

Using Sediment Particle Size Class Analysis to Better Understand Urban Land-Use Effects

Jason A. Hubbart

University of Missouri
Department of Forestry
203-Q ABNR Building, Columbia
Missouri, USA, 65211.
United States of America

Abstract

A nested-scale experimental watershed study design was used to demonstrate rainfall-runoff and sediment particle size class variability in a representative urbanizing watershed in central Missouri, USA. On average, sediment particle size classes were almost twice as large (2.0 to 500 μ m size range) in headwaters, relative to an urban setting. Eighty percent of total sediment in the headwaters was between 216 and 357 μ m but only 40% in the urban setting. A 13.2 mm rainfall event resulted in a doubling of streamflow 1.4 m³/s to 2.9 m³/s but resulted in more than quadrupling the concentration of particle size classes ranging from 0.2 to 67.65 μ m. Results illustrates the need to better understand fine particle suspended sediment concentrations in surface runoff from urbanizing systems relative to that flowing from agricultural and/or forest environments. Future work holds important implications for understanding the effects of urbanization on sediment loading, aquatic ecosystem health, and water quality.

Keywords: Land-use, sediment, particle size class, urbanization, water quality

1.0 Introduction

Restoration of water quality in impaired watersheds requires understanding the complex interconnections between hydrologic processes, climate, land-use, water quality, ecology, and human socioeconomics. Unfortunately, information regarding those relationships is often inadequate or absent. A lack of technology and analytical tools has contributed to imprecise decision-making resulting in a lack of progress towards identifying and prioritizing mitigation strategies. It is therefore not surprising that intense debates are taking place in communities, globally, regarding the magnitude and implications of water quality problems and the potential for natural resource restoration and sustainability (Law et al. 2008).

Pollution transport from diffuse sources is most often driven by meteorological events (i.e. precipitation). Precipitation events are, therefore, highly correlated to pollutant loadings from a given watershed (Novotny and Olem 1994). Suspended sediment is one of the main causes of water quality impairment in freshwater systems (USEPA 2006). Sediment is a naturally occurring and necessary element in stream ecosystems. Either a lack or an excess of stream sediment can be equally damaging to stream geomorphologic and ecological functions. Streams deprived of sediments can experience increased channel erosion, habitat degradation, nutrient depletion, and significantly altered biological health (e.g. fish populations).

For example, increased light penetration due to lowered turbidity can reduce primary productivity thus breaking down the stream ecosystem food web, and give non-native, sight feeding fish a competitive advantage over native species (Kondolf 1997). Sediment also provides a valuable nutrient source for invertebrate populations (Dodds and Whiles 2004, Koirala 2009). However, excess fine sediment can fill the interstitial spaces of gravel in spawning beds; reduce available oxygen needed by fish embryos, and cause gill inflammation and eventual death to young and susceptible fish (Kondolf 1997). There is a need to better understand natural and anthropogenic sediment loading processes, with particular focus on fine particle classes, especially given the potential for smaller sediments to be transported from expanding urban landscapes. Unlike many other water quality constituents of concern, identification of sediment impaired watercourses is complicated since sediment in streams and rivers has both natural and anthropogenic sources. Consequently, quantifying the level of impairment and thus mitigation efficacy is confounded by a lack of understanding of background (i.e. pre-settlement) sediment loads.

In most urban stream systems land use changes in the watershed over time have dramatically altered the hydrology and sediment loading to the system. Urban systems are often the least resilient to additional perturbation due to compounded effects of development including (but not limited to) increased imperviousness, removal of vegetated canopies, and natural depressions, which are graded to a uniform slope (Brooks et al. 2003). Following construction, impervious surfaces impede infiltration and most rainfall becomes runoff. Natural drainage systems become rapidly overwhelmed, incising the stream channel, eroding banks, and increasing downstream discharge. Effects to water quality are often first observed in altered sediment loading regimes. The ability to quantify those effects using in-situ particle size class instruments may provide valuable insights towards improving future management and policy initiatives.

Turbidity measurements are the most common means for determining suspended sediment concentration (SSC) (Pruitt 2003). However, accuracy can be much improved by conducting gravimetric analyses of manually collected water samples or by automatic water samplers (Edward and Glysson 1999, Davis 2005). Gravimetric methods involve filtering the sediment from a known sample volume using a vacuum filtration process (ASTM 2007). Using a series of different sized filters, information about particle size distribution of the sample can be obtained. However, sample collection and laboratory analyses using these methods tend to be prohibitively expensive, complex, labor intensive, and prone to human error (Gray and Gartner 2009).

1.1 Laser Particle Diffraction

Recent innovations in suspended sediment monitoring include fully automated in-situ devices capable of continuously sensing and logging suspended sediment concentrations and particle size classes. Commercially available instruments include those that use bulk optics, acoustics, pressure differentials, and laser optics. Bulk optics instruments measure the turbidity of the water, where turbidity is an expression of the optical properties of the water that cause light to be scattered and absorbed rather than transmitted directly through solution (Gray and Gartner 2009). Other instruments currently used to quantify SSC include acoustic backscattering technology, portable Acoustic Doppler Current Profilers (ADCP) (Gray and Gartner 2009) and Laser Diffraction analyzers (Agrawal and Pottsmith 2000).

Laser Diffraction instruments measure optical scattering of light over a wide range of angles, providing a multi-parameter measurement corresponding to a wide range of particle sizes (Agrawal and Pottsmith 2000). Laser diffraction instruments use specially constructed detectors that detect light scattering effects of particles of individual particle size classes. The total volume of particles is used to estimate total concentration independent of particle density or size distribution. Laser diffraction instruments also estimate mean particle size by computing the ratio of total particle area to total particle volume. Notably, many laser diffraction instruments estimate a volumetric concentration (i.e. $\mu\text{l/l}$) of sediment as opposed to a mass concentration (Agrawal and Pottsmith 2000), and therefore require estimates of particle density to make the mass conversion to mg/l .

1.2 Particle Size Class Detection: The LISST Streamside

One of the most recent LD instruments available on the market is manufactured by Sequoia Scientific, Inc. (Seattle, WA, USA). Laser In-Situ Scattering and Transmissometry (LISST) instruments were originally developed for marine sediment studies but the technology has evolved for deployment in freshwater systems. The LISST-StreamSide is designed for monitoring sediment in shallow rivers, streams, and ponds (Figure 1). A pump is placed in the water body to pump water to the particle analyzer for analysis. After analysis the water sample is returned to the source, thus, eliminating handling and lab processing of the sample. The LISST-StreamSide senses particle sizes ranging from 1.9 to 387 μm (note: $1\mu\text{m} = 3.95 \times 10^{-5}\text{inch}$). Validation studies of the LISST indicate that the instrument is able to estimate particle class density within an accuracy of plus or minus 10 to 20%, with greater accuracy for smaller particle classes (Agrawal and Pottsmith 2000, Gartner et al. 2001). The dynamic range of the LISST is 1:200. Therefore, the largest size that can be measured is 200 times the smallest size. This range is spread out over 32 ring detectors that are logarithmically spaced such that each upper size bin is 1.18 times the lower size. For example, the ring that represents 5 μm covers a range of 4.7 – 5.54 μm , while with larger particles, the ring that represents 200 μm covers a range of 179.2 – 211.5 μm . Therefore, the ring that detects larger particle size has a much broader sensitivity range as compared to smaller size classes, thus reducing resolution and accuracy (Gartner et al. 2001). There are many reasons for this configuration including design considerations to maximize the number of individual size classes while minimizing error. One result is higher accuracy at smaller size classes, and reduced resolution of larger particle size classes.



Figure 1. Example LISST deployment.

The following case study was undertaken to quantify particle distribution during the month of March 2010 under conditions of typical spring rainfall in an Ozark border stream of central Missouri, using a nested-scale watershed study design to test the effects of land-use on sediment regime. A sub-objective was to characterize particle size class distribution during a typical spring rainfall event. The LISST-StreamSide provides high resolution SSC and particle size distribution data that are not achievable through traditional methods of sediment sampling. Therefore, results were expected to provide newly quantified relationships between rainfall, runoff, particle size class concentrations and land-use. The ability to quantifiably distinguish these relationships by laser particle diffraction would be a truly novel approach to achieving improvements to water quality. It is worthy of mention that methods and information generated from this work are widely adaptable to other regions, globally.

