9	--
Arsenic	.1 mg/kg	8.2	11.0	6.7	38	8.5	11	6.3	10	14	8	8.5	8.6	7.5	33
Barium	1 mg/kg	610	840	560	46	680	690	580	670	750	570	655	670	620	--
Berlyllium	.1 mg/kg	1.6	2.0	1.3	45	1.6	2.2	1.5	2.0	2.6	1.6	1.7	1.7	1.6	--
Cadmium	.1 mg/kg	.30	.40	.10	38	.2	.6	.2	.60	1.2	.30	.5	.6	.4	4.96
Chromium	1 mg/kg	58	74	44	40	57	93	52	73	97	60	61	62	58	111
Cobalt	1 mg/kg	9.2	12	6.8	[1]68	11	16	8.7	13	16	10	12	13	10	--
Copper	1 mg/kg	17	27	15	51	18	22	17	27	43	21	19	20	17	149
Iron	1,000 mg/kg	25,000	32,000	21,000	46	27,000	34,000	21,000	33,000	43,000	26,000	26,500	27,000	24,000	--
Lead	1 mg/kg	22	65	18	31	20	55	17	28	54	21	23	23	21	128
Lithium	1 mg/kg	30	45	24	40	30	46	25	39	63	31	30	30	28	--
Manganese	10 mg/kg	540	700	410	62	670	1,100	500	1,000	2,000	660	710	810	560	--
Molybdenum	1 mg/kg	1.1	1.5	.74	18	.84	1.0	.75	1	4	<LRL	.9	.9	.8	--
Nickel	1 mg/kg	24	31	18	47	25	41	21	33	43	26	28	29	24	49
Selenium	.1 mg/kg	.5	1.2	.40	[1]8.5	.40	.50	.30	.7	1.4	.2	.4	.4	.4	--
Silver	.5 mg/kg	<LRL	<LRL	<LRL	--	<LRL	<LRL	<LRL	<LRL	.8	<LRL	<LRL	<LRL	<LRL	--
Strontium	1 mg/kg	130	240	110	40	130	140	120	160	210	130	140	140	140	--
Sulfur[2]	1,000 mg/kg	260	420	170	[1]2	160	200	120	555	1,400	310	395	470	310	--
Thallium	50 mg/kg	<LRL	<LRL	<LRL	--	<LRL	<LRL	<LRL	<LRL	<LRL	<LRL	<LRL	<LRL	<LRL	--
Tin	.1 mg/kg	2.2	3.4	1.6	30	2.1	3.0	1.1	2.3	4.2	1.2	.9	.9	.9	--
Titanium	50 mg/kg	4,000	4,500	3,400	37	3,900	4,900	3,700	4,800	4,800	3,800	4,200	4,200	4,100	--

Table 15. Statistical summary of particle size, trace element, nutrient, and carbon concentrations, and radionuclide activities in surface-soil, channel-bank, suspended-sediment, and streambed-sediment samples collected from Mill Creek watershed, Johnson County, northeast Kansas, 2006–2007.—Continued

[mg/kg, milligrams per kilogram; dpm/g, disintegrations per minute per gram; n, number of samples collected; PEC, probable effect concentration; µm, micrometer; LRL, laboratory reporting level; <, less than; --, not applicable]

