Quantifying Suspended Sediment Loading in a Mid-Missouri Urban Watershed Using Laser Particle Diffraction

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by

Graham W. Freeman
Thesis Advisor: Jason A. Hubbart, Ph.D.
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The undersigned, appointed by the dean of the Graduate School, have examined the thesis entitled

Quantifying Suspended Sediment Loading in a Mid-Missouri Urban Watershed Using Laser Particle Diffraction

Presented by Graham Freeman,

a candidate for the degree of M.S. Forestry

and hereby certify that, in their opinion, it is worthy of acceptance.

Dr. Jason A. Hubbart

Dr. Stephen H. Anderson

Dr. Richard P. Guyette

DEDICATION

I would like to dedicate this thesis to my family. To my Mom and Dad for their constant support and encouragement and to my deceased Grandmother.

ACKNOWLEDGMENTS

I would like to thank my family for their constant love and support not only through my graduate research experience but throughout my entire life. I would also like to thank my brother and sister who have always been there for me in times of need. I would like to especially thank my Grandmother who in many ways provided and cared for me throughout my entire life.

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Quantifying Suspended Sediment Loading in a Mid-Missouri Urban Watershed Using Laser Particle Diffraction

Graham Freeman

Thesis Advisor: Jason A. Hubbart

ABSTRACT

Soil erosion and suspended sediment is one of the most pervasive pollutants of freshwater impairment. High concentrations of suspended sediment can alter or damage physical, chemical, and biological status of aquatic ecosystems, which may lead to serious water quality issues. While suspended sediment is one of the most common sources of water impairment it is often difficult to quantify and characterize due to the expense and amount of labor associated with traditional sediment sampling techniques. New technologies have been developed to monitor suspended sediment in-situ, eliminating much of the labor and expense associated with traditional methods of suspended sediment monitoring. The following research used laser diffraction particle analyzers to quantify suspended sediment concentration (SSC) and particle size in an urbanizing, Mid-Western watershed during the spring of 2010. A nested-scale study design with three sub-basins was used to examine the effects of land-use on suspended sediment trends. Sub-basins were categorized as headwater (36% forested, 55% agriculture), suburban (36% forested, 36% agricultural), and urban (67% urban). Mean SSCs were estimated to be 66.0, 70.0, and 86.0 µl/l for the headwater, suburban, and urban sub-basins (respectively). Mean sediment size was estimated to be 151.0, 111.0,

and 79.0 µm for the headwater, suburban, and urban sub-basins respectively. Total sediment loads measured at the headwater, suburban, and urban monitoring sites were 13,183, 27,369, and 42,854 tonnes (respectively). Sediment yield was approximately 170.0, 153.0, and 208.0 tonnes/km^2 for the headwater, suburban and urban sub-basins respectively. Mean suspended sediment concentrations were highest (86.0 µl/l) in the urban sub-basin and lowest (66.0 µl/l) in the headwater sub-basin. Mean sediment particle size decreased with linear distance of the stream from the headwater (151 µm), to the suburban (111.0 µm), and exited the watershed through the urban (79.0 µm) sub-basin. This pattern may indicate that as suspended particles are transported downstream they become physically weathered. Results also indicate that higher concentrations of smaller soil particles may be transported to the stream from urban terrestrial processes relative to headwater and suburban sub-basins. Total sediment yields were highest in the urban sub-basin and lowest in the suburban sub-basin. Total sediment yields decreased from the headwater to the suburban sub-basin possibly indicating that particles eroded in the upper portion of the watershed are deposited in the channel in the suburban reaches of the stream. Total sediment yield increased through the suburban to the urban sub-basin, which may be largely attributable to increased channel erosion between the suburban and urban gauging sites. Few studies have examined the relationships between land-use and sediment flux in the Mid-West. This study illustrates how land-use affects sediment trends. As land-use continues to change, the ability to protect and enhance water quality will depend on how well scientist, land managers, and policy makers understand the relationships between land-use and hydrological processes.

CHAPTER I: INTRODUCTION

Understanding how relationships between water flow regimes (i.e. quantity and timing), climate, and land use affect suspended sediment transport, concentration and loading is vital for water quality management and restoration. Suspended sediment is one of the most ubiquitous constituents of water pollution globally (Clark, 1985). The United States Environmental Protection Agency's (USEPA) biological assessment of 1,392 randomly selected wadeable streams indicated that 42% of those streams are in poor biological condition (USEPA, 2006), causing billions of dollars of physical, chemical, and biological damage to freshwater systems annually (Oskerkamp et. al., 1998, Clark et. al., 1985). In the Midwestern United States, there is an ongoing need for studies that seek to characterize and improve the understanding of sediment flux and supply information for science-based management and policy decisions.

Since the 1970s there has been increasing interest to better understand mechanistic processes involved in contaminant transport (Horowitz, 2003), water-quality, reservoir sedimentation, channel and harbor silting, and related ecological and recreational impacts (Walling, 1977; Ferguson, 1986; De Vries and Klavers, 1994; Horowitz, 1995; Horowitz et al., 2001). The demand for quality information pertaining to sediment flux is often driven by the need to determine total maximum daily loads (TMDLs) for sediment (Horowitz, 2003). A TMDL consists of point and nonpoint load allocations pertaining to the contributing area of a particular stream segment. A TMDL exceeding water quality standards is identified by calculating whether, a) The TMDL surpasses Environmental Protection Agency (EPA) set standards, and/or b) The TMDL surpasses the Waste Assimilative Capacity (WAC). The WAC is the quantity of waste and contaminant loads that can be discharged into the environment without damage or use impairment of a receiving body of water, atmosphere, or land, minus the natural load (Novotny and Olem, 1994). Figure 1 presents the procedure for listing water bodies on the 303d list and developing TMDL's.

While setting a TMDL for sediment may be a reasonable goal, its translation to erosion and sediment release units for different land users upstream is a daunting task without a thorough understanding of water and sediment transport characteristics in the entire watershed (Frankenberger et al., 1999; Tim and Jolly, 1994). Almost 17% of all TMDLs focus on excessive sediment or its presumed impact on biological communities (Keyes and Radcliffe, 2002). It is therefore ironic, that while the need for suspended sediment data has continuously increased, there has been a 65% decrease of United States Geological Survey's (USGS) sediment monitoring stations in the United States (Gray and Glysson, 2002). The lack of Federal investment for long-term monitoring requires that independent researchers carry out studies that supply sediment load information to land-managers and policy makers.

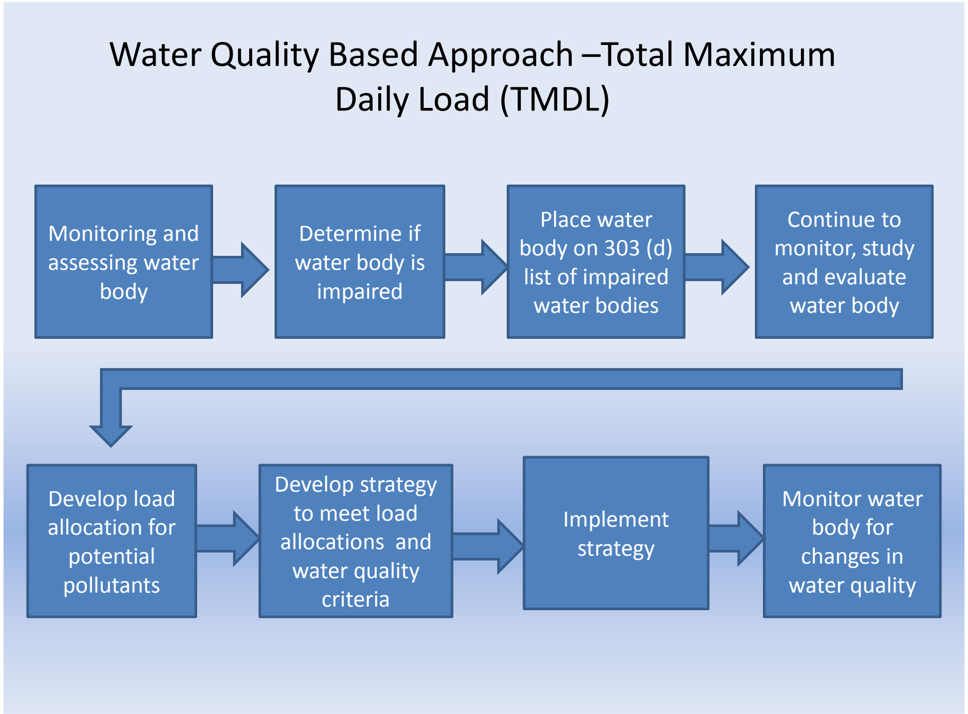

Figure 1. Basic approach of listing impaired water bodies on the 303 (d) list and developing and implementing total maximum daily loads.

BACKGROUND

Sediment loading threatens the availability of freshwater resources, harms aquatic habitat, and alters stream geomorphology, and physical and chemical properties of water (Foster and Charlesworth 1996; Kondolf, 1997; Oshwald, 1972; Owens et. al., 2005; Wood and Aarmitage, 1997). Sediment transported in suspension can harm freshwater ecosystems by reducing the transmission of sunlight, increasing surface water temperatures, and interfering with metabolic processes of aquatic biota. The reduction of sunlight transmission by sediment can restrict or eliminate photosynthesis, thus dramatically influencing the aquatic food chain. Suspended sediment often acts as a conveyance system for other pollutants including heavy metals, nutrients, and other pollutants (Foster and Charlesworth, 1996; Oshwald, 1972; Russell et. al, 1998; Uri, 1999). The effects of sediment on freshwater biota and aesthetics can also reduce opportunities for recreational activities. High concentrations of suspended sediment can increase the cost of water treatment and can damage pumps and turbines. Sediment that settles out of suspension can fill reservoirs; impede navigation and water conveyance systems, and increase frequency and severity of flooding by reducing channel capacities (Uri, 1999; Holmes, 1998; Williams, 1989).

While there are many negative effects of excessive suspended sediment, it is noteworthy that too little sediment (below natural background levels) can cause just as damaging effects to stream geomorphologic and ecological functions as too much sediment. Generally, water bodies deprived of sediment are associated with dams and reservoirs. Streams deprived of sediment often exhibit increased channel erosion and channel incision because water that is lacking in sediment has greater potential energy to expend on erosion processes. The excess energy causes channel incision (down cutting of the streambed) and coarsening (larger particle sizes) of bed materials. Since channel erosion results from flow energy dissipation, the increased magnitude and occurrence of high flows can result in dramatically increased channel erosion (Wolman and Schick, 1967; Booth and Henshaw, 2001). This process will continue until reaching equilibrium and bed material can no longer be moved by flows. Water bodies deprived of sediment also significantly alter aquatic habitat. Increases in light penetration, due to low turbidity, can give non-native, sight feeding fish competitive advantages over native non-sight feeding fish (Kondolf, 1997). Sediment also provides an important source of nutrients in aquatic food web (Dodds and Whiles, 2004; Koirala, 2009). Studies are needed that will improve the understanding of positive and/or negative impacts of sediment on aquatic ecosystems and water quality.

Identifying how land-use and land-cover impact suspended sediment processes is difficult due to the buffering capacity of a watershed. The buffering capacity of a watershed is closely related to the sediment delivery ratio (Walling, 1999). The sediment delivery ratio is the ratio of sediment delivered at the catchment outlet to gross erosion within a basin (Walling, 1983). Studies using erosion plots and catchment studies showed that erosion rates are sensitive to land-use change and human activities (Walling, 1999). However, sediment can be temporarily or permanently stored on slopes, bases of slopes, in flood plains, or in stream channels thus reducing the sediment yield at the catchment outlet and confounding sediment flux estimates. The sediment delivery ratio is influenced by a variety of geomorphologic and environmental factors including location of sediment sources, slope and relief characteristics, vegetative cover, drainage pattern, channel conditions, and soil characteristics (Walling, 1983). The long list of confounding factors related to erosion and sediment transport only further illustrate the need to understand the relationships between suspended sediment processes and land use.

Pollutants entering water bodies originate from point and nonpoint sources. Point source pollutants enter the water body from identifiable locations (i.e. storm drains, wastewater treatment plants, or industrial discharge drains). Point source pollutants are therefore much easier to regulate than non-point source pollutants because the location and cause of pollution identifiable. Because the source of nonpoint pollutants is often unknown or diffuse, regulating and monitoring nonpoint pollution is much more difficult.

Numerous studies have attempted to identify origins of suspended sediment and the percentage of sediment originating from varying land use types and land covers. Studies showed that the source of sediment is often topsoil from agricultural fields, disturbed forest, or mining activities (Collins et al., 1997; Walling and Fang, 2003; Owens et al., 2000; Mohta et al., 2003). Urban expansion and development were shown to have a significant impact on sediment loads. In an urbanizing watershed near Baltimore, MD and metropolitan D.C, Wolman and Schick (1967) showed sediment concentrations transported from construction zones ranging from 3000-150,000 ppm. These results were significantly higher relative to natural or agricultural catchments where the highest concentration recorded was 2000 ppm (Wolman and Schick, 1967). Sediment yields from catchments undergoing construction ranged from several thousand to 49,000 tonnes km^{-2} $year^{-1}$. Sediment yields in smaller catchments were generally higher because larger percentages of total area were under construction at any given time (Wolman and Schick, 1967). While urbanization (i.e. construction) can drastically increase suspended sediment yields, surface erosion and delivery often decrease due to increased impervious areas (Wolman and Schick, 1967). However, as surface erosion decreases channel erosion may increase due to increasing frequency and volume of channel shaping flows (Hammer, 1972).

Changes in land use, particularly urbanization coupled to increasing impervious areas, were shown to significantly alter watershed hydrology (i.e. infiltration, storage, runoff rates, peak discharges) and drastically alter downstream channels (Booth, 1990; Arnold and Gibbons, 1996). Channel enlargement (channel erosion and incision) is a common stream geomorphological response to urbanization and increased impervious area (Booth, 1990), and thus a significant source of urban stream total sediment yield (Trimble, 1997; Nelson and Booth, 2002; Fraley et. al, 2009). Neller (1988) showed that erosion rates were three to six times greater in an urban channel compared to a nearby rural channel. Increased in-channel sediment production in the urban stream was attributed to increased runoff associated with urbanized areas (Neller, 1988). Given that land-use changes in urban/urbanizing watersheds can have significant impacts on in-stream sediment erosion, there is a great need for improved understanding of sediment processes in urban watersheds.

It was shown that a significant portion of suspended sediment originates from streambanks in non-urban settings. A study was conducted in northeastern Missouri to examine the effects of land-use, stream order, and season on stream bank erosion in two claypan watersheds (Willet, 2010). The two watersheds selected in the study were over 50% cultivated. Results from the study indicated that 41-71% of the total stream sediment load originated from stream bank erosion. In many cases, terrestrial erosion is thought to be the main source of sediment in stream (Owens et al., 2005) but Willet (2010) showed that in stream contributions of sediment can make up a significant, if not dominant portion of the streams total sediment budget. Consistent with Willet (2010), Devereux et al. (2010) showed stream bank erosion to be the dominant source (up to 98%) of suspended sediment in Piedmont/Coastal Plain watershed in Maryland. In the Piedmont region of Georgia, Mukundan (2010) showed that in-stream erosion made up the dominant source (81 to 98%) of suspended sediment and that suspended sediment originating from agricultural and forested land-use areas made up a very small percentage (~ 10%) of the total sediment load.

Nelson and Booth (2002) produced pre-development and post-development estimates of sediment yields in the Issaquah Creek Watershed in King County, Washington mixed-use watershed. They used total suspended sediment (TSS) yield coefficients, unit area discharge, the Universal Soil Loss Equation (USLE), matrix, creep rate, unit area erosion, and regression analysis methods to estimate sediment yields. Models were validated using a half century of observations to confirm sediment budget predictions (Nelson and Booth, 2002). The watershed drains 144 km^2 and contained forested (73%), urban (18.1%), open water (0.1 %), mining (0.6%), agricultural (4.5%), landfill (0.8%), construction (0.3%), and road (2.6%) land-use areas. Results showed sediment production for Issaquah Creek of 6,400 tonnes yr^{-1} at the outlet. The largest contributor of sediment production was the forested land-use (3,264 tonnes). The major erosion sources in the forested land-use areas were soil creep, landslides, and road-surface erosion. The Issaquah study estimated an increase in sediment production from pre-development (24 tonnes km^{-2} $yr^{-1)}$ to post-development (44 tonnes km^{-2} yr^{-1}). Thus, increased channel erosion due to urbanization contributed 20% of the total sediment budget.

In a study by Trimble (1997) in San Diego Creek Watershed, California (50% urban, 50% rural and agriculture), it was determined that approximately 67% of the total sediment budget was from in-stream erosion. Results from Trimble (1997) are consistent with Nelson and Booth (2002) where 20% of the total sediment budget was from in-stream erosion in a watershed that was 19% urban. The Issaquah Creek Watershed study showed how watersheds are particularly susceptible to large increases in sediment load due to urbanization practices that alter the natural land-use and hydrology of the watershed. Improved understanding of how land-use and land-cover affect sediment processes in urbanizing watersheds in the Midwest will lead to enhanced water quality and resource management in those dynamic systems.