2.0 Methods

2.1 Case Study: The Hinkson Creek Watershed, Central Missouri, USA

In the state of Missouri, USA, more than 350 water bodies have been identified as impaired or limited for a variety of beneficial uses since 2000. This figure is 15% higher than the national average of 25% fresh water impairment per state. This is particularly significant considering Missouri is one of nine central U.S. states that contribute more than 75% of upland nitrogen and phosphorus entering the Gulf of Mexico, U.S. (Alexander et al. 2008). The Hinkson Creek Watershed (HCW) is located within the Lower Missouri-Moreau River Basin (LMMRB) in central Missouri (Figure 2). The HCW was instrumented with a nested-scale experimental watershed study design in the fall of 2008 to study contemporary land-use and urbanization effects on hydrologic processes, water quality, and localized land-use effects on climate and biological community health. In general, nested watershed study designs use a series of sub-basins within a larger watershed to study environmental variables and partition land-use types to facilitate quantification of land-use effects. Sub-basins are often partitioned based on dominant land-use and characteristics of the hydrologic system (Capel et al. 2008). A nested watershed study design enables researchers to quantifiably ascertain the influencing patterns and processes observed at each location (Pickett et al. 1997, Hubbart et al. 2007, Karwan et al. 2007). Each of five fully automated gauging stations monitors stage as well as a complete suite of climate variables. Instrumentation in the HCW is complimented by a United States Geological Survey gauging station (USGS-06910230) that has collected data intermittently since 1966 (Figure 1, site 4).

Hinkson Creek flows through a catchment basin of approximately 231km². The creek flows approximately 52km in a southwesterly direction to its confluence with Perche Creek, ultimately flowing into the Missouri River. Elevation ranges from 177m at the confluence of Perche Creek to 274m above mean sea level (msl) in the headwaters. 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). Average annual temperature and precipitation is approximately 14°C and 980mm, respectively. Soil types range from loamy till with a well developed clay pan in the uplands (Chapman et al. 2002) to thin cherty clay and silty to sandy clay in lower reaches. Urban areas are primarily residential (ca. 108,000 residents) with progressive commercial expansion. Land-use for the entire watershed is approximately 34% forest, 38% pasture and crop land, 25% urban area, with the remaining land area in wetland, open or shrub/grassland areas. Table 1 lists the land-use area (assuming five land-use divisions) and stream length for each of the nested treatments, as well as the entire watershed.

Table 1. Total and cumulative contributing (km), and land-use (%) areas and stream length for each of five monitoring gauge sites in the Hinkson Creek Watershed, Missouri, USA.

Cumulative Contributing Area	Total Area (Km ²)	Stream Length (km)	Wetland/Open Water (% Area)	Urban (% Area)	Forest (% Area)	Shrub/Grassland (% Area)	Pasture/Crop (% Area)
Monitoring Site 1	77	20	2	5	36	2	55
Monitoring Site 2	101	27	2	6	36	2	54
Monitoring Site 3	114	32	2	11	36	2	49
Monitoring Site 4	180	40	2	16	36	1	44
Monitoring Site 5	206	49	2	23	34	1	39
Watershed Area	231	52	2	25	34	1	38

In 1998, the Missouri Department of Natural Resources (MDNR) identified a portion of the LMMRB as critical for controlling erosion and nonpoint source pollution (MDNR 2006). Watershed restoration efforts in the LMMRB were accelerated by mandates of the Clean Water Act (CWA) and subsequent law suits. Hinkson Creek watershed is representative of the LMMRB with respect to hydrologic processes, water quality, climate and land-use and was one of the first water bodies in Missouri to be placed on the Clean Water Act (CWA) 303d list of impaired waters.

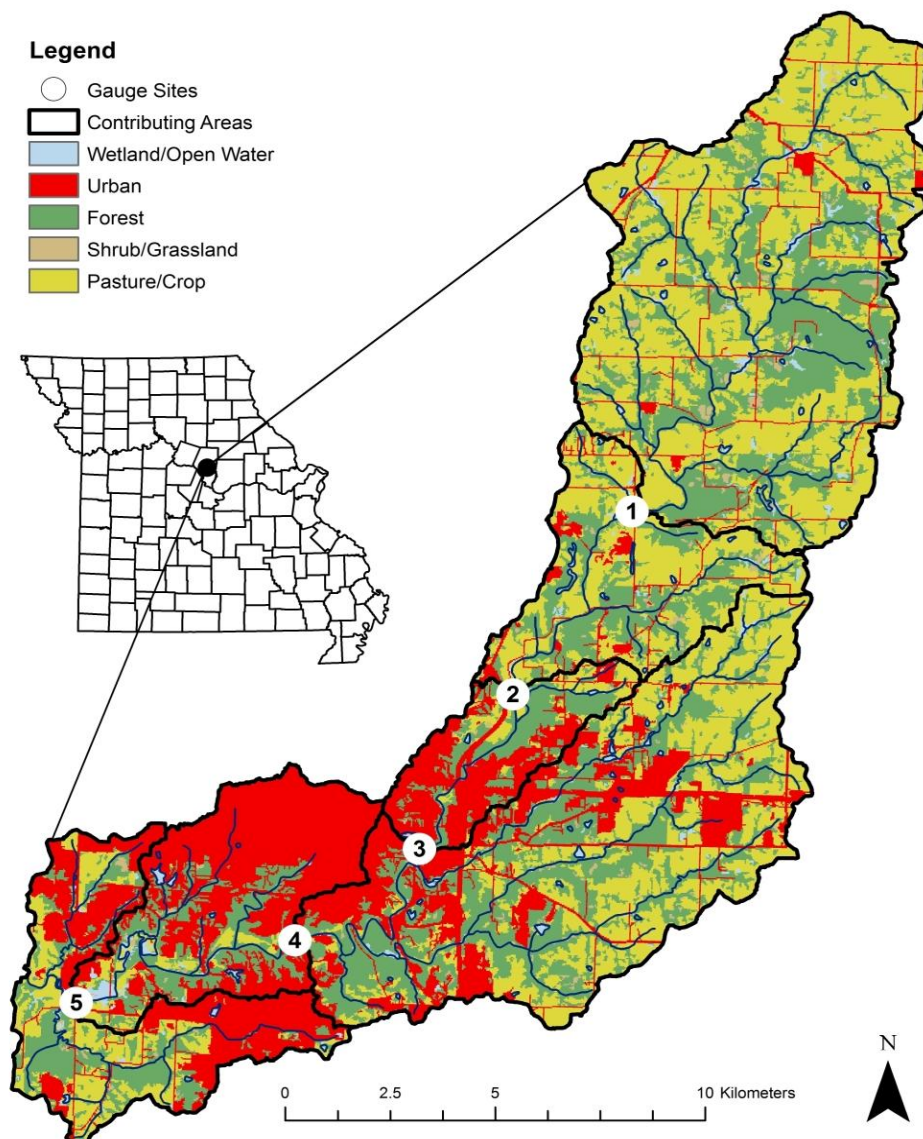


Figure 2. Locations of five permanent gauging stations in the Hinkson Creek Watershed, Missouri, USA. sites one, three, and five are the location of the particle analyzers used in the current study.

2.3 LISST Analyses Protocol

2.31 Grab Sampling for Monthly Analysis

Grab samples (2000 ml) were collected at regular times four days/week (Monday, Wednesday, Friday, Saturday) at sites one, three, and five (Figure 2) in the HCW during the month of March 2010 and used for particle size class analyses. Samples were collected in an upstream direction from the streambank using a swing sampler, as to avoid disruption of bottom sediments. All samples were stored at a temperature of 4 °C and processed within seven days of collection. Water samples were run through the LISST in the laboratory. Sampling specifications are easily programmed through a graphics touch display on the LISST. Primary analyses settings include a pre-sampling background check, which allows for automatic calibration of the instrument using deionized or other clean water sources, and sampling duration. For the current work 30 second sample durations (approximately 0.6 liters) were used to optimize sampling accuracy. Precipitation and flow were measured at the site four climate station and USGS stage monitoring site. The total contributing area draining to sites one, three and five is 77 km², 114 km², and 206 km² respectively. In general, sites one and three are primarily forested and agricultural/pasture lands, while site five is approximately 25% urban, much of which is high-density (~40-60% impervious surface) (Table 1).

