Quantifying Urban Stormwater Suspended Sediment Particle Size Class Distribution in the Central U.S.

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by

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Quantifying Urban Stormwater Suspended Sediment Particle Size Class Distribution in the Central U.S.

Presented by Elliott Kellner,

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Quantifying Urban Stormwater Suspended Sediment Particle Size Class Distribution in the Central U.S.

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Thesis Advisor: Jason A. Hubbart

ABSTRACT

Stormwater samples were analyzed from 17 urban monitoring sites (n = 272) during spring 2011 to better understand urban land use suspended sediment contributions to receiving water bodies in central Missouri, USA. Samples from receiving water bodies had higher total concentrations of suspended sediment (323 µl/l and 319 µl/l, respectively) relative to urban sites (205 µl/l), which contained approximately 35% less total sediment. However, mean particle size was significantly lower ($p < 0.001$) from urban sites (59 µm) relative to receiving waters (167 µm and 131 µm, respectively). Receiving waters had higher silt volumes (173 µl/l and 148 µl/l, respectively) relative to urban sites (124 µl/l). The percentage of silt volume to total sediment volume for urban stormwater and receiving water bodies was 60%, 46%, and 53%, respectively. Over the course of the study period, silt volume increased by more than 43% and 53% in receiving waters. Collectively, results indicate a disproportionate contribution of fine sediment from the urban environment. Receiving waters' particle size class dynamics suggest the presence of a climate-driven punctuated equilibrium of sediment transport, which was not apparent in urban areas. This study represents one of the first suspended sediment particle size class investigations of an urban environment and holds global implications for urbanizing watersheds and aquatic ecosystem health.

CHAPTER I: INTRODUCTION

Background

Suspended sediment is one of the primary causes of freshwater impairment in the United States (USEPA, 2006). Impacts on water quality are often first observed in altered sediment loading regimes (Hubbart and Freeman, 2010). Suspended sediment can affect the biological, chemical, and physical health of aquatic ecosystems (Schillinger and Gannon, 1985; Domagalski, 2001; Uri, 2001; Walling, 2008). Unfortunately, non-point source diffuse pollutants such as suspended sediment are also variably impacted by natural and anthropogenic origins and are consequently difficult to quantify and manage (Karwan et al., 2007; Hubbart and Freeman, 2010; Huang, 2012). It is therefore not surprising, given its critical role in water quality degradation and impairment of aquatic and riparian ecosystem health that suspended sediment has been the focus of a wide array of research (Gao, 2008).

Sediment is a natural component of aquatic ecosystems, playing fundamental roles in geomorphological and ecological functioning (Wass and Leeks, 1999). Too little sediment can result in increased channel erosion, nutrient depletion, and increased light penetration; the latter of which is an effect of lowered turbidity that can reduce primary productivity, thus altering the stream food web (Walling, 2008; Biedenharn et al., 1997). Conversely, too much sediment is associated with a host of deleterious environmental effects. For example, high concentrations of suspended sediment can reduce transmission of sunlight, thereby reducing photosynthesis and algal productivity (Uri, 2001; Keyes and Radcliffe, 2002; Campbell et al., 2005). Too much suspended sediment can also abrade or clog the gills of aquatic organisms, inhibit the feeding efficiency of filter feeders (i.e. mussels), obstruct sight feeders (i.e. most fish), and adversely affect macroinvertebrate communities by smothering benthic habitat (Keyes and Radcliffe, 2002; Campbell et al., 2005; Owens et al., 2005). Berg and Northcote (1985) found that the territorial, gill-flaring, and feeding behavior of juvenile coho salmon (*Oncorhynchus kisutch*) was disrupted by exposure to high concentrations of suspended sediment; suggesting a link between suspended sediment and salmonid population fitness. Sediment can also be a transport mechanism for many water quality constituents (Keyes and Radcliffe, 2002), including heavy metals, pesticides, polychlorinated biphenyls (PCBs), dioxins, fecal coliforms, and bound nutrients such as phosphorous (Schillinger and Gannon, 1985; Wass and Leeks, 1999; Domagalski, 2001; Walker and Hurl, 2002; Campbell et al., 2005; Brady and Weil, 2008; Gao, 2008). Excess suspended sediment is deposited in reservoirs, thereby reducing water storage capacity and increasing flooding (Uri, 2001; Keyes and Radcliffe, 2002; Walling, 2008).

Research has demonstrated the variability of erosion and sediment yield spatially and temporally (Wass and Leeks, 1999; Uri, 2001). While meteorological events tend to be the primary drivers of pollution transport from non-point sources (Hubbart and Gebo, 2010), anthropogenic activities such as land clearance, cultivation, and mining activity have been shown to increase both soil erosion and sediment yield by an order of magnitude or more (Walling, 1999; Walling and Fang, 2003). Studies have repeatedly and conclusively shown that land use change modifies hydrologic regimes, thus altering erosion rates and sediment flux (Karwan et al., 2007; Freeman, 2011). Urbanization has been identified as one of the greatest detriments to aquatic system health, by means of altered runoff processes and natural flow regimes (Booth and Jackson, 1997; Booth et al., 2002; Brezonik and Stadelmann, 2002). Therefore studies are greatly needed to quantify the relationship between urban land uses and suspended sediment flux.

Brown et al. (2005) described urbanization as “the transformation of land from rural land uses, such as agriculture, to urban land uses, such as housing”. Therefore, the term “urbanization” describes a broad array of land use activities and landscape changes (Konrad and Booth, 2005). The development of the urban landscape is characterized by vegetation clearing, construction, soil compaction, ditching and draining, and expansion of impervious surfaces (i.e. roads, parking areas, sidewalks, etc.), all of which can alter watershed runoff processes (Booth and Jackson, 1997). Utilization of drainage networks to remove stormwater from urban catchments reduces overland and subsurface flow paths, thereby transmitting greater volumes of surface flow to streams, and reducing evapotranspiration and/or aquifer recharge (Booth and Jackson, 1997). Konrad and Booth (2005) identified four hydrologic characteristics related to urban runoff processes: 1) greater frequency of high flows, 2) reapportionment of water from base flow to storm flow, 3) greater daily variation in stream flow, and 4) reduction in low flow. The increase in peak flows can alter stream geomorphology, incise channels and intensify bank erosion processes (Hubbart and Freeman, 2010; Huang, 2012). Neller (1988) showed that an urban stream displayed rates of channel bank erosion 3.6 times greater than a nearby rural stream, attributing the difference to urban development and altered runoff volume. Booth and Jackson (1997) reported an increase in the frequency of “sediment-transporting and habitat-disturbing” flows by more than a factor of ten, in urban streams. Similarly, Brezonik and Stadelmann (2002) reported that mean concentrations of suspended solids were more than 24 times greater in streams within watersheds containing construction sites.

Considering the potential detrimental impacts of urbanization on freshwater quality, coupled to increasing urban expansion and population growth worldwide (Brown et al., 2005), there is an ongoing desire to better understand urban impacts on water quality and stream ecosystem health to improve management of urban aquatic resources. One common measure of urbanization is imperviousness (Brown et al., 2005). Impervious surfaces can increase the frequency and magnitude of storm flows by reducing (or eliminating) the infiltration capacity of the soil, thereby increasing the volume of overland flow and transport of pollutants to receiving waters (Booth and Jackson, 1997; Booth et al., 2002; Brezonik and Stadelmann, 2002; Brown et al., 2005). Klein (1979) reported observable aquatic impairment at 12% and severe impairment at 30% impervious surface in an urban watershed in Maryland, USA. Booth and Jackson (1997) noted that 10% impervious surface area in a watershed produces a quantifiable, and thus definable, loss of aquatic ecosystem form and function. Paul and Meyer (2001) claimed that a threshold of 10–20% impervious surface is necessary for maintaining stream ecosystem integrity in developed watersheds. However, Booth et al. (2002) noted that any amount of impervious surface can impact water quality.

Studies have shown that urban development can affect the particle size distribution of sediment loads to receiving waters. By altering overland flow processes, fine sediment is transported to channels throughout the year (Booth and Jackson, 1997). This is an important observation since many of the harmful effects of excess suspended sediment are associated with fine-grained sediment particles less than 2 mm (Owens et al., 2005). A study of deposited sediment in the Hinkson Creek Watershed in central Missouri, USA, showed that the lower urban reaches of Hinkson Creek had 10 to 64% higher fine sediment (particles < 2 mm) concentration relative to the rural portions of the creek (MDNR, 2004). Hubbart and Freeman (2010) used a nested-scale experimental watershed study design to investigate suspended sediment size class distribution in Hinkson Creek. They identified a 450% increase in the concentration of the smallest particle size class (2.06 µm) in an urban stream reach during and directly following precipitation events. With a doubling of stream flow (1.4 m^3/s to 2.9 m^3/s), the concentration of fine sediment was more than quadrupled. Ultimately, increases in fine sediment delivery are known to significantly alter grain distribution of the stream bed (Jobson and Carey, 1989; Booth and Jackson, 1997). This issue could be important since alteration of sediment particle size distribution can have lasting effects on water quality and aquatic ecosystems (Owens et al., 2005). For example, Walker and Hurl (2002) noted that heavy metals, which can adversely affect the biological and chemical health of streams, often preferentially adsorb to finer particles. Owens et al. (2005) noted that many of the harmful effects of excess suspended sediment are specifically associated with fine-grained sediment particles (< 2 mm), which are more chemically active (sorbing contaminants more easily due to greater surface area), and more apt to fill interstitial spaces (a danger to benthic communities).

In a 2010 article considering the relationship between land use and erosion, Hubbart and Gebo presented the results of a study investigating the composition of suspended sediment in Hinkson Creek, in Missouri, USA. Data were collected during March, 2010. While analyzing sample values of average total concentration (µl/l) and mean particle size (µm), they noted a distinct negative trend in both parameters correlated to stream distance and urbanization. As the water in the channel flowed downstream, it was comprised of decreasing sediment concentration and particle size. Identification of a cause for the reduction lay outside the scope of their study, but Hubbart and Gebo (2010) postulated that the explanation could be due to either anthropogenic impacts, settling of larger particles as a result of variations in flow volume and velocity, or further erosion of particles suspended within the water column. In additional work in the Hinkson Creek Watershed, Freeman (2011) showed that urban study sites exhibited higher total concentrations of suspended sediment than headwater or suburban gauging stations.

However, the differences between the land use types were not statistically significant ($p > 0.05$). Freeman (2011) also found that samples collected from urban sites exhibited significantly ($p < 0.001$) lower values for mean particle size than headwater or suburban sites. Freeman (2011) concluded that sediment yield was likely correlated to land use, but that the difference in mean particle size could be attributable to either in-stream weathering or land use. While previous studies conducted in Hinkson Creek Watershed identified evidence of urban land use impacts on suspended sediment particle characteristics, all studies to date compared separate reaches of Hinkson Creek to one another. No previous study in Hinkson Creek Watershed specifically analyzed urban stormwater runoff for comparison to receiving waters. This suggested the need for more research on the contribution of sediment by urban catchments to receiving waters, thus supplying the impetus for the current work.

Objectives

Given the outcomes of previous suspended sediment investigations in the Hinkson Creek Watershed of central Missouri (Hubbart and Freeman, 2010; Hubbart and Gebo, 2010; Freeman, 2011), the objectives of the following investigation were to a) compare total concentration (µl/l), mean particle size (µm), silt volume (µl/l), and particle size class distribution between urban stormwater samples versus receiving water samples, b) compare particle distribution metrics between 17 urban stormwater sampling sites, and c) investigate the relationships of particle distribution metrics of urban stormwater sampling sites and specific land use characteristics of each sub-basin including drainage area (km^2), total impervious surface area (km^2), and percent imperviousness (%). Considering results from previous work, study results should provide quantitative evidence of a higher concentration of fine sediment from the urban environment relative to receiving waters. If true, this finding will hold important implications for urban receiving water body quality and aquatic ecosystem health.

CHAPTER II: METHODS

Study Site

Urban stormwater sampling sites were located within the Flat Branch Catchment (FBC), an urban sub-basin (approximately 10 km^2) of the Hinkson Creek Watershed (HCW, 231 km^2) with average impervious surface area of 31.4% (Table 1, Figure 1). Flat Branch Catchment includes more than 60% of the city of Columbia, population approximately 108,000 (USCB, 2011), and drains commercial, urban, and residential headwater areas consisting predominately of impervious and high to low density urbanized areas (MSDIS, 2005) (Table 2, Figure 1). Flow was monitored on Flat Branch Creek approximately 100 m upstream from the confluence with Hinkson Creek.