Simon et al. (2004) estimated median suspended sediment concentrations and loads during bankfull discharge events from different eco-regions across the United States. Results indicated that suspended sediment concentrations and loads were significantly different for different eco-regions. Suspended sediment concentrations and yields for the Interior Lowlands (222 mg/l, 0.59 tonnes/km^2/day) and Central Irregular Plains (1020 mg/l, 8.18 tonnes/km^2/day) eco-regions (i.e. Midwestern eco-regions). Results from the Interior Lowlands and Central Irregular Plains were significantly different than results from Arizona-New Mexico Plateau (4143 mg/l, 6.5 tons/km^2/day) and Northern Rockies (30.13 mg/l, 0.05 tons/km^2/day) eco-regions (Simon et al., 2004). Differences in topography, soils, climate, land-use, vegetative cover and basin size can significantly affect erosion rates and suspended sediment trends (Nelson and Booth, 2002; Simon et al., 2004; Walling, 1999) which makes drawing inference from suspended sediment studies in different regions difficult.

A study conducted by Coulter et al. (2004) in the Bluegrass Region of Eastern Kentucky used a paired watershed study design to examine how land-use affects suspended sediment concentrations. Within three paired watersheds, one watershed was dominated by agricultural land-use, one predominately urban land-use, and a third watershed had nearly equal percentages of urban and agricultural land-use types (i.e. mixed use). During the one year study period 26 grab samples were collected to characterize turbidity and total suspended solids as well as other non-point source environmental pollutants. In the agricultural, mixed-use, and urban watersheds, average annual suspended sediment concentrations were 14.8, 23.4, and 21.7 mg/l respectively. Results indicated that suspended sediment concentrations were higher in the in the urban and mixed land-use watersheds compared to the agricultural watershed. Bales et al. (1999) showed similar results as Coulter et al. (2004) with higher suspended sediment concentrations in the urbanizing and mixed-used watersheds compared agricultural watersheds. Correll et al. (1999) examined the effect of land-use on suspended sediment concentrations in three sub-watersheds with land-uses dominated by row crops, pasture, and forested land-uses. Results indicated that suspended sediment concentrations were highest (703 mg/l) in the row crop sub-watershed and lowest (36 mg/l) in the forested watershed (Correll et al., 1999). Studies that quantify the effects of land-use on suspended sediment trends are of particular importance as land is converted from agriculture and forests to urban land-uses.

ESTIMATING SUSPENDED SEDIMENT

The Sediment Rating Curve

Sediment rating curves are often used to estimate suspended sediment when there is sparse distribution of sediment data and/or when sediment sampling programs are unable to characterize local sediment concentrations (Walling, 1977; Gray and Gartner, 2009). To estimate a sediment rating curve relationships must be established between flow and sediment concentrations (Simon et al., 2004; Porterfield, 1972). The most common rating curve for sediment is the power function:

$$C_s = aQ^b. \tag{1}$$

where C_s is sediment concentration (mass/volume), Q is discharge (volume/time), and a and b are dimensionless regression coefficients (Asselman, 2000). Variables a and b are estimated by the ordinary least squares regression of the log transformed variables C_s and Q (Singh and Durgunoglu, 1989). Sediment rating curves are considered 'black box' models in part because a and b in Equation 1 have no physical basis. However, some authors have tried to explain the coefficients with physical interpretations (Asselman, 2000). Morgan (1995) suggested the a-coefficient represents an index of erosion potential; high a values represent materials that are weathered and transported easily. The b-coefficient represents the stream's erosive potential, where high b values represent streams that exhibit larger increases in sediment loads with small increases in discharge (Morgan, 1995). Inaccuracies of sediment rating curves occur due to the statistical methods for fitting the curve and scattering of points about the line (Asselman, 2000). Asselman (2000) showed that rating curves obtained from least squares regression of log-transformed data tend to underestimate sediment transport rates by 10 – 50%. Much of this error can be eliminated by applying simple correction factors (Walling and Webb, 1988), subdividing data sets into seasonal or hydrologic groupings (Asselman, 2000; Horowitz, 2003), or using truncated rating curves relating only the highest quartiles of suspend sediment concentration SSC to river flow (Meybeck et al., 2003; Simon et al., 2004). The use of sediment rating curves has become particularly important in the development of sediment total maximum daily loads (TMDL) (Horowitz, 2003). While Equation 1 is the most common rating function for suspended sediment rating curves, there are other functions that are used to provide a better fit (e.g. linear, polynomial) (Horowitz, 2003).

Traditional Methods of Measuring Suspended Sediment

Suspended sediment concentration is often estimated via gravimetric analyses of water samples collected manually or by automatic water samplers (Edward and Glysson, 1999; Bent et al., 2003; Davis, 2005). However, sample collection and laboratory analyses using these methods tend to be expensive, difficult, and labor intensive (Gray and Gartner, 2009). In the United States, gravimetric analyses are most often determined using one of two analytical methods: the suspended sediment concentration (SSC) method and the total suspended solids (TSS) method (Gray et al., 2000). The procedure for an SSC analysis involves measuring the dry weight of sediment from the total volume of a water sample (Gray et al., 2000). There are several other similar methods for measuring suspended sediment; most involve measuring the dry weight of sediment from a known volume of a subsample of the original (Gray et al., 2000). Figure 2 shows method differences between the SSC methods and the TSS method. The main difference between the SSC and TSS methods is that the TSS methods analyze a sub-sample of the larger sample and the SCC method analyzes the entire sample. Analyzing SSCs via TSS methods can produce larger errors if the concentration of sand sized particles in a sample is greater than 25% (Gray et al., 200). Errors related to high sand concentrations are associated to rapid settling velocities of sand and the difficulty of collecting a sub-sample that has a representative concentration of the larger sample (Glysson et al., 2000; Gray et al., 2000). When sand concentrations are less than 25 % the SSC and TSS methods are comparable (Gray et al., 2000). Ultimately, traditional methods of collecting and analyzing suspended sediment lack the capacity to produce high-resolution data sets and tend to be expensive, time consuming, and labor intensive.

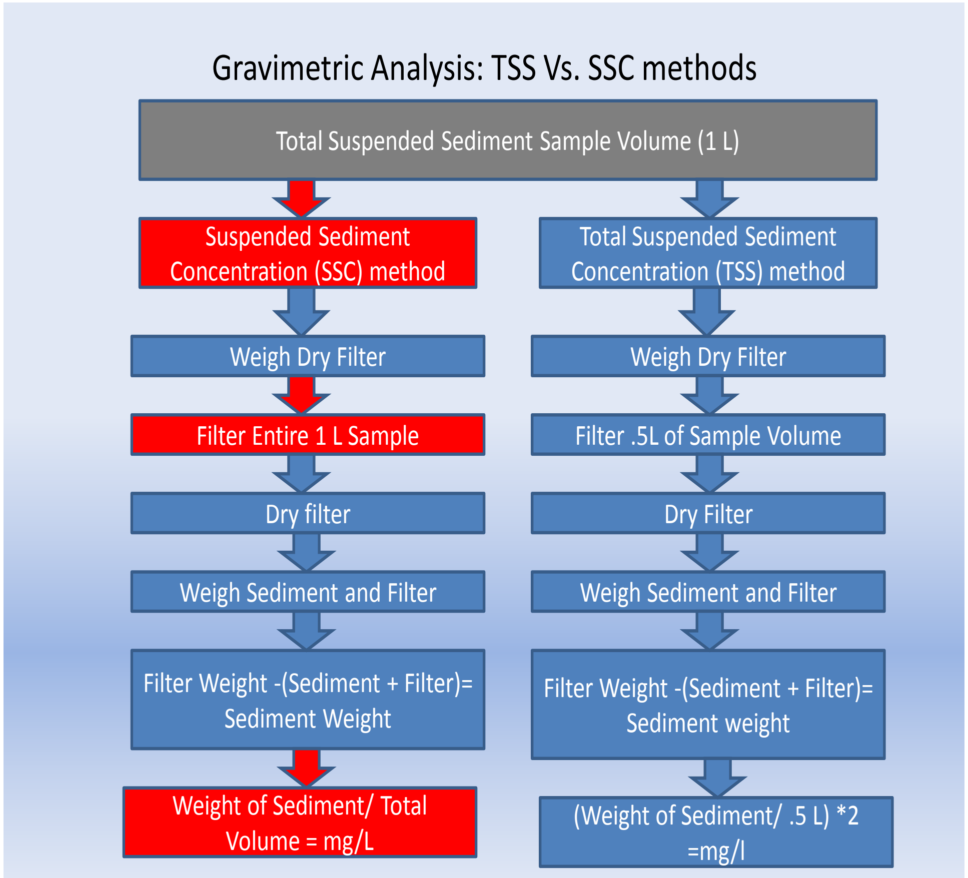

Figure 2. Flow chart illustrating the difference between suspended sediment concentration method and total suspended solids method for analyzing suspended sediment. Major differences between the two methods are highlighted red.

Contemporary Methods of Measuring Suspended Sediment

Recent advances in suspended sediment monitoring include *in situ* fully automated devices that continuously sense and log suspended sediment and particle size classes. Commercially available instruments include those that use bulk optics (turbidity), acoustics, pressure differentials, and laser optics to monitor suspended sediment (Gray and Gartner, 2009). Bulk optics (turbidity) 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 in a straight line, or directly through solution. Bulk optics instruments sense the fraction of the light transmitted through a sample (Gray and Gartner, 2009). Other instruments currently used to quantify SCC include acoustic backscattering technology and portable Acoustic Doppler Current Profilers (ADCP) (Gray and Gartner, 2009; Urick, 1975). The acoustic backscattering method requires empirical calibrations of SCC estimates for representative cross-sectional values (Gray and Gartner, 2009). Another new technology for estimating SCC measures pressure differences of water between two fixed elevations. The pressure at each elevation is sensed simultaneously with highly sensitive pressure transducers. From the measured pressure difference, the density of the water is calculated and SSC is inferred after adjusting for water temperature (Gray and Gartner, 2009).

Laser Diffraction (LD) instruments measure optical scattering of light over a wide range of particle angles, providing a multi-parameter measurement. The name, laser diffraction, is derived from Maxwell's equations, which are a set of four equations governing the behavior of magnetic and electric fields that are used to describe the light scattering properties of spheres (Jonasz, 1991; Agrawal and Pottsmith, 2000; Eshel et al., 2004). The propagation of electromagnetic waves provides an estimate of homogenous spheres (Born and Wolf, 1975; Eshel et al., 2004), which provides a way to estimate particle size characteristics by observing the scattering at small forward angles from light diffraction by spherical particles (Born and Wolf, 1975; Swithenbank et al., 1976; Jonasz, 1991). When light hits a small particle a portion of the light is scattered or reflected. The angular distribution of the scattered light is dependent on the size, shape, orientation, composition, and structure of the particle (Jonasz, 1991). Laser diffraction methods for determining PSDs and volumetric SSC are largely insensitive to change in color and composition. However, as particles differ from assumed spherical shapes there may be bias in estimated PSDs (Agrawal and Pottsmith, 2000; Grey and Gartner, 2009). When particles are non-spherical, the averaged cross sectional area of all the particle's possible orientations to the beam may be larger than a spherical particle of equal volume (Jonasz, 1991). This may lead to a non-spherical particles being attributed to larger size fractions, or a shift of the PSDs to coarser distributions (Eshel et al., 2004).

Laser diffraction detectors are placed on the focal plane of a receiving lens of focal length f (eq. 2). All rays of light coming from the scattering particle at a particular angle θ to the lens optical axis reach the detector at a radius equal to:

$$r = f\theta \tag{2}$$

where r is the ring detector radius, f is focal length, and θ is the angle between the particle and the lens optical axis (Agrawal and Pottsmith, 2000). The light that is not scattered passes through a hole in the center of the detector and is detected by a photo-diode. The light sensed by the diode provides a transmissometer function that compensates for attenuation of scattered light that reaches detector rings. A transmissometer is an detector that senses the ability of a substance to transmit light. Each ring on the detector represents a narrow range of logarithmically increasing scattered angles. At each logarithmically spaced ring on the detector the optical power is measured for the corresponding size range of the ring. The rings are logarithmically spaced because as the particle size decreases the observed scattering angle increases logarithmically. The scattered optical power of large particles peak at small angles (inner rings) and the scattered optical power of small particles peak at large angles (outer rings). The total optical power sensed by the detector rings is the sum of the contributions from each size class weighted by the concentration in the size class. The optical power distribution from the ring detectors provides the essential information to estimate particle size distribution (Agrawal and Pottsmith, 2000). The inversion of the power distribution sensed by the ring detector produces an area distribution of particles. From the area distribution, the volume distribution is estimated by multiplying the area in any size class by the median diameter in that particular size class. The total particle size concentration is quantified by summing the volume concentration in each size class. The total concentration is obtained regardless of particle density or size distribution (Agrawal and Pottsmith, 2000). The mean particle size is estimated by calculating the ratio of total particle area to total particle volume. Many laser diffraction instruments estimate volumetric concentration as opposed to a mass concentration (Agrawal and Pottsmith, 2000) because the optical power distribution is converted to an area distribution via a mathematical inversion process. Volumetric results can be compared to gravimetric suspended sediment data by estimating or assuming a density for suspended sediment. No information about particle mass or density is obtained in the analysis (Agrawal and Pottsmith, 2000; Pedocchi and Garcia, 2006).

The LISST-100 is a submersible laser diffraction instrument manufactured by Sequoia Scientific, Inc, using the same technology as the LISST Streamside (used in this study, see Methods). A study was conducted on the Colorado River (Melis et al., 2003) to increase the temporal and spatial resolution of suspended sediment data and to validate laser diffraction particle analyzers. Point data were obtained by averaging 16 samples collected every two minutes over a 24-hour period. Seven hundred twenty LISST point measurements compared closely (within approximately 15%) with cross-sectional integrated suspended sand, silt and clay data collected near the site using a D-77 isokinetic bag sampler (Melis et al., 2003).

Laboratory tests conducted by Agrawal and Pottsmith (2000) showed the LISST-100 accurately estimated the size of glass spheres from a known size distribution. While no percent errors were given, visual observations of published results indicated the LISST-100 estimated the size of the glass within approximately 10 to 15% of the true value. Laboratory tests comparing weighted concentrations of materials with known densities vs. LISST estimated total volumetric concentration of particles indicated that the LISST was able to retrieve estimates within approximately 20% accuracy for all materials tested. Notably, as particle size increased the error also increased at an average rate of approximately 7% (Agrawal and Pottsmith, 2000; Gray et al., 2001). In a study conducted by Gartner et al. (2001), a LISST-100 was evaluated for particle size and volume estimation accuracy using polymer spherical particles. Consistent with previously published results (Agrawal and Pottsmith, 2000), it was shown the LISST was able to determine particle size to within 10 to 20% with largest errors in the largest size classes.

Since detector rings are logarithmically spaced, each upper size class bin is 1.18 times the lower size. The result is decreased resolution with increasing particle size. For example, the ring that represents 5µm covers a range of 4.7 – 5.54µm. While the ring that represents 200µm covers a range of 179.2 – 211.5µm. The result is that the ring that detects larger particle size has a much broader sensitivity range as compared to smaller size classes, thus reducing resolution (Gartner et al., 2000).

There are currently several commercially available LD instruments available on the market, all manufactured by Sequoia Scientific, Inc. Laser In-Situ Scattering and Transmissometry (i.e. LISST) instruments were originally developed for marine sediment studies but the technology is evolving for deployment in freshwater systems (Agrawal and Pottsmith, 2000). The LISST-Streamside utilizes the same technology as the instruments described, but is designed for monitoring sediment in shallow rivers, streams, and ponds. An in-stream pump supplies water to the particle analyzer for analysis at pre-determined time intervals. After analysis, the water sample is returned to the source, thus, eliminating handling and lab processing of the sample (see Methods section for more information) (Hubbart and Freeman, 2010; Hubbart and Gebo; 2010).

OBJECTIVES

The general objective of the following research was to characterize suspended sediment concentrations and loading in a mixed use, urbanizing watershed and to develop relationships between suspended sediment load and land-use. Specific objectives were to a) Provide estimates of suspended sediment flux (i.e. suspended sediment concentration and sediment loads) at each nested land-use gauge site during the historic wet season (i.e. March through June), b) Develop sediment rating curves during the period of study and compare predicted to observed suspended sediment concentrations, c) Quantify relationships between land-use and observed sediment trends, d) Compare mean particle size between each land-use area, and e) partition sediment flux during base flows from sediment flux during storm flows.

HYPOTHESES

The following hypotheses address the specific objectives above:

Ho_1: Suspended sediment concentrations will not differ between nested land-use areas of the study.

Ha_1: Suspended sediment concentrations will differ between each nested land-use area of the study.

Ho_2: Suspended sediment loads will not differ between each nested land-use area of the study.

Ha_2: Suspended sediment loads will be different through each nested land-use are of the study.

Ho_3: Sediment rating curves will not be differ between each nested study site.

Ha_3: Sediment rating curves will differ between each nested study site.

