CHARACTERIZATION OF SEDIMENT TRANSPORT FROM URBAN, URBANIZING, AND RURAL WATERSHEDS IN JOHNSON COUNTY, KANSAS, 2006-08

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Abstract Although construction activities and urban land are frequently cited as causes of increased suspended-sediment transport, sediment loads have rarely been quantified from urbanizing watersheds since the widespread implementation of erosion-control practices at construction sites. In cooperation with the Johnson County Stormwater Management Program, the U.S. Geological Survey studied sediment transport across a continuum of land-use conditions (rural, urbanizing, urban) and watershed scales (3-66 mi^2) within Johnson County, Kansas. Suspended-sediment samples were collected along with continuous monitoring of streamflow and turbidity to characterize suspended-sediment transport at nine stream sites within an urbanizing, 57-mi^2 watershed (Mill Creek) as well as from the four other largest (49-66 mi^2) watersheds (Blue River, Cedar, Indian, and Kill Creeks) in Johnson County. Simple linear regression analysis between turbidity and suspended-sediment concentration was used to compute sediment loads in 5- to 15-minute increments at monitoring sites.

Sediment yields from the smallest watersheds (3-12 mi^2) with increased construction activity within the Mill Creek watershed were approximately two-three times larger than those from established urban or rural watersheds. Sediment concentrations at these sites were larger for prolonged periods, often remaining elevated after stormflows had receded. Within the Mill Creek watershed, watersheds with substantial regulation by reservoirs and those occupied by stable, urban land uses had the smallest sediment yields in Johnson County. However, among larger (49-66 mi^2) watersheds, sediment yield from the only large, mostly established urban watershed (Indian Creek) was more than twice that of the urbanizing Mill Creek watershed, and was as much as 4.6 times that of predominantly rural watersheds. Sediment yield from the 63-mi^2 Indian Creek watershed was similar to yields observed from small (5-11 mi^2), construction-affected sites within Mill Creek. The implication of these findings is that sediment yields can increase relatively rapidly in response to upstream construction in small watersheds (3-12 mi^2), whereas sites downstream from relatively larger (49-66 mi^2) watersheds can take decades longer to adjust to upstream urbanization. Sediments transported by Indian Creek likely result from stream channel erosion, resuspension of sediments deposited from earlier urban construction, and erosion from specific construction sites, such as stream-channel disturbance during bridge renovation.

INTRODUCTION

Urbanization has been shown to cause substantial change to the form, flow, and ecology of streams. Construction activities have been shown to result in substantial sediment deposition in stream channels, which in turn can obstruct flow and cause localized flooding, and can affect native aquatic biota (Wolman and Schick, 1967; Guy, 1970; Wood and Armitage, 1997; U.S. Environmental Protection Agency, 2006). Sediment yields from specific historical highway or building construction sites have ranged from 2,300 to 140,000 tons/mi^2/year, compared to those composed of agricultural (420-2,750 tons/mi^2/year), forest (15-110 tons/mi^2/year), or established urban watersheds (430-2,400 tons/mi^2/year) (Wolman and Schick, 1967; Vice and others, 1969; Guy, 1970; Walling and Gregory, 1970; Yorke and Herb, 1978; Owens and others, 2000). Erosion and sediment-controls (such as silt fences, mulch berms, rock checks, settling watersheds, and ground cover) are now widely implemented across the United States and have been shown to decrease off-site sediment yields by 60 to 80 percent (Yorke and Herb, 1978). When the construction phase is finished, increased impervious surface area routes more rainwater directly to streams, resulting in larger peak stormflows, which can transport deposited sediments and incise or widen stream channels (Wolman, 1967; Trimble, 1997; Leopold and others, 2005).

A lack of knowledge exists regarding the timing and extent to which water quality and stream habitat respond to urbanization. This lack of knowledge can be attributed in part to difficulties quantifying water-quality conditions at small spatial and temporal scales. This study was performed to better understand how urbanization affects sediment transport under improved erosion-controls and across watershed (3-66 mi^2) scales in Johnson County, Kansas.

STUDY AREA

Urbanization has negatively affected streams in Johnson County, Kansas, located in the southeastern corner of the Kansas City metropolitan area. Streams draining urban areas in the county have been documented to transport more water, sediment, nutrients, and bacteria than streams draining rural areas (Rasmussen and others, 2008). Streambed sediments in urbanized watersheds have among the largest concentrations of many organic contaminants, as well as decreased macroinvertebrate diversity (Lee and others, 2005; Poulton and others, 2007).