Hinkson Creek is classified as a Missouri Ozark border stream located in the transitional zone between Glaciated Plains and Ozark Natural Divisions (Thom and Wilson, 1980). The creek flows approximately 42 kilometers to its confluence with Perche Creek in a southwesterly direction, ultimately flowing into the Missouri River. Flow was monitored approximately 0.5 km upstream of the confluence of Hinkson and Flat Branch Creek at a United States Geological Survey gauging station (USGS-06910230) that has collected data intermittently since 1966. Based on analysis of climate data collected by the Midwestern Regional Climate Center from 1973 through 2012, average annual temperature and precipitation in Columbia, Missouri were approximately 12.5 ºC and 1041.9 mm, respectively. Soil types for both Flat Branch Catchment and the HCW range from thin cherty clay and silty to sandy clay in lower reaches to loamy till with a well-developed claypan in the uplands (Chapman et al., 2002).

Table 1. Hinkson Creek Watershed Land Use/Land Cover Summary, source: Missouri Spatial Data Information Service (MSDIS), 2005.

Land Use/Cover	**Count (pixel)**	**Area (hectare)**	**Percentage**
Impervious	12414	1117.26	4.81
High Intensity Urban	5752	517.68	2.23
Low Intensity Urban	35205	3168.45	13.63
Barren or Sparsely Vegetated	358	32.22	0.14
Cropland	29856	2687.04	11.56
Grassland	98768	8889.12	38.24
Deciduous Forest	64112	5770.08	24.82
Evergreen Forest	1642	147.78	0.64
Deciduous Woody/Herbaceous	878	79.02	0.34
Woody-Dominated Wetland	2851	256.59	1.10
Herbaceous-Dominated Wetland	221	19.89	0.09
Open Water	6247	562.23	2.42
Total	**258304**	**23247.36**	**100.00**

Table 2. Flat Branch Catchment Land Use/Land Cover Summary, source: Missouri Spatial Data Information Service (MSDIS), 2005.

Land Use/Cover	**Count (pixel)**	**Area (hectare)**	**Percentage**
Impervious	1296	116.64	12.72
High Intensity Urban	1681	151.29	16.49
Low Intensity Urban	4427	398.43	43.44
Cropland	48	4.32	0.47
Grassland	972	87.48	9.54
Deciduous Forest	1548	139.32	15.19
Evergreen Forest	106	9.54	1.04
Woody-Dominated Wetland	74	6.66	0.73
Open Water	39	3.51	0.38
Total	**10191**	**917.19**	**100.00**

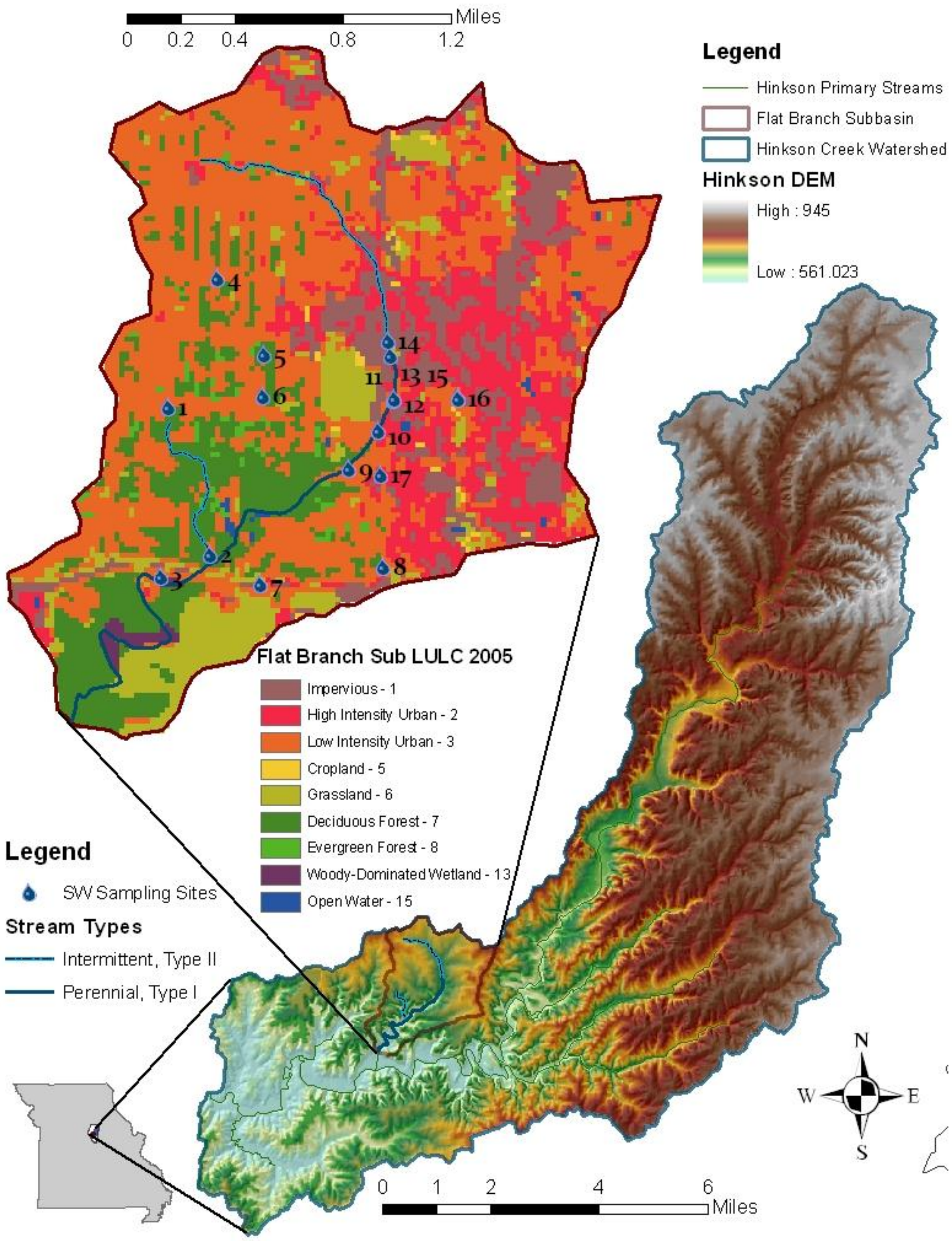

Figure 1. Flat Branch Catchment and 17 stormwater sampling sites, nested in the greater Hinkson Creek Watershed located in central Missouri, USA.

Urban Sampling Sites

Stormwater monitoring sites (n = 17) were located at urban drainage outfalls. A range of monitoring site locations were selected with varying characteristics to capture landscape heterogeneity and provide a basis for comparison to receiving waters Flat Branch and Hinkson Creeks. The urban sample site sub-catchments were quantitatively characterized by drainage area (ha), percentage imperviousness (%), and total impervious surface area (ha). Flow at urban stormwater sampling sites was not monitored in the current work. Table 3 lists monitoring sites numbered in order of drainage distance. Impervious surfaces included structure footprints, walkways, 8.5 m wide roads, and parking areas. Stormwater sampling sites 1 and 2; 4, 5, and 6; and 7 and 8 were nested sites. Sites 15 and 16 were paired sub-catchments co-located with sites 12, 13, and 14, which were nested above site 11 (Figure 1). Flat Branch Catchment was delineated using ArcGIS based on a 30 m digital elevation model (DEM) assisted by Hydrology Tools and Spatial Analyst in ArcGIS (Figures 2 and 3). The Missouri Spatial Data Information Service (MSDIS) was utilized for land use and land cover data for the study region. Channel mapping was conducted using National Hydrologic Data (NHD) provided by the United States Geological Survey (USGS), which classifies streams as type I Perennial, and type II Intermittent.

Table 3. Land use characteristics of urban stormwater sampling sites in Flat Branch Catchment in the Hinkson Creek Watershed, central Missouri, USA.

Site #	Total Impervious (ha)	Total Area (ha)	Impervious (%)
1	5.7	17.6	32.3
2	14	66.9	20.9
1,2*	19.7	84.6	23.3
3	1.6	7.9	20.3
4	7	23.7	29.6
5	12.5	41.7	30.1
6	5.5	22.2	24.7
4,5,6*	25	87.6	28.6
8	32.3	55.4	58.3
7	15.5	35.6	43.6
7,8*	47.8	91	52.6
9	1.1	2.8	39.7
10	9.1	15.6	58.2
17	6.5	11.2	58.5
15*	4	7.1	55.9
16*	14.6	21.8	66.9
12	18.9	23.5	80.4
13	3.4	3.6	95
14	149.9	322.3	46.5
11	10	17.1	58.4
**	200.9	395.6	50.8
Total	**311.8**	**696.1**	***Avg.*** **44.8**

Avg.= Average

*Nested Streams

**Sites 15,16 paired streams

**Sites 12,13,14,15,16 nested in 11

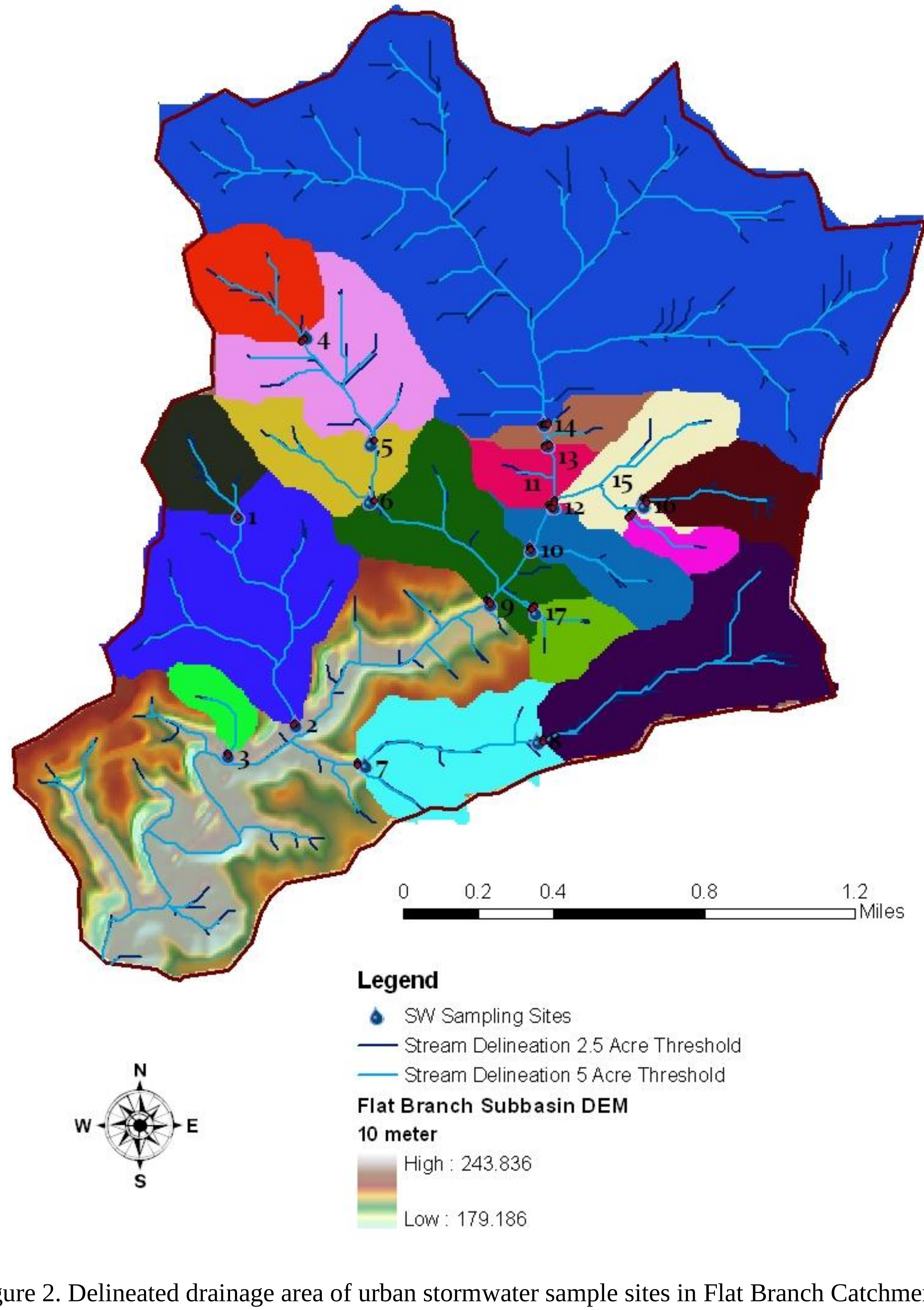

Figure 2. Delineated drainage area of urban stormwater sample sites in Flat Branch Catchment, Hinkson Creek Watershed, central Missouri, USA.