Ho_4: Mean particle size will not vary between land use types

Ha_4: Mean particle size will vary between land use types

CHAPTER II:

METHODS

STUDY SITE

This study was conducted in the Hinkson Creek Watershed (HCW) located in the Lower Missouri-Moreau River Basin (LMMRB, HUC 10300102) in central Missouri (Figure 3). Hinkson Creek originates northeast of Hallsville, Missouri and flows 42 km southwesterly to Perche Creek, southwest of Columbia, Missouri (Figure 3). Elevation ranges from 274 m.a.s.l in the headwater to 177 m.a.s.l at the confluence of Perche Creek (USACE, 1971). The HCW encompasses approximately 22,790 ha. Urban land use occupies 20.7% of the watershed, 11.5 % is in row crops, 38.2 % grassland, and 26.9 % forested with approximately 60% of the total area inside the city limits of Columbia (MORAP, 2005; MODNR, 2011). The current population of Columbia, Missouri is 108,500 (USCB, 2011). The upper portion of the watershed is mainly comprised of rural agriculture and wooded areas, whereas the lower portion of the watershed is mainly urbanized (MODNR, 2011). In general, soils in the HCW are prairie-forest transitional; poor to well drained, and are easily erodible in part due to steep slopes (Perkins, 1995). Soils in the upper portion of the HCW are predominately loamy till with an underlying claypan and thin cherty clay. In the lower portion of the HCW, soils are silty to sandy clay (Chapman et al., 2002). Hinkson Creek is a Missouri Ozark border stream located in a transitional zone between Glaciated Plains and Ozark Natural Divisions (Thom and

Wilson, 1980). Missouri Ozark border streams generally originate on level uplands underlain by shale and descend into hilly terrain underlain by limestone (Pfleiger, 1989). Average discharge from 1967 to 2008 was estimated to be 1.55 m^3/s, from data collected at a U.S Geological Survey gauging station (#06910230) (site #2, Figure 3).

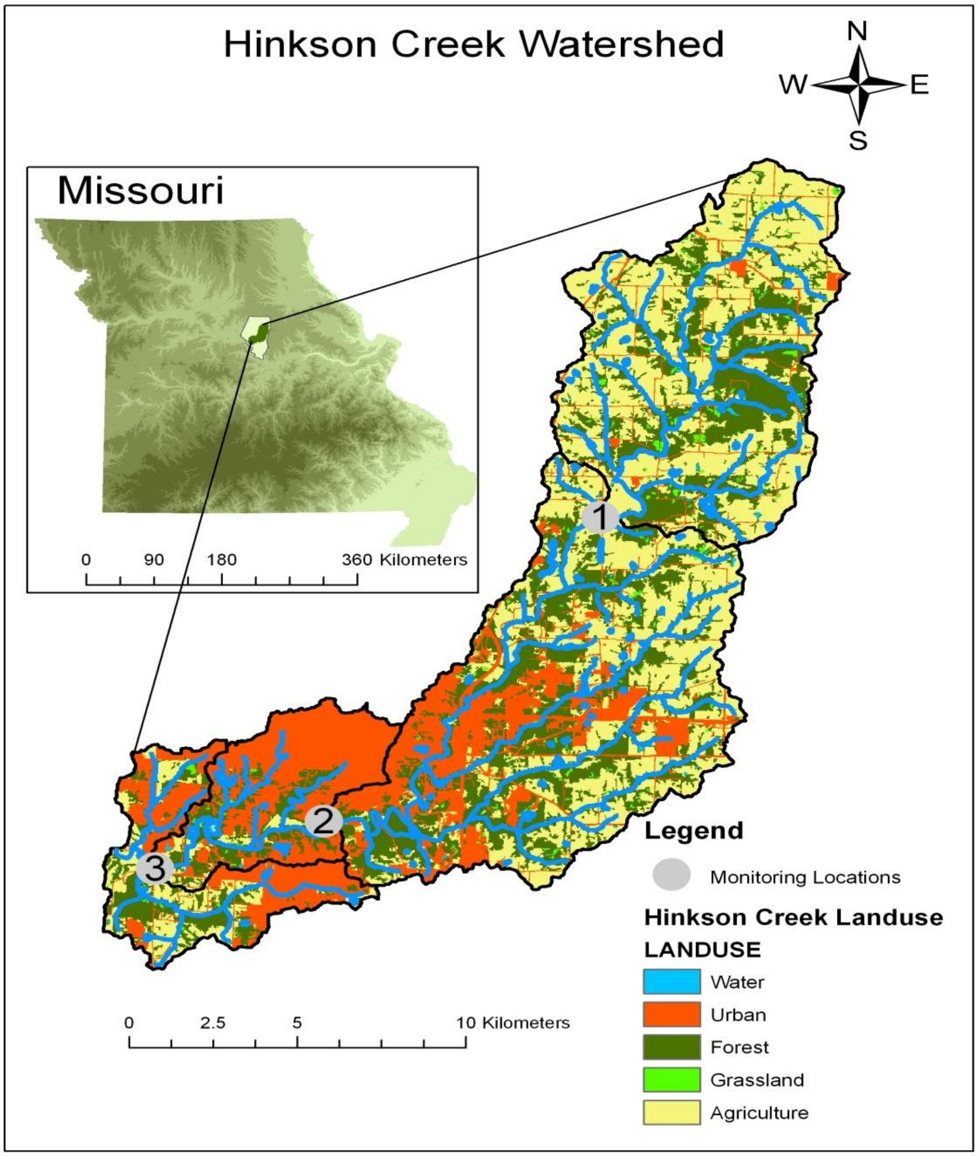

Figure 3: Headwater (1), suburban (2), and urban (3) gauging site sub-basins and contributing urban, forest, agriculture, grassland, and water land-use areas located in Hinkson Creek Watershed, MO. Contributing and land-use areas determined using ESRI ArcGIS with 10 m digital elevation model from the National Elevation Dataset and 30 m land-use cover from the National Land Cover Data Set. Permanent hydroclimate stations and suspended sediment instruments are located at sites 1, 2, and 3.

Climate

Missouri climate is characterized by strong seasonality, and is dominated by continental polar air masses in the winter with summers influenced by maritime and continental tropical air masses (Nigh and Shroeder, 2002). Data analyzed from Sanborn Field climate station, (located on the University of Missouri campus), from 2001 to 2010 indicated average annual precipitation of 1108.6 mm and average daily temperature of 13.3 °C. The average daily relative humidity is 67.5%. The historical wettest months are March through June when 61% of the region's annual precipitation falls (on average). The growing season is approximately 215 days, and the driest periods of the year occur from November to March (Nigh and Shroeder, 2002).

Soil Characteristics

Soil types of the HCW are highly variable. Soils generally have lower infiltration rates (slow to very slow) in the upper portion of the watershed but increase at the lower end of the watershed (MODNR, 2011). However, the lower portion of the watershed has an increasing percentage of urban areas, which are associated with impermeable surfaces (MODNR, 2010). Typical characteristics of major soils series found within HCW are presented in Table 1 and Table 2.

Table 1. Typical characteristics of all major soil series found in the Hinkson Creek Watershed located in central Missouri. Derived from Boone County, Missouri Soil Survey (NRCS, 2003).

Typical Characteristics of Major Soil Series in HCW					
Series	**Depth Class**	**Drainage Class**	**Permeability**	**Parent Material**	**Slope Range (%)**
Bardley	Moderately Deep	Well	Moderate	Colluvium Over Clayey Residuum	20 to 45
Clinkenbeard	Moderately Deep	Well	Moderately Slow	Clayey Colluvium	20 to 70
Hatton	Very Deep	Moderately Well	Very Slow	Loess Over Fine Silty Pedisediment	2 to 5
Keswick	Very Deep	Somewhat Poorly	Slow	Loess Over Clayey Till	5 to 14
Leonard	Very Deep	Poorly	Slow	Fine-Silty Loess over Till	2 to 6
Menfro	Very Deep	Well	Moderate	Fine-Silty Loess	3 to 45
Mexico	Very Deep	Somewhat Poorly	Very Slow	Loess Over Pedisediment	1 to 3
Weller	Very Deep	Moderately Well	Slow	Loess	2 to 9
Winfield	Very Deep	Moderately Well	Moderate	Fine Silty Loess	5 to 45
Winnegan	Very Deep	Moderately Well	Slow	Clayey Till	14 to 35

The upland ridge that surrounds and extends into the upper areas of HCW is associated with the Mexico-Leonard association, formed from fine-silty loess over pedisediment and glacial till. The Mexico-Leonard association is poorly to somewhat poorly drained, with permeability varying from slow to very slow. Table 2 shows infiltration and permeability rates. Slopes generally range from one to six percent. Most row crops in HCW are grown in Mexico-Leonard soil associations. The Mexico-Leonard soil association constitutes roughly 20% of the watershed (NRCS, 2003; MODNR, 2011).

Table 2. Classification of soil permeabilities and infiltration rates. (USEPA, 1981; Ward and Trimble, 2004).

Infiltration Class	**Infiltration Rate (mm/hr)**
Very Slow	<1.27
Slow	1.27 - 3.81
Moderate	3.81 - 7.62
High	>7.62
Permeability Class	**Premeability Rate (mm/hr)**
Very Slow	<1.5
Slow	1.5 - 5.0
Moderately Slow	5.0 - 15.0
Moderate	15.0 - 51.0
Moderatly Rapid	51.0 - 500.0
Rapid	>500.0

The soils in the central and upper areas of HCW are characterized by Keswick-Hatton-Winnegan soil association. These soils cover nearly 50% of the watershed. The Keswick-Hatton-Winnegan association forms from loess over clayey till and fine-silty pedisediment and is moderately well drained with slow to very slow permeability's. Slopes range from two to 35%. The land-cover outside urban areas is predominantly a mix of pasture and woodlands (NRCS, 2003; MODNR, 2011).

In the central to lower areas of HCW the soil type is Weller-Bardley-Clinkenbeard association. This soil is located mainly inside the city limits of Columbia, MO. Up to 40% of the Weller-Bardley-Clinkenbeard association is located in urban land use. The Weller silt loam, formed in deep loess, is located on summits, shoulders, and benches. Weller silt loam is moderately well drained with low permeability. Slopes of the Weller silt loam are commonly between two and nine percent. The back slopes downhill from Weller soils are comprised mainly of Bardley-Clinkenbeard complex. This complex is often very stony with slopes between 20 and 40%. The Clinkenbeard complex is well drained with moderate permeability (NRCS, 2003; MODNR, 2010).

Lowland soils near the confluence of Perche Creek are dominated by Menfro-Winfield association. This soil association makes up only five percent of HCW. Menfro-Winfield soils formed in deep, fine-silty loess. This soil association is common in upland areas of the Midwest that are in close proximity to large rivers. The Menfro-Winfield soils are commonly found in close proximity to rivers because the loess is transported from floodplains by wind and deposited in upland areas. These soils are well drained with moderate permeability (Soil Survey Staff, 2003; MODNR, 2011).

The bottomlands of Hinkson Creek are relatively narrow, usually less than 0.40 km wide, with a variety of soils formed by alluvial processes. Bottomland soils exhibit a wide range of textures, drainage types, and permeabilities. Within the city of Columbia, urban development of bottom land, alluvial soils has been minimal since being largely cleared in the early 1900's for agriculture (NRCS, 2003; MODNR, 2010). Land management of bottomland areas has not changed since that time.

Water Quality

In 1998, the Missouri Department of Natural Resources (MDNR), Division of Environmental Quality, Water Protection Program, Water Pollution Control Branch placed a 14 mile segment of Hinkson Creek on the list of impaired water bodes under section 303 of the federal Clean Water Act. Hinkson Creek was listed as impaired for protection of warm water aquatic life with the source of impairment listed as unknown. A history of fish kills, physical alterations of streams channels and adjacent riparian corridors and other problems linked with urbanization are suspected to have resulted in impairment of beneficial uses (MDNR, 2011). Some typical problems associated with streams in urban regions include larger more frequent floods and lower base flows due to impervious surfaces; increases in soil erosion with subsequent deposition in streams; water contamination from urban storm water flows; and degradation of aquatic habitat due to pollutants and physical alterations of stream channel. Although the MDNR was not able to conclusively identify a source of impairment, sporadic water quality studies showed at times E. coli concentrations were too high, and toxicity was found for various constituents. Excessive sediment in Hinkson Creek was identified by visual inspection of turbidity as a possible source of impairment (MDNR 2006, 2009). Notably, visual inspections did not provide quantitative data, further illustrating the need for research in the watershed providing suspended sediment data.

Concurrent Research in Hinkson Creek Watershed

A nested scale study was initiated in HCW in the winter 2008 to characterize hydroclimatic variables across the multi-use, urbanizing watershed. Hydroclimate stations were strategically placed throughout the watershed to capture key differences in varying land-use areas (i.e. forested, agricultural, suburban, and urban). Five gauging stations were installed (Hubbart and Freeman, 2010, Hubbart and Gebo, 2010, Hubbart et al., 2010), and this work focuses on three of those sites to quantify distributed land-use affects on sediment loading. Nested watershed study designs use a series of sub-basins inside a larger watershed to examine environmental variables. Inside each of the sub-basins, the same sets of environmental data are collected, but the study design at each location is adapted to address the varying characteristics of the local setting. Sub-basins are often determined based on dominant land use and complexity of the hydrologic system (Hubbart et al., 2010; Capel et al., 2008; Hubbart et al., 2007). A nested watershed study design enables researchers to quantifiably ascertain the influencing patterns and processes observed at each location (Pickett, 1997). The nested scale watershed study design used in this project will supply information to calculate differences in discharge, sediment concentration, mean particle size class, and sediment loading between sub-basins. Suspended sediment and hydroclimate monitoring stations were located as follows:

- Site 1, located in Hinkson Creek headwaters, on Rogers Road (39° 01.418' N, 92° 14.761' W)
- Site 2 is collocated with the USGS gauging station (mentioned previously) at the bridge on Old Route K Road (38° 55.670' N, 92° 20.391' W)
- Site 3 is located at the Scott Boulevard/ Highway TT bridge (38° 54.847 N, 92° 24.011 W), (Figure 3).

Figure 6 shows hypsometric curves (percent contributing area versus elevation) for contributing areas draining to site 1, site 2, site 3, the HCW outlet, and the entire HCW.

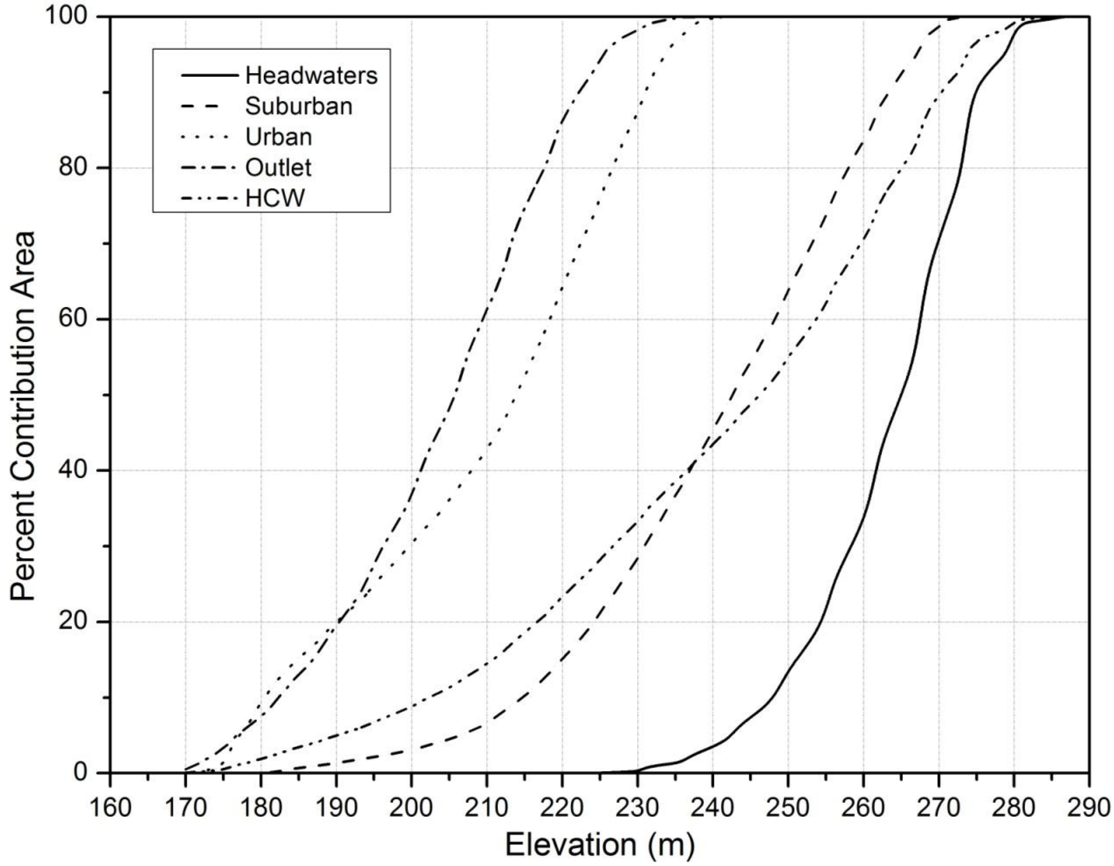

Figure 4. Hypsometric curves showing percent contributing area versus elevation for headwater, suburban, urban sub-basins, HCW outlet, and entire HCW.

The total contributing area draining to the outlet of Hinkson Creek is 230.8 km^2. Site 1 has a contributing drainage area of 77.4 km^2 with the dominant land use pasture/row crops (55.2%). Site 2 is dominated by forested land use (36.2 %) with a total contributing area of 102.1 km^2. Site 3 has a contributing area of 26.3 km^2 and the dominant land-use is urban (66.9%). Total contributing area and land use for each gauging station is presented in Table 3.

Table 3. Total contribution area, land-use, and cumulative contributing land-use area for three hydro climate and suspended sediment monitoring sites in Hinkson Creek Watershed, Located in Central Missouri.