Johnson County consists of gently rolling uplands with hilly areas along the streams. Soils in the county generally consist of erosive to moderately erosive silt and silty clay loams. Infiltration of precipitation to ground water is limited in most areas of the county due to relatively impermeable limestone and shale. Because of limited ground water capacity, most stormflow likely originates from overland or shallow subsurface flow. Streambeds are typically composed of gravel, cobble, rock, and bedrock; and, thus, bedload is not considered a substantial part of the stream-sediment load. Channel banks are composed primarily of silt and silty clay loams, with occasional limestone and shale outcrops. Monitoring sites were located at nine stream sites within the urbanizing Mill Creek watershed, and at the downstream most location (considering site suitability) in the four other largest watersheds (Blue River, Cedar, Indian, and Kill Creeks) in Johnson County, Kansas (Lee and others, 2009).

Property tax data and aerial photography were used to define land use and impervious surfaces (defined as areas occupied by buildings and pavement) in Johnson County (Johnson County Automated Information Mapping System, written commun; 2009; table 1). Undeveloped areas (such as agricultural and grassland) are the predominant land use in the southern and western parts of the county, primarily in the Cedar, Kill Creek, and the Blue River watersheds. Indian Creek and subwatersheds in the eastern and southern parts of the Mill Creek watershed consist primarily of older (pre-1990) urban areas and have the most impervious surface (greater than 30 percent). Changes in impervious surface immediately prior to and during the study period (from the spring of 2005-08) were used to quantify urban construction upstream from monitoring sites. Within the Mill Creek watershed, the largest increases in impervious surface were in the western (upstream from sites in the Clear Creek watershed; sites CL1 and CL2) and south-central (upstream from site MI4) parts of the watershed (see detailed map in Lee and others, 2009). Among larger watersheds, Indian and Mill Creek had the largest increases in impervious surfaces prior to and during the study period (table 1). Eight large (greater than 30-acre) surface-water impoundments are present within study area that regulate approximately 18 percent of the Cedar Creek watershed, 11 percent of the Kill Creek watershed, and 10 percent of the Mill Creek watershed (none exist in the Blue River and Indian Creek watersheds). Numerous smaller impoundments are upstream from monitoring sites in the primarily rural and more recently urbanized portions of the county (Blue River, Cedar, Kill, and Mill Creek watersheds).

METHODS

Monitoring sites in the Blue River, Indian Creek, and Mill Creek watersheds were operated from February 2006 through November 2008 (table 1). Sites in the Cedar and Kill Creek watersheds were removed from operation in December 2007, and thus data analyses involving these stations only consider data from February 2006 through December 2007 (table 1). Streamflow and water-quality data were not collected during much of the winter due to freezing conditions; computations of streamflow and sediment loading exclude these periods from analysis from all sites. Monitoring sites were equipped with streamgages and water-quality monitors (YSI Inc.[1]) equipped with specific conductance, water temperature, and model 6136 turbidity sensors. Streamflow rating development, water-quality monitor installation and maintenance, suspended-sediment sample collection, and quality assurance procedures are described in detail in Lee and others (2009). Stormflows were estimated by substracting base flow (defined as wastewater and ground-water inputs; Wahl and Wahl, 2006) from the continuous streamflow record.

Regression Models Regression analysis was used to relate suspended-sediment concentration (SSC) and the median of turbidity values (fig. 1) collected across the stream cross section. SSC and turbidity values were log-transformed to better approximate normality and homoscedasticity in the distribution of regression residuals. After development of the regression relation, variables were retransformed 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. Regression methods used in this study generally follow guidelines (see Lee and others, 2009, for exceptions) described in Rasmussen and others (2009). Continuous SSC and suspended-sediment load computations, uncertainty, and duration curves are available on the World Wide Web at URL http://ks.water.usgs.gov/Kansas/rtqw. SSC/turbidity relations for the downstream-most sites in the five largest watersheds (Blue River, Cedar, Indian, Kill, and Mill Creeks) were developed from a county-wide study published by Rasmussen and others (2008).

[1] Use of brand and firm names is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey

Table 1 Stormflow and suspended-sediment yield, and stormflow-weighted sediment concentrations from Johnson County monitoring sites 2006-2008.

[mi^2, square miles; mg/L, milligrams per liter; --, no data]