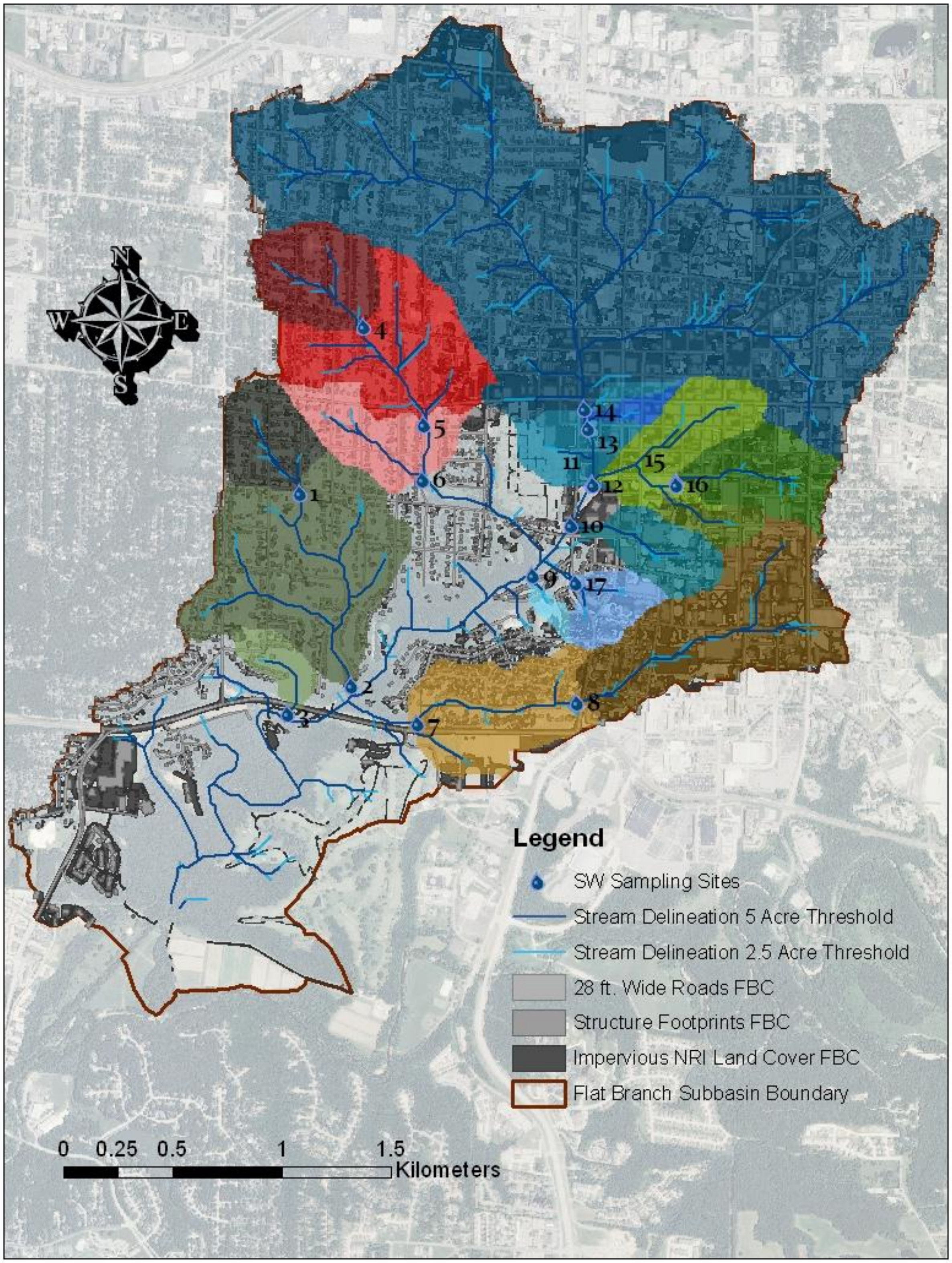

Figure 3. Urban stromwater drainage areas with impervious surfaces, structures, and roads in Flat Branch Catchment, Hinkson Creek Watershed, central Missouri, USA.

Event Sampling

Two liter grab samples were collected at each of the 17 urban stormwater sampling sites during 16 runoff-causing rainfall events (n = 272 stormwater samples) from February 24, 2011 to June 27, 2011. This time period corresponds to the historic wet season in Missouri (Nigh and Schroeder, 2002). Sites were sampled in the following order: 7, 8, 17, 15, 16, 12, 11, 10, 9, 14, 13, 4, 5, 6, 1, 2, 3. Order of sampling was determined so as to minimize travel time and limit the duration of the sampling process, which ranged from 1.75 to 2.5 hrs. Daily samples from Hinkson and Flat Branch Creeks were collected with Sigma automated water samplers. Only samples collected on the dates of the 16 precipitation events were used for sediment analysis comparisons with stormwater samples.

A LISST-Streamside was used for analyzing stormwater samples. Traditional methods of particle separation including dry or wet sieving, particle settling, or electrical resistance are often time and labor intensive, and can destroy natural aggregates (Gartner et al., 2001). After a series of 1970's papers suggested suspended particle size could be estimated from the scattering of light, several companies (CILAS, Leeds and Northrup, Malvern Instruments, and others) began developing research grade instruments capable of such measurement (McCave et al., 1986). Laser diffraction instruments measure optical scattering of light over a range of diffraction angles, providing a multiparameter measurement corresponding to a range of particle sizes (Agrawal and Pottsmith, 2000). Agrawal and Pottsmith (1994) developed a fully in-situ autonomous instrument, which led to production of the LISST (laser in-situ scattering and transmissometry) family of instruments distributed by Sequoia Scientific, Inc. LISST devices use a series of logarithmically-sized ring detectors to measure the angular scattering distribution of light diffracted by suspended particles (Gartner et al., 2001). Since development, LISST instruments have been shown to provide accurate measurements of particle size distribution and concentration (Traykovski et al., 1999; Gartner et al., 2001; Mikkelsen and Pejrup, 2001; Serra et al., 2001). Expressed in gravimetric units, the device operates at a resolution of < 1 mg/l (Sequoia Scientific, 2013). The device is capable of estimating particle size classes ranging from silt to very fine sand, 2.5 to 500 μm (Agrawal and Pottsmith 2000; Hubbart and Freeman, 2010). The device calculates total concentration as equivalent to the total volume of particles. Mean particle size is computed by the ratio of total particle volume to total particle area (Agrawal and Pottsmith, 2000). The LISST-Streamside partitions sediment less than 500 μm into 32 logarithmically-scaled particle size classes, and was therefore deemed appropriate for the current work to investigate if a higher concentration of fine sediment (i.e. silt fraction) may be transported from urban environments relative to receiving waters. Additional information regarding laser diffraction technology, the LISST family of instruments, and the LISST-Streamside specifically, can be found in Freeman (2011), and accessed via the Sequoia Scientific website (http://www.sequoiasci.com).

Data Analysis

Suspended sediment data were totaled for each precipitation event, analyzed independently, and also aggregated for the measurement period. To better investigate temporal trends in the sediment concentrations (e.g. initial sediment flushing) and thus increase meaningfulness of the analysis, the measurement period was split into two equal time periods (2/24/2011 to 4/25/2011; and 4/26/2011 to 6/27/2011) and compared. Additionally, as an exploratory analysis to provide a higher resolution assessment of seasonal changes in particle size class distributions, the study period was divided into eight smaller segments (2/24-2/27; 3/4-3/8; 4/22-4/25; 5/1-5/5; 5/12-5/15; 5/20-5/24; 6/13-6/17; and 6/27). Time period segments were delineated in this manner to group precipitation/sampling events occurring within a week of one another. Descriptive statistics were generated and accompanied by one-way analysis of variance (ANOVA) to detect significant differences ($p < 0.05$) between mean values of the three sites. In the event that significant differences between sites did occur, ANOVA was followed with *post hoc* multiple comparison tests of specific means using Tukey's honestly significant difference test (Smith, 1971). Investigation of relationships between land use characteristics (total impervious area, percentage imperviousness, drainage area) and particle metrics (average total concentration, silt volume, mean particle size) of the seventeen urban sampling sites was conducted via simple linear regression (Peck and Devore, 2012).

CHAPTER III: RESULTS AND DISCUSSION

Climate During Study

Climate from February 24, 2011 to June 27, 2011 was characteristically variable for the spring and early summer seasons in the Hinkson Creek Watershed. Total precipitation, average temperature, and average flow (Q) in Hinkson Creek were approximately 449 mm, 15 $^{\circ}$C, and 3.2 m^3/s, respectively (Table 4). Minimum flows differed only slightly between Hinkson Creek and Flat Branch Creek (HC: 0.15 m^3/s; FB: 0.05 m^3/s). Unsurprisingly, given substantial differences in drainage area, maximum and average flows of Flat Branch Creek showed considerable contrast to Hinkson Creek, which had values several orders of magnitude larger than Flat Branch (3.16 m^3/s vs. 0.19 m^3/s for average flow and 35.09 m^3/s vs. 1.86 m^3/s for maximum flow). Due to event timing and sampling logistics, not every precipitation event during the study period was sampled (Figure 4). Regardless, the large sample size (16 events x 17 sites = 272 distributed stormwater samples) provided compelling quantitative information supporting the method and pertaining to suspended sediment dynamics of the urban sites versus receiving waters of Flat Branch and Hinkson Creeks.

Table 4. Climate descriptive statistics encompassing the period of monitoring (February 24, 2011 to June 27, 2011) for Hinkson Creek Watershed, Missouri, USA. Where * = total.

	PPT (mm)	Ta (°C)	FB Avg Q (m^3/s)	HC Avg Q (m^3/s)
Mean	448.57*	15.19	0.19	3.16
Minimum	0.00	-3.50	0.05	0.15
Maximum	51.82	35.00	1.86	35.09
Std Dev	8.15	9.97	0.24	4.94

PPT = Precipitation, Ta = Air Temperature, Q = Flow, Std Dev = Standard Deviation
FB = Flat Branch Creek, HC = Hinkson Creek

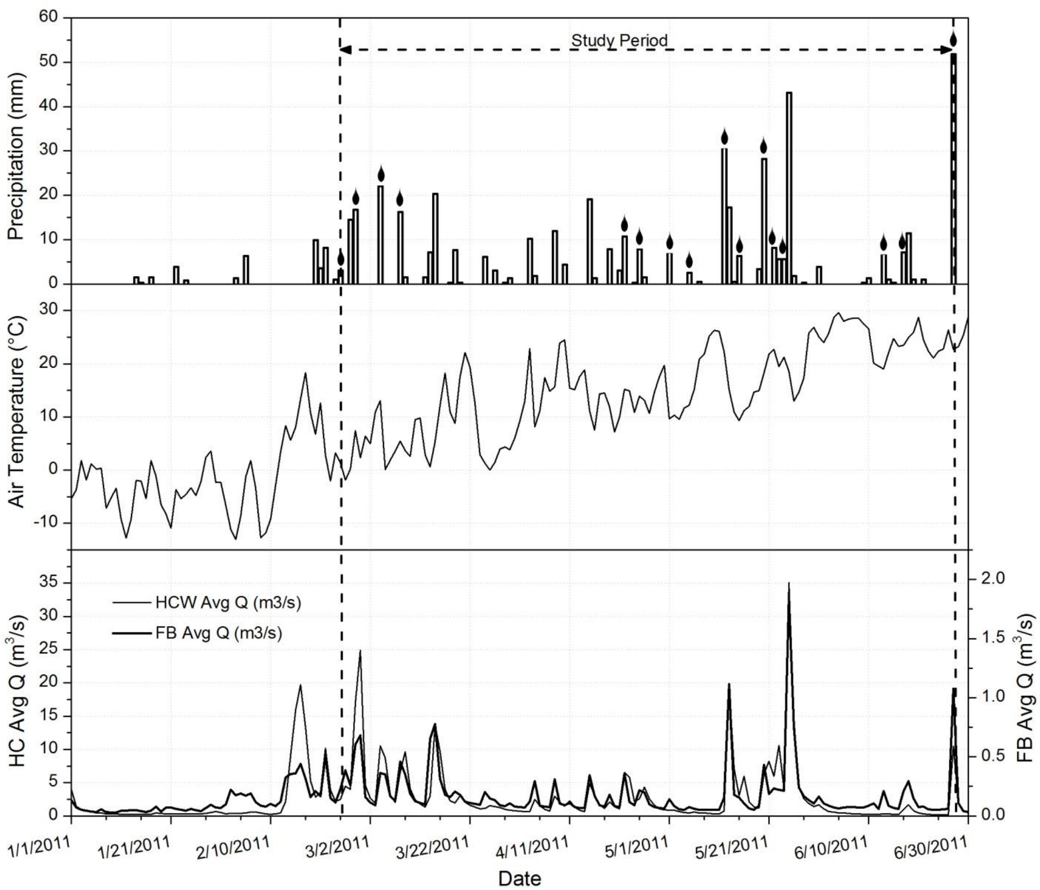

Figure 4. General climate encompassing the period of study (February 24, 2011 through June 27, 2011) for Hinkson and Flat Branch Creeks, central Missouri, USA. Raindrops in precipitation graph (top) indicate precipitation event sampled.