Contributing Areas	**Total Area**	**Water**	**Urban**	**Forest**	**Grassland**	**Pasture/Crop**
Component Sub-watersheds	km^2	% Area	% Area	% Area	% Area	% Area
Site 1	77.4	2.4	4.8	36.0	1.6	55.2
Site 2	102.1	1.6	25.2	36.2	1.1	35.9
Site 3	26.3	3.1	66.9	23.1	0.6	6.2
Confluence with Perche Creek	25.0	1.7	44.6	26.4	0.9	26.4
Cumulative Contributing Areas	km^2	% Area	% Area	% Area	% Area	% Area
Site 1	77.4	2.4	4.8	36.0	1.6	55.2
Site 1+2	179.5	1.9	16.4	36.1	1.3	44.2
Site 1+2+3	205.8	2.1	22.8	34.5	1.3	39.4
Entire HCW	230.8	2.1	25.2	33.6	1.2	38.0

Figure 5 shows a basic schematic of gauging stations. Manual cross sections using the Incremental Cross Section method (Dingman, 2008) were conducted to construct rating curves to estimate flow (m^3/s) from stage data. The incremental cross section method involves measuring flow velocity at the center of equal intervals across a stream or river. Flow is then determined by multiplying flow velocity, cross section area, and depth of flow, resulting in an estimate of volume flow per unit time. The summation of each flow measurement increment provides an estimate of total discharge (ASTM, 2008b, Dingman, 2008). A rating curve is created by plotting the relationship between stage (water depth) and discharge and fitting a curve to the points (ASTM, 2008c). The rating curve allows discharge (dependent variable) to be estimated from the stage (independent variable). This method is useful to scientists and land managers because stage is much easier to measure relative to discharge. LISST-Streamsides (Sequoia Scientific, Inc) were co-located with hydroclimate stations to estimate particle size distribution and volumetric suspended sediment. Sensors, variables sensed, and sampling intervals at each monitoring site are presented in Table 4.

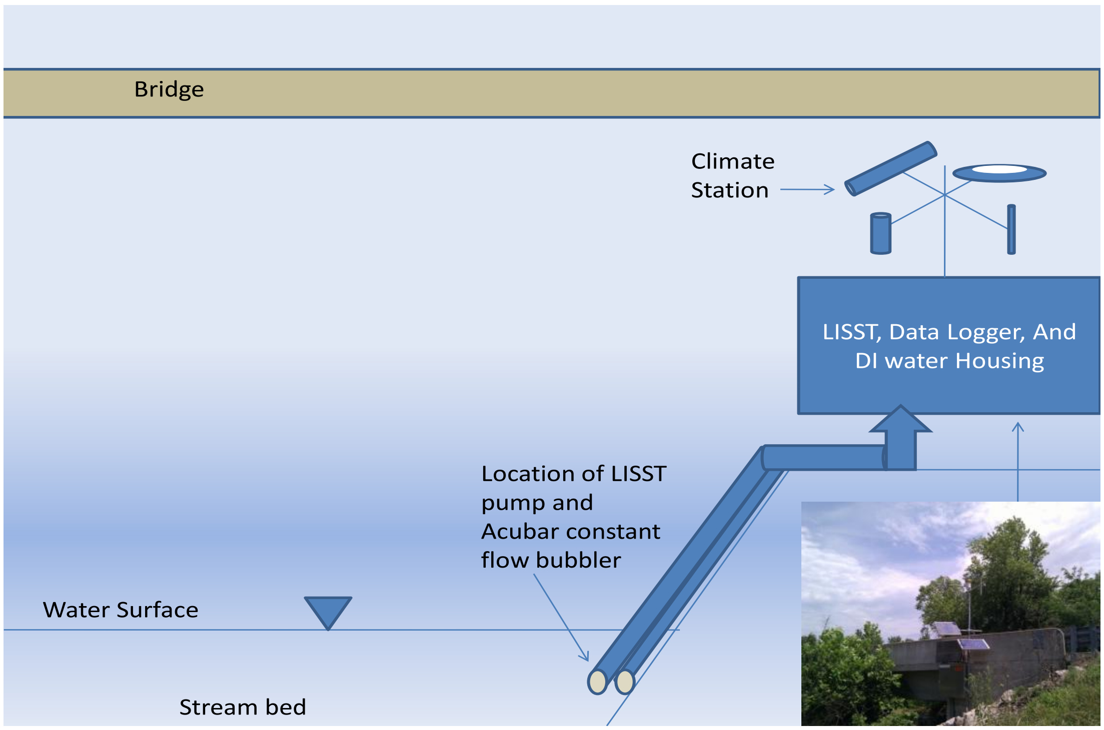

Figure 5.Generalized schematic of basic hydroclimate station design for monitoring sites located in the Hinkson Creek Watershed located in Central Missouri.

Table 4. Sensors and variables measured at each scale-nested hydroclimate station in Hinkson Creek Watershed located in Central Missouri. The instruments used in this study included the Sutron constant flow bubbler and the LISST particle analyzers.

Variable Sensed	**Units**	**Sensor Model**	**Sensing Interval**
Accubar Constant Flow Bubbler	mm	Sutron, 56-0133	10sec
Suspended Sediment	µl/l	Sequoia Scientific, Inc. LISST	60min
Air Temperature	°C	Vaisala, HMP45C	30sec
Soil Temperature	°C	CS 107	30sec
Relative Humidity	%	Vaisala, HMP45C	30sec
Wind Speed	m/s	Met-One 034B	30sec
Wind Direction	Deg	Met-One 034B	30sec
Vegetative/Snow Depth	cm	SR50A, Sonic Range Sensor	30sec
Soil Volumetric Water Content	%	CS 616	30sec
Precipitation	mm	TE525WS Rain Gage	30sec
Radiation	W/m^2	LI200X, LI-COR Pyranometer	30sec

Rating Curves

Rating curves are generally developed using a stage-equivalent discharge relationship to accurately estimate flow across a range of depths (Dottori et al., 2009). Accurately estimating discharge was critical for this study to correctly estimate the total sediment load. Rating curves were constructed by manually measuring discharge using the incremental cross section method presented earlier from the winter of 2008 through the end of the study period. The most common equation for discharge rating curves involves fitting a power function to the observed stage-discharge points. The power function is as follows:

$$Q = ah^b \quad (3)$$

where a and b are constants and Q and h are instantaneous stage and discharge values (Yu, 2000). Equation 3 is not always a suitable rating curve for all stage depths

(Shiklomanov et al., 2005). While this rating function is the most common, there are several reason why other functions and segmentation of curves (multi-phase) into two or more segments may be necessary. For example, the characteristics of the stage-discharge relationship are largely defined by the shape of the channel cross section (Kennedy, 1984). Changes in the rating curve slope often coincide with stage values when a expansion or narrowing of the channel occur (Shiklomanov et al., 2006), there is a sudden repositioning of control of the stream in either the upstream or downstream direction when the water reaches a certain stage (Overleir and Reitan, 2005), or there is a change in friction as the water level reaches a certain stage (Herschy, 1999; Lambie, 1978). The power equation has only two fitted parameters a and b and may not allow for the approximation of complex shape relation Q=$f(h)$ over an entire range of stages, where Q (discharge) is a function of h (stage) (Shiklomanov, 2006). When the stage-discharge relationship becomes too complex to be approximated by a single power function, it is recommended that a piecewise approximation should be conducted to construct a rating curve with different segments for variable flow ranges (Schmidt and Yen, 2002; Shiklomanov et al., 2006). Another commonly used rating curve approximation to the stage-discharge relationship is an mth order polynomial (Herschy, 1985; Krashnikikov, 1987):

$$Q' = \beta_0 + \beta_1 H^1 + \beta_2 H^2 + \cdots + \beta_m H^m \quad (4)$$

Where $\beta_{0,}$ $\beta_{1...}$ β_m are fitted parameters, Q is discharge, H is stage, and m is the exponent of the polynomial function. A high order polynomial approximation of the stage-discharge relation could theoretically be used to fit the shape of any rating curve (Shiklomanov et al., 2006). The advantage of the polynomial approximation is the ability to fit stage-discharge curves with breaking points or inflections (Grigorjev et al., 1977; Garvin, 1982; Lesnikova, 1973; Herschy, 1985). In this study rating curves were constructed by using Equation 3 and a combination of linear and polynomial equations. Estimates of total discharge, water yield, and discharge statistics were calculated by inserting stage data into the rating equations.

Partitioning Base Flow and Storm Flow

An important component of this study was to partition how much sediment was transported during periods of base flow relative to storm flow events. Hydrograph analyses were used to determine the periods of time when stream flow was entirely base flow and days when direct runoff contributed to stream flow. Key to this process was to identify starting and ending points of surface runoff. Direct runoff begins when stream flow starts to increase and the ending point can be indentified when a plot of the log flow rate against time becomes a straight line (Chapman, 1999). There are several graphical methods for separating base flow from direct runoff (Chow et al., 1988). Graphical methods are not very efficient for long time periods and are somewhat subjective, resulting in inconsistent results from the same flow data (Lim et al., 2005). The Web Based Hydrograph Analysis Tool (WHAT) uses digital filters to analyze high frequency signals from low frequency signals (Lyne and Hollick, 1979). Base flow is generally associated with water discharged from groundwater storage. The groundwater discharge creates a smoothing effect. Therefore, in the frequency spectrum of a hydrograph, long waves tend to be associated with base flow while high frequency variability of the streamflow will primarily be caused by surface runoff (Eckhardt, 2005). Thus, separating storm flow from base flow is similar to signal analysis and processing (Eckhardt, 2005). Arnold et al. (1995) showed that the digital filter base flow separation methods estimated base flow to within 11% of manual separation. A study by Arnold and Allen (1999) showed that results from digital filter separation agree with manually separated base flow estimates (R^2 value 0.82). Lim et al. (2005) showed that the WHAT method compared well (Nash-Sutcliffe Coefficient > 0.9) with digital filters used by Arnold and Allen (1999). The WHAT eliminated subjectivity often associated with manual base flow separations methods and provided quick results for long time series (Lim et al., 2005). For an in depth analysis of WHAT please refer to Lim et al., 2005 (see references). Given previously published positive results, WHAT was used in this work to separate days when stream flow was entirely from base flow and when direct runoff was contributing to total stream flow. Suspended sediment concentrations and loads were then separated into base flow and storm flow contributions to estimate how much sediment flux was associated with different periods of the hydrograph.

In-Situ Laser Particle Diffraction

Particle diffraction analysis instruments (the LISST Streamside) were used to quantify suspended sediment in Hinkson Creek during the spring runoff season of 2010 (March through June, 2010). The sediment data collected by the LISST instruments (Figure 6) provided information allowing comprehensive comparison of sediment trends between different land-uses and land-covers in the HCW. Deploying LISST's at the previously mentioned sites allowed for comparison between the headwater (site 1), which served as a reference, suburban/mixed land-use (site 2), and urban (site 3) near the confluence of Perche Creek. Statistical Analysis of Variance (ANOVA) test was used to determine if suspended sediment concentration and mean particle sizes are statistically different between gauging stations.

Instrument output specifications and sample settings for the particle analyzers used in this work are presented in Table 5 and Table 6 respectively. Particle analyzers were programmed to sense and log particle size distribution (PSD) and suspended sediment concentration (SSC) every hour on the hour. Average sampling duration was set to 60 seconds (volume sampled = 2.54 liters). Particle analyzers performed a clean water background calibration every 3rd sample with de-ionized (DI) water stored in a 95 liter water reservoir placed so that DI water would gravity flow on demand. During the clean water background check the scattering distribution of DI water is compared to the factory calibrated scattering distribution. This allows the instruments to adjust for differences in the scattering distribution when calculating PSD and SSC. A pump located in the stream, pumped the turbid water sample to the LISST located at a safe distance from the stream to avoid water damage from flooding (Figure 5). Two pump configurations were used during this study. The first pump that was used in this study was made by Sequoia Scientific Inc. The pump provided by Sequoia Scientific was concealed in a waterproof box along with a circuit board pump controller that was wired to the LISST for LISST communication with the pump. The second pump used in the study was a Mini-Monsoon from Proactive Environmental Products. The mini-monsoon pump is completely submergible, more durable, and much less susceptible to water damage compared to the pump provided by Sequoia Scientific Inc. Both pumps used in this study were powered from a 12 volt battery that was charged by solar panels. A turbid inlet line was run from the pump to the particle analyzers. To protect the turbid inlet line from biological growth, flood damage, and vandalism the line was run through a two inch PVC conduit. After analysis, water was returned to the stream through the PVC conduit. Particle analyzers were located 10.5 m, 10.5 m, and 20.5 m from the pump at site 1, site 2, and site 3 respectively. The elevation difference between the pump and the particle analyzers was 4.0 m, 4.5 m, and 6.0 m for sites 1, 2, and 3 respectively. A 30-second intake flush was performed before each sample analysis to ensure any residual water left in the line from the previous sample was removed. These sample settings were chosen to optimize power use at the remotely powered gauge sites (i.e. solar power) while maximizing sampling accuracy.

Laser diffraction particle analyzers require a significant amount of maintenance to accurately estimate suspended sediment concentration and particle size distribution. Particle analyzers optics can be fouled by sediment and biological growth. Clean water calibration, flushing and regular cleaning can mitigate problems associated with dirty optics. In this study particle analyzers were cleaned on a weekly basis using cotton q-tips and soapy water mix. De-ionized water reservoirs were also filled on a weekly basis to ensure clean water calibrations were performed every 3rd sample. A small amount of chlorine was added the de-ionized water to mitigate biological growth in the optics chamber.

Table 5. Output parameters of all LISST instruments deployed in Hinkson Creek Watershed, Central Missouri, during the spring of 2010.

Column	Parameter	Description
1	Date in MM/DD/YYYY	Date of sample
2	Time in HH:MM:SS	Time of sample
3	Total Volume Concentration (µl/l)	Total concentration of all particles sizes
4	Mean Size (µm)	Mean size of particles in suspension
5	Standard Deviation (µm)	Standard deviation of particle size
6	Optical Transmission	Optical transmission of during sampling
7	D10 (µm)	Diameter at which 10% of the sample is finer
8	D16 (µm)	Diameter at which 16% of the sample is finer
9	D50 (µm)	Diameter at which 50% of the sample is finer
10	D60 (µm)	Diameter at which 60% of the sample is finer
11	D84 (µm)	Diameter at which 84% of the sample is finer
12	D90 (µm)	Diameter at which 90% of the sample is finer
13	D60/D10	Hazen uniformity coefficent
14	Particle surface area cm^2	Particle surface area
15	Fraction of sediment in the silt fractoin <64 µm	Fraction of silt size particles
16	Silt Volume Cocentration (µl/l)	Concentration of silt sized particles
17	Battery Voltage (V)	Voltage of battery powering instrument
18	Water tank level (%)	Water level of clean water tank
19:50	Volume concentration for size class 1-32 (µl/l)	Sediment concentration for each particle size class

Table 6. Sample configurations for all LISSTs deployed in Hinkson Creek Watershed located in Boone County, Missouri, during the spring of 2010.

Function	Setting	Volume (liters)
Sample Interval	60 min	n/a
Sample Duration	60 sec	0.18
Clean Water Background	Every 3 Samples	2.55
Intake Flush	30 sec	1.2
Clean Water Flush	15 sec	0.21
Post Sample Flush	5 sec	0.07

Figure 6. LISST-Streamside located in a gauging station box at site 2 in Hinkson Creek Watershed, MO.

Using laser diffraction to estimate suspended sediment of freshwater streams in situ is very new technology. The technology has not been widely validated in freshwater systems, and it has not been used or validated at all in Midwestern streams, where precipitation, streamflow and suspended sediment regimes may be very different than other regions. Validation is necessary to ensure the accuracy of LISST's estimates of suspended sediment concentration and mean particle size. Therefore, peripheral data were collected during this project to validate LISST accuracy including the gravimetric (Hubbart et al. in preparation), and depth integrated cross section methods. Gravimetric suspended sediment methods (Melis et al., 2003; Williams et al., 2007) involve collecting a known sample volume and filtering out the sediment using a vacuum filtration process. Prior to use, filters are rinsed with clean water, dried, and weighed. After filtration, sediment and filter are dried and weighed. After the weight of the filter is subtracted the weight of the sediment per known volume is calculated by subtracting the dry filter weight from the filter with sediment (ASTM, 2007). Using a series of different sized filters, information on particle size distribution of the sample is estimated.

Daily grab samples were collected from each site for coupled gravimetric and LISST analysis in the lab. The LISST analysis of daily grab samples ensured suspended sediment data were obtained if unforeseeable events occurred that caused instruments in the field to fail (e.g. power failure, bio-fouling, or optical transmissions below optimal thresholds). Grab samples analyzed using both the LISST in the laboratory as well as gravimetric method allowed estimation of suspended sediment particle density and comparisons between LISST's estimates (volumetric analysis, ul/l) and gravimetric analysis (mg/l). Grab samples were collected each day starting at noon at site 1 proceeding to sites 2, and 3. All grab samples collected in HCW were collected in between noon and 2:00 pm every day during this study.

Estimating Sediment Particle Density

To compare volumetric (µl/l) SSCs to other studies that investigated gravimetric (mg/l) SSC estimates of suspended sediment particle density were necessary. Suspended sediment particle densities multiplied by the volumetric SSC produces a gravimetric SSC. Suspended sediment particle density can be estimated if the volumetric concentration and gravimetric concentration of a single sample is known. Researchers at Sequoia Scientific Inc. (manufacture of LISST-StreamSide) recommend dividing the gravimetric concentration (mg/l) by the volumetric concentration (µl/l) to produce estimates of density in mg/µl. During the course of this study suspended sediment grab samples were collected four times a week from all sampling locations. Suspended sediment concentrations for each sample were analyzed by volumetric methods (i.e. laser diffraction) as well as gravimetric methods (i.e. filtration). This produced paired volumetric and gravimetric SSCs for each sample. Density estimates for all samples collected over the course of the study were averaged resulting in an estimate of average particle density for each gauging site.