					Stormflow yield (acre-feet/mi^2)			Suspended-sediment yield (tons/mi^2)				Stormflow-weighted sediment concentration (mg/L)			
Stream	Predominant upstream land use	Site designation	Watershed area (mi^2)	Percentage impervious surface (percentage increase from 2005-08)	2006	2007	2008	2006	2007	2008	Mean annual suspended-sediment yield from 2006-08 (tons/mi^2/year)	2006	2007	2008	Stormflow-weighted sediment concentration from 2006-08 (mg/L)
Monitoring sites within the Mill Creek watershed															
Clear Creek	Urbanizing	CL1	5.5	11.3 (4.5)	200	700	800	200	1,830	1,360	1,130	740	1,800	1,200	1,430
Clear Creek	Urbanizing	CL2	11	13.1 (3.8)	270	700	910	180	1,360	1,090	880	490	1,400	890	1,020
Coon Creek	Rural/impounded	CO1	5.1	10.8 (1.8)	280	760	1,170	60	230	350	210	150	220	220	210
Little Mill Creek	Urban	LM1	8.8	30.7 (1.9)	400	810	930	160	550	470	400	290	500	370	410
Little Mill Creek	Urban	LM2	12	27.1 (1.6)	270	660	680	130	570	620	440	350	640	680	610
Mill Creek	Urban/impounded	MI3	2.8	35.1 (3.1)	560	940	1,060	220	380	330	310	290	290	230	270
Mill Creek	Mixed	MI4	20	24.8 (4.2)	370	800	880	300	730	650	560	590	670	540	600
Mill Creek	Mixed	MI5	32	17.8 (2.9)	280	570	670	190	530	730	490	500	690	800	700
Mill Creek	Mixed	MI7	57	18.8 (2.9)	250	610	730	180	630	690	500	540	750	700	690
Sites at outlets of other largest watersheds in Johnson County															
Blue River	Rural	BL5	66	4.4 (0.9)	180	640	770	230	580	980	600	970	660	930	830
Cedar Creek	Rural	CE6	59	7.6 (1.5)	150	560	--	90	520	--	200*	420	680	--	630*
Indian Creek	Urban	IN6	63	30.1 (2.6)	570	900	1,000	540	1,330	2,390	1,420	700	1,100	1,700	1,280
Kill Creek	Rural	KI6b	49	4.1 (0.7)	100	480	--	44	360	--	140*	330	550	--	510*