Constituent	Laboratory reporting level	Surface-soil samples (mg/kg) n = 9			Mann Whitney U[1]	Channel-bank samples (mg/kg) n = 9			Suspended-sediment samples (mg/kg) n = 48			Streambed-sediment samples (mg/kg) n = 4			PEC (MacDonald and others, 2000)
		Median	Maximum	Minimum		Median	Maximum	Minimum	Median	Maximum	Minimum	Median	Maximum	Minimum	
Trace elements—Continued															
Total organic carbon	1,000 mg/kg	15,000	20,000	6,000	[1]13	9,000	12,000	7,000	16,000	36,000	10,000	8,000	10,000	8,000	--
Uranium	.05 mg/kg	<LRL	<LRL	<LRL	--	<LRL	<LRL	<LRL	<LRL	<LRL	<LRL	<LRL	<LRL	<LRL	--
Vanadium	1 mg/kg	78	88	65	38	78	100	73	100	150	76	82	83	80	--
Zinc	1 mg/kg	82	120	62	39	78	140	71	160	320	110	99	110	90	459
Nutrients															
Nitrogen	100 mg/kg	2,000	2,000	800	[1]10	900	1,000	700	1,900	4,000	1,200	1,100	1,300	1,100	--
Phosphorus	100 mg/kg	560	650	390	28	510	540	460	890	1300	590	645	710	510	--
Carbon															
Total carbon	1,000 mg/kg	16,000	26,000	7,000	[1]10	10,000	13,000	7,000	22,000	42,000	11,000	12,500	14,000	12,000	--
Radionuclides															
^{7}Beryllium	.04 dpm/g	<LRL	<LRL	<LRL	--	<LRL	<LRL	<LRL	23.5	76.3	8.4	1.0	1.5	.7	--
^{137}Cesium	.07 dpm/g	.29	.44	<LRL	[1]14	<LRL	.15	<LRL	<LRL	.19	<LRL	<LRL	.1	.1	--
"Excess" ^{210}Lead	.07 dpm/g	1.84	3.39	.78	[1]6	.48	1.18	.02	7.4	21.9	2.6	1.4	2.1	1.1	--

[1]Indicates a statistically significant difference (p-value less than 0.05) between surface-soil and channel-bank samples as determined from the nonparameteric Mann Whitney test (Helsel and Hirsch, 2002).

[2]Sulfur was only analyzed in 12 of the 48 suspended-sediment samples.