Receiving Waters and Urban Stormwater Comparison

Table 5 shows results of analyses comparing total concentration (µl/l), silt volume (µl/l), and mean particle size (µm) between urban stormwater samples, Hinkson, and Flat Branch Creek. Samples from Hinkson and Flat Branch Creeks had higher total concentrations of suspended sediment (323 µl/l and 319 µl/l, respectively) than the urban sites (205 µl/l). In the current work, Hinkson Creek and Flat Branch Creek also had higher silt volumes (173 µl/l and 148 µl/l, respectively) relative to the urban sites (124 µl/l). One-way ANOVA showed that, at the

0.05 significance level, the mean values for total concentration and silt volume were not significantly different ($p > 0.261$ and $p > 0.757$, respectively). However, a comparison of the ratio of silt volume to total concentration of suspended sediment from urban stormwater, Flat Branch Creek, and Hinkson Creek (60, 46, and 53%, respectively) indicated a disproportionate contribution of fine sediment from the urban environment to receiving waters. According to Tukey's *post hoc* multiple comparison test results, mean particle size of urban sites (59 µm) was significantly different ($p < 0.001$, CI = 0.05) from Hinkson (131 µm) and Flat Branch (167 µm) sites (Table 5, Figures 5 and 6).

Table 5. Descriptive statistics of suspended sediment parameters, comparing urban and receiving waters in Hinkson Creek Watershed, central Missouri, USA.

	Total Concentration (µl/l)	**Mean Size (µm)**	**Silt Volume (µl/l)**
SW Mean	205	59	124
SW Min	65	28	33
SW Max	376	144	304
SW Std. Dev	101	35	75
FB Mean	319	167	148
FB Min	15	19	1
FB Max	1924	292	1461
FB Std. Dev	510	95	361
HC Mean	323	131	173
HC Min	36	10	4
HC Max	1317	313	1293
HC Std. Dev	381	91	340

SW = Stormwater Samples (n=272)

FB = Flat Branch Creek (n=16)

HC = Hinkson Creek (n=16)

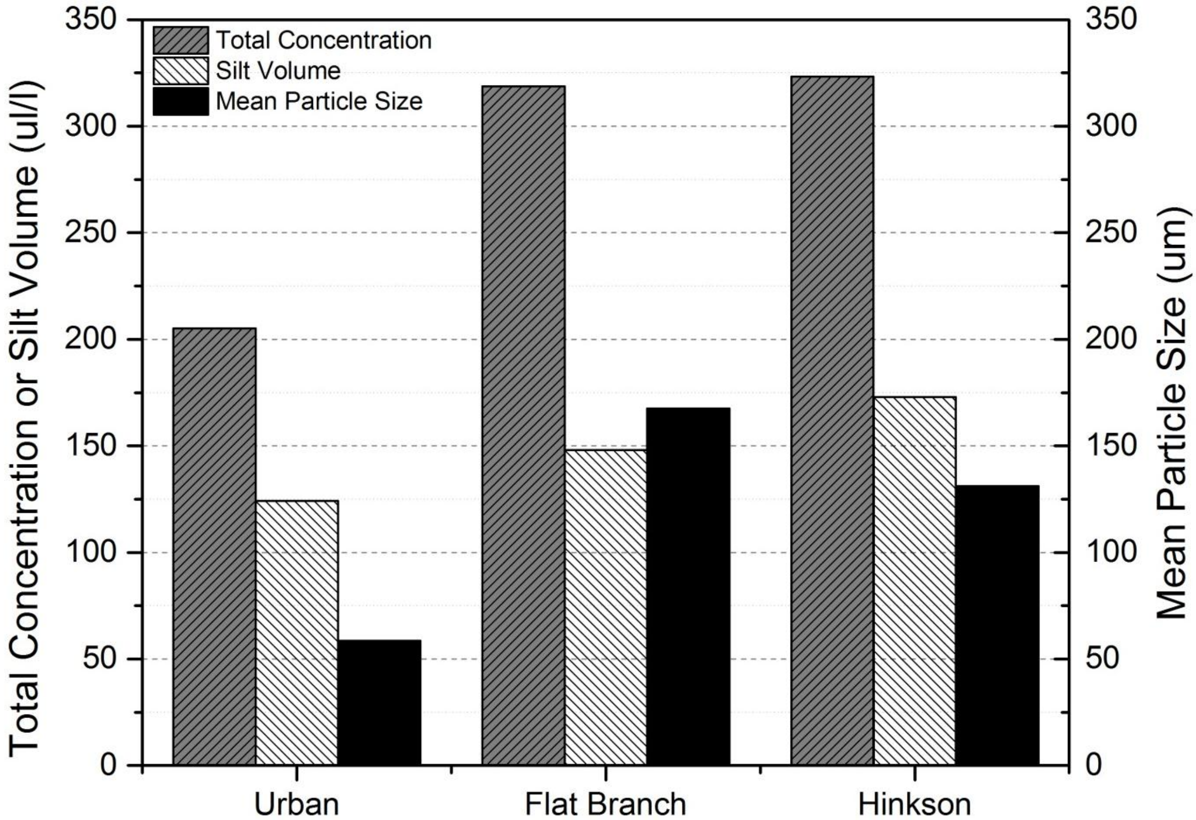

Figure 5. Comparison of suspended sediment parameters for urban sampling sites and receiving waters in Hinkson Creek Watershed, central Missouri, USA.

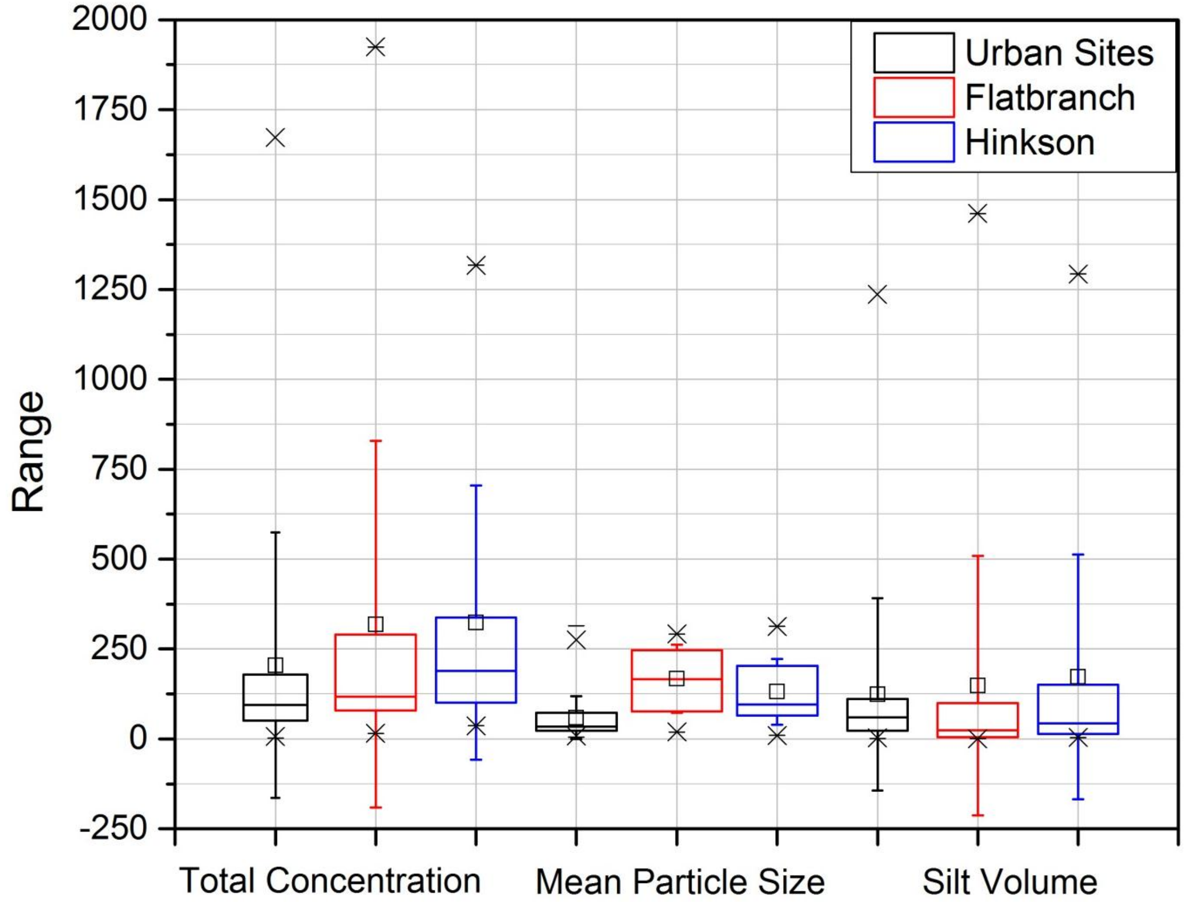

Figure 6. Boxplot of suspended sediment descriptive statistics for urban sampling sites and receiving waters in Hinkson Creek Watershed, central Missouri, USA (x denotes 99th percentile when above, and 1st percentile when below; negative sign denotes maximum when above, minimum when below; square denotes mean; whiskers denote one standard deviation).

Booth and Jackson (1997), and Hubbart and Freeman (2010) noted that urban land use could alter the sediment composition of receiving waters by contributing high concentrations of small particles. Specifically, Hubbart and Freeman (2010) identified a 450% increase in the concentration of the smallest size class (2 µm) in urban reaches of Hinkson Creek. Stormwater samples collected from the 17 urban sites contained significantly ($p < 0.001$) smaller particles, as demonstrated by a mean particle size more than 55% smaller than receiving waters. This result supports the findings of Freeman (2011), who showed that mean particle size was significantly smaller ($p < 0.001$) in urban reach samples relative to headwater or suburban reaches. While the results of Freeman (2011) could in part reflect the effects of stream distance and particle erosion processes, the results of the current work support the hypothesis that urban land uses may mobilize a disproportionate quantity of fine sediment relative to agricultural, rural, and wildland cover types (e.g. forest, grassland, and wetland), thereby highlighting the need for continued research.

The ability to quantify the disproportionate contribution of fine sediment from urban areas to natural watercourses is a novel benefit of the laser diffraction technology. Suspended sediment has traditionally been considered a non-point source pollutant. However, the novel method applied in this study (the coupling of laser diffraction technology with land use characteristics and hydroclimatic data) shows promise in terms of ability to identify anthropogenic sources of suspended sediment.

Urban stormwater runoff samples contained 35% less total sediment than samples from receiving waters. This is noteworthy because it is well accepted that too little suspended sediment can "starve" a watercourse, resulting in increased channel erosion, nutrient depletion, increased light penetration, and altered stream food webs (Walling, 2008; Biedenharn et al., 1997). Too little sediment can constitute an imbalance in an aquatic ecosystem. Within many fluvial systems exists a balance of forces, which determines rates of sediment erosion, deposition, and transport (Brooks et al., 2003). One method of describing such a balance is a dynamic equilibrium model, defined as a system in which interdependent compensatory variables change in relation to one another, thereby maintaining a condition sufficiently stable to preserve equilibrium (Bull, 1975; Brooks et al., 2003). Lane (1955) proposed a proportionality to illustrate the concept of stream dynamic equilibrium.

$$Q_S \times D_{50} \propto Q_w \times S$$

Where Q_s is sediment discharge, D_{50} is bed sediment median size, Q_w is stream flow, and S is stream slope. Alteration of any single variable could produce stream disequilibrium, and proportional changes in other variables. For example, increased stream flow (velocity and/or depth) could increase the tractive forces exerted by the water column on the stream bank and bed, thereby eroding more material and increasing sediment discharge (Biedenharn et al., 1997; Brooks et al., 2003). Likewise, decreased suspended sediment in a watercourse could increase stream flow velocity, thereby increasing in-stream erosion via channel scouring (Biedenharn et al., 1997; Brooks et al., 2003). Therefore, the contribution of sediment deficient urban stormwater could be leading to channel incision and bank erosion in Flat Branch Creek. Such effects could constitute further adverse impacts of urban land use on aquatic ecosystems.