*Data considered only from 2006-07

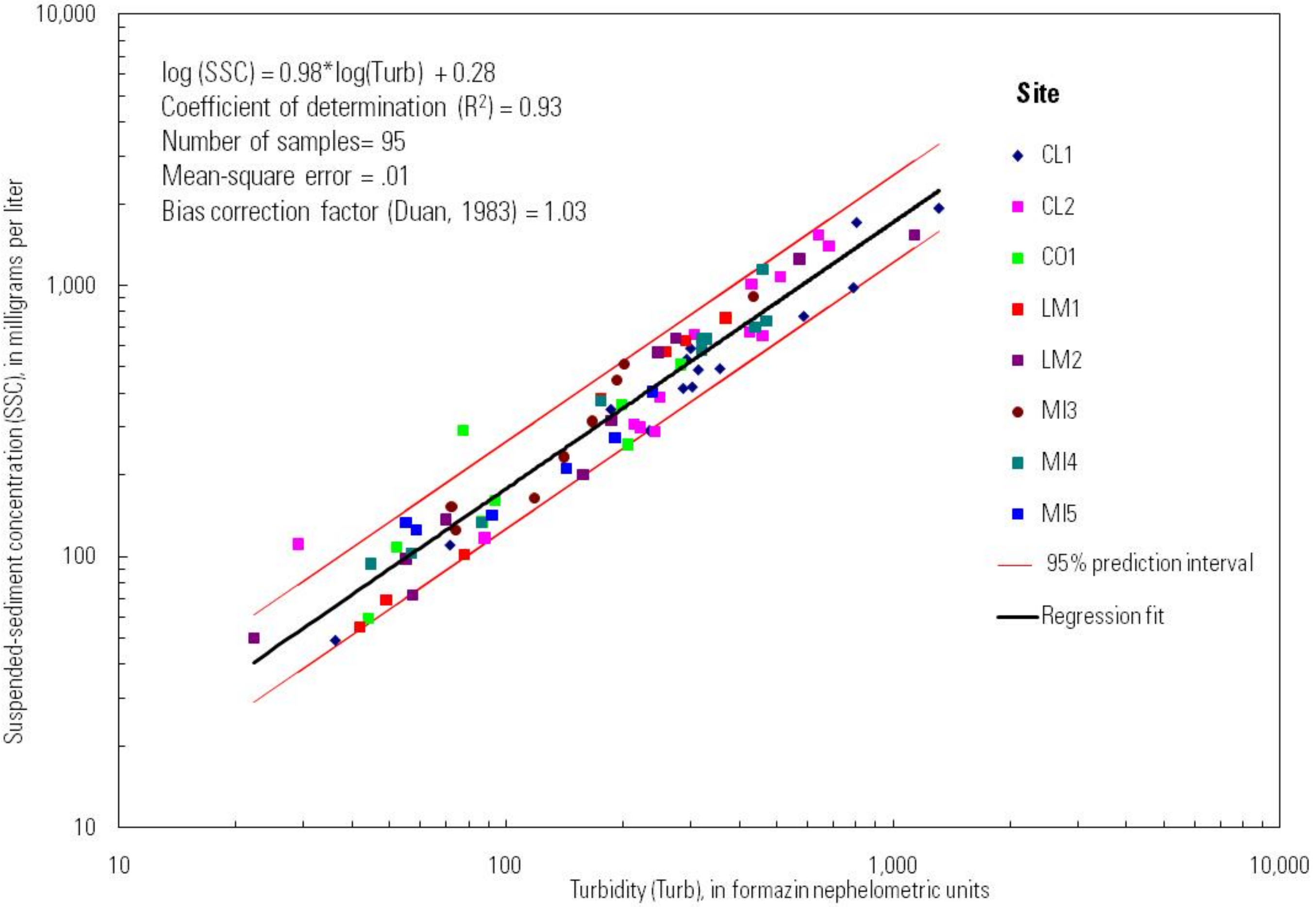

Figure 1 Regression relation between suspended-sediment concentration and turbidity at Mill Creek sites, 2006-08 (site designations from table 1).

In addition to the distribution of SSC, the grain size and color of suspended sediment are the primary factors that affect the SSC/turbidity regression (Rasmussen and others, 2009). Turbidity has been shown to accurately estimate SSC in northeast Kansas streams with a preponderance of silt- and clay-sized sediment (Rasmussen and others, 2008; Lee and others, 2009). Silt- and clay-sized sediment composed most of the suspended-sediment samples at all Mill Creek sites, as only 2 of 95 samples had less than 89 percent silt/clay particles. Particle-size distributions often were the finest during high-flow conditions, indicating that sand-sized material generally was not suspended within stream channels.

A single regression model (as opposed to multiple, site-specific models) was developed between turbidity and SSC data for eight of the nine Mill Creek sampling sites (fig. 1; regression relations for the most downstream sites were developed using regression models from Rasmussen and others, 2008). Samples in which turbidity values were greater than maximum sensor limits were not included in the regression relation. Turbidity explained 93 percent of the variability in SSC data, residuals generally were evenly distributed around the fit, and individual sampling sites did not exhibit consistent bias in relation to the regression line (fig. 1). Relations were aggregated because SSC/turbidity relations were similar among sampling sites because soils in the Mill Creek watershed are similar in terms of particle size, mineralogy, and organic content (Evans, 2003); and data analyzed among multiple sites (Lee and others, 2009) indicated consistent relations and estimates of sediment loading among sites.

Estimating Periods of Turbidity Truncation YSI model 6136 turbidity sensors can record values to 1,200 to 2,000 formazin nephelometric units--the maximum recordable value varies among sensors. When in-stream turbidity values are larger than maximum sensor values, sensors record the maximum value, resulting in underestimation of actual in-stream turbidity. Truncation of turbidity measurements for only minutes can bias results because truncation typically occurs when sediment loads are largest. Varying duration of truncation biases comparisons of sediment loads and yield among sampling sites. Estimates of turbidity during periods of truncation were performed as described and evaluated in Lee and others (2009). During the study period, 3.4 (site MI3) to 11.3 (site CL1) hours of data were truncated. Sediment loads increased from 0 (site MI3) to 10.7 (site CL1) percent among sampling sites after addition of sediment loads estimated during periods of turbidity truncation.

Estimating Sediment Loading During Periods of Missing Turbidity Data 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. During base-flow conditions, gaps in the continuous turbidity record were estimated by extrapolating values before and after the missing period. When turbidity data were missing during an individual storm, loads were estimated for the entire storm using data from nearby sites (methods are described in detail Lee and others, 2009). Missing turbidity data resulted in estimation of the most sediment loading at sites IN6 (52 percent), CL2 (23 percent), MI5 (14 percent), and KI6b (12 percent); all other sites had less than 10 percent of data estimated. Sensor failure at site IN6 during a storm that exceeded the 25-year peak flow was estimated to transport 94,400 tons of sediment, 52 percent of the load for the entire study period.

PRECIPITATION AND STORMFLOW

Rainfall during 2006 (36.4 in.) and 2007 (44.5 in.) is considered "normal" (between the 25th and 75th percentile of annual rainfall), whereas rainfall during 2008 (49.5 inches) is considered high (greater than the 75th percentile of annual rainfall; National Oceanic and Atmospheric Administration, 2009). The maximum observed rainfall for a single day at Olathe, Kansas (central to the study area), was 5.8 in. on July 30, 2008 (National Oceanic and Atmospheric Administration, 2009)--larger than the 10-year daily recurrence interval (5.3 in.), but smaller than the 25-year recurrence interval (63 inches) estimated for Johnson County (Overland Park Stormwatch, 2009).