Evaluating Stream Cross-Section Sediment Distribution

An additional fieldwork objective in this study was to evaluate the LISST's estimation of suspended sediment from a single point relative to sediment concentration variability in a cross section of the creek. This is of particular importance since the LISST turbid inlet was located in the same location throughout the study. It is important to quantify the suspended sediment relationship between point estimates relative to the entire stream cross section to accurately estimate sediment loading. Conceivably, the LISST point estimate could overestimate, or underestimate the true cross section averaged estimate. To characterize suspended sediment across an entire cross section depth, integrated sampling techniques were used (Porterfield, 1972; ATSM, 2007; ATSM, 2008) using a DH-48 Depth Integrated Sampler (Porterfield, 1972). The DH-48 is a lightweight water sampler used to collect isokinetic depth integrated suspended sediment samples. Isokinetic samplers are designed to collect water at the same velocity of the stream (e.g. if the stream velocity is 0.3 m/s or greater, water will enter the sampler at the same ambient stream velocity). Inflow efficiency is the ratio of the sample velocity entering the bottle to the ambient stream velocity. The DH-48 can reliably sample to a depth of nine feet at sea level and velocities between 0.30 and 2.74 m/s. The sampler is limited to this range of velocities because the inflow efficiency must be between 90 to 100 % to collect a representative sample (FISP, 2010).

The DH-48 sampler is lowered towards the bottom of the channel then raised at a steady rate that allows the sampler's bottle to be filled to the optimal volume. The rate that the sampler is lowered and raised is referred as the transit rate (ASTM, 2008). The transit rate that the sampler is lowered is based on depth and velocity of stream flow (Edwards and Glysson, 1970). There are two methods that are commonly used to determine the spacing and the location of the depth integrated sampling (Edwards and Glysson, 1970; ASTM, 2008). The Equal Discharge Increment Method (EDI) requires that the stream channel be divided in equal horizontal increments. The second method is the Equal Width Increment Method (EWI) discussed earlier for stream cross section work. Transit rate is determined for the EWI method by calculating the transit rate of the interval with the greatest discharge (Edwards and Glysson, 1970). The transit rate of the vertical transect with the maximum discharge is then applied to the entire cross section. Using the EWI method will sometimes not fill an entire sample bottle, allowing the same sample bottle to be used for multiple vertical transects. Notably, there are advantages and disadvantages for each method; however, if used properly they yield the same result. The EDI method requires some previous knowledge of stream flow distribution across the stream channel, which may not be available. The EWI method does not require any pervious knowledge of discharge but may require a greater number of channel increments to be sampled (Edwards and Glysson, 1970).

In the current study the EWI method was used to assure comparable results with stream cross section (i.e. flow) estimates. Equal Width Increment, DH-48 sampling at the headwater, suburban, and urban gauging sites was conducted throughout the study period. When flows were below the lower limit of the sampler's effective range, grab samples were collected. All samples collected using the DH-48 sampler or other methods were analyzed using a LISST, as well as gravimetric lab methods to determine a gravimetric suspended solid concentration. Depth integrated sampling helped validate LISST estimates, provided sediment discharge data, and provided additional information to evaluate the particle analyzer’s ability to accurately estimate stream cross section suspended sediment values. There are several situations which reduce the accuracy of depth integrated sampling. During low flows only a narrow portion of the stream will flow at a rate that meet minimum sampling velocities. This means a small fraction of the total verticals will be samples at isokinetic rates. During high flows, stream velocities may not meet the minimum velocity requirement. When minimum velocity requirements are not met during high flows a representative transit rate cannot be established for depth integrated sampling. When minimum velocities are not met depth integrated suspended sediment sampling results are not accurate and the results are unreliable. The purpose of the depth integrated sampling was to create an offset coefficient to adjust the point based sample results of the LISST turbid inlet so that they were more representative of the entire cross section.

Daily and Monthly Sediment Loading

Combining sediment data and discharge at each site yielded estimates of daily and monthly sediment loading and provided necessary information to develop a sediment rating curve. Total sediment load for each site was calculated by:

$$\text{Load } (m^3/day) = [Q\ (m^3/day)]\ [SSC\ (\mu l/l) * 1x10^{-6}] \qquad (5)$$

where Q is daily discharge, SCC is suspended sediment concentration, and $1x10^{-6}$ is a unit conversion factor to convert suspended sediment concentrations in µl/l to suspended sediment concentrations in m^3/m^3 (Horowitz, 2003). The Kruskal-Wallis one-way analysis of variance by ranks was used to determine if median sediment loads were statistically different between sampling sites. The Kruskal-Wallis one-way analysis of variance is similar to one-way ANOVA but the data is replaced by ranks (Kruskal and Wallis, 1952). Estimated sediment loads were used to calculate suspended sediment yields and create suspended sediment rating curves for each gauging station.

Estimating Sediment Yield

Sediment yield is defined as mass or volume of sediment measured at a gauging station per unit area of the watershed drainage area to that gauging station (Asselman, et al., 2003; Walling and Web, 1996). Sediment yields were calculated to provide an estimate of sediment delivery per unit area of the watershed, and to aerially normalize the observed sediment load. Normalizing the sediment load by the drainage area allows observed sediment yields and delivery to be compared to other watersheds of different sizes and land use characteristics (Lee et al. 2009). There are generally two methods for calculating suspended sediment yields. The first method is calculated by dividing the total observed sediment load at a gauging site by total contributing area draining to the gauging site. This process was repeated in subsequent sub-basins; however, calculated sediment yields will reflect cumulative effects of suspended sediment loads and land-use drainage areas from all sub-basins upstream. This method of calculating suspended sediment yields will be referred to as Cumulative Sediment Yield (CSY). Secondly, suspended sediment yields of individual sub-basins within a nested watershed study design is calculated by subtracting the sediment load from the upstream sub-basins from the total sediment load of the downstream sub-basin and dividing by drainage area of the downstream sub-basin (Lee et al., 2009; Walling and Webb, 1996). From here forward, sediment yields for individual sub-basins are referred in text as Sub-Basin Sediment Yields (SBSY). Table 7 shows example calculations of CSY and SBSY. Quantifying sediment yield at each of the three land-use gauge stations allow for comparisons of sediment yield between watersheds with similar land-uses and provided insights to in-stream suspended sediment processes.

Table 7. Example computations of Cumulative Sediment Yield (CSY) and Sub-Basin Sediment Yield (SBSY) using hypothetical sediment loads and contributing areas.

Subasin	**CA**	**SBA**	**SL**	**Calc. for SBSY**	**SBSY**	**Calc. for CSY**	**CSY**
#	km^2	km^2	Tonnes	eqn.	tonnes/km^2	eqn.	tonnes/km^2
1	10	10	2	SBSY 1 = SL1 / CA1	0.2	CSY1 =SL1/CA1	0.2
2	30	20	20	SBSY 2 = (SL2-SL1)/(CA2-CA1)	0.9	CSY2 = SL2/CA2	0.7
3	50	20	50	SBSY 3 = (SL3-SL2)/(CA3-CA2-CA1)	1.5	CSY3 = SL3/CA3	1.0
4	90	40	200	SBSY 3 = (SL4-SL3)/ (CA4-CA3-CA2-CA1)	3.75	CSY4= SL4/CA4	2.2

CA = Cumulative Drainage Area, SBA =Sub-Basin Area,SL= Sediment Load SBSY=Sub-Basin Sediment Yield, CSY= Cumulative Sediment Yield

Sediment Rating Curves

Suspended sediment rating curves were developed by relating suspended sediment concentrations to discharges over a range of discharge events. The most common rating curve is constructed by log-transforming discharge and SCC data and fitting a power function to the curve (De Vries and Clavers, 1994; Horowitz, 2003). The rating curves relate SSC to water discharge, with the water discharge as the independent variable (De Vries and Klavers, 1994; Phillips et al., 1999; Asselman, 2000, Horowitz, 2003). There are however several ways to construct rating curves using a variety of different regression techniques (Horowitz, 2003). In this study linear regression equations were fitted to observed data. Linear rating equations were selected because they provided a better fit to the log-transformed data compared to other power and polynomial equations. Accuracy of the sediment rating curves was assessed using the Nash-Sutcliffe (NS) efficiency parameter (Nash and Sutcliffe, 1970) as follows:

$$N\ S = \frac{v_o N - \sum_{i=1}^{N}\left(x_i - y_i\right)^2}{v_o N} = 1 - \frac{\sum_{i=1}^{N}\left(x_i - y_i\right)^2}{\sum_{i=1}^{N}\left(x_i - \overline{x}\right)^2} \qquad (6)$$

where v_o is the variance of observed values, N is the number of data points, x_i is the observed value, y_i is the corresponding predicted value, and $\overline{x}$ is the average observed value for the study period. The Nash-Sutcliffe method quantifies how well the suspended sediment rating curve (i.e. model) predicts observed variability relative to the mean observed value. When modeled sediment loads are in perfect agreement with measured loads, NS equals 1.0. NS values can be less than zero which indicates poor agreement between modeled and measured sediment loads. Sediment rating curve accuracy was also assessed for accuracy using total percent difference (Horowitz, 2003; Walling, 1977):

% Diff. = [(predicted value) – (measured value)] / (measured value)] x100 (6)

CHAPTER III

RESULTS

Results will be presented by first discussing the climate, discharge, and hydrology of HCW. Next, results will be presented that focus on suspended sediment concentrations, base flow concentrations, mean particle sizes, and particle densities. Finally, suspended sediment loads, yields, and rating curves results will be presented.

HYDROCLIMATE

Climate was generally wetter than usual during the period of this work. All Climate data (available online) were obtained from Sanborn Field located on the University of Missouri campus. Total precipitation during the study period was 583.2 mm (Table 8). During the spring wet season of 2010, the average daily temperature and relative humidity were 17.08 °C (SD = 7.46) and 67.87% (SD = 15.72) respectively. During the 2010 water year (Oct 1 2009 – September 31 2010), HCW received 1638.3 mm of precipitation which is 48% more precipitation than the 10 year average of 1108.6 mm. Table 9 shows precipitation and temperature comparisons between the 2010 water year and the 10 year water year (WY) average. Although 61% of HCW's precipitation historically falls from the beginning of March through the end of June, only 35.6% of HCW's annual precipitation fell during the wet season of 2010. The equivalent percentage based on the 10-yr average of annual precipitation is 53% (similar to the long-term average). Figure 7 and Figure 8 show times series of climate variables for the 2010 water year and study period (3/1/2010 through 6/30/2010).

Table 8. Descriptive climate statistics for the spring wet season (3/1/2010 to 6/30/2010) in the Hinkson Creek Watershed located in Central Missouri.

Statistic	Precip (mm)	Temp (°C)	Rel. Hum. (%)
Total	583	-	-
average	-	17.1	68.9
max	-	30.1	96.5
min	-	0.3	35.7
stdev	-	7.5	15.7

Table 9. Average precipitation for 2000 through 2010 water years, and the 2010 water year (10/1/2009 through 9/31/2010). Data collected from Sanborn Field on the University of Missouri's Campus in Columbia, MO.

Year	Total Precip (mm)	Average Temp (°C)
10 Yearr Average	1108.6	13.3
Water Year 2010	1638.3	13.1
% Difference	47.8	-1.4

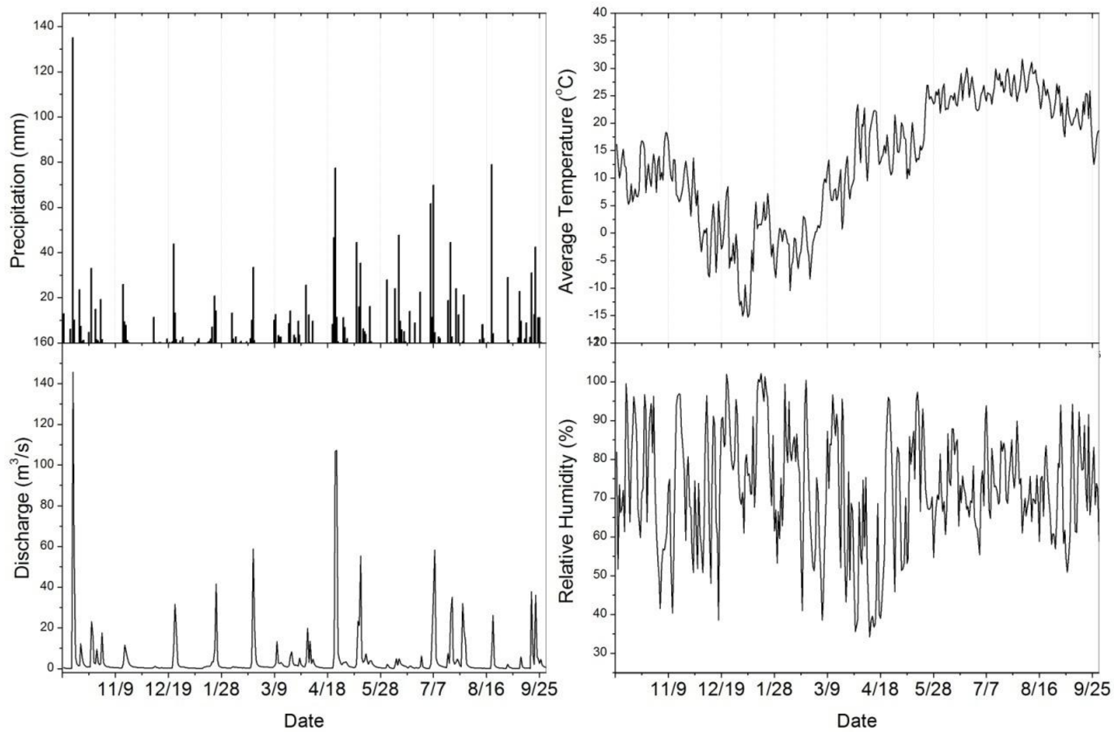

Figure 7. Average daily climate variables, precipitation, discharge from USGS gauging station at site 2, Average Temperature (°C), and Relative Humidity (%) for water year 2010 (10/1/2010 to 9/31/2010). Climate data collected from Sanborn Field located on the University of Missouri campus in Columbia, MO.

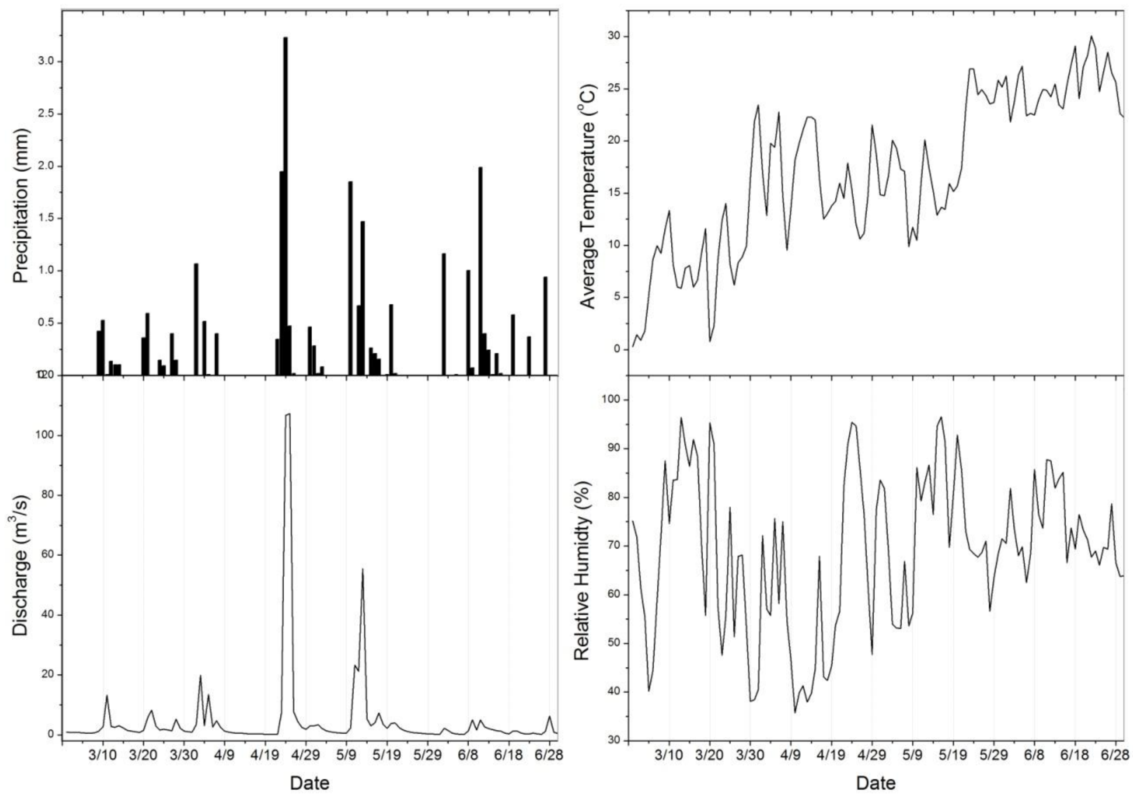

Figure 8. Average daily climate for study period (3/1/2010 to 6/30/2010), where discharge reflects data from the USGS flow gauging station (site 2). Climate variables collected at Sanborn Field located on the University of Missouri campus in Columbia, Missouri.