2.32 Event-Based Sampling

A LISST Streamside was deployed at site four (Figure 2) in the HCW during the dates of March 27th through March 31st 2010 to analyze water samples during a typical spring rainfall event. Water samples were run through the LISST on an hourly basis. 60 second sample durations (approximately 1.1 liters) were used to optimize sampling accuracy. Precipitation and flow was measured at the site four climate station and USGS stage monitoring site. The total contributing area draining to site four (LISST location) is 180 km². Land use draining to site four is dominated by pasture and cropland comprising 44% of the land area, followed by 36% forests and 16% urban with the remaining being evenly distributed between shrub/grassland and wetlands or open water. Local area surrounding site four is primarily low intensity development.

3.0 Results and Discussion

3.1 Month of March Analysis

Weather during the month of March 2010 was typical for the central Missouri wet season (Figure 2). Average temperature and average stream flow during the month of March was 7.5 °C and 2.4 m³/s respectively. Total precipitation for March was 72 mm. Five appreciable precipitation events occurred during the month, with an average event depth of 12.4mm. Of the five events, three were larger events concluding on March 10th, 21st, and 28th with average precipitation of 16.2 mm. These events yielded notable peak flows averaging 16.3 m³/s, and ranging from 7.1 to 28.6 m³/s (Figure 3, climate graph). Peak flows resulted in two large sediment transport events following the March 10th and 22nd precipitation events (Figure 3, sediment graphs).

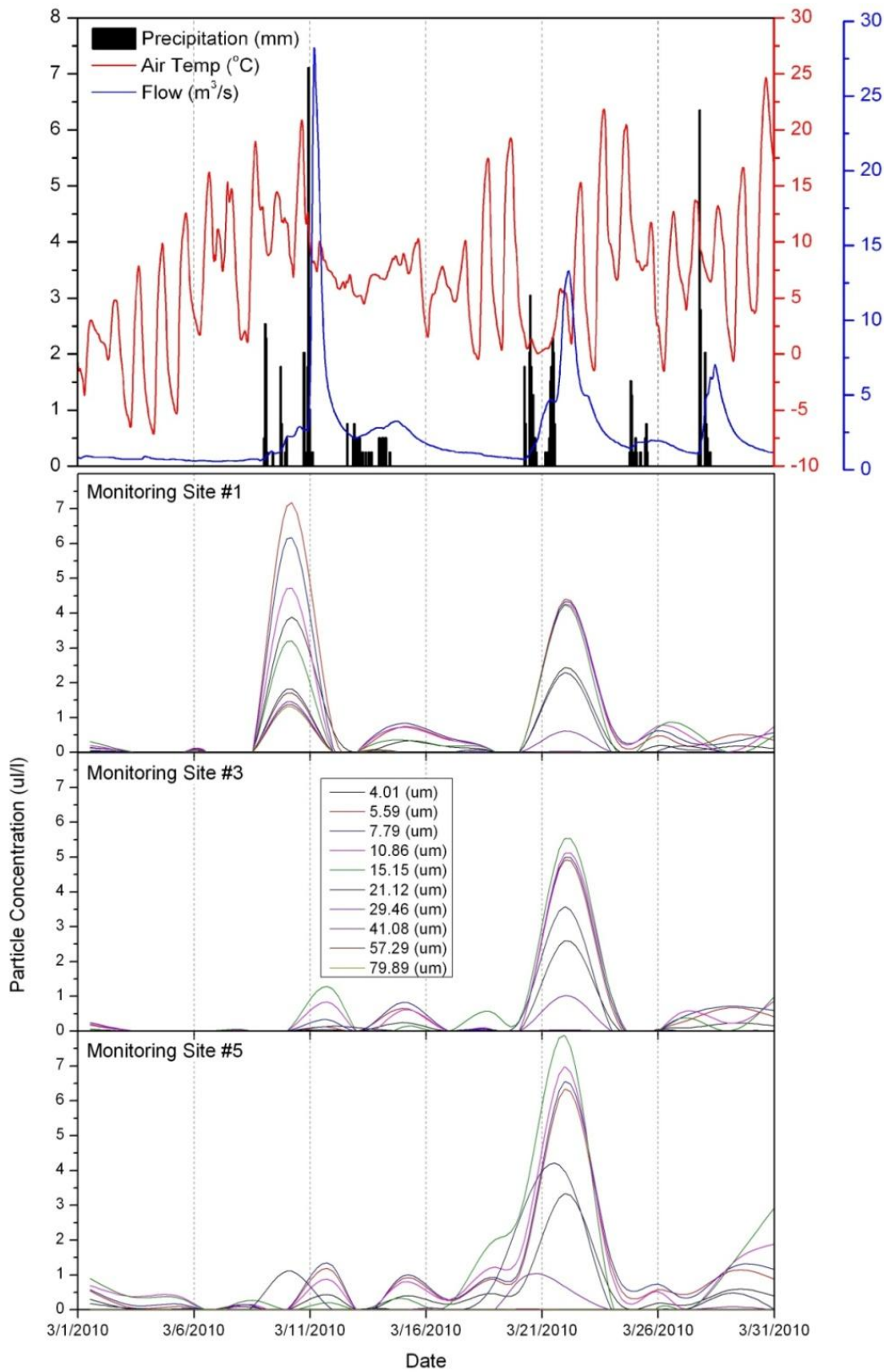


Figure 3. Precipitation and streamflow (top), and select sediment particle classes measured at sites one, three, and five in the Hinkson Creek Watershed, Columbia, Missouri, USA.

Figure 4 shows typical post-storm flow conditions in March 2010 at each of the three nested monitoring sites of the current study where average total concentration of sediment ($\mu\text{l/l}$) at monitoring sites one, three and five was approximately 51, 25 and 27 $\mu\text{l/l}$ respectively.

Corresponding mean particle size was approximately 213, 168, and 119 μm respectively (Figure 5). Average total concentration of suspended sediment subsequent to the March 10th and 22nd peak flow events at the three monitoring sites was approximately 83, 41 and 47 $\mu\text{l/l}$ and 47, 56 and 72 $\mu\text{l/l}$ at sites one, three and five respectively. It is notable that total sediment concentration was at least twice as high at monitoring site one relative to sites three and five subsequent to the March 10th event, while this relationship was reversed subsequent to the March 22nd precipitation event (Figure 3).

There were no appreciable precipitation events prior to the month of March in 2010. Therefore, March weather produced the first large sediment fluxes of the year, providing an opportunity to examine the effects of heavy spring rains on a sediment primed system and variation in particle class separations at different locations in the watershed. Results indicated a flux of sediment, in particular larger particle sizes, at site one following the March 10th precipitation event. The magnitude of the site one sediment flux subsequent to the March 10th event was twice the sediment flux concentration at sites three and five. Whether this result was due to land use or varying precipitation regime throughout the watershed provides impetus for future investigation. However, since the sediment load did not occur at sites three and five subsequent to the first major precipitation event, it is conceivable that larger particles settled from suspension prior to reaching sites three and five, which are 12 and 29 km downstream, respectively, from site one. This may also help to explain the sediment flux observed subsequent to the March 22 precipitation event during which a larger fraction of sediment was detected at site five.



Figure 4. Typical post-rainfall event stage on March 28th 2010 at monitoring sites one, three, and five (from the top to bottom), in the Hinkson Creek Watershed, Columbia, Missouri, USA.

Given sufficient time and runoff volume, larger sediment particle classes will be transported out of the watershed. However, it should also be considered that larger sediment may be eroded in transit, thus being reduced in size and potentially detected as smaller particles at the watershed terminus. Despite clear trends in the results, precise quantifiable variation in particle analyses, including total concentration and particle size classes, cannot be achieved with the sampling regime used in the current work. The findings here, however, point to the potential of LISST devices (or similar such devices) to provide new information that could be improved with higher resolution data (e.g. daily or hourly).