Impervious surfaces transport more rainfall to streams. Stormflow yields (total stormflow divided by upstream drainage area) from the urbanized Indian Creek watershed were more than two times the yields of other large watersheds during the driest year (2006) and from 1.3 to 1.9 times that of other large watersheds in 2007 and 2008 (table 1). Within the Mill Creek watershed, subwatersheds with the most impervious surface (sites LM1 and MI3) had by far the largest stormflow yields during 2006, but had only marginally larger stormflow yields compared to most other monitoring sites in the watershed during wetter years in 2007 and 2008.

SEDIMENT TRANSPORT THROUGHOUT JOHNSON COUNTY

Sediment transport relative to urbanization and watershed size Stormflow and sediment loading were computed for each calendar year at each monitoring site, and were normalized by drainage area (suspended-sediment yield) and by total stormflow volume (stormflow-weighted sediment concentration; SWSC) to better compare results among watersheds of varied size and hydrology. Mean annual sediment yields were calculated by summing sediment loads from 2006 to 2008, dividing by drainage area and the number of years (3 for all sites except Cedar and Kill Creeks). Sites in the Clear Creek tributary of the Mill Creek watershed (sites CL1 and CL2) had the largest mean annual increase in impervious surface from 2005 through 2008 (site CL1, 1.12 percent per year; site CL2, 0.95 percent per year), and had largest mean annual sediment yields (site CL1, 1,130 tons/mi^2/year site CL2, 880 tons/mi^2/year). Mean annual sediment yields observed from the south-central part of the watershed (site MI4; 560 tons/mi^2/year; fig. 2) were much smaller than sediment yields in the Clear Creek basin, despite similar amounts of construction (1.04 percent per year increase in impervious surfaces upstream from site MI4; fig. 2). Smaller sediment yields observed in the south-central part of the watershed are likely because site MI4 is downstream of a larger watershed (20 mi^2), which affords more opportunity for sediment deposition in and around the larger, less-sloping stream channel. The correlation (spearman's rho = 0.74) between the extent of construction and sediment yield (fig. 2) indicate that despite intermediate sediment deposition and management practices designed to limit erosion from construction sites, substantial increases in sediment transport were recorded at small (5-11 mi^2) watershed scales as a result of recent construction activity. Because of dilution and sediment deposition between construction and monitoring sites, sediment concentrations are likely substantially larger directly downstream from construction sites. Factors, such as the location, slope, and management practices of construction sites, and sediment deposition in larger watersheds are important to sediment transport processes and contribute to the variability exhibited in relations among Mill Creek sites.

Sites in the Mill Creek watershed most regulated by upstream impoundments (site CO1, 39 percent; site MI3, 36 percent) had the smallest average sediment yields (210 tons/mi^2/year and 310 tons/mi^2/year). Sites downstream from relatively mature urban land use (sites LM1 and LM2) without the presence of upstream impoundments also had among the smallest sediment yields (400 and 440 tons/mi^2/year) within Mill Creek, but were slightly larger than yields than those observed from the nearby, larger (49-59 mi^2) rural Cedar and Kill Creek Watersheds during 2006 and 2007.