DISCHARGE ESTIMATION

Rating Curves

In this study a combination of equations were used to approximate the stage-discharge relationship. Multiple equations were used to provide a better fit to different stage windows of the hydrograph. Using multiple equations allows for a more accurate representation of the stage discharge relationship especially when there are abrupt changes in the slope of the stage discharge relationship (Yu, 2000; Shiklomanov et al., 2005). Table 10 shows rating equations for all gauging stations in Hinkson Creek Watershed utilized in this work. Figure 9 shows graphs of rating curves for each site located in HCW. Rating equations were created for each site by fitting a line to the observed points. At sites 1 and 2, a third order polynomial was fitted to stages above 0.5523 m and 0.3030 for sites 1 and 2 respectively similar to previous work where multiphase functions were used (Yu, 2000; Shiklomanov et al, 2005). A linear line was fitted to the data below 0.5523 m and 0.3030 m for sites 1 and 2. At site 3 a power function was fitted to all observed points as per Overleir and Reitan (2005). Rating curves with multiple segments were needed at sites 1 and 2 because there was a change in the slope of the observed stage-discharge relationship that could not be accurately approximated with a single rating equation. At site 3 a single power function was used to approximate the stage-discharge relationships. A segmented rating curve approximation was applied to site 3, using a linear/polynomial/power combination. However, results from the segmented approximation did not provide as reliable estimates of flow as the single power function model. Rating equations developed from manually measured discharge measurements were used to create estimates of total discharge (m^3) and to develop sediment rating curves.

Table 10. Rating equations and stage range for rating equations for each gauging station located in Hinkson Creek Watershed

Site	Rating Equatoin 1	Stage Range (m)	R^2	Rating Equation 2	Stage Range (m)	R^2
Headwaters	$y = 12.794x^3-17.502x^2+10.57-2.6548$	0.5523- max	0.999	y = .0472x	0-0.5523	1.0
Suburban	$y=-0.7788x^3+17.908x^2-9.2459x+1.1784$	0.303-max	0.999	y=0.8286x	0-0.303	1.0
Urban	$y = 5.136x^{1.8118}$	Entire Range	0.940	-	-	-

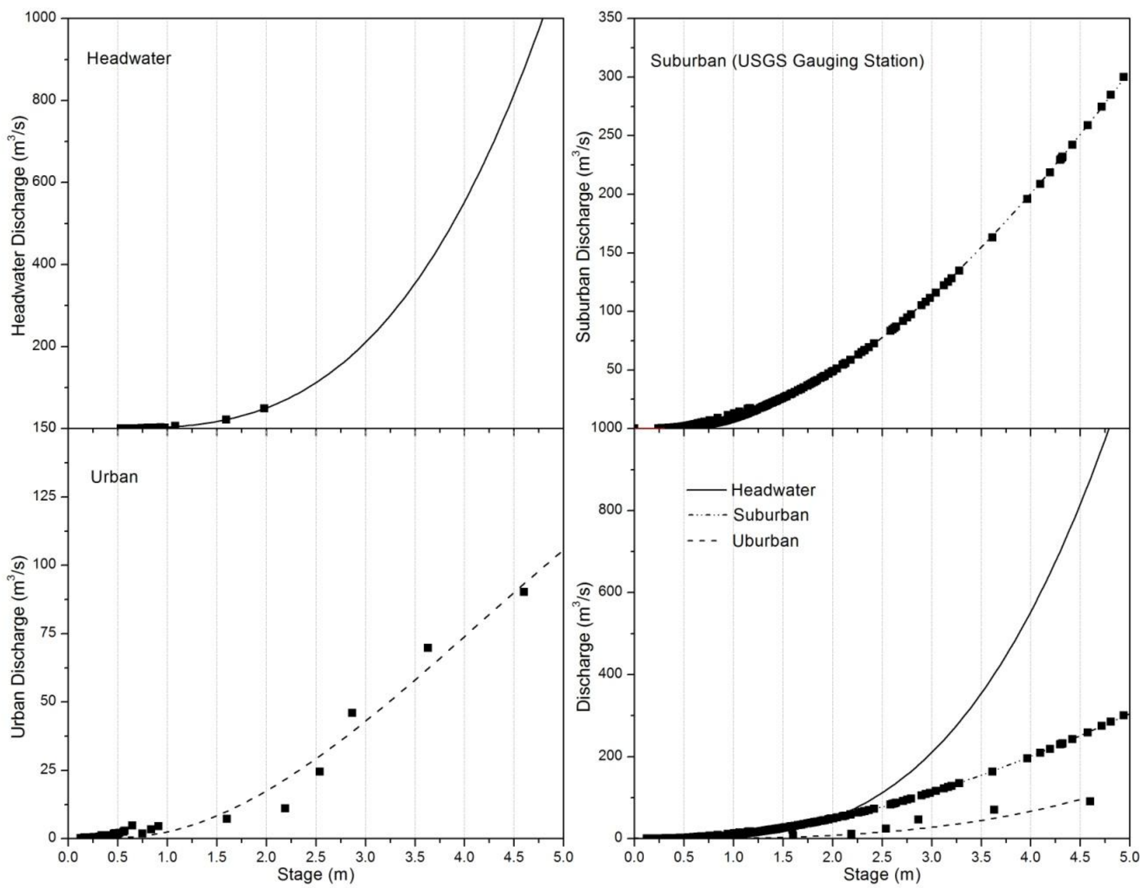

Figure 9. Discharge rating curves for each gauging site utilized in the current research located in Hinkson Creek Watershed, Missouri.

Discharge

Table 11 shows total discharge passing through each gauging site during the period of study (3/1/2010 to 6/30/2010) and percent differences for each gauging site. Total water flow volume for the headwater, suburban, and urban land-use gauging station was 2.97×10^7 m^3, 4.24×10^7 m^3, and 6.167×10^7 m^3 respectively.

Table 11. Total discharge for the study period (3/1/2010 to 6/30/2010) and percent differences for headwater, suburban, and urban gauging locations located in Hinkson Creek Watershed, Missouri.

Site	Total Discharge (m^3)	% Diff. From Headwater	% Diff. From Suburban
Headwater	2.97E+07	0	-30
Suburban	4.24E+07	43	0
Urban	6.16E+07	108	45

Storm Flow and Base Flow

Table 12 shows results from the WHAT analysis for contributions of storm flow and base flow to the total volume of discharge. At the headwater gauging station (site 1) 2.25×10^7 m^3 of discharge was storm runoff and 7.12×10^6 m^3 of discharge was base flow. The suburban site exhibited similar trends with 3.34×10^7 m^3 from storm runoff and 1.07×10^7 m^3 from base flow. At the urban land-use gauging station 4.19×10^7 m^3 of discharge was from storm runoff and 1.974×10^7 m^3 was from base flow.

Table 12. Total discharge for headwater, suburban, and urban gauging sites and volume contributions of storm flow and base flow. Storm flow and base flow contributions were determined using the Web Based Hydrograph Analysis Tool (WHAT) for three gauging sites located in Hinkson Creek Watershed, MO.

Site	Total Discharge (m^3)	Stormflow Contribution (m^3)	Baseflow Contribution (m^3)	% Baseflow
Headwater	2.97E+07	2.25E+07	7.12E+06	24
Suburban	4.91E+07	3.34E+07	1.57E+07	32
Urban	6.16E+07	4.19E+07	1.97E+07	32

Mean Daily Discharge

Table 13 shows descriptive statistics for mean daily discharge for each gauging site located in Hinkson Creek Watershed. Average hourly discharge was 2.8 m^3/s, 4.7 m^3/s, and 6.4 m^3/s for the headwater, suburban, and urban land-use gauging stations respectively.

Table 13. Mean daily average descriptive discharge statistics during the spring study period (3/1/2010 to 6/30/2010) for headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed in Central Missouri.

Discharge (m^3/s)	Headwater	Suburban	Urban
Average	2.8	4.7	6.4
Min	0.0	0.1	2.0
Max	334.8	320.0	406.0
Stdev	18.5	20.2	25.6

Historic Flows

A USGS gauging station, located at site 2, has been monitoring discharge intermittently since 1966. The USGS gauging station located at site 4 was operating from 1967 to 1981, 1987 to 1991, and 2007 to present. Average daily discharge (m^3/s) and total annual discharge (m^3/year) from the USGS gauging station is presented in Table 14 and Table 15 respectively. From 1967 through 1981 that average and median daily discharge was 1.46 and 0.26 m^3/s. From 1987 through 1991 the average and median daily discharge was 1.27 and 0.19 m^3/s. The most current data from the USGS gauging site is from 2007 through 2010 had an average and median daily discharge of 3.85 and 0.63 m^3/s. The average annual discharge from the USGS gauging site was 4.59×10^7, 4.01×10^7, and 1.21×10^8 m^3/year for 1967-1981, 1987-1991, and 2008-2010 periods respectively.

Table 14. Mean and median daily discharge observed at the Hinkson Creek USGS gauging station (#06910230) co-located with suburban gauging station in Hinkson Creek Watershed, Columbia, Missouri.

Water Year	**Mean Daily Q (m^3/s)**	**Median Daily Q (m^3/s)**
1967	0.45	0.06
1968	1.25	0.22
1969	3.09	0.70
1970	2.52	0.34
1971	0.93	0.21
1972	0.72	0.08
1973	3.08	0.59
1974	2.78	0.84
1975	1.31	0.25
1976	0.78	0.14
1977	0.47	0.08
1978	1.24	0.17
1979	0.94	0.08
1980	0.37	0.03
1981	1.92	0.05
Average (1967-1981)	1.46	0.26
1987	1.18	0.27
1988	0.85	0.12
1989	0.91	0.15
1990	2.47	0.20
1991	0.94	0.20
Average (1987-1991)	1.27	0.19
2008	4.48	0.67
2009	2.61	0.36
2010	4.47	0.85
Avereage (2008-2010)	3.85	0.63

Table 15. Annual total discharge estimations from Hinkson Creek USGS gauging station (#06910230) collected with suburban gauging station in Hinkson Creek Watershed, Columbia, Missouri.

Water Year	**Yearly Discharge (m^3/yr)**
1967	1.41E+07
1968	3.93E+07
1969	9.76E+07
1970	7.95E+07
1971	2.92E+07
1972	2.26E+07
1973	9.70E+07
1974	8.76E+07
1975	4.14E+07
1976	2.45E+07
1977	1.48E+07
1978	3.90E+07
1979	2.97E+07
1980	1.18E+07
1981	6.04E+07
Average (1967-1981)	4.59E+07
1987	3.72E+07
1988	2.68E+07
1989	2.88E+07
1990	7.79E+07
1991	2.98E+07
Average (1987-1991)	4.01E+07
2008	1.42E+08
2009	8.22E+07
2010	1.40E+08
Average (2008-2010)	1.21E+08

The average annual discharge from the USGS gauging site indicates that average annual discharge from 2008 – 2010 was 203% greater than the average annual discharge from 1987 – 1991 (Table 15). While there are no detailed, historic climate data sets available for the region, yearly precipitation average over the span of several decades are available (Table 16). From 1971 to 2000 the average yearly precipitation was 1024.38 mm. The average annual precipitation from 2008 to 2010 was 1418.48 mm. This is 38.50% greater than the 1971 to 2000 average. It is worth mentioning that average annual discharge doubled while average annual precipitation increased by 38.5 %. In the time between 1993 and 2005 the impervious surface area in HCW also over doubled from 7% to 21% impervious. These results have important implications for suspended sediment transport in HCW since with increasing impervious are more precipitation will become attributed to direct runoff which can lead to higher magnitude discharges (Arnold and Gibbons, 1996; Booth, 1990; Leopold, 1968). Larger discharges also have more energy to erode channel materials and drastically increase sediment loads (Fraley et al., 2009; Neller, 1988; Nelson and Booth, 2002; Trimble, 1997).

Table 16. Average annual precipitation for Hinkson Creek Watershed, MO.

Year	Average Precipitation (mm)
1961-1990	1019
1971-2000	1024
2008-2010	1418

SUSPENDED SEDIMENT CONCENTRATION AND MEAN SIZE

Particle analyzers were programmed to sample every hour on the hour. Data gaps occurred due to equipment malfunctions, pump failure, and equipment damage. When data gaps were relatively short (i.e. several hours), moving averages were used to fill missing data. The averages were made between the last two observations and next observed data point after the gap. Hourly time series of SSC in Figure 10 illustrate data gaps larger than several hours. Daily averages were used in analyses to overcome limitations due to data gaps in hourly time series. Data obtained from daily grab samples were used to help fill missing data and to derive daily averages. Daily averages were calculated by averaging all data points within the 24 hour time period for that day. If data gaps were large (i.e. several days), data collected for grab samples served as the daily averages. To analyze how representative grab samples were of daily averages regression analysis was preformed to relate daily grab sample SSCs to daily averages of hourly SSC. Using a regression equation, daily grab samples were adjusted to represent daily averages. Results from this analysis indicated that the total difference between average daily mean SSC and grab sample SSC is less than 2%. This indicates that over the course of the study period, using daily samples as averages had negligible effect on average daily mean suspended sediment concentrations. Figure 11 shows average daily suspended sediment concentration (µl/l) with data gaps filled following the above procedures, precipitation, and discharge for all monitoring sites during the study period.

Table 17 shows descriptive statistics for total concentration and mean sediment size measured at all gauge sites from 3/1/2010 to 6/31/2010 with the LISST streamside. During the study period average hourly concentrations were 63.5 µl/l, 72.2 µl/l, and 95.0 µl/l for the headwater, suburban, and urban land-use areas respectively. The forested head water exhibited concentration ranges from 0.001 µl/l to 2517 µl/l. Suburban and urban land-use areas exhibited ranges from 0.001 µl/l to 1393 µl/l and 0.001 µl/l to 1596 µl/l respectively. Average hourly mean particle size was 152 µm, 106 µm, and 72 µm for the headwater, suburban, and urban land-use areas respectively.

Table 17. Hourly descriptive statistics for total concentration and mean sediment size for the spring study period (3/1/2010 to 6/30/2010) for headwater, suburban, and urban gauging stations in Hinkson Creek Watershed, Missouri.

Headwater	**Total Conc. (µl/l)**	**Mean Size (µm)**
Average	63.5	151.9
Min	0.0	0.9
Max	2517.7	398.0
Stdev	152.9	116.9
Suburban		
Average	72.2	106.2
Min	0.0	0.0
Max	1393.1	398.0
Stdev	129.5	306.9
Urban		
Average	95.0	71.9
Min	0.0	398.0
Max	1523.0	406.4
Stdev	177.9	71.4

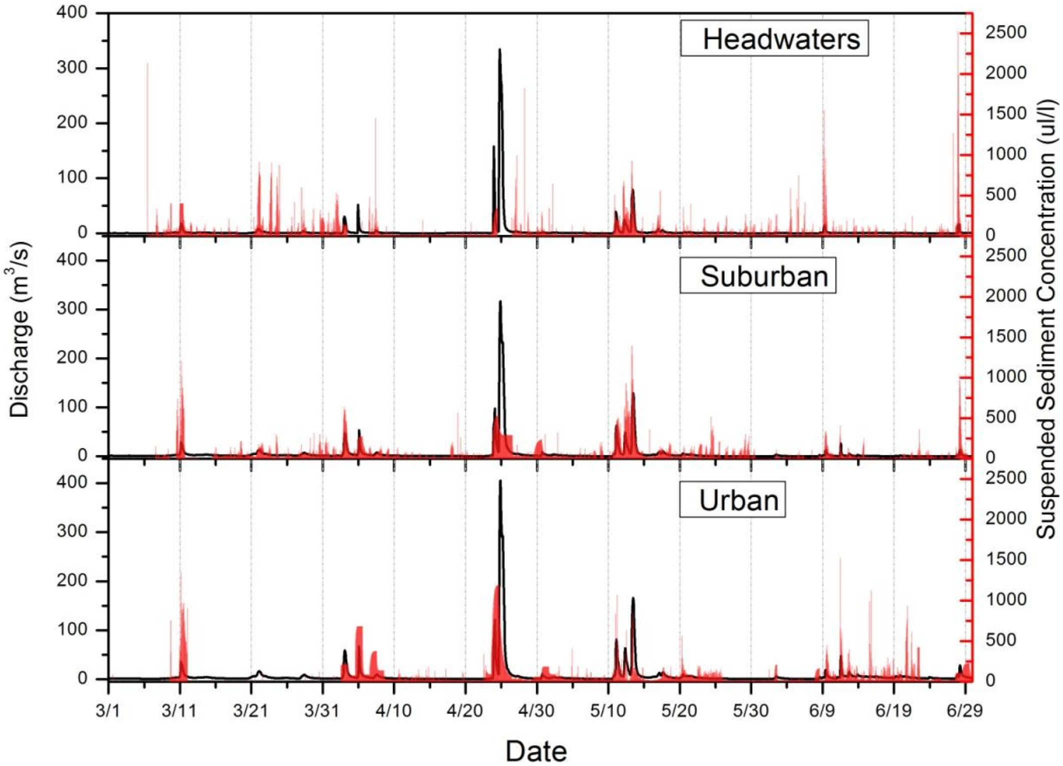

Figure 10. Hourly suspended concentration and discharge for headwater, suburban, and urban gauging stations in Hinkson Creek Watershed, MO. This figure illustrates data gaps that occurred during the study period (3/1/2010 to 6/30/2010).