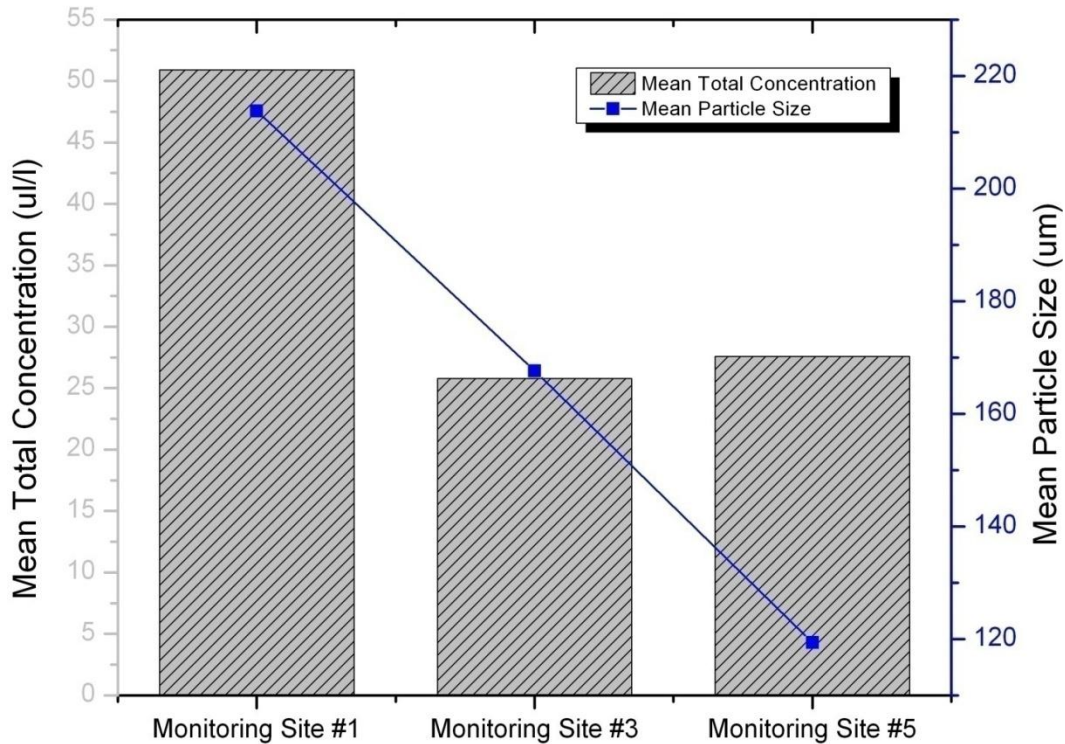


Figure 5. Mean concentration (u/l), and mean particle size (um) for the month of March 2010 at three permanent monitoring sites located in the Hinkson Creek Watershed, Columbia, Missouri, USA.

Total sediment concentrations were higher at monitoring site one subsequent to the March 10th precipitation event. In general, at sites three and five, the ratio of smaller size classes to larger size class particles decreased such that total suspended sediment was primarily composed of finer particles at site five. This previously unquantified information may be attributed to either naturally occurring or anthropogenic effects, discussed previously in this article. However, exacting the mechanisms associated with these results is beyond the scope of the current analysis and requires evaluation of higher resolution time-series data over a longer period of time. Figure 6 shows a cube-root transform of average monthly data from each monitoring site. It is of interest to note the gradual change from a higher number of larger particle size classes at site one to a higher concentration of smaller size classes at site five. This relationship may be better visualized as percent of total concentration by the lumped particle size classes shown in pie charts (Figure 7). Figures 6 and 7 show a clear shift in particle size classes corresponding with linear stream distance and land use changes proceeding from site one.

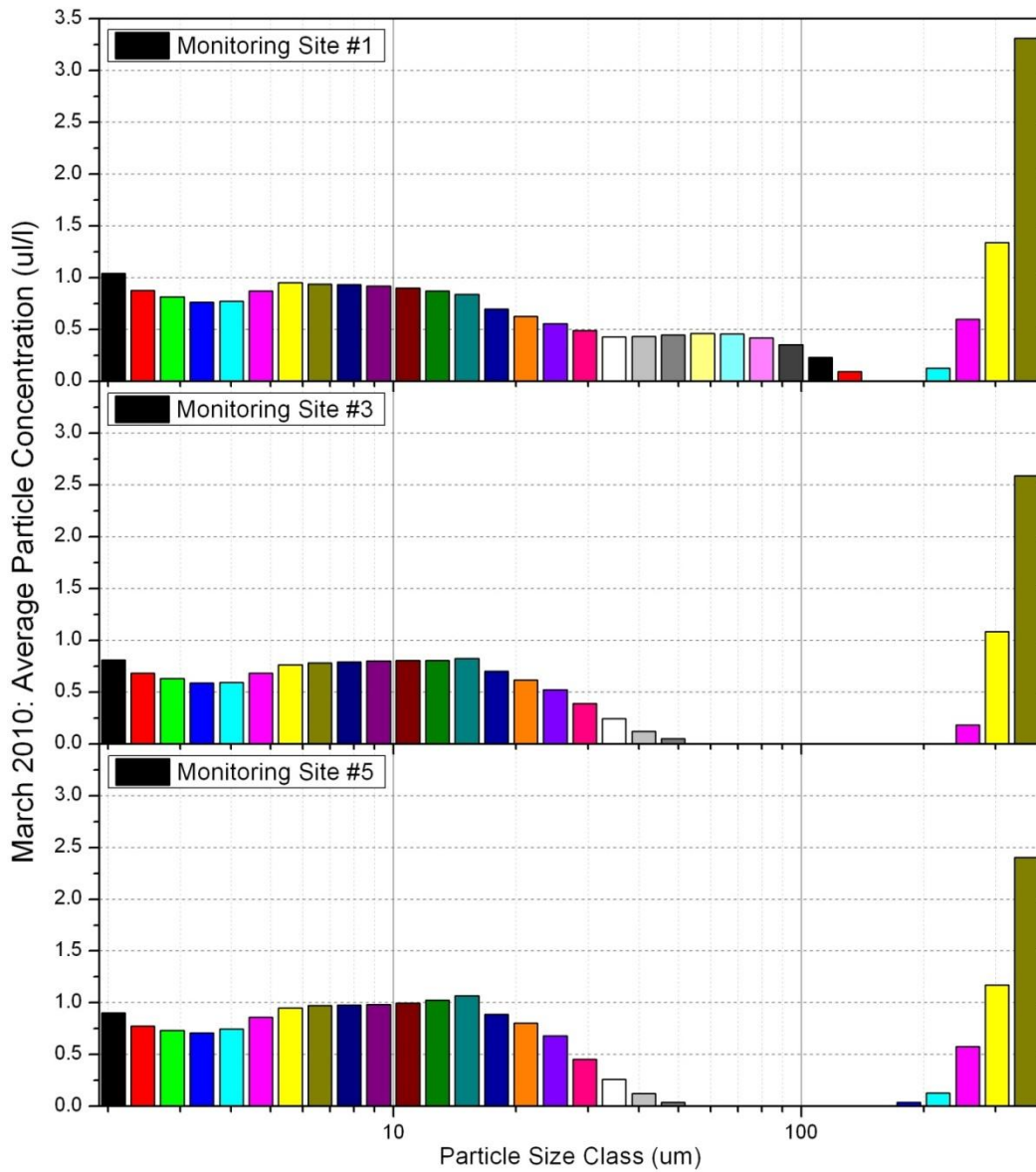


Figure 6. Average particle class concentration (µl/l) pre- and post-storm particle size class concentrations (log₁₀) shown by cube-root transform in the Hinkson Creek Watershed, Columbia, Missouri, USA.

As expected there was a dramatic increase of PSC concentrations with increased flow (Figure 2). However, concentrations of fine particles are on average quantifiably higher relative to large particle classes at sites three and five relative to site one (Figures 6, 7). Further, the ratios of large to small size class concentrations appear to be negatively correlated between land-use types and flow events, depending on the location in the watershed (e.g. forest or agriculture land-use vs. urban). These ratios have not been previously quantified in the Midwest and are seldom available anywhere globally, further illustrating the potential of the LISST to significantly improve the knowledge base of sediment and particle size class transport processes and land use effects.

Figure 7 shows that the largest particle classes (lumped: 216.66 to 356.79 µm) comprised almost 80% of the total concentration of suspended sediments at site one during the month of March 2010, whereas this size class comprised only 58% (on average) of the total concentration at site five. At site five smaller PSC’s comprised almost 40% of the total concentration. This result points to a potential punctuated equilibrium of sediment flux in this system, such that the movement of sediment depends on event magnitude and the ability to transport the sediment. The sediment will therefore settle until subsequent events of sufficient magnitude to move it occur. This relationship is well illustrated in Figure 8, which shows the percent change of average PSC concentration between the sites further indicating a transition from larger particle classes at site one to smaller particle classes at site five.