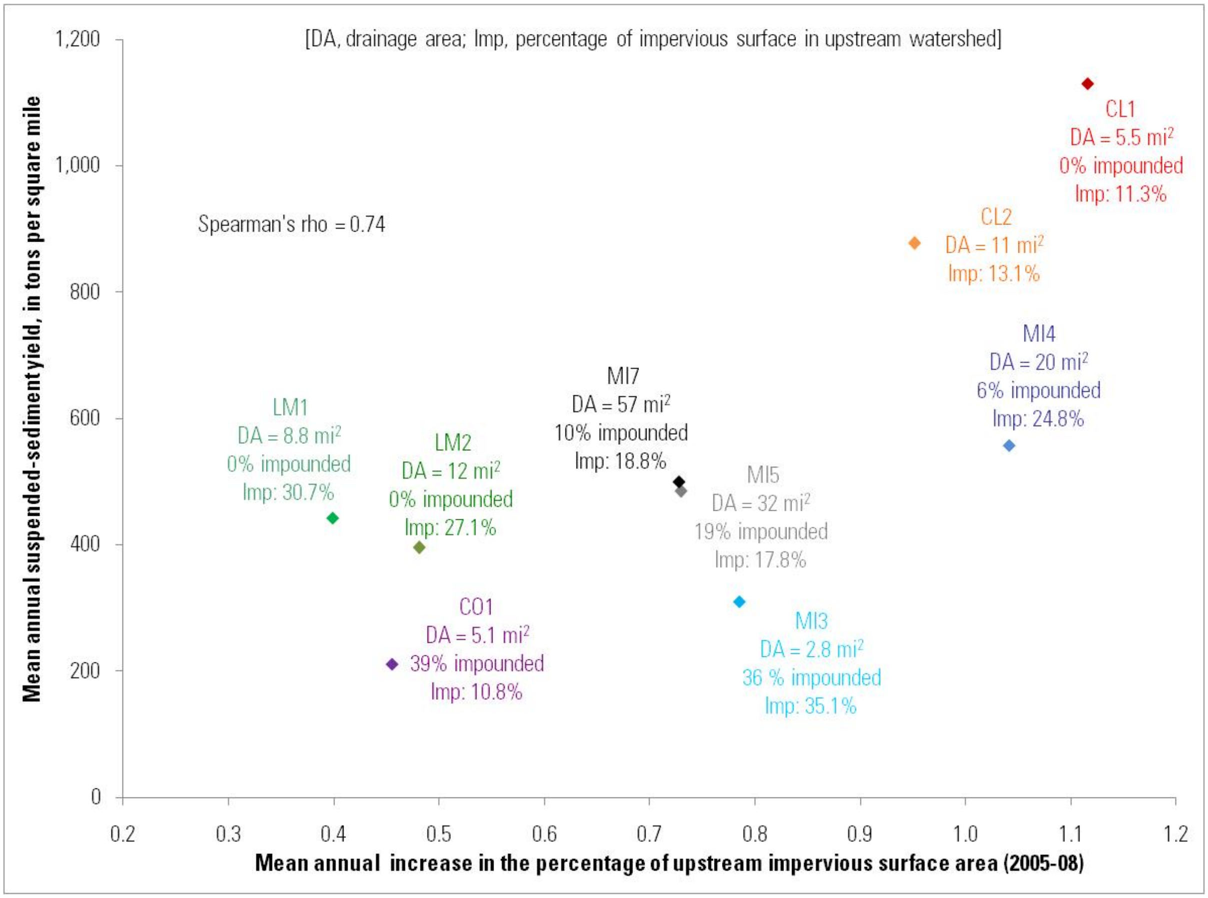

Figure 2 Mean annual sediment yields from 2006 to 2008 compared to mean annual increases in upstream impervious surface from 2005 to 2008 at monitoring sites in the Mill Creek watershed, Johnson County, Kansas (site designations from table 1).

Although the rate of urbanization in the Indian Creek watershed (site IN6; 0.65 percent mean annual increase in impervious surface from 2005-08) is similar to that of Mill Creek watershed (site MI7; 0.73 percent mean annual increase in impervious surface from 2005-08), sediment yields from site IN6 (1,420 tons/mi^2/year) from 2006 to 2008 were nearly three times that of site MI7 (500 tons/mi^2/year) and were larger than construction-affected sites in Clear Creek (site CL1, 1,130 tons/mi^2/year; site CL2, 880 tons/mi^2/year). Mean annual SWSCs at site IN6 (1,280 mg/L) were almost twice those of site MI7 (690 mg/L), and only marginally less than site CL1 (1,430 mg/L). Indian Creek has few small, and no large impoundments to trap sediments, and land-use primarily consists of established residential and commercial areas, similar to the Little Mill Creek watershed (sites LM1 and LM2) within Mill Creek. However sediment yields from sites most similar to site IN6 (stable urban land use with no impoundments; sites LM1 and LM2) were less than one-third of those in the Indian Creek watershed. These results indicate differences in the rate in which the urbanization affects the sediment transport in large and small watersheds.

While upstream construction increased downstream sediment transport relatively rapidly (within years) in small (3-12 mi^2) watersheds, several factors likely delay or extend the effects of urbanization in larger watersheds. Increased impervious surface area in the mature urban watersheds result in larger, faster stormflows with more capacity to erode stream channels and resuspend sediments deposited from legacy construction activities. In addition, construction activities done to repair existing infrastructure, such as bridge renovation, could increase sediment loads without being recognized as construction activity using spatial analysis techniques.

Evaluation of sediment concentrations during varied streamflow conditions Increases in the magnitude, and duration of SSC values, and subsequent increases in fine sediment deposition to streambeds have been linked to decreases in the diversity of fish and macroinvertebrate communities (Newcombe, 1991; 2003; U.S. Environmental Protection Agency, 2006). To compare the magnitude and duration of SSC values among sites, 5- or 15-minute estimates of sediment concentration were sorted by the streamflows in which they occurred, and then averaged for each one-half percentage of streamflow values exceeded (for example, SSC values were averaged during streamflow values exceeded between 0.5 to 1.0 percent of the time, for those exceeded 1.0 to 1.5 percent of the time, etc.). SSC values were averaged from observed peak flows to streamflows exceeded 0.1 percent of the time and during streamflows exceeded 0.1 to 0.5 percent of the time to improve definition of SSC values during the most extreme flow conditions. SSC data (x-axis) data were compared to the percentage of the time streamflow values are exceeded (log-scale; y-axis) to evaluate the frequency of sediment concentrations among sites (fig. 3, 4). Data from the Mill Creek Watershed were compared from 2006 through 2008 (fig. 3), data from the five largest watersheds were compared from 2006 through 2007 (data were not collected from the Cedar and Kill Creek sites in 2008; fig. 4).