In order to identify temporal trends in the sediment concentrations (e.g. initial sediment flushing), and to increase the resolution of the aggregated data, the wet season was split into two equal time periods (February 24, 2011 to April 25, 2011; and April 26, 2011 to June 27, 2011). Particle distribution metrics were not consistent throughout the study and showed key differences between the two study periods (Table 6). For example, in urban samples, silt volume declined from 134 µl/l to 118 µl/l, and mean particle size increased slightly from 57 µm to 60 µm during the study period. This finding may be indicative of normal winter deposition and spring flushing processes, the dynamics of which provide impetus for future work. Both Hinkson and Flat Branch Creeks exhibited declines in concentrations of the largest three particle size classes

(255.85 µm, 302.13 µm, and 356.79 µm) from the first period to the second (Figure 7). To improve graphical visualization, Figure 7 data were cubed-root transformed. No numerical analyses were performed on transformed data. Flat Branch Creek showed an increase in the concentrations of fine sediments (size classes 5.59 µm through 15.15 µm), as did Hinkson Creek, which also showed an increase in the concentrations of the four smallest size classes (2.06 µm through 3.39 µm). It is notable that in addition to providing general information regarding the effects of land use on suspended sediment particle size class composition, this study method may also be useful for identifying temporal trends in particle size class composition, which could be used to better understand the seasonality of sediment mobilization and transport.

The differences in sediment composition between the two sampling periods defined above are largely attributable to hydroclimate. The two periods of measurement were characterized by a 24% difference in total precipitation, with approximately 200 mm during the first period (February 24, 2011 to April 25, 2011) and 248 mm during the second period (April 26, 2011 to June 27, 2011). The first period was characterized by consistent precipitation and smaller events, while the second period was characterized by higher variability in precipitation, with a few large events separated by dry periods that corresponded to extended durations of low flow. Average flow (Q) for Hinkson Creek was 3.54 m^3/s during the first half of the measurement period (February 24, 2011- April 25, 2011) and 2.79 m^3/s during the second half (April 26, 2011- June 27, 2011) reflecting a reduction in flow of more than 20%. Higher flows accompanied by higher velocities are capable of mobilizing larger-sized particles, and holding higher particle concentrations in suspension. Thus, the dissimilarity of particle size distributions of samples from the two seasons (Figure 7) is likely, at least in part, a result of the creeks' capacities to suspend a higher proportion of large particles under higher flow conditions.

Although flow was not measured at the urban drainage outfalls, presumably similar hydrographs as receiving waters dominated the urban drainage sub-catchments. Though beyond the scope of the current work, future studies should include coupled flow urban suspended sediment monitoring and/or modeling.

Table 6. Descriptive statistics of average suspended sediment parameters of 17 urban sampling sites during different sampling periods in Flat Branch Catchment, central Missouri, USA.

Statistic	**Total Concentration (µl/l)**	**Mean Size (µm)**	**Silt Volume (µl/l)**
February 24 to April 25, 2011			
SW Mean	205	57	134
SW Min	94	29	33
SW Max	346	143	254
SW Std Dev	95	43	79
FB Mean	387	175	110
FB Min	77	34	2
FB Max	1134	292	329
FB Std Dev	406	99	129
HC Mean	355	163	136
HC Min	85	63	12
HC Max	1188	280	671
HC Std Dev	418	82	262
May 2 to June 27, 2011			
SW Mean	205	60	118
SW Min	65	28	43
SW Max	376	144	304
SW Std Dev	109	31	77
FB Mean	278	163	170
FB Min	15	19	1
FB Max	1925	287	1461
FB Std Dev	581	97	455
HC Mean	304	112	195
HC Min	36	10	4
HC Max	1317	313	1293
HC Std Dev	379	95	391

SW = Stormwater (Urban)

FB = Flat Branch Creek

HC = Hinkson Creek

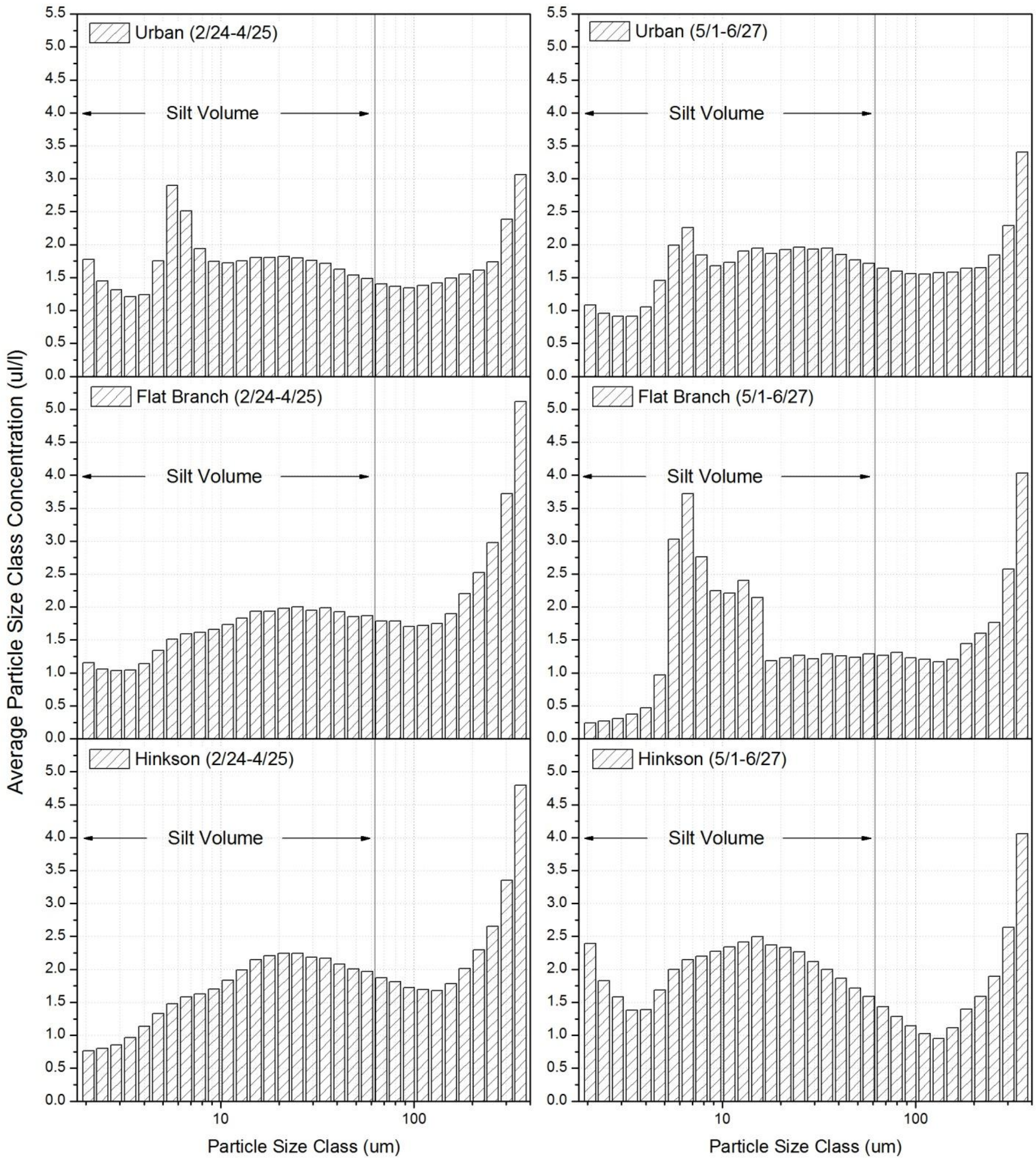

Figure 7. Average particle size class distributions (cube-root transformed) of urban stormwater sites and receiving waters in Hinkson Creek Watershed, central Missouri, USA; represented in two measurement periods.

Considering the primary role of climate in determining pollutant transport (Novotny and Olem, 1994) it is expected that differences in precipitation dynamics would correspond to the differences in suspended sediment concentration and particle distribution of the current study. The current work is distinct because it is one of the first studies to illustrate such dynamics using laser particle diffraction in an urban environment. Larger magnitude precipitation events are likely to mobilize more sediment and larger sediment particles due to increases in overland flow and higher velocities. Table 6 shows that, for the urban sites, total concentration (µl/l) and mean particle size (µm) increased from the first to the second period, while silt volume (µl/l) decreased. However, climate alone does not account for the contrasting pattern of the receiving waters, which instead showed decreases in total sediment concentration of more than 14% and 28% for Hinkson and Flat Branch, respectively. While mean particle size decreased by only 6% from one period to the next for Flat Branch, mean particle size of samples from Hinkson Creek decreased by more than 31%. Silt volume increased by more than 43% and 53% for Hinkson and Flat Branch, respectively. The particle size distributions shown in Figure 7 further illustrate this change. One possible explanation for this distinct result could be a "punctuated equilibrium" of sediment flux.

Hubbart and Gebo (2010) theorized the presence of a temporal punctuated equilibrium of sediment flux in Hinkson Creek, as opposed to a steady-state (i.e. constant concentration) flux. Clague (1986) used the term *punctuated equilibrium* to describe the Quaternary stratigraphic record of British Columbia, pointing towards extended durations of sediment accumulation, punctuated by brief depositional events. Similarly, Gomi et al. (2005) noted climate-driven cycles of accumulation and depletion of sediment supply. A hydrologic system characterized by a punctuated equilibrium would be subject to phases of sediment loading during periods of low flow, and sediment flushing during larger magnitude precipitation/flow events (Hubbart, 2012). Such a description closely matches the conditions present in this study. The consistent precipitation and flow of the first period, in addition to saturated soil conditions resulting from a relatively wet winter season, likely produced a system of sediment flux similar to the continual steady-state gradual flux model. Conversely, the high precipitation variability of the second period may have resulted in a punctuated equilibrium, wherein fine sediment mobilized during small precipitation events settled in the channel as a result of low flows, building up over time until a large event (e.g. May 12: 30.73 mm; May 25: 43.18 mm; June 27: 51.82 mm) flushed the accumulated sediment downstream, resulting in samples containing relatively higher concentrations of fine particles.

The observation of a temporal punctuated equilibrium of sediment flux in Hinkson Creek (Hubbart and Gebo, 2010) is further supported by comparison of particle size class distributions from the eight smaller study periods (Figures 8, 9, 10, and 11). While some periods exhibited little variation and relatively low sediment concentrations (periods 1, 2, 4, 5, and 7), others showed the high concentrations and/or specific size class spikes expected of sediment flushing events (periods 3 and 6 for Flat Branch, and periods 3 and 8 for Hinkson). Interestingly, flushing events did not occur on the same dates for the urban sites, and Flat Branch and Hinkson Creeks (periods 6 and 8). These results support the argument that climate is not the sole factor driving suspended sediment dynamics, but rather contrasting and competing upland and/or in-stream processes are contributing to suspended sediment flushing in the watershed. It is noteworthy that the meaningfulness of the analysis based on the eight study period segments should be carefully considered, as the sampled precipitation events, and therefore the eight study period segments, were not evenly distributed temporally.