It further implicates land-use effects, such as those produced by agriculture and/or greenfield (i.e. undeveloped) development, which may incite erosion of larger particle classes relative to urban and re-development lands which preferentially diffuse smaller particle classes due to preexisting compaction and increased impervious surface cover. This finding holds important implications as smaller particle classes could instigate a greater degree of stream ecosystem damage compared to larger particle classes.

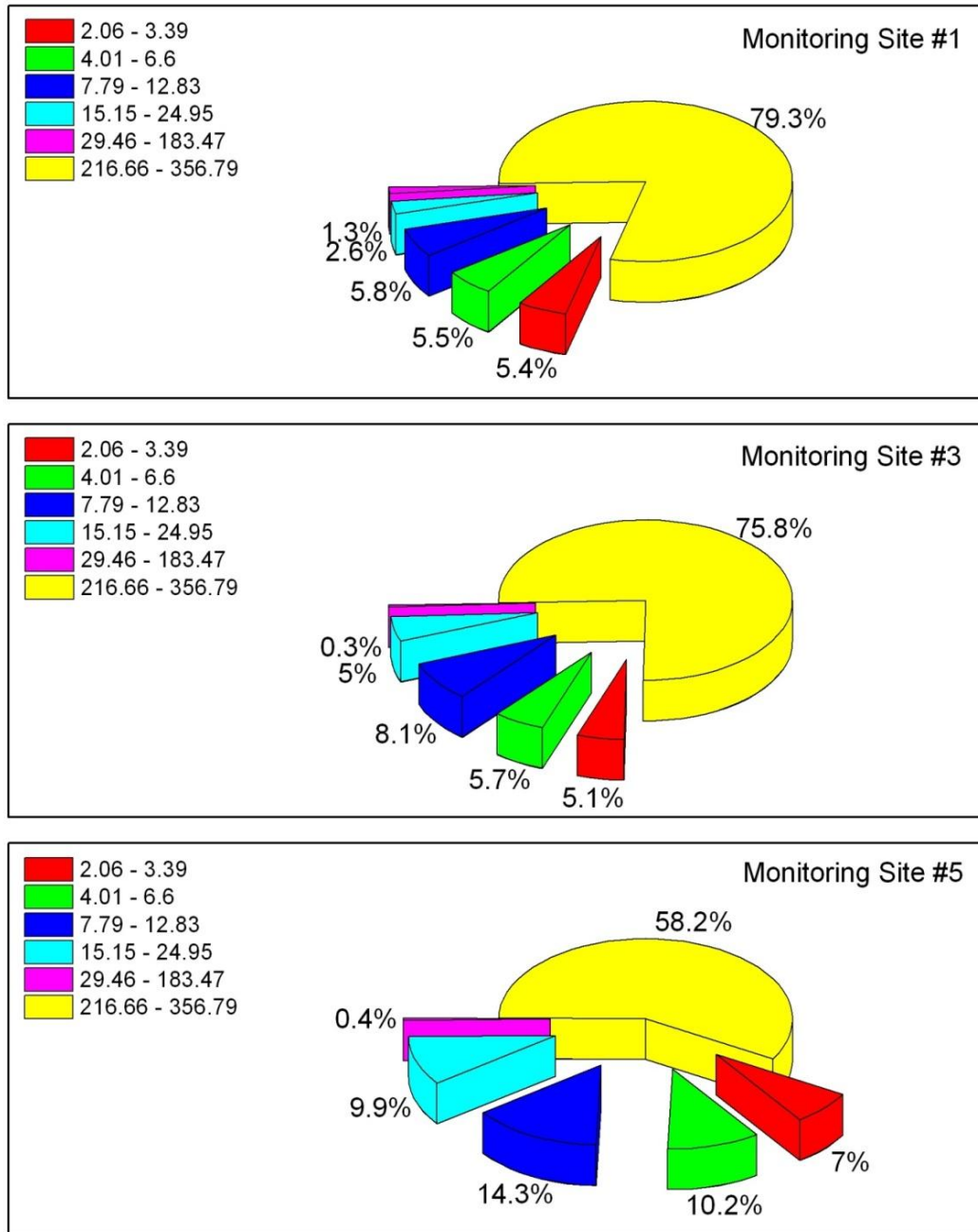


Figure 7. Pre- and post-storm lumped particle class concentrations presented as percent of total from grab samples collected in the Hinkson Creek Watershed, Columbia, Missouri, USA.

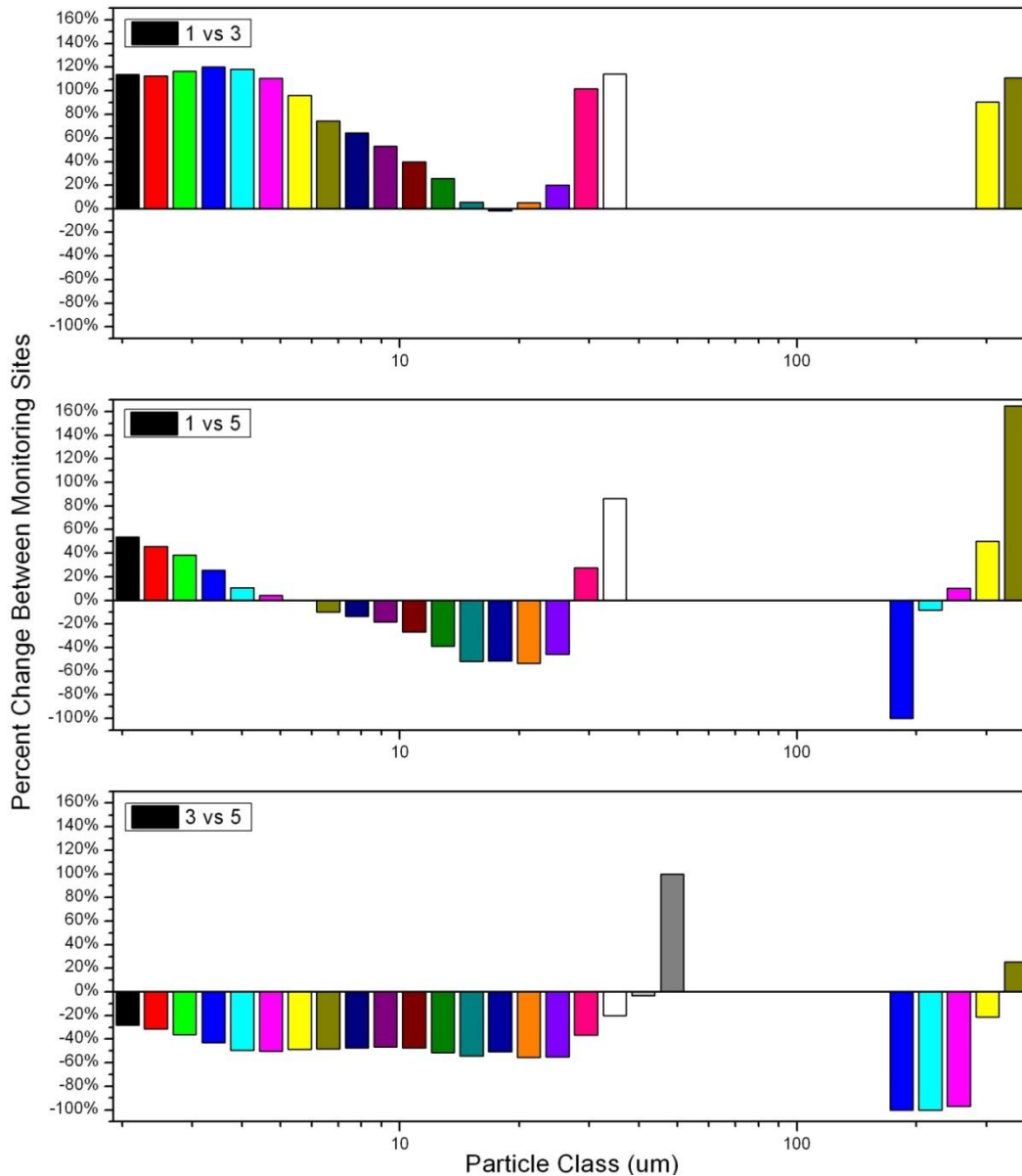


Figure 8. Percent change in average particle class concentrations for the month of March 2010 at three monitoring sites in the Hinkson Creek Watershed, Columbia, Missouri, USA.