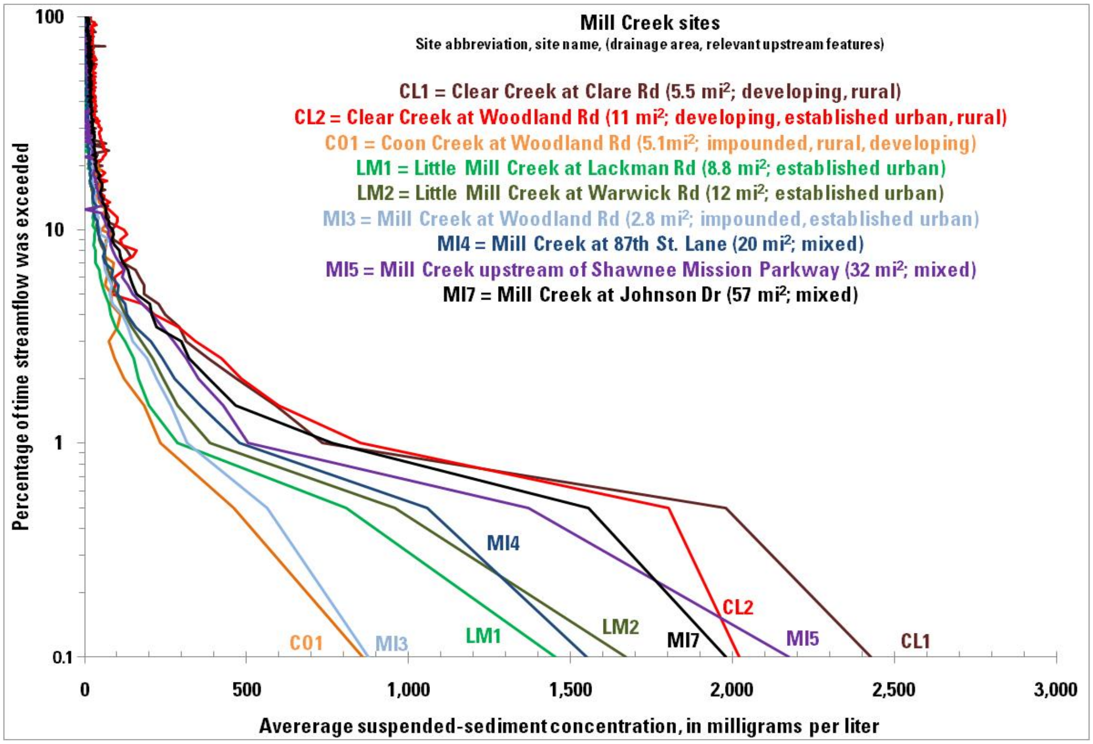

Figure 3 Mean turbidity-computed sediment concentrations during varied streamflow exceedance values among sites in the Mill Creek watershed, Johnson County, Kansas, 2006-2008.

Sediment concentrations at sites within the urbanizing Clear Creek watershed (sites CL1 and CL2) were generally larger than concentrations at other sites in the Mill Creek watershed during streamflow values exceeded less than 10 percent of the time. Larger SSC values during stormflow conditions in the Clear Creek watershed in comparison to other sites indicated that more sediment remains in suspension as storms recede to low-flow conditions, likely increasing fine-sediment deposition on the streambed. Mean sediment concentrations were smallest during the most extreme streamflows (exceeded less than 0.1 percent of the time) at site CO1 (860 mg/L) and site MI3 (880 mg/L) because of sediment retention in upstream reservoirs. Established, urban sites had among the smallest sediment concentrations during 1 to 10 percent exceedance intervals, but had larger SSC values (site LM1, 1,450 mg/L; site LM2, 1,670 mg/L) during the most extreme flows relative to nearby impounded watersheds. The largest subwatersheds in the Mill Creek watershed (sites MI5 and MI7) with mixed rural, urbanizing, and rural land use had larger sediment concentrations during 0.1 to 10 percent streamflow exceedance levels than did established urban and impounded sites.