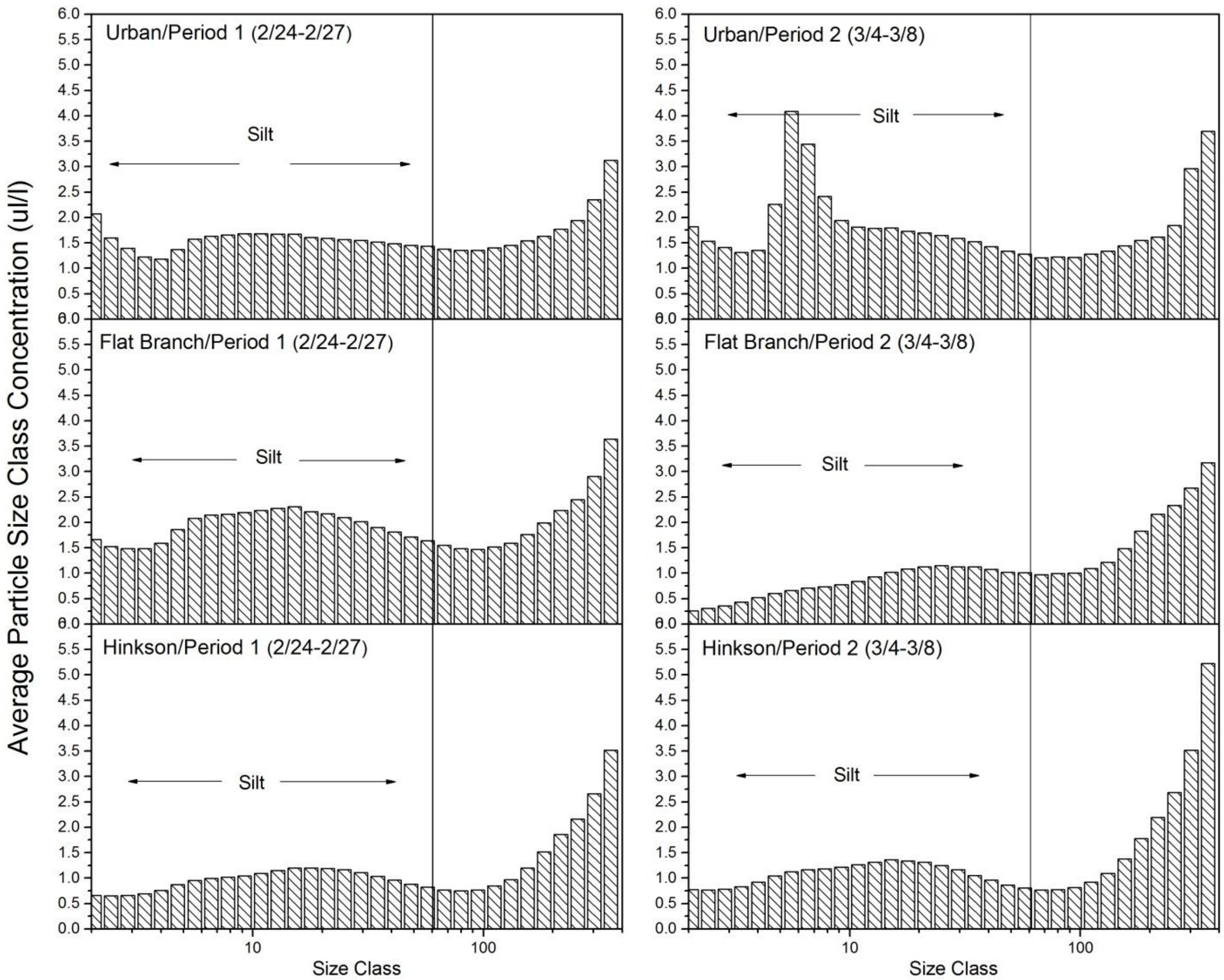

Figure 8. Average particle size class distributions (cube-root transformed) of urban stormwater sites and receiving waters in Hinkson Creek Watershed, central Missouri, USA, during periods 1 (2/24-2/27) and 2 (3/4-3/8).

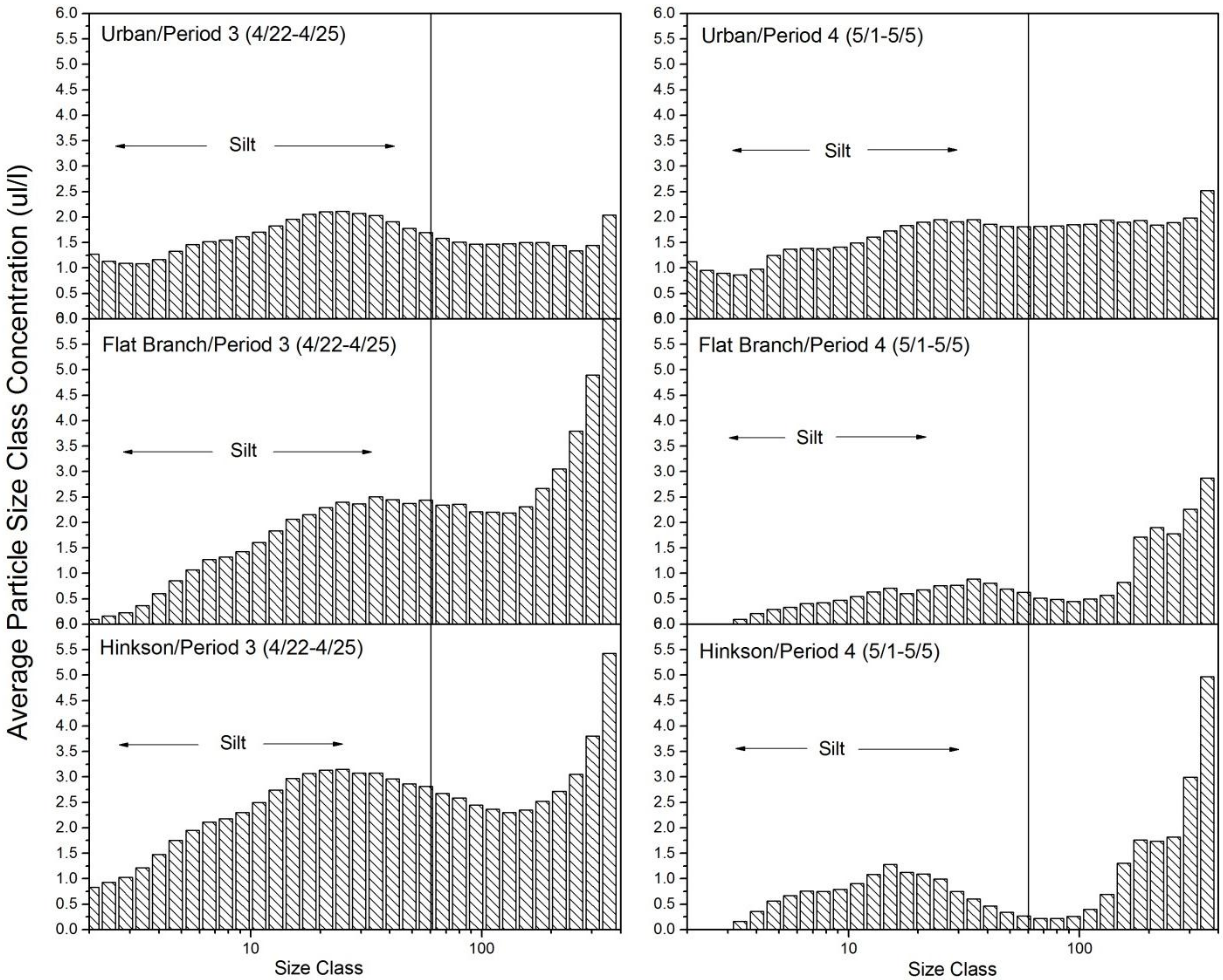

Figure 9. Average particle size class distributions (cube-root transformed) of urban stormwater sites and receiving waters in Hinkson Creek Watershed, central Missouri, USA, during periods 3 (4/22-4/25) and 4 (5/1-5/5).

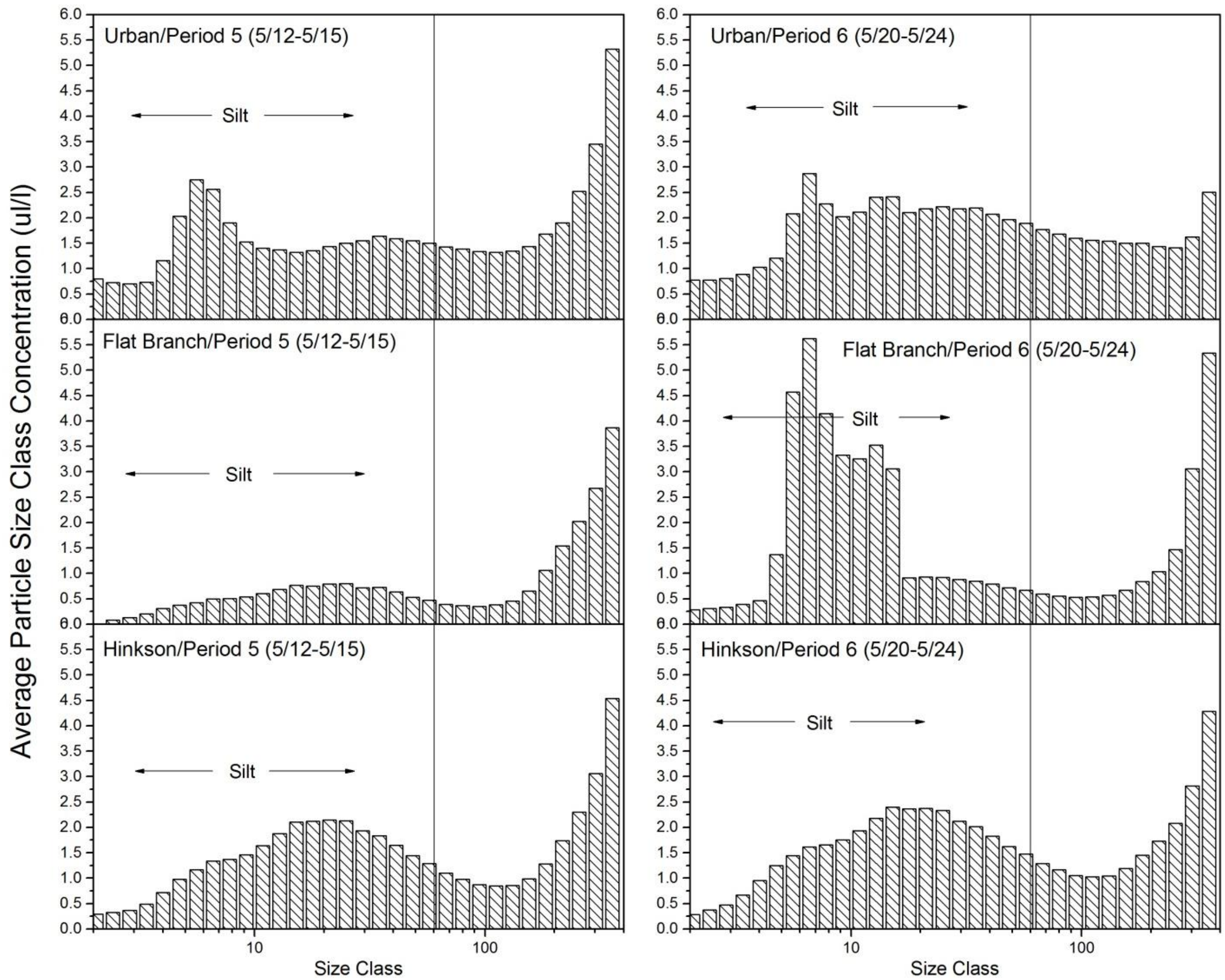

Figure 10. Average particle size class distributions (cube-root transformed) of urban stormwater sites and receiving waters in Hinkson Creek Watershed, central Missouri, USA, during periods 5 (5/12-5/15) and 6 (5/20-5/24).

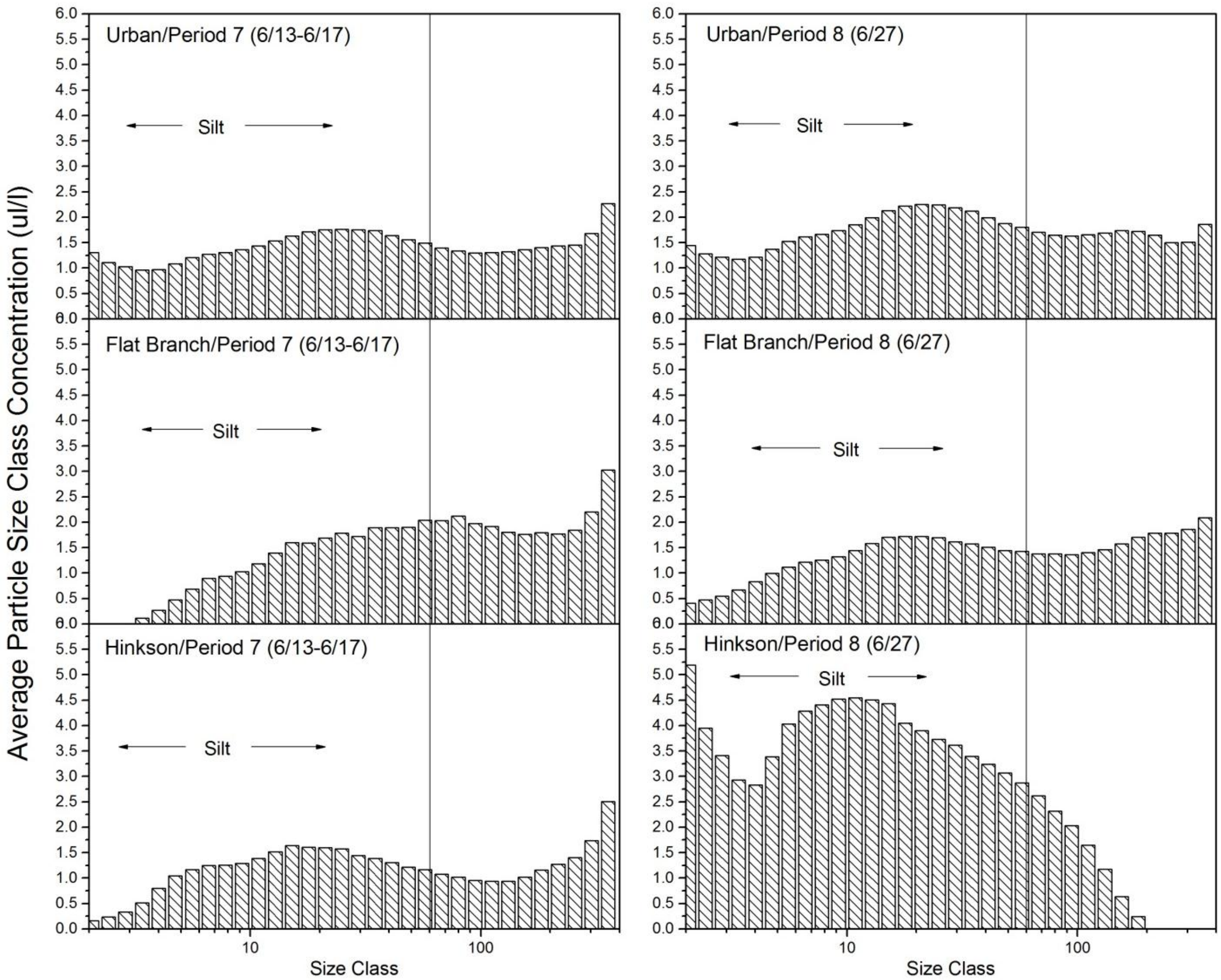

Figure 11. Average particle size class distributions (cube-root transformed) of urban stormwater sites and receiving waters in Hinkson Creek Watershed, central Missouri, USA, during periods 7 (6/13-6/17) and 8 (6/27).