3.2 March 27-31 Event Analysis

Weather during the four day period of March 27 – 31, 2010 was typical with average temperature and average stream flow was 12.8 °C and 2.4 m³/s respectively (Figure 9). On March 28th a 13.2 mm precipitation event occurred. Resultant peak flow was 7.0 m³/s. Average pre- and post-storm flow was 1.4 m³/s and 2.9 m³/s respectively. Total concentration of suspended sediment during pre- and post-event conditions was approximately 29 and 75 µl/l respectively. Average PSC was 142 and 116 µm during pre- and post-event conditions respectively. Notably, total suspended sediment was approximately three times higher post-event, while average particle size was almost 20% lower in post event, higher flow conditions.

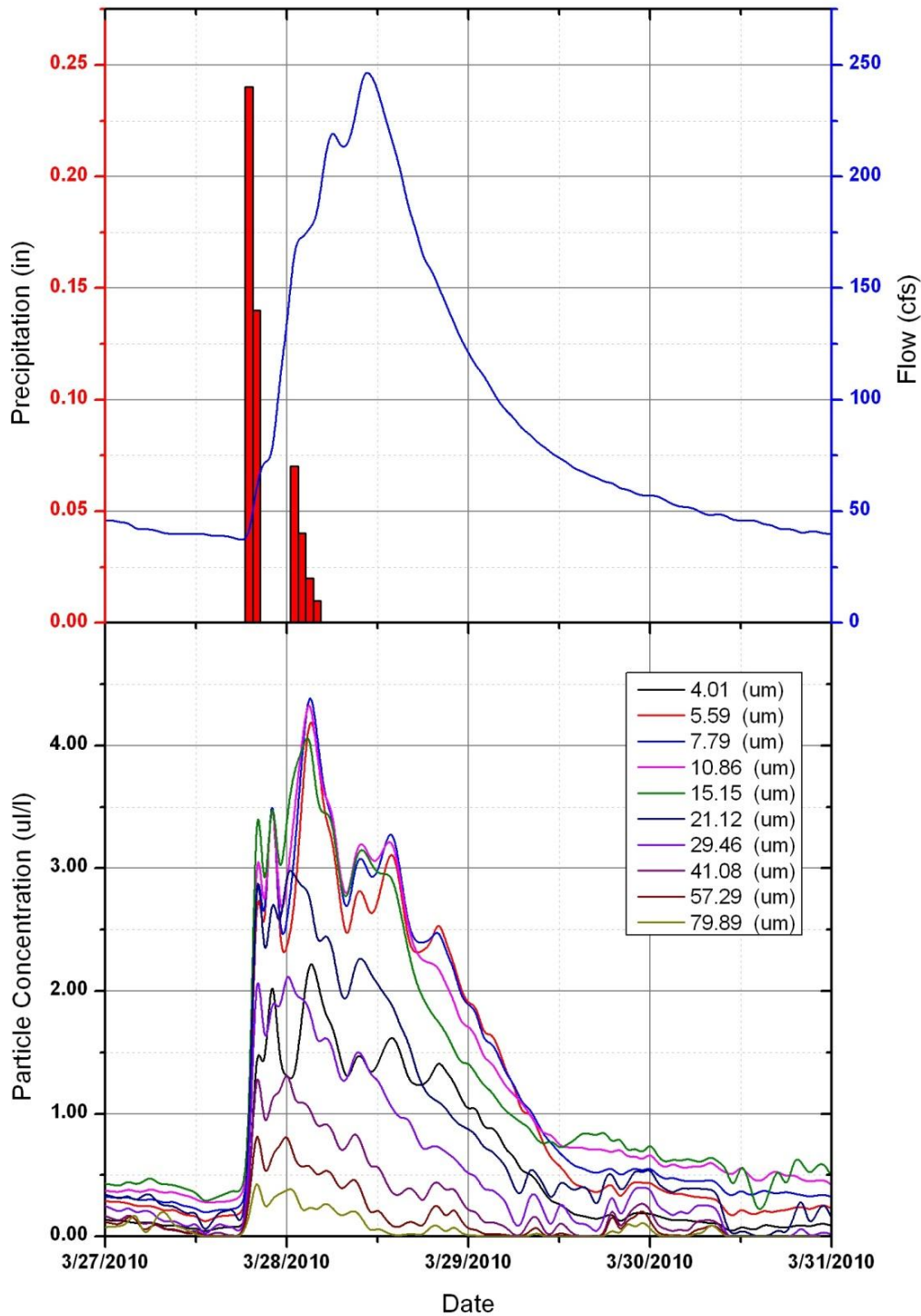


Figure 9. Precipitation and streamflow (top), and select sediment particle class concentrations measured at site four in the Hinkson Creek Watershed, Columbia, Missouri, USA.

Therefore, while total concentrations were higher in post-event flow recessions, the ratio of smaller size classes to larger size class particles decreased such that total suspended sediment had a higher composition of finer particles in the urban setting. This previously unknown information may be attributable to naturally occurring or anthropogenic effects. Figure nine shows selected particle class concentrations during the period of study. As expected there is a dramatic increase of all PSC's shown with increased flow, however, the concentrations of finer particles are quantifiably higher relative to larger particle classes. The relative ratios of larger to smaller size class concentrations have not been previously quantified.

Figures 10 and 11 illustrate pre- and post-storm event particle class concentrations. Figure 10 reflects a cube-root transform of the data for improved visual inspection of the concentration differences. Results show that a 13.2 mm rainfall event resulted in greatly increased particle concentrations, especially in the smaller size classes during this event. Figure 11 further illustrates this finding listing the relative percent of total concentration for each size class.

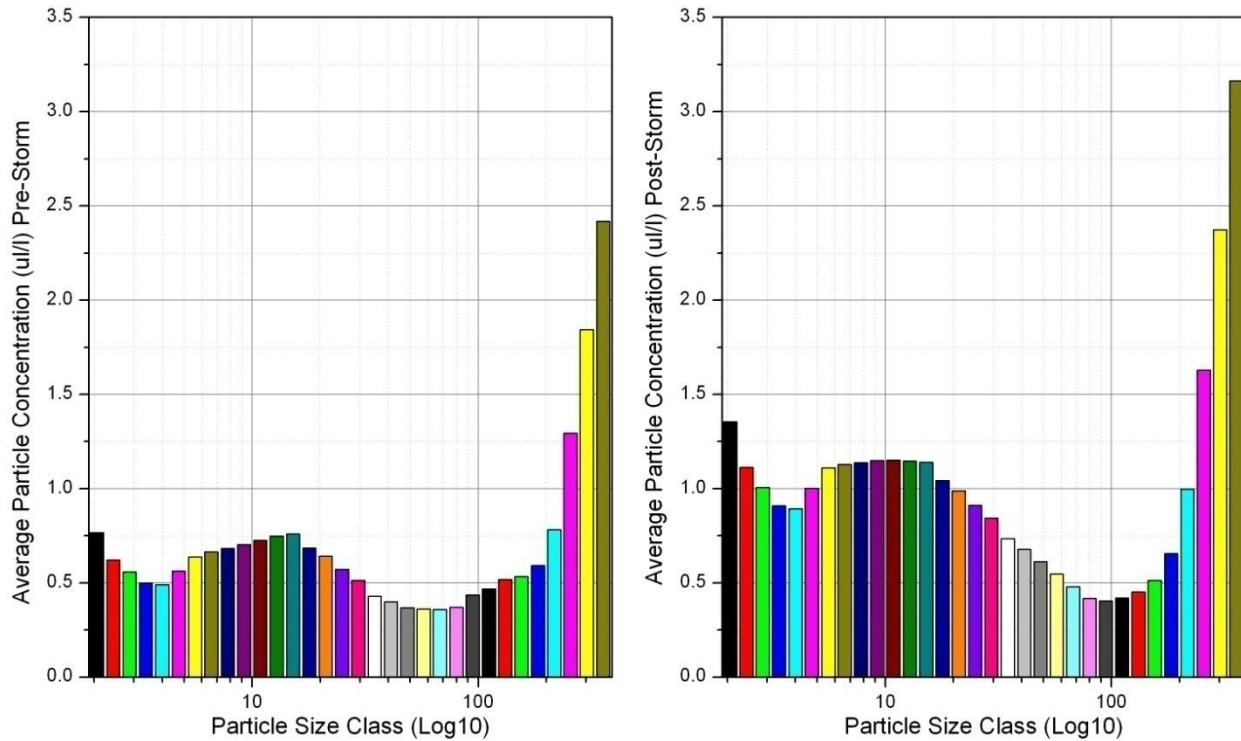


Figure 10. Average particle class concentration (µl/l) pre- and post-storm of particle size class concentrations (log10) shown with cube-root transform in the Hinkson Creek Watershed, Columbia, Missouri, USA.