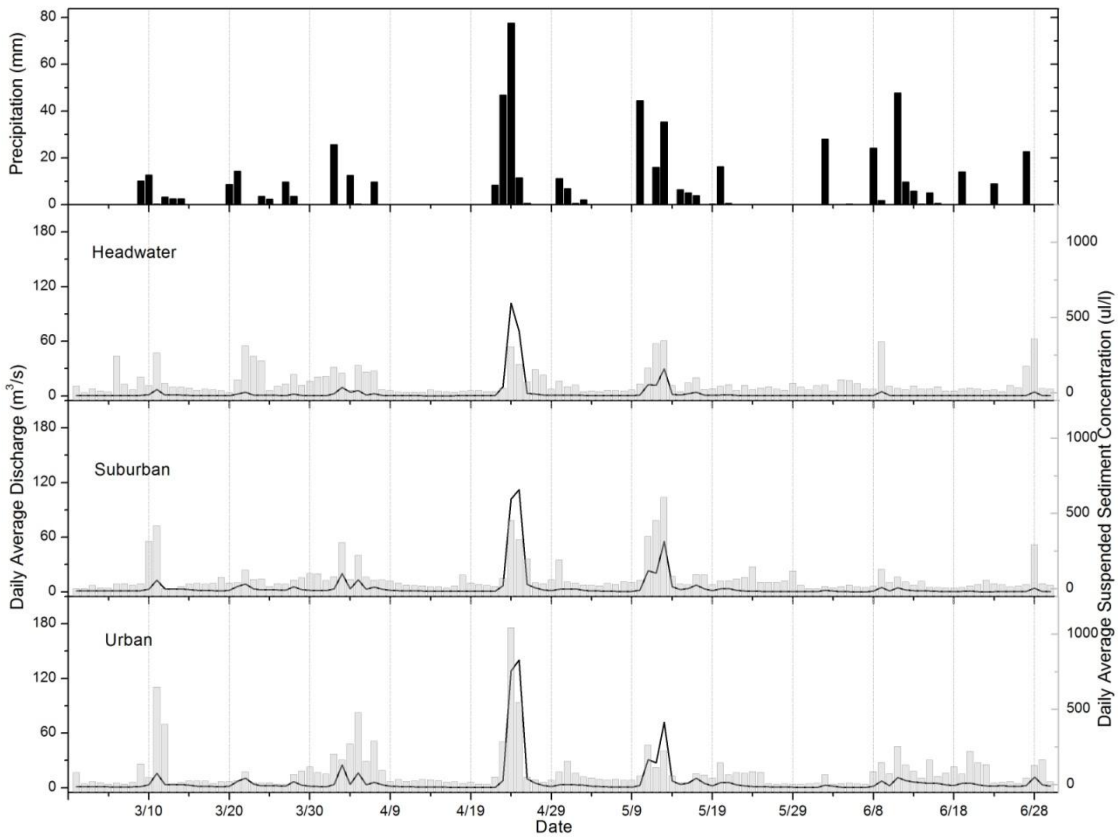

Figure 11. Daily precipitation, average discharge, and average daily suspended sediment concentration (gaps filled) for headwater, suburban, and urban gauging sites located in the Hinkson Creek Watershed, MO.

Table 18 shows daily averages and descriptive statistics for total concentration and mean size of suspended sediment collected at gauging stations. Figure 13 shows daily average suspended sediment concentration and mean size. Site 1, located in the agricultural and forested region of the HCW shows average daily concentration of 65.7 (SD = 81.9) µl/l. Average daily particle size for site 1 was 151.1 (SD = 70.6) µm. Site 2, located in the suburban land-use area has an average concentration of 69.5 (SD = 102.2) μl/l. Average daily mean particle size for site 2 was 111.0 (SD = 77.2) μm. The urban land-use gauging station exhibited an average daily concentration of 86.0 (SD = 66.8) μl/l. Average daily mean size for the urban land-use site was 79.4 (SD = 66.8) μm.

ANOVA statistical tests ($P < 0.05$) results indicated that mean suspended sediment concentration was not statically different between the headwater, suburban, and urban gauging sites (P value = 0.31). However, mean particle size was significantly different between the headwater, suburban, and urban gauging sites (P value < 0.001). Figure 12 shows box and whisker plots for SSC and mean particle size for the headwater, suburban, and urban sub-basins.

Table 18. Daily total concentration and mean size descriptive statistics for headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, Missouri.

Headwater	**Total Conc (μl/L)**	**Mean Size (μm)**
Average	65.7	151.1
Min	0.7	3.2
Max	358.4	356.8
Stdev	81.9	70.6
Suburban		
Average	69.5	111.0
Min	0.0	0.6
Max	605.7	356.8
Stdev	102.2	77.2
Urban		
Average	86.0	79.4
Min	2.0	5.1
Max	1043.1	353.2
Stdev	137.8	66.8

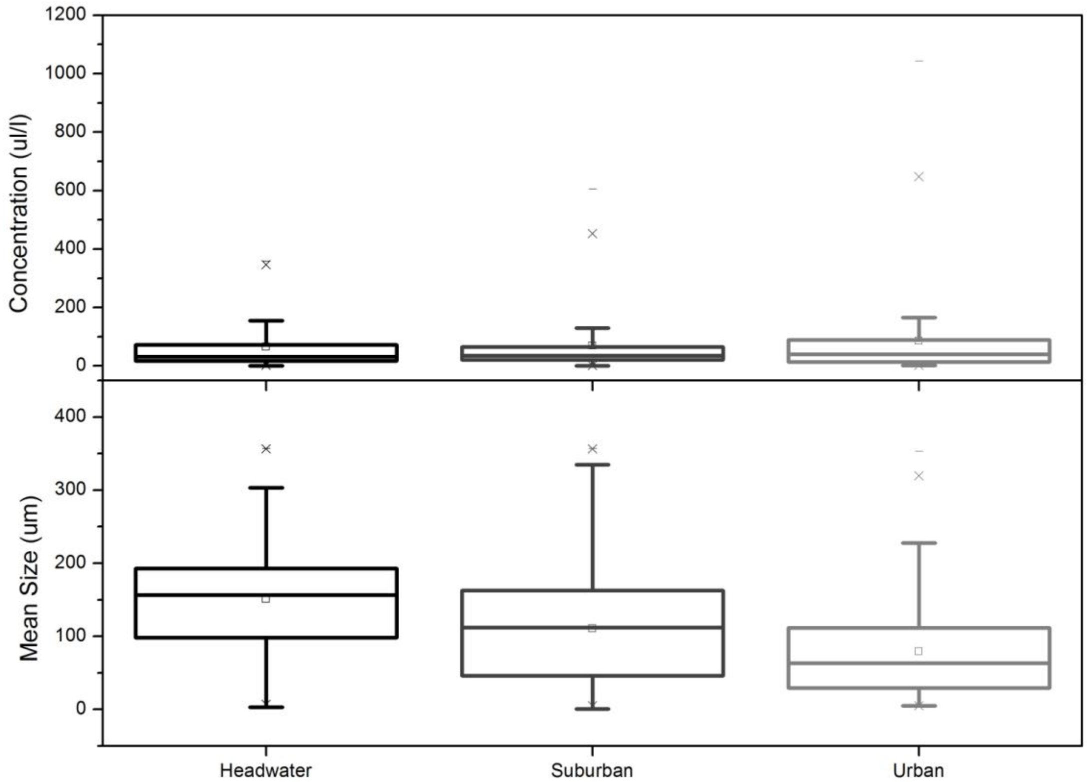

Figure 12. Box and whisker plot for suspended sediment concentration and mean size for headwater, suburban, and urban sub-basins in Hinkson Creek Watershed.

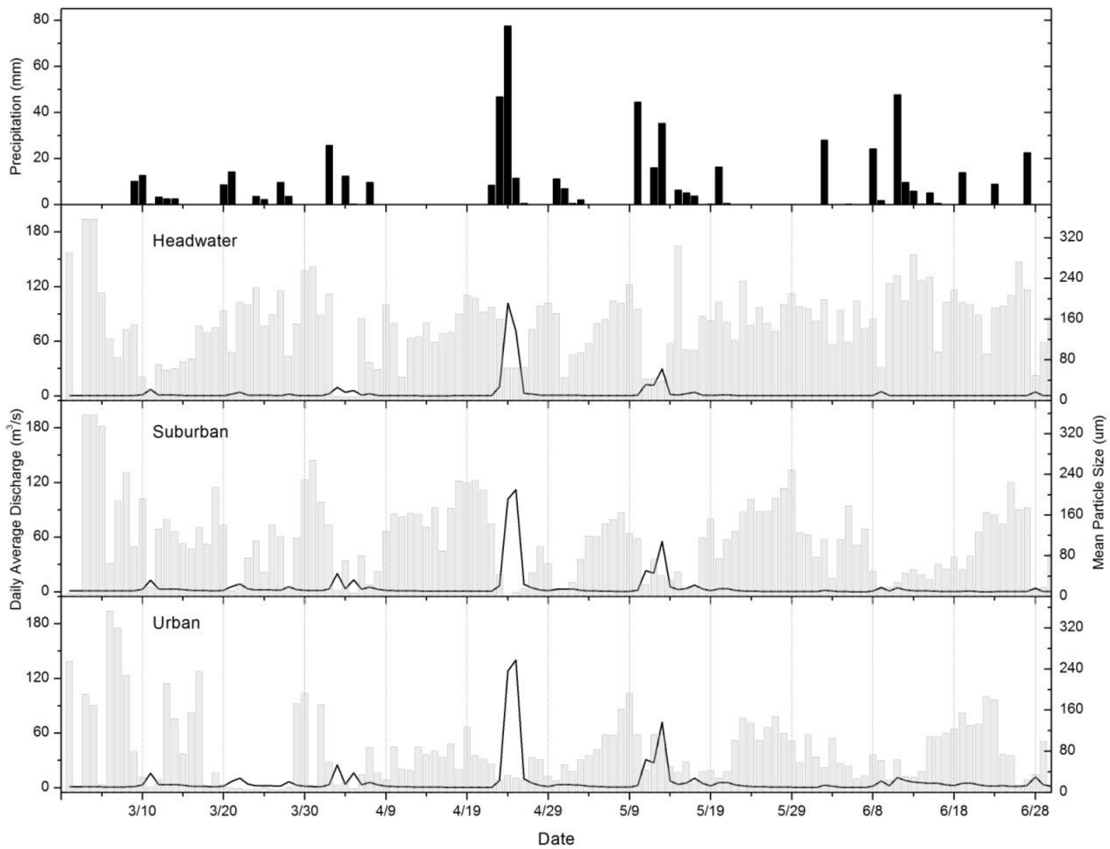

Figure 13. Bar Chart of daily average mean sediment size from 3/1/2010 to 6/30/2010 for headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, Missouri.

Base Flow and Storm Flow Generated Suspended Sediment

Estimates of average daily suspended sediment concentration were calculated during base flow periods and storm flow periods. Averages were estimated by separating days under base flow conditions from days where overland flow was contributing to discharge. Table 19 shows average SSCs for periods of base flow and periods of storm flow. Average SSC for the headwater gauging site was 90.9 µl/l and 38.0 µl/l for storm flow and base flow conditions respectively. The suburban land use area exhibited an average concentration of 102.8 µl/l for storm flow and 44.5 µl/l for base flow. The urban land use area had an average storm flow concentration of 128.0 µl/l and average base flow concentration of 34.8 µl/l.

Table 19. Average suspended sediment concentration during storm flow and base flow conditions at headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, Missouri.

Site	Average Stormflow Conc. (µl/l)	Average Baseflow Conc. (µl/l)
Headwater	90.9	38.0
Suburban	102.8	44.5
Urban	128.0	34.8

Estimating Suspended Sediment Particle Density

As shown, laser diffraction estimates of suspended sediment concentration are volumetric estimates (µl/l). Most published studies use gravimetric estimates. To compare results from this study to other studies, volumetric estimates of sediment load were converted gravimetric estimates. Table 20 shows average particle density at each site. The headwater, suburban, and urban gauging sites had average densities of 2,047.6, 1,944.5, and 1,710.6 kg/m^3 .

Table 20. Estimates of suspended sediment particle density obtained from grab samples during the spring wet season (3/1/2010 to 6/30/2010) for headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed, Central Missouri.

Site	**Density (kg/m^3)**	**Number of Samples**
Headwater	2047.6	70.0
Suburban	1944.6	69.0
Urban	1710.6	70.0

Gravimetric and Volumetric Comparisons

Table 21 shows descriptive statistics from gravimetric and volumetric analysis of grab samples collected at each gauging site of this study. Based on daily grab sample results, average gravimetric and volumetric suspended sediment concentration for the headwater gauging site was 68 (SD =146.1) mg/l and 148 (SD = 325.9) µl/l respectively. The suburban gauging location had an average gravimetric and volumetric suspended sediment concentration of 82.5 (SD = 163.1) mg/l and 81.7 (SD = 139.0) µl/l respectively. Average gravimetric and volumetric suspended sediment concentration for the urban gauging station was 104.8 (SD = 204.9) mgl/l and 112.5 (SD = 205.9) µl/l respectively.

Table 21. Descriptive statistics comparing gravimetric and volumetric comparisons from daily grab samples for headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed.

Headwater	**Gravimetric**	**Volumetric**
Units	mg/l	µl/l
Average	68.0	148.0
Median	20.1	52.8
Min	1.5	0.6
Max	953.2	2128.3
Stdev	146.1	325.9
Suburban		
Average	82.5	81.7
Median	21.9	20.7
Min	4.3	1.3
Max	875.9	686.6
Stdev	163.1	139.0
Urban		
Average	104.8	112.5
Median	34.6	25.2
Min	4.6	2.3
Max	1195.0	1191.4
Stdev	204.9	205.9

Using the densities in Table 20 daily average volumetric SSC (µl/l) were converted to daily average gravimetric SSCs (mg/l) (Table 22). Gravimetric SSCs were calculated to be 134.0, 135, and 147 mg/l at the headwater, suburban and urban gauging sites respectively.

Table 22. Daily averages based on hourly data for volumetric and gravimetric suspended sediment concentrations for particle analyzers deployed at the headwater, suburban, and urban gauging stations.

Site	**Volumetric SSC**	**Gravimetric SSC**
#	µl/l	mg/l
Headwater	65.7	134.0
Suburban	69.2	135.0
Urban	86.0	147.0

Depth Integrated Cross Section Sediment Concentrations

Table 23 shows results from depth integrated suspended sediment sampling compared to point observation (i.e. LISST pump turbid inlet) of suspended sediment. The sample size of depth integrated samples for the headwater, suburban, and urban gauging sites were 10, 11, and 13 (respectively). As mentioned earlier, the purpose of this analysis was to determine how representative the LISST estimates (point based) of SCC were to cross section averages of SCC. Results indicated that at the headwater and urban gauging sites the LISST's estimates of suspended sediment underestimated the cross section suspended sediment average by 51.6%. and 74.1 % respectively. At the suburban gauging site the LISST overestimated the cross sectional suspended sediment concentration value by 58.3%. Figure 14 shows measured mean suspended sediment concentration and depth integrated adjusted mean suspended sediment concentrations observed at the headwater, suburban, and urban gauging sites. Results from depth integrated sampling were unreliable for a number of reasons (see the following text), and because of that will not be used any further in this analysis. Depth integrated sampling requires a specific range of stream velocities (0.3 - 2.7 m/s) to take isokinetic samples. During lower flow sampling events, only a very narrow portion of the streams total width met the minimum velocity requirement. At least half of the depth integrated suspended sediment sampling events were conducted when only a narrow portion of the stream met minimum velocity requirements. Therefore many of the transect samples were not isokinetic. When stream velocities are below the minimum threshold, depth integrated sampling techniques do not provide an accurate representation of cross sectional suspended sediment concentrations (Edwards and Glysson, 1970). Similarly, during some high flow events minimum stream velocity requirements (i.e. greater than 0.3 m/s, required by the method) were not met. Low velocities during high flow events were somewhat unexpected.

Despite the result, it is generally agreed that during higher flow events (i.e. storm flow) suspended sediment concentrations are well mixed across the stream channel (Edwards and Glysson, 1970; Porterfield, 1972). On that basis, we assumed that our point based sampling provided accurate assessment of a well-mixed stream cross section. It is also worth mentioning that the vast majority of scientific literature investigating suspended sediment use point-based, or grab-sample based sampling methods (Horowitz, 2003; Lee et al, 2009; Brooks, 2010).

Table 23. Results from depth integrated sediment sampling for headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, Missouri. Table shows suspended sediment concentration from depth integrated sediment sampling techniques as well as results from the turbid inlet point sample. Not A Number (NAN) were observed due to equipment malfunctions.