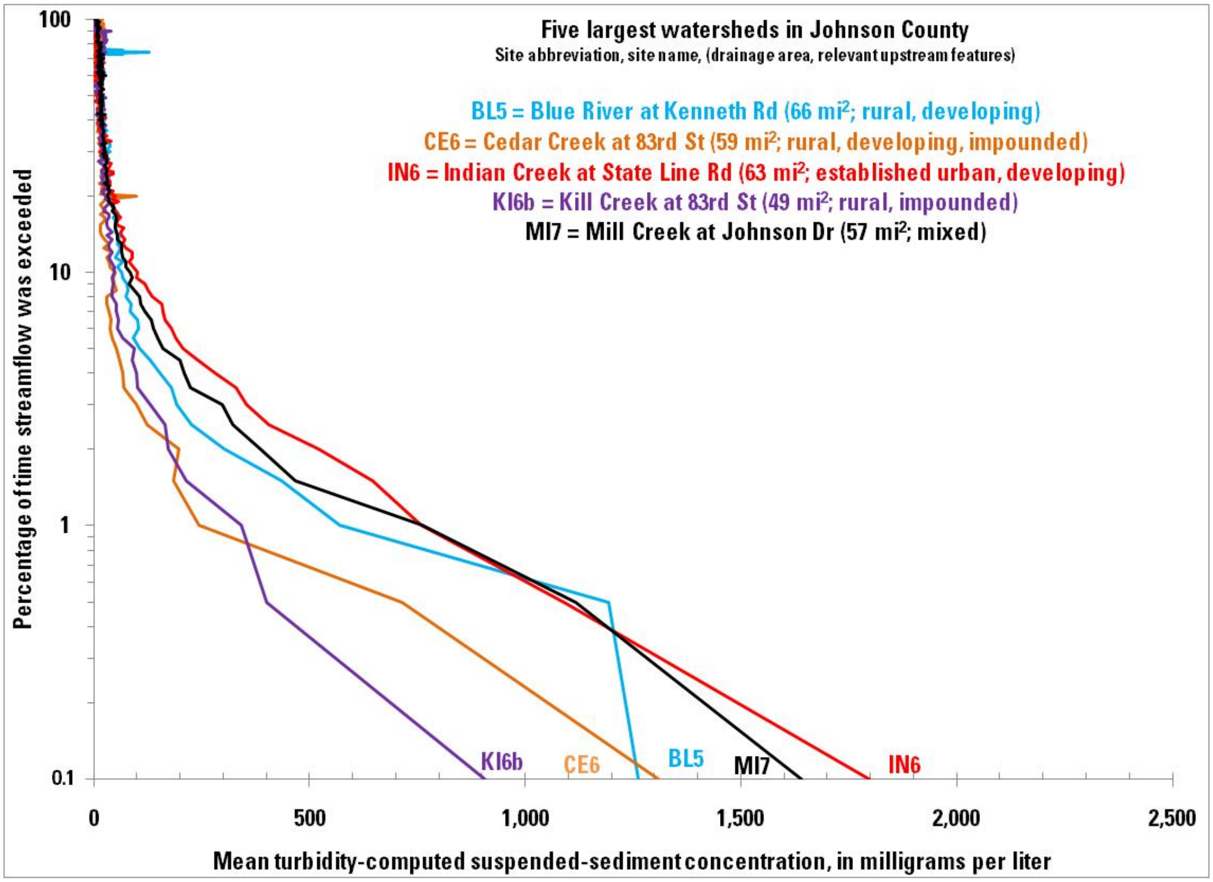

Figure 4 Mean turbidity-computed sediment concentrations during varied streamflow exceedance values among the five largest watersheds in Johnson County, Kansas, 2006-2007.

Among the larger watersheds, mean sediment concentrations were similar during relatively low-flow conditions (greater than 10 percent streamflow exceedance), but were quite different during steamflow conditions less than 10 percent of the time. Despite established urban land use in the Indian Creek watershed, SSC values were generally largest during streamflow conditions exceeded between 0.1 to 10 percent of the time relative to other large watersheds. Average sediment concentrations only marginally increased during streamflow values exceeded less than 0.1 percent of the time relative to values exceeded between 0.1 to 0.5 percent of the time in the Blue River, indicating that sediment supplies were becoming limited during the most extreme flow conditions. Rural Cedar and Kill Creek sites had much smaller sediment concentrations during the 1 to 10 percent streamflow exceedances; however concentrations were much larger in the Cedar Creek watershed during peak flow conditions, potentially indicating increased sediment transport from urbanizing areas in the eastern and southern parts of the watershed.

DISCUSSION

Despite improvements in erosion control at construction sites in the past 50 years, monitoring in Johnson County indicated that recent and ongoing construction activities contributed the largest sediment loads at 3- to 12-mi^2 watershed scales. Increased SSC values as a result of construction activity can have important consequences to aquatic ecosystems, such as decreased primary production as a result of reduced light penetration, and changes to the structure of aquatic communities as a result of increased fine-sediment deposition on streambeds. Differences in sediment yield among smallest (> 12 mi^2) and medium-sized (49 to 66 mi^2) established, urban watersheds indicate that land-use changes may affect sediment transport in small watersheds within years, whereas sediment transport and channel forms in larger watersheds (49 to 66 mi^2) may be affected over decades. Lags between landscape disturbance and downstream sediment transport in larger watersheds are likely caused by stream-channel expansion resulting from increased stormflows.

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