The largest particle class (356.79 µm) comprised almost 50% of the total concentration of suspended sediments in the pre-event flow condition, whereas in the post-precipitation flow event condition it comprised nearly 44%, a 12.5% difference (Figure 12). The smallest particle class (2.06 µm) concentrations in pre and post-precipitation event conditions was 0.8 and 3.4 % respectively reflecting a more than 450 % difference in post flow conditions after only a 13.2 mm precipitation event! This finding is remarkable given that the 13.2 mm precipitation event doubled the amount of flow from 1.4 m³/s to 2.9 m³/s, but more than quadrupled the concentrations of finer particles of sediment. While this trend may seem unsurprising to some, the ability to quantify the differences is novel, and the potential to use this type of information to better understand the effects of land-use, and in particular urban land-use, will supply never before available information to land managers wishing to mitigate proportionally increased fine sediments emanating from urban developments that might not otherwise be transported to the stream channel in forested and/or agricultural lands.

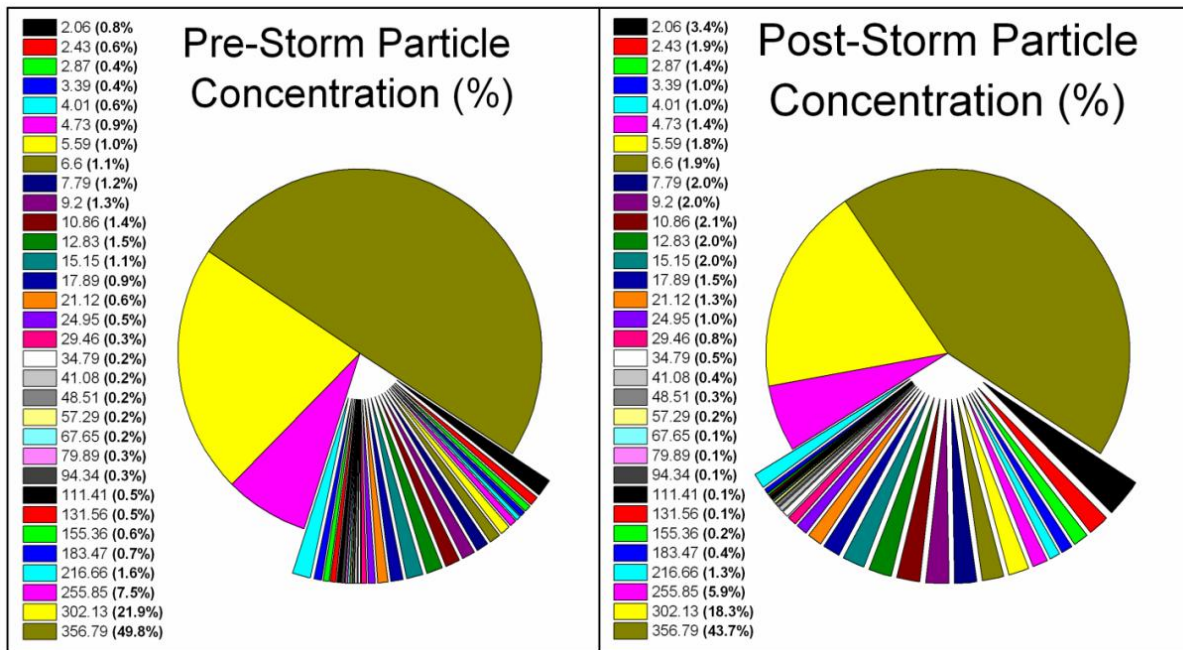


Figure 11. Pre- and post-storm particle class concentrations presented as percent of total from samples collected in the Hinkson Creek Watershed, Columbia, Missouri, USA.

It is interesting to note that in post-precipitation event runoff conditions, particle classes 94.34 through 155.36 um decreased. This could be explained in part by LISST accuracy limitations and/or doubling of volume and thus a volume-based reduction of sediment size class by dilution. It may also be that at these concentrations the high silt and clay composition may lead to flocculation of particles and thus higher estimated concentrations such as those in the 17 to 57 um size classes. Elucidating these differences necessitates study replication, much longer data time series, plus quantifiable characterization of soil class separations.

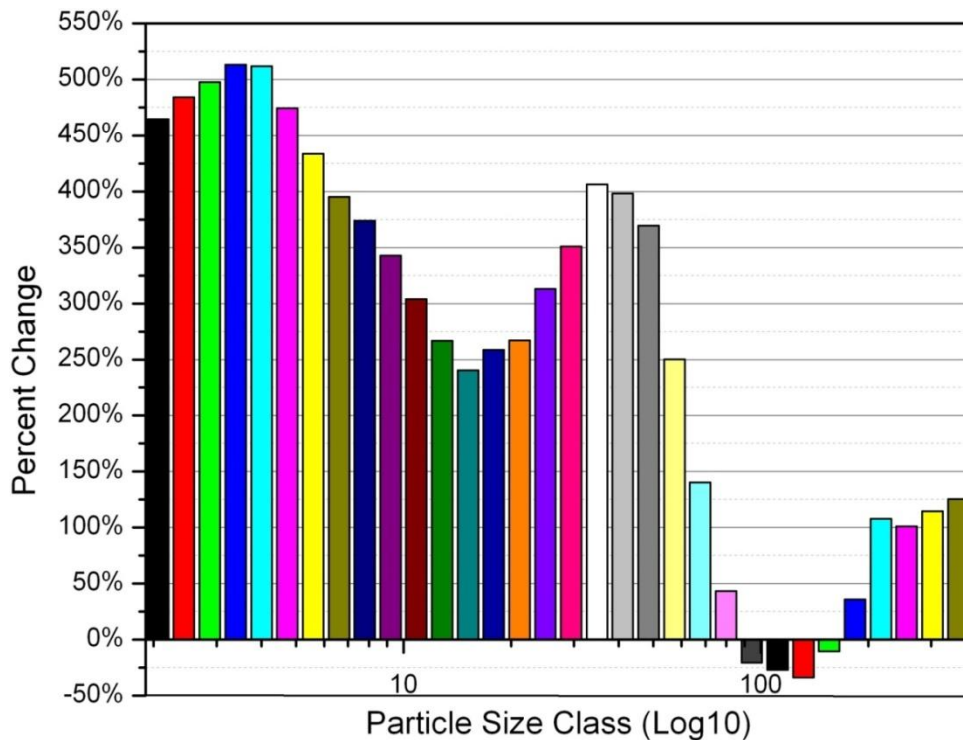


Figure 12. Percent change in particle class concentrations pre- and post-rainfall in the Hinkson Creek Watershed, Columbia, Missouri, USA.

3.3 Considerations

A basic assumption of LISST on-board computations is that all particles are homogeneous spheres. This may not hold true, especially in soils with a large silt or clay component, which are, on average, not spherical. Further, while the LISST Streamside measures particle sizes between 2.5 and 500 μm (Agrawal and Pottsmith, 2000), smaller particles (i.e. $<2.5 \mu\text{m}$) may aggregate into flocs, producing a signal in larger PSC's and potentially skewing results. Similarly, larger particle classes may represent lightweight flocs or biological material. Further, during high flows it is possible to get larger sediment particles in suspension. The same is true during slow flows, but the larger particles may not be heavy grains of sand that are unable to stay in suspension. Finally, while volumetric estimates of sediment concentrations are useful, volumetric indices are not the conventional unit for presenting sediment concentrations. In general, lacking in sample specific information, the conversion from $\mu\text{l/l}$ to mg/l is conducted assuming a particle density of 2.65 g/cm^3 (i.e. the density of silica). However, it is likely that mass concentrations calculated in this manner will not correlate well to traditional gravimetric estimations. It is therefore advisable to calibrate laser diffraction technology with gravimetric methods. In spite of potential complications, instrument configuration can generate data that have the potential to improve the mechanistic understanding of suspended sediment concentrations and yield in fresh water supplies. LISST technology may therefore advance the current level of understanding of suspended sediment and particle size concentrations across a wide variety of land-use types and runoff events, facilitating greater understanding and, therefore, improved management of freshwater resources.