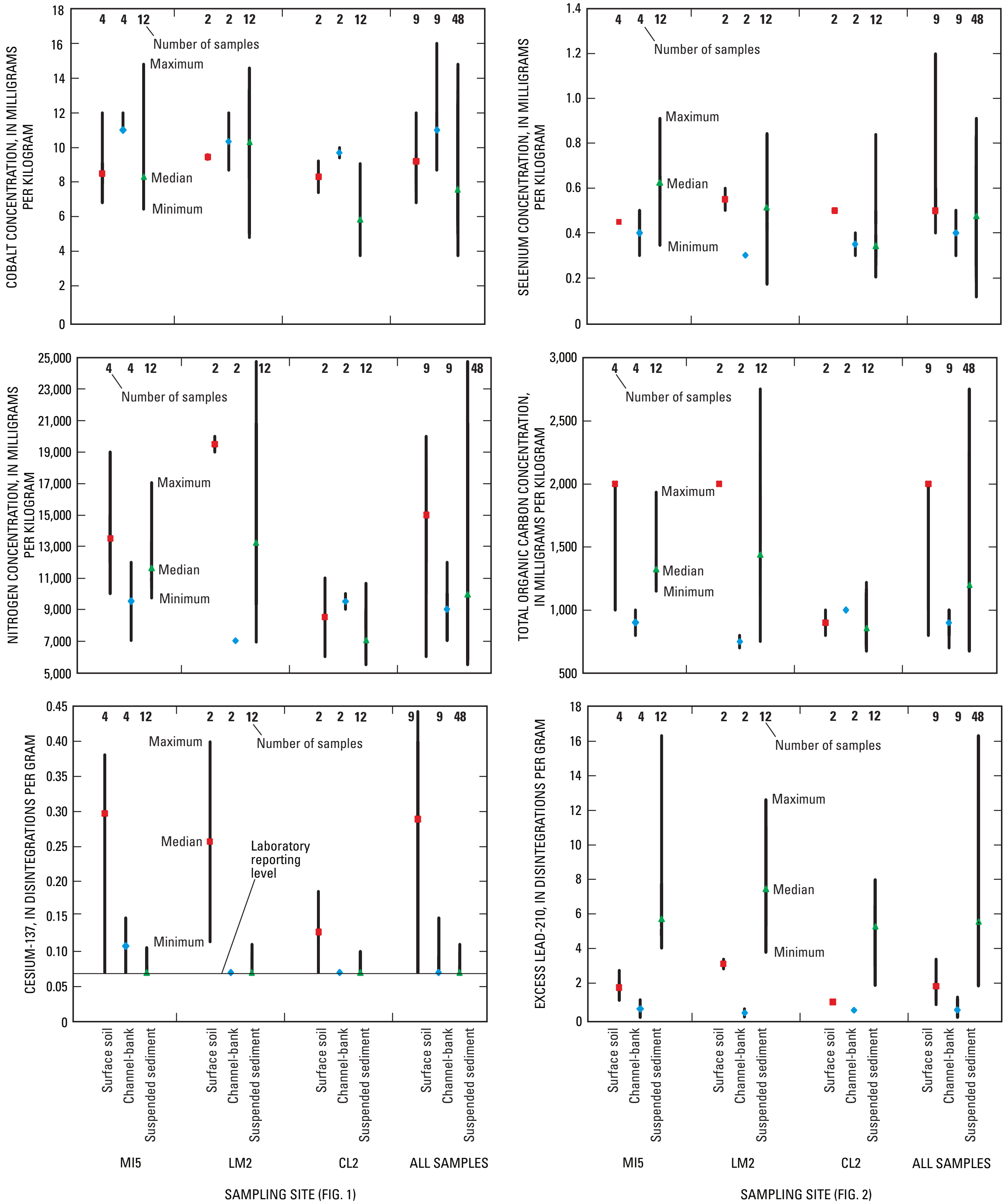


Figure 23. Comparison of selected trace elements, nutrients, total organic carbon, and radionuclides in surface-soil, channel-bank, and suspended-sediment samples in selected Mill Creek watersheds, 2006.

predict suspended-sediment sources, 47 of the 48 suspended-sediment samples collected would have been completely attributed to surface soils (table 16). Because excess ^{210}Pb (and ^{7}Be) is deposited to surface soils by atmospheric deposition during precipitation events, activities in suspended sediments originate from both surface soils and precipitation. Similarly, ^{7}Be was not detected in surface soil or channel-bank material, but was detected in all suspended-sediment samples (table 15).

Unlike ^{7}Be and excess ^{210}Pb (which are continuously contributed to surface soils), atmospheric contributions of ^{137}Cs peaked in 1963, but are essentially nonexistent today (Ritchie and McHenry, 1990). Twenty-five of the 48 of ^{137}Cs analyses would have been completely attributed suspended sediment to channel-bank sources, indicating that contributions of ^{210}Pb and ^{7}Be from precipitation bias sediment source estimates (table 16). However source estimates using ^{137}Cs (and other constituents) may be biased, as concentrations and activities have been shown to decrease with soil depth (especially in uncultivated soils; Walling and Woodward, 1992). Sediments eroded by rills and gullies at depths greater than the 1-inch deep sampling zone would likely be biased toward channel-bank sources. Because properties of individual constituents can bias sediment source estimates, multi-constituent approaches have been used to offset the bias of single-constituent estimates (Walling and Woodward, 1995; Collins and others, 1998, Russell and others, 2001, Walling, 2005). However, it is not certain that combining biased estimates will result in accurate attribution of suspended-sediment sources. In this study, redistribution of soil profiles because of urban construction, large variability in constituent values within source types, and relatively few (18) source samples precluded identification of a consistent chemical and radionuclide signature among source types.

In addition to study-specific factors, other sources of error inherent to the methodology limited the potential accuracy of sediment source estimates. First, processes of soil erosion and transport selectively transport sediments of smaller grain size relative to original source material (Poesen and Savat, 1981). Trace elements (Horowitz, 1991) and radionuclides (He and Walling, 1996) sorb to smaller grain-sized sediments at larger concentrations, with the magnitude of this effect varying among constituents and soil type (Horowitz, 1991; Russell and others, 2001). Thus a single grain-size correction factor cannot adequately compensate for the varying affects of size selection in erosion and deposition processes. Second, sorption of dissolved trace elements and radionuclides from precipitation to streambed- and suspended sediments disrupt the potential chemical linkage of suspended sediments to surface soil and channel-bank material. (Olsen and others, 1986; Walbrink and others, 1998). Third, because constituent concentrations can decrease with the depth of the soil profile (Walling and Woodward, 1992), erosion by rills and gullies (deeper incisions in the soil surface), likely result in smaller concentrations of trace elements and radionuclides than those observed in the upper inch of the soil profile. Soil disturbance from urban construction likely promotes rill and gully formation, falsely indicating channel-bank sources of suspended sediment at monitoring sites.