Relative to receiving waters, particle size distributions for urban stormwater samples did not show marked differences between sampling periods (Figures 7, 8, 9, 10, and 11). This could be attributed to altered fluvial geomorphology of the urban drainage system. Whereas the channel beds of Hinkson and Flat Branch Creeks are comprised of sediment, gravel, and bedrock, the urban sampling sites were located at the outfalls of concrete drainage ditches and metal pipes. Such smooth-surfaced channels are predisposed to more laminar flow, and likely facilitate the accumulation of far less sediment during the “loading periods” than do the natural channel beds of the receiving waters, which are characterized by greater surface roughness and sinuosity. Greater surface roughness and channel meandering yield slower velocity at higher flows, which in turn results in settling of larger quantities of sediment (Brooks et al., 2003). Moreover, water retention ponds and reservoirs likely serve to buffer the urban sub-catchments’ sediment yield against climate-driven fluctuations.

Previous research in the watershed (Hubbart and Gebo, 2010; Freeman, 2011) identified increases in fine-grained sediment in urban/downstream locations relative to headwaters. The results of the current work support those findings. One possible explanation for these observations is in-stream weathering of sediment. Sediment is mechanically weathered via abrasion as it is transported through fluvial networks (Sklar et al., 2006). This process, in combination with preferential deposition, can in some cases lead to a pattern of downstream fining (Heller et al., 2001). Vannote et al. (1980) proposed the “river continuum concept”, which describes river systems in terms of physical and biological gradients from headwaters to mouth. Given the results of previous studies, it is conceivable that a particle size gradient exists with increasing stream distance within Flat Branch and Hinkson Creeks. Therefore, the contribution of large concentrations of fine sediment in the lower reaches of the watershed via urban stormwater may not be as ecologically detrimental as results from the current study might otherwise suggest. According to the “river continuum concept”, aquatic communities suited to predominantly fine sediment may have evolved in downstream reaches. Conversely, previous studies have shown that resupply of poorly-sorted grains from terrestrial sources commonly off-sets the process of downstream fining (Heller et al., 2001; Sklar et al., 2006). However, in the case of the Hinkson Creek Watershed, resupply by disproportionate amounts of fine-grained sediment from urban stormwater, as opposed to the naturally poorly-sorted grains, would constitute a compounding excess fine sediment problem. Such questions provide impetus for future work in the watershed.

Urban Stormwater Inter-Site Comparisons

Particle distribution metrics (average total concentration, mean particle size, silt volume) of the 17 individual urban stormwater sampling sites exhibited considerable variability (Table 7). Linear regression analysis showed relatively weak correlations between single land use factors and particle metrics (Appendix A). The r^2 values for nine separate regressions (each land use parameter versus each particle metric) ranged from < 0.01 to 0.17. However, when regression analyses were performed on specific ranges of the land use parameters and particle metrics, stronger correlations were found. For example, a connection between percentage imperviousness (≤ 30%) and mean particle size (r^2 = 0.66). However, after 30% imperviousness, increasing noise in the data reduced the reliability of the relationship. This could be due to decreased amounts of available sediment in some areas characterized by a large portion of impervious surfaces (Colosimo and Wilcock, 2007). Silt volume was also found to be related to percentage imperviousness (≤ 30%) (r^2 = 0.67). Specifically, the particle size classes from 4.73 to 29.46 µm displayed r^2 values ranging from 0.52 to 0.68 when regressed with imperviousness (≤ 30%). Interestingly, larger and smaller size classes did not show the same correlations. Drainage area (< 10 ha) also exhibited correlations with certain particle size classes. The r^2 values for particle size classes 41.08 to 216.7 µm ranged from 0.51 to 0.96, with an increasing upward trend. The limitation of this correlation to small sub-catchments could be due to issues of scale. Increasing scale is commonly accompanied by increasing complexity in the mosaic of land use types.

These results support the findings of Klein (1979), Booth and Jackson (1997), Brown et al. (2005), and Fitzgerald et al. (2012), all of whom reported links between land use area (e.g. imperviousness and drainage area) and alterations of stream hydrology and water quality. For example, Klein (1979) reported observable aquatic impairment at 12% and severe impairment at 30% impervious surface in an urban watershed in Maryland, USA. Booth and Jackson (1997) noted that 10% impervious surface area in a watershed produces a quantifiable, and thus definable, loss of aquatic ecosystem form and function. Similarly, the current work shows a connection between imperviousness and the contribution of fine sediment to the aquatic environment. However, the results of this study also support the work presented by Bledsoe and Watson (2001) and Colosimo and Wilcock (2007), who suggested that physical alterations in stream dynamics were affected by a combination of several different factors. In the current work, no single land use factor explained the urban sub-catchment observations. Imperviousness (≤ 30%) was shown to be correlated with fine sediment, while drainage area (< 10 ha) correlated strongly with larger particle fractions. Future works should address the mechanistic explanations for these observations, which were beyond the scope of this study.

Table 7. Average (n = 16 runoff events) particle distribution metrics for 17 urban stormwater sites in Flat Branch Catchment, central Missouri, USA.

Site #	**Total Concentration (µl/l)**	**Mean Size (µm)**	**Silt Volume (µl/l)**
1	195	132	63
2	333	108	221
3	120	85	68
4	101	45	76
5	118	39	91
6	264	43	167
7	168	37	126
8	131	44	100
9	145	56	47
10	142	67	94
11	168	40	121
12	98	29	80
13	157	60	104
14	356	83	91
15	210	46	145
16	430	39	334
17	350	49	183

Despite the high degree of variability in particle size class distributions from the 17 urban sites, the 99th and 1st percentiles of size classes 4.73 µm to 7.79 µm were centered at higher concentrations than most other classes (Figure 12). These size classes (including 9.2 µm to 12.83 µm) are also of interest because their 1st percentiles were not located at zero and were more consistently present in the samples collected from the urban sites relative to larger-sized particles. High concentrations of these size classes (4.73 µm to 12.83 µm) can also be observed in the distributions shown in Figure 7. Interestingly, these are the same size classes that comprise the high concentration of small particles visible in the second period Flat Branch Creek distribution (Figure 7), suggesting that the urban sub-catchments may have been the source of the increased fine sediment during the second measurement period. The particle size distributions are additional evidence that urban land uses may adversely affect aquatic ecosystems by mobilizing and transporting disproportionately high concentrations of fine sediment to receiving waters via urban stormwater.

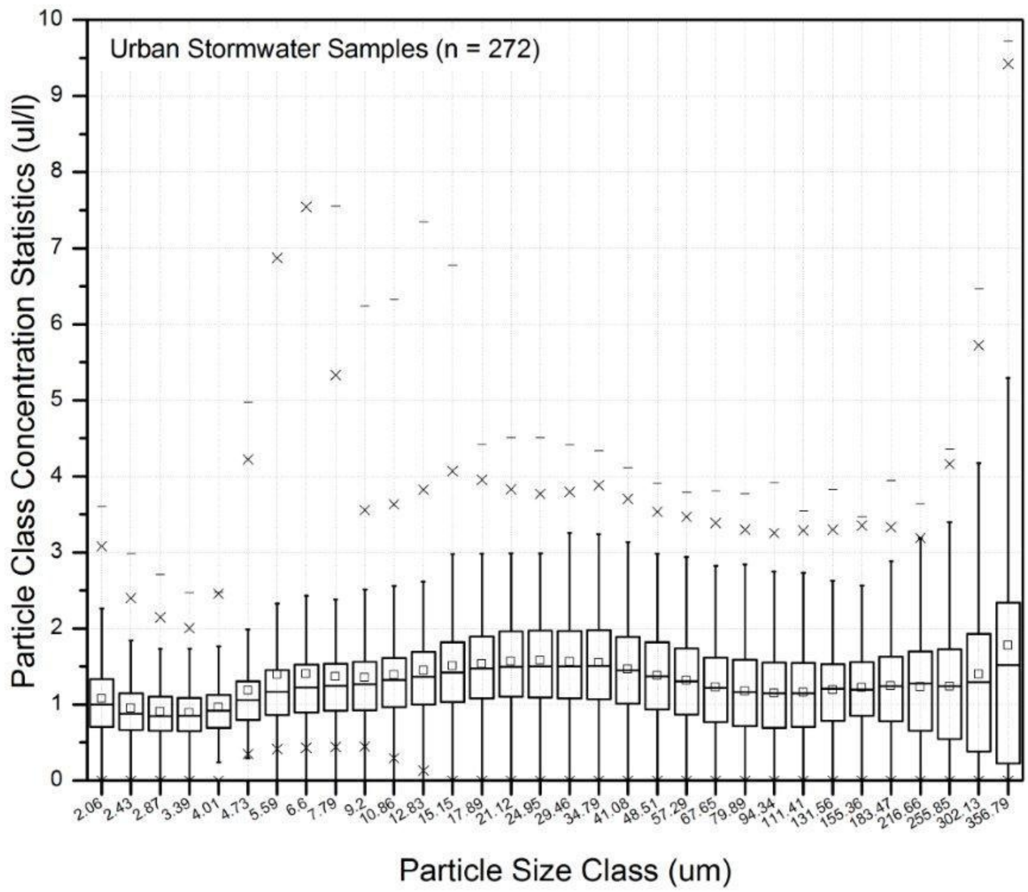

Figure 12. Boxplot of average particle size distributions of 272 urban stormwater samples collected in Flat Branch Catchment, central Missouri, USA (x denotes 99th percentile when above, and 1st percentile when below; negative sign denotes maximum).

Hubbart and Gebo (2010) showed that total concentration and mean particle size decreased with increasing stream distance. The current study did not identify that trend in the urban sampling sites (Table 7). The nested sub-catchments (i.e. sites 1 and 2; 4, 5, and 6; 7 and 8) provided an opportunity to track downstream changes in suspended sediment composition by comparing the particle distribution metrics between upstream and downstream sites. Downstream decreases in means of total concentration (µl/l), silt volume (µl/l), and mean particle size (µm) were not significant at the CI = 0.05 level. Trends at some sites, for some metrics did not exist. For example, sites 6, 5, and 4 showed no definable trend for mean particle size (43 µm, 39 µm, 45 µm, respectively). Though not statistically significant, some sites did show trends similar to those reported by Hubbart and Gebo (2010). For example, sites 6, 5, and 4 showed a decreasing downstream trend for total concentration (264 µl/l, 118 µl/l, and 101 µl/l, respectively) with a total decrease of more than 61%. Total suspended sediment concentration decreased from site 2 to site 1 by more than 41%. All of these sites showed similar reductions in silt volume from upstream to downstream sites. The explanation for these trends was unclear. The altered fluvial geomorphology of the lined surfaces and more laminar flow of the urban drainage system are unlikely to facilitate a large volume of sediment settling. The answer could be attributable to increased flow volume at downstream sites, which would result in diluted concentrations of suspended sediment. However, flow was not measured at urban stormwater sites in this study, providing impetus for future research.