4.0 Conclusions

This case study is among the first quantification of sediment transport by particle size class from a dynamic urbanizing watershed in the Central U.S. Watershed studies, such as the representative urban watershed used in this work, utilizing experimental watershed study designs can provide novel information to watershed managers, enabling them to make science-based decisions to meet local and national water quality standards. This study demonstrated that during typical March rainfall in central Missouri, almost twice as much sediment was transported at a point approximately 40 km downstream from the headwaters site. On average, particle classes transported were almost twice as large (2.0 to 500 μm size range) in the headwaters, where land-use is primarily forest and agriculture. Eighty percent of the total sediment at the headwaters site (site one) was between 216 and 357 μm , while that number was reduced to almost 40% at site five, approximately 40 km downstream. Other results indicated that a 13.2 mm (0.52 in) rainfall event resulted in a doubling of streamflow ($1.4 \text{ m}^3/\text{s}$ ($51 \text{ f}^3/\text{s}$) to $2.9 \text{ m}^3/\text{s}$ ($102 \text{ f}^3/\text{s}$) but resulted in more than quadrupling the concentration of particle size classes ranging from 0.2 to 67.65 μm . This result illustrates the need to better understand fine particle suspended sediment concentrations in stormwater runoff from urbanizing systems relative to that flowing from agricultural and/or forest environments. Continued work may therefore hold important implications for understanding the effects of urbanization on sediment loading, instream biota, and sustainable water quality and water resource related commodities.

Results further emphasize the probability of proposed sediment transport punctuated equilibrium as opposed to a continual steady state, gradual flux. These relationships in the HCW likely persist in other watersheds. The LISST Streamside and other similar devices hold promise for helping to better understand these phenomena. However, validation using gravimetric methods is strongly advised. In watersheds the size of the Hinkson Creek Watershed, comprehensive management approaches that examine not only the volume of water causing impairments and the variable use landscape, but also the pollution load being transported are imperative. In the HCW, and other similarly affected watersheds globally, the work presented here is timely given Federal mandates to provide quantifiable estimates of total pollutant loading. Given the range of land-uses and scale of the watershed, the HCW serves as representative watershed supplying common ground to encourage cooperation, trust and innovation, between watershed stakeholders to reach a common goal to improve and sustain water quality.

Acknowledgments

This project has been funded wholly or in part by the United States Environmental Protection Agency and the Missouri Department of Natural Resource under assistance agreement (#G08-NPS-17) to the University of Missouri. The contents do not necessarily reflect the views and policies of the Environmental Protection Agency or the Missouri Department of Natural Resources, nor does mention of trade names or commercial products constitute endorsement of recommendation for use.

Other funding and support is provided by the Missouri Department of Conservation, and the U.S. Geological Survey. Special thanks are extended to scientists of the Interdisciplinary Hydrology Laboratory, and multiple reviewers whose comments greatly improved this paper.

References

- Agrawal YC, Pottsmith HC (2000): Instruments for Particle Size and Settling Velocity Observations in Sediment Transport. *Marine Geology* 168:89–114.
- Alexander, R.B., R.A. Smith, G.E. Schwarz, E.W. Boyer, J.V. Nolan, and J.W. Brakebill. 2008. Differences in phosphorus and nitrogen delivery to the Gulf of Mexico from the Mississippi River basin. *Environmental Science & Technology*, 42(3): 822-830.
- ASTM (American Society for Testing and Materials). 2007. D 3977 – 97 Standard methods for determining sediment concentrations in water samples.
- Brooks, K.N., P.F. Ffolliott, H.M. Gregersen., and L.F. DeBano. 2003. *Hydrology and the management of watersheds*, 3rd ed. Iowa State University Press, Blackwell Publishing, USA.
- Capel, P.D., K.A. McCarthy, and J.E. Barbash. 2008. National, holistic, watershed-scale approach to understand the sources, transport, and fate of agricultural chemicals. *Journal of Environmental Quality* 37: 983-993.
- Chapman, S.S., J.M. Omernik, G.E. Griffith, W.A. Schroeder, T.A. Nigh, and T.F. Wilton. 2002. *Ecoregions of Iowa and Missouri (color poster with map, descriptive text, summary tables, and photographs)*: Reston, Virginia, U.S. Geological Survey (map scale 1:1,800,000).
- Davis, B.E. 2005. A guide to proper selection of federally approved sediment and water-quality samplers. United States Geological Survey. Available at <http://pubs.usgs.gov/of/2005/1087>.
- Dodds, W.K. and M.R. Whiles. 2004. Quality and quantity of suspended particles in rivers: continent-scale patterns in the United States. *Environmental Management* 33: 355-367.
- Edwards, T.E. and G.D. Glysson. 1999. Field methods for collection of fluvial sediment. *Techniques of Water-Resources Investigations* 3:89. United States Geological Survey.
- Gartner, G.W., R.T. Cheng, P.F. Wang, and K. Richter. 2001. Laboratory and field evaluation of the LISST-100 instrument for suspended particle size determinations. *Marine Geology* 175: 199-219.
- Gray, J.R. and Gartner, G.W. 2009. Technological advances in suspended-sediment surrogate monitoring, *Water Resources* 45: 1-20.
- Hubbart, J.A., T.E. Link, J.A. Gravelle, and W.J. Elliot. 2007. Timber Harvest Impacts on Hydrologic Yield in the Continental/Maritime Hydroclimatic Region of the U.S. In: *Special Issue on Headwater Forest Streams*, *Forest Science*, 53(2): 169-180.
- Karwan, D.L., J.A. Gravelle, and J.A. Hubbart. 2007. Effects of Timber Harvest on Suspended Sediment Loads in Mica Creek, Idaho. In *Special Issue on Headwater Forest Streams*, *Forest Science*, 53(2): 181-188.
- Koirala, A.M. 2009. An evaluation of pre- and post-timber harvest water quality in low-order streams in the Missouri Ozarks. PhD Dissertation, Graduate School, University of Missouri-Columbia
- Kondolf, G.M. 1997. Hungry water: effects of dams and gravel mining on river channels. *Environmental Management* 21:533-551.
- Law, N. L., L. Fraley-McNeal, K. Cappiella, and R. Pitt. 2008. Monitoring to demonstrate environmental results: guidance to develop local stormwater monitoring studies using six example study designs. Center for Watershed Protection, Ellicott City, MD USA.
- MDNR. 2006. Stream Survey Sampling Report. Phase III Hinkson Creek Stream Study, Columbia, Missouri, Boone County. Prepared by the Missouri Department of Natural Resources, Field Services Division, Environmental Services Program, Water Quality Monitoring Section.
- Novotny, V., and H. Olem. 1994. *Water Quality. Prevention, Identification, and Management of Diffuse Pollution*. New York: Van Nostrand Reinhold.
- Pickett, S.T.A., W.R. Burch, S.E. Dalton, T.W. Foresman, J.M. Grove, and R. Rowntree. 1997. A conceptual framework for the study of human ecosystems in urban areas. *Urban Ecosystems* 1: 185-199.
- Pruitt, B.A. 2003. Used of turbidity by States and Tribes. *Proceedings of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates*. United States Geological Survey 1250: 31-46. Available at <http://pubs.usgs.gov/circ/2003/circ1250/>.
- Thom, R.H. and J.H. Wilson. 1980. The Natural Division of Missouri. *Transactions, Missouri Academy of Sciences*, 14: 1-23.
- USEPA (US Environmental Protection Agency). 2006. *Wadeable Streams Assessment: a collaborative survey of the nation's streams*. EPA 841-B-06-002. Office of Research and Development and Office of Water, US Environmental Protection Agency, Washington, DC.