Table 16. Mean percentage of suspended sediment attributed to surface soils for constituents with significant differences between surface soil and channel-bank material, Mill Creek watershed, Johnson County, northeast Kansas, February 2006 and June 2007.

Constituent	Percentage of suspended sediment attributed to surface soil (+/- 95-percent confidence interval of median)	Number of values greater than 100 percent (of 48)	Number of values less than 0 percent (of 48)
Cobalt	160 (+/- 86)	34	5
Selenium	55 (+/- 83)	19	14
Total nitrogen	41 (+/- 31)	8	9
Total organic carbon	22 (+/- 34)	6	12
Cesium^{-137}	-6 (+/- 22)	0	25
Excess Lead^{-210}	320 (+/- 120)	47	0

Summary and Conclusions

The U.S. Geological Survey, in cooperation with the Johnson County Stormwater Management Program, conducted an investigation from February 2006 through June 2007 to characterize the transport and sources of suspended sediment in the urbanizing Mill Creek watershed in Johnson County, northeast Kansas. Sediment transport and sources were assessed spatially by continuous (5-minute) monitoring of streamflow and turbidity, as well as the sampling of suspended sediment at nine sites in the Mill Creek watershed. The study period was normal in terms of precipitation volume, more or less precipitation would result in increased or decreased sediment loads and yields relative to this study period. Watersheds with the most construction activity contributed substantially more sediment (per unit area) than established urban or less-developed watersheds. Sediment transport downstream from construction sites was more limited by the transport capacity (streamflow), whereas availability of sediment supply played a larger role downstream from urbanized watersheds. Sediment loads (per unit area) generally decreased from headwater to downstream sites, likely because of sediment deposition in larger, less sloping stream channels primarily during small storms. Sediment deposited by small storms is likely available for transport by subsequent, larger storms. Storms with increased precipitation intensity transported more sediment at eight of the nine sampling sites, and recent sediment transport decreased observed sediment loads at two of the nine sampling sites. Surface-water impoundments trapped sediments, decreasing sediment loads observed downstream.

Stormflow and sediment yield were compared between Mill Creek sites and four additional, large watersheds monitored in Johnson County (Blue River, Cedar, Indian, and Mill Creeks) during the same study period. In contrast with results from smaller subwatersheds within Mill Creek, sediment load (per unit area) in the most urbanized watershed in Johnson County (Indian Creek) were more than double that of other large watersheds. Potential sources of this sediment include legacy sediment from earlier urban construction, accelerated stream-channel erosion, or erosion from specific construction sites, such as stream-channel disturbance during bridge renovation. This finding suggests that sediment loads in large, developing watersheds (such as Blue River, Cedar and Mill Creek) may remain elevated decades after the majority of development is complete.

Samples collected from surface soils, channel banks, suspended sediment, and streambed sediment were analyzed for nutrients, trace elements, and radionuclides. None of the samples had concentrations of trace elements larger than applicable probable effect concentrations. Suspended-sediment samples had smaller grain-size distributions than surface or channel-bank soils, thus trace element and radionuclide concentrations were multiplied by a correction factor to improve comparison to surface-soils and channel-bank material. Although concentrations and activities of cobalt, nitrogen, selenium, total organic carbon, cesium-137, and excess lead-210 were significantly different among source types, variability in source estimates among constituents and sites precluded accurate estimation of sediment source. Redistribution of soil horizons by urban construction, enrichment of constituent concentrations during sediment transport, and inability to accurately represent rill and gully erosion biased potential estimates of suspended-sediment source.

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