Cumulative Suspended Sediment Comparisons

Figure 13 shows cumulative mass plots of suspended sediment [total concentration (µl/l), mean particle size (µm), and silt volume (µl/l)] based on overall averages of urban monitoring sites and receiving waters. The slopes of the urban vs. Hinkson and Flat Branch Creeks' trend lines for total concentration (µl/l) increased sharply after 1000 µl/l and 2500 µl/l, indicating a disproportionate contribution of total suspended sediment (≤ 500 µl/l). A similar trend was observed at approximately 3000 µl/l. The most visible difference between particle metrics was observed in mean particle size. Neither of the trend lines (urban vs. Flat Branch, urban vs. Hinkson) intersects nor parallels the 1:1 line, illustrating the disproportionate contribution of fine sediment from the urban environment. The concentrations of Hinkson and Flat Branch Creeks support the hypothesized threshold condition wherein events of a certain magnitude produce disproportionately stronger responses in sediment flux between systems. Moreover, the sharp increases in trend line slope of the total concentration and silt volume plots further support the possibility of a punctuated equilibrium in the receiving waters, where intermittent large precipitation events result in the punctuated flushing of deposited sediment. Although larger climate events produced correspondingly higher sediment flux within Hinkson and Flat Branch Creeks, these results indicate that on average, urban sites transported relatively consistent suspended sediment concentrations. This difference suggests buffering, perhaps by engineered structures (e.g. detention facilities). These results show clear alteration of urban flow and sediment concentration regimes relative to receiving water bodies, and justify the need for longer-term investigations that monitor both sediment size class concentration and flow. Figure 13 illustrates the potential of combined laser diffraction technology, land use characteristics and hydroclimatic data to identify detailed effects on the sediment size class composition of different watercourses by corresponding runoff-causing events.

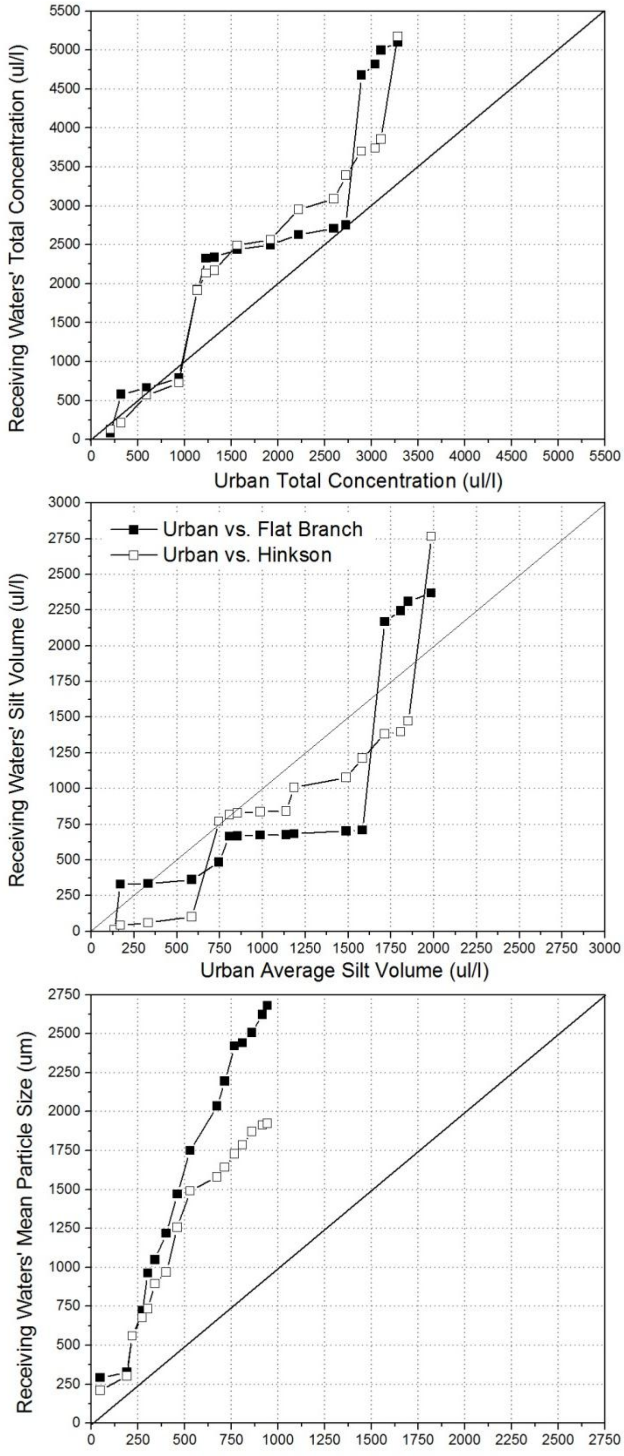

Figure 13. Cumulative suspended sediment metrics comparing urban sites to Hinkson and Flat Branch Creeks in central Missouri, USA.

Methodological Discussion

The current work utilized laser diffraction technology to analyze particle distribution metrics. While such technology is relatively fast and convenient compared to the often time and labor intensive traditional methods of particle analysis (e.g. dry or wet sieving), there are certain noteworthy limitations. Laser diffraction instruments estimate particle metrics utilizing an assumption of spherical particle shape (Agrawal and Pottsmith, 1994). Therefore, the presence in a water sample of particles lacking a spherical shape (e.g. clay particles, organic material) could lead to measurement error (Konert and Vandeberghe, 1997). To correct for such issues, initial laser diffraction measurements can be verified by comparing results to traditional methods (e.g. pipette). In the event that significant differences exist between laser diffraction and traditional measurements, the laser diffraction instrument can be calibrated for the monitoring site using local sediment samples of known volume (Gartner et al., 2001). However, it is important to note that such site-specific calibration can introduce additional error if an inadequate number of samples are collected and/or if samples are unrepresentative (Gartner et al., 2001). Issues associated with particles lacking a spherical shape can also be addressed by setting a coarser lower threshold for the silt fraction (e.g. 6.2 μm vs. 2 μm, as per Konert and Vandeberghe, 1997).

LISST devices utilize a series of logarithmically-sized ring detectors, which sense diffracted light over a given angular range (Gartner et al., 2001). The LISST-Streamside is engineered to estimate particle size classes ranging from 2.5 to 500 μm (Agrawal and Pottsmith, 2000). However, particles or aggregates larger than 500 μm can be included in the largest size class, leading to overestimation of the largest particle size class bin. Similarly, particles smaller than 2.5 μm (e.g. clay, organic material) can be pooled in the smallest particle size class resulting in overestimation (Agrawal and Pottsmith, 2000). Currently, no method of correction exists, providing impetus for future methodological improvements.

Given the assumption of normally distributed data (normality) by parametric tests such as one way ANOVA, used in the current work to test for significant differences between sites, suspended sediment data (average total concentration, mean particle size, and silt volume) were subjected to normality testing to verify statistical results. The Shapiro-Wilk test was chosen, which has been shown to be a powerful formal normality test (Shapiro and Wilk, 1965; Razali and Wah, 2011). Test results showed particle metric data for the three sites (urban stormwater, Flat Branch Creek, and Hinkson Creek) were not normally distributed (excepting mean particle size of Flat Branch Creek). However, additional normality tests showed that neither average flow of Hinkson and Flat Branch Creeks, nor the magnitude of precipitation events were normally distributed. Considering the fact climate is the primary driver of pollutant transport (Novotny and Olem, 1994), and climatic events are stochastic in nature, it may be unreasonable to expect suspended sediment data to follow a normal distribution. Therefore, the decision was made to analyze actual particle metric values, as opposed to analyzing transformed data.

Considering particle metric data were not normally distributed, a series of non-parametric statistical tests were run to verify the results of one way ANOVA. The Mann-Whitney U test was chosen, which has been shown to be an appropriate comparison test for samples that violate the parametric assumption of normality (Mann and Whitney, 1947). The non-parametric tests confirmed that mean particle size of urban stormwater was significantly different than Flat Branch and Hinkson Creeks ($p = 0.00$ and $p < 0.001$, respectively); and that differences in silt volume and average total concentration between the three sites were generally not significant at the 0.05 confidence interval. The only contrast between results from parametric and non-parametric tests was that Mann-Whitney results showed average total concentration of urban stormwater was significantly different than that of Hinkson Creek ($p < 0.02$). It is noteworthy however, that statistical research has shown replacement of *t*-type tests by non-parametric alternatives such as Mann-Whitney does not consistently improve the results of statistical testing (Zimmerman, 1987). These results support the decision to use one way ANOVA in the current work.

The current work reported particle metric values in volumetric units (µl/l) as opposed to the more traditional gravimetric (mg/l). While volumetric units are commonly converted to gravimetric units via a variety of methods (e.g. assumed particle density), recent studies have highlighted the difficulties associated with such conversion (Brown et al., 2012; Hubbart et al., 2013, in submission). Considering the additional error that could be potentially introduced by the use of common conversion methods, it is reasonable to consider the contextually appropriate application of the two indices. For example, questions of sediment loading and yield may be most appropriately addressed using mass/gravimetric methods, since the studies concern transfers of mass between systems (Walling, 1999; Wass and Leeks, 1999; Walling and Fang, 2003). Conversely, water quality questions, such as the effects of excess sediment concentrations on aquatic biota, may be more aptly addressed via volumetric methods, since the studies concern relative proportions of a given constituent within a water body. Notably, the labor and time saved by utilizing contemporary volumetric methods, and the degree of detail provided by such technology (e.g. particle size class analysis), constitute a cogent argument in favor of considering the volumetric parameter as a “stand alone” index for applications such as water quality, particle size class distribution, and in-situ monitoring.

CHAPTER IV: CONCLUSIONS

Suspended sediment is a primary cause of freshwater impairment (USEPA, 2006). Excess suspended sediment can threaten aquatic communities and jeopardize downstream structures (Keyes and Radcliffe, 2002; Campbell et al., 2005; Owens et al., 2005). Urbanization is linked to increased rates of sediment flux and changes in sediment particle size class and composition (Booth and Jackson, 1997). Considering the impact on the physical, chemical, and biological health of freshwater resources, there is a need for improved quantitative understanding of urban stormwater sediment contributions to receiving water bodies (Hubbart and Freeman, 2010; Hubbart and Gebo, 2010).

Stormwater samples were collected from 17 urban monitoring sites in the city of Columbia, and from two receiving water bodies, Flat Branch and Hinkson Creeks, in the Hinkson Creek Watershed, central Missouri, USA. Samples were analyzed for four particle distribution metrics: total concentration (µl/l), mean particle size (µm), silt volume (µl/l), and particle size class distribution. Urban stormwater samples contained approximately 35% less total sediment than receiving waters, indicating a possible reduction in the suspended sediment content of the receiving waters. The percentage of silt volume to total sediment volume for urban stormwater and receiving water bodies was 60, 46, and 53%, respectively. Urban samples also exhibited significantly different mean particle size ($p < 0.001$) with the lowest mean particle size (59 µm), which was more than 55% less than receiving waters. The particle size classes of 9.2 µm to 12.83 µm were consistently higher in concentration in urban stormwater samples relative to receiving waters. Fine sediment concentrations (4.73 to 29.46 µm) were shown to correlate with percentage imperviousness (≤ 30%), while larger particle fractions (41.08 to 216.7 µm) correlated strongly ($r^2 = 0.71$) with drainage area (< 10 ha). Particle distribution metrics in the receiving waters showed quantifiable changes from the first measurement period (February 24, 2011 to April 25, 2011) to the second (April 26, 2011 to June 27, 2011), with silt volume increasing by more than 43% and 53% for Hinkson and Flat Branch Creeks, respectively. These changes in suspended sediment dynamics from the first period to the next, and comparison of particle size class distributions from eight smaller period segments, suggest the potential presence of a climate-driven punctuated equilibrium in receiving waters, as opposed to the more consistent suspended sediment concentrations transported in urban runoff. A number of urban sites exhibited decreases in total concentration and silt volume between upstream and downstream locations by as much as 61%.

Results provide compelling evidence that urban stormwater runoff contributes disproportionate quantities of fine sediment to receiving water bodies, while simultaneously starving watercourses via reduced total sediment concentration. The results emphasize the need for continued research on urban stormwater utilizing stage-dependent automated sampling methods. This study provides science-based quantitative information from an urbanizing watershed for land and water resource managers seeking to address the impact of urbanization on aquatic ecosystem health and freshwater resources.

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APPENDIX A:

Results of Regression Analysis of Land Use Characteristics and Particle Metrics for 17 Urban Sampling Sites

Regression	Pearson's r	r^2	Adj.-r^2
Avg. Total Conc. Vs. Total Imperv.	0.364	0.13249	0.07466
Avg. Total Conc. Vs. Drainage Area	0.39308	0.15451	0.09814
Avg. Total Conc. Vs. % Imperv.	-0.00362	1.31E-05	-0.06665
Silt Vol. Vs. Total Imperv.	-0.07963	0.00634	-0.0599
Silt Vol. Vs. Drainage Area	-0.06077	0.00369	-0.06273
Silt Vol. Vs. % Imperv.	0.11808	0.01394	-0.0518
Mean Part. Size Vs. Total Imperv.	0.15149	0.02295	-0.04219
Mean Part. Size Vs. Drainage Area	0.23253	0.05407	-0.00899
Mean Part. Size Vs. % Imperv.	-0.41623	0.17324	0.11813