Headwaters			
Date & time	**Depth Int.(μl/l)**	**Point Observation (μl/l)**	**% Diff. From Depth Int.**
3/13/10 13:00	154.2	8.5	-94.5
3/27/10 13:00	93.3	94.9	1.8
4/10/10 13:00	1174.1	17.9	-98.5
4/17/10 12:00	166.6	12.5	-92.5
4/30/10 19:00	538.4	237.5	-55.9
5/7/10 14:00	59.3	13.9	-76.6
5/21/10 15:00	89.9	25.5	-71.6
5/27/10 12:00	93.8	49.1	-47.7
6/6/10 13:00	100.9	165.9	64.3
6/18/10 15:00	35.2	19.4	-45.0
Suburban			
3/20/10 13:00	125.7	56.1	-55.4
3/27/10 15:00	32.4	59.1	82.4
4/10/10 14:00	231.0	131.4	-43.1
4/17/10 13:00	27.8	9.2	-67.0
4/22/10 14:00	19.1	34.9	82.3
5/7/10 18:00	37.5	69.8	86.1
5/21/10 13:00	73.1	65.8	-10.0
5/27/10 14:00	14.5	125.5	767.7
6/6/10 14:00	56.9	2.8	-95.1
6/18/10 16:00	42.5	22.3	-47.5
6/27/10 14:00	29.7	12.0	-59.4
Urban			
3/18/10 14:00	144.5	7.7	-94.7
4/10/10 15:00	289.8	18.4	-93.7
4/17/10 14:00	37.6	20.8	-44.8
4/26/10 15:00	167.9	23.7	-85.9
5/7/10 17:00	19.4	20.3	4.5
5/13/10 17:00	539.4	161.1	-70.1
5/22/10 15:00	177.7	72.4	-59.2
5/27/10 15:00	nan	9.7	-
6/6/10 15:00	50.3	4.5	-91.0
6/9/10 12:00	901.8	110.8	-87.7
6/10/10 15:00	663.0	75.4	-88.6
6/15/10 11:00	438.3	36.3	-91.7
6/18/10 13:00	644.3	86.4	-86.6

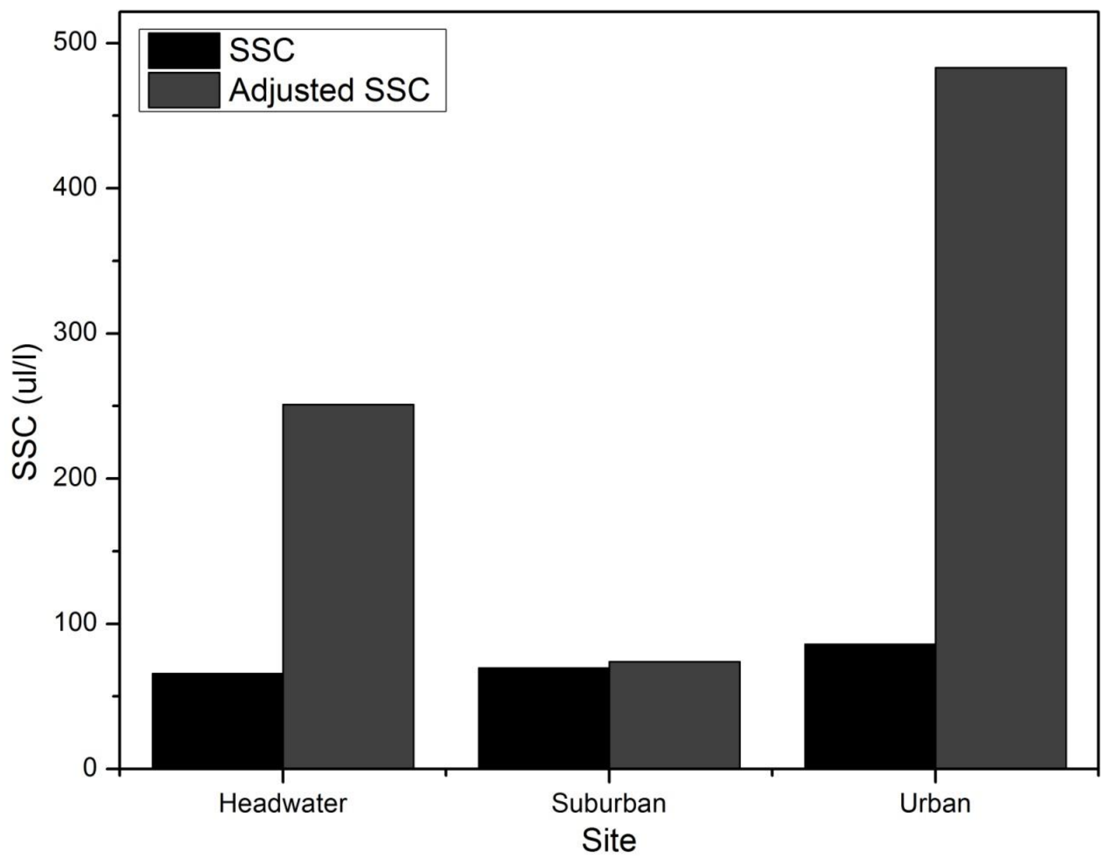

Figure 14. Point-based and depth integrated adjusted suspended sediment concentrations for the headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, Missouri.

Suspended Sediment Load

Daily average discharge and suspended sediment concentrations were used to estimate daily sediment load in m^3/day and tonnes/day (where, 1 tonne = 1000kg). Volumetric estimates (m^3/day) were converted to gravimetric estimates (tonnes/day) by using the estimated particle densities shown in Table 20. Total sediment load for each site is presented in Table 24. The total load, for this study period, was calculated by summing the daily sediment loads for each site over the course of the study period (3/1/2010 to 6/30/2010). Using that method, total sediment load for the headwater, suburban, and urban sites was 13,183 tonnes, 27,369 tonnes, and 42,854 tonnes respectively during the period of study.

Table 24. Total Sediment load for headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed, Missouri.

Site	Total Load (m^3)	Total Load (Tonnes)
Headwater	6,438	13,183
Suburban	14,075	27,369
Urban	25,051	42,853

Average daily sediment load for the headwater gauging station was 108.1 (SD = 565.5) tonnes/day. The suburban land-use gauging station had an average daily sediment load of 224.3 (SD = 1,038.8) tonnes/day. Average daily sediment load for the urban land-use gauging station was 351.3 (SD = 2065.7) tonnes/day It is important to note that daily averages of sediment loads may not represent central tendencies. The median of daily sediment load may be more representative of central tendencies because mean sediment loads may be skewed by large discharge events (Simon et al., 2004). The median daily sediment load was 1.08, 4.23, and 7.0 tonnes/day for the headwater, suburban, and urban gauging stations. Descriptive statistics for daily sediment load are presented in Table 25. Figure 15 shows box and whisker plot of suspended sediment loads for the headwater, suburban, and urban sub-basins. The Kruskal-Wallis one-way analysis indicated daily median sediment loads were significantly different between the headwater, suburban, and urban gauging sites. This is noteworthy because as previously mentioned there was no significant difference in mean suspended sediment concentrations between the sites using ANOVA. The significant difference in median sediment load using Kruskal-Wallis is likely attributable to the differences in discharge between gauging sites. The Kruskal-Wallis test was used to analyze differences between medians compared statistical differences in sediment loads because median sediment loads are likely more representative of the central tendencies of daily sediment loads compared to mean daily sediment loads.

Table 25. Descriptive statistics for daily sediment load for headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed, MO.

Headwater	**Load (m^3/day)**	**Load (tonnes/day)**
Average	52.8	108.1
Median	1.1	2.2
Min	0.0	0.0
Max	2,679.1	5,485.7
Stdev	276.2	565.5
Suburban		
Average	115.4	224.3
Median	4.2	8.2
Min	0.0	0.0
Max	3,994.4	7,767.4
Stdev	534.2	1,038.8
Urban		
Average	205.3	351.3
Median	7.0	12.0
Min	0.1	0.1
Max	11,560.5	19,775.9
Stdev	1,207.6	2,065.7

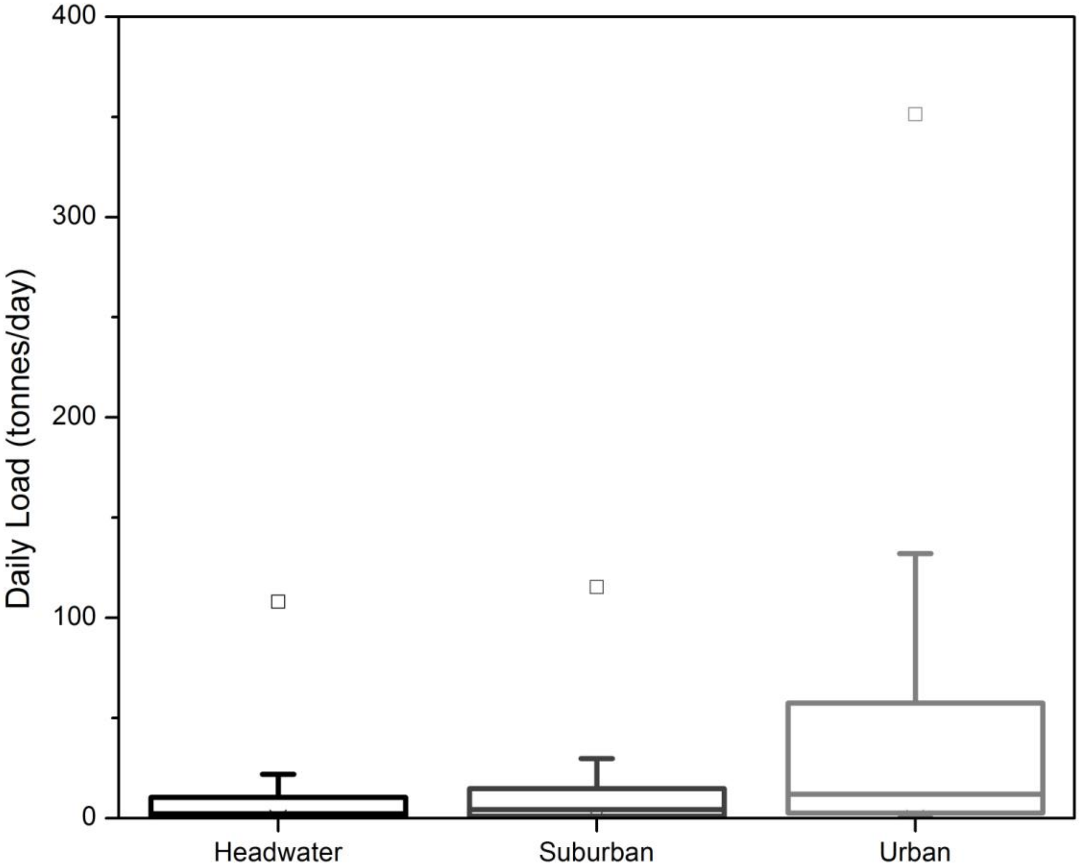

Figure 15. Box and whisker plot of daily suspended sediment load for the headwater, suburban, and urban sub-basins located in Hinkson Creek Watershed.

Base flow and Storm Flow Sediment Loads

Since a majority of a streams total sediment budget is generally transported during periods of high flow (Gray and Gartner, 2009), an important component of this study was to determine how much of the sediment load at each site was generated during base flow and how much was from storm flow during the spring wet season. Separating the amount of suspended sediment transported during base flow from suspended sediment transported during high flows have important management implications. The current draft of the Hinkson Creek TMDL recommends discharge reductions as a surrogate to reduce pollutant loading (MODNR, 2011). Separating the amount of sediment loading during base flow periods from storm flow periods may provide some insight on how discharge reductions could reduce pollutant loads. Storm flow was separated from base flow using the Web based hydrograph Analysis Tool (WHAT) system. Table 26 shows sediment load allocations for storm flow and base flow for gauging locations located in the headwater (site1), suburban (site 2), and urban (site 3) land-use areas. As expected, the majority of sediment load for all sites was transported during periods of storm flow. In the headwater 98.0% of the total sediment load was transported during periods of storm flow. The suburban and urban land-use gauging sites exhibited similar trends with 97.1% and 98.8 % (respectively) of the total load being transported during periods of storm flow.

Table 26. Sediment load contributions from storm flow and base flow for headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, MO.

Site	Contribution (tonnes)	% of Total
Headwater Storm Flow	12922.1	98.0
Headwater Base Flow	261.3	2.0
Suburban Storm Flow	26589.0	97.1
Suburban Base Flow	780.3	2.9
Urban Storm Flow	42353.4	98.8
Urban Base Flow	500.0	1.2

Sediment Yield

Table 27 shows Cumulative Sediment Yield (CSY) and Sub-Basin Sediment Yield (SBSY) for the headwater, suburban, and urban gauging sites. The CSY for the suburban gauging station is 10.7% and 26.9% less that the CSY values from the headwater and urban gauging site respectively. The CSY in the headwater is 18.3% less than the CSY at the urban gauging station. The SBSY decreases through the headwater, suburban, and urban gauging station. The SBSY in the headwater is 22% greater than SBSY for the suburban. SBSY at the urban gauging site is 323% and 246% greater than the SBSY at the suburban and headwater.

Table 27. Cumulative sediment yield and sub-basin sediment yield for headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, Missouri.

Site	Cumulative Area	Sub-Basin Area	Cumulative Sediment Yield	Sub-Basin Sediment Yield
#	km^2	km^2	tonnes/km^2	tonnes/km^2
Headwater	77.4	77.4	170.3	170.3
Suburban	179.5	102.1	152.5	139.0
Urban	205.8	26.3	208.2	588.7

Suspended Sediment Rating Curves

Table 28 shows measured sediment load, rating curve estimated sediment load, and percent difference for each gauging site located in HCW. The total measured load for the headwater was 13,183.4 tonnes and the total predicted load was 18,370.6 tonnes. The rating curve method overestimated observed loading by 28.2 %. The measured total load for the suburban land use area was 27,369.4 tonnes and the predicted value was 18,441.3 tonnes. Thus the predicted load was 48.4% less than the observed load. Total measured sediment load for the urban land use area was 42,853.5 tonnes and the predicated total sediment load was 48,300.0 tonnes, resulting in a modeled 11.3% over prediction. The Nash-Sutcliffe efficiency parameters comparing the observed versus estimated rating curve sediment load predicted SCC resulted in 0.44, 0.85, and 0.83 for the headwater, suburban, and urban sediment rating curves respectively.

Table 28. Measured sediment load, rating curve estimated sediment load, percent difference, and Nash-Sutcliffe efficiency parameter (NS) for headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed, Missouri.

Site	Measured Load	Estimated Load	% Difference	Nash-Sutcliffe
#	Tonnes	Tonnes	%	#
Headwater	13,183.4	18,370.6	28.2	0.44
Suburban	27,369.4	18,441.3	-48.4	0.85
Urban	42,853.5	48,300.0	11.3	0.83

CHAPTER IV

DISCUSSION

HYDROCLIMATE

Suspended sediment transport involves a series of processes; including particle detachment, overland transport, and subsequent movement and/or storage in the stream channel (Walling, 1983). A substantial amount of transported suspended sediment can also originate from channel bank erosion. It was shown that 40 to 80% of suspended sediment of transported in streams originates from channel banks (Nelson and Booth, 2002; Simon et al, 2000; Trimble, 1997, Willet, 2010). Suspended sediment transportation processes are driven by precipitation events and are determined by soil characteristics. The spring runoff season was chosen for this study because according to the historic record, the majority of annual precipitation falls during this time period in central Missouri. It was shown that the majority of a stream’s total sediment load is also transported during periods of high flows, which are correlated with larger, more frequent precipitation events. Historically 61% of HCW's annual precipitation falls between March and June, which coincides with the study period of this project (3/1/2010 through 6/30/2010. Since erosion and subsequent delivery and transport of sediment particles is correlated to precipitation events, the results presented in this work may reflect higher volumes of suspended sediment transport during the 2010 water year than might be expected during “normal” water years. During the study period, HCW received 36% of the total annual 2010 precipitation. This could be inferred to imply that more suspended sediment was transported later in the water year, a potentially poor assumption since sediment flux is velocity and volume dependent. It is important to note that an increase in total precipitation in HCW may lead to higher antecedent soil moisture conditions and thus highly mobile soils. This study was conducted during the third consecutive wet year, where total precipitation was well above historical averages, which may have resulted in dramatically elevated antecedent soil moisture conditions and thus erosion (Wei et al., 2007) as shown in previous work (Reichenberger et al. 2007; Brooks et al., 2003). On this basis, the results stemming from this work may provide valuable insights to future projected climate change scenarios that predict higher quantities of precipitation in the Central U.S. (IPCC, 2007).

DISCHARGE AND WATER YIELD

Accurate estimates of discharge were important for this study because water provides the mechanism for sediment transport and discharge estimates were necessary to calculate sediment loading (equation 5). By quantifying the discharge and water yield at each gauging station, relationships between land-use, discharge, and water yield were estimated.

Total Discharge

Figure 16 shows total discharge and total drainage area for each gauging station located in HCW. The total discharge at the suburban gauging location was 65.6 % greater than discharge at the headwater gauging site, coinciding with a 20.4% increase in urban area. The total discharge at the urban site increased by 25.5% from the suburban site as the amount of urban area also increases by 41.7 % relative to the suburban sub-basin. As urban land-use area increases, the amount of impervious area also increases and less water is able to infiltrate into the soil (Corbett et al., 1997, Leopold, 1968), and thus becomes surface runoff. Increases in watershed impervious area alters the hydrology of the stream and can cause lower base flows and higher, more frequent peak discharges (Leopold, 1968; MODNR, 2011). While total discharge would be expected to increase as the drainage area of the site increases (for example: in gaining streams), the increase in total discharge between sites 1 and 2 is likely due, at least in part, to the large increase in impervious surface area. Increasing discharges observed in HCW are consistent with other studies that have shown increased discharge with increasing urbanization (Jennings and Jarnagin , 2002; Rose and Peters, 2001; White and Greer, 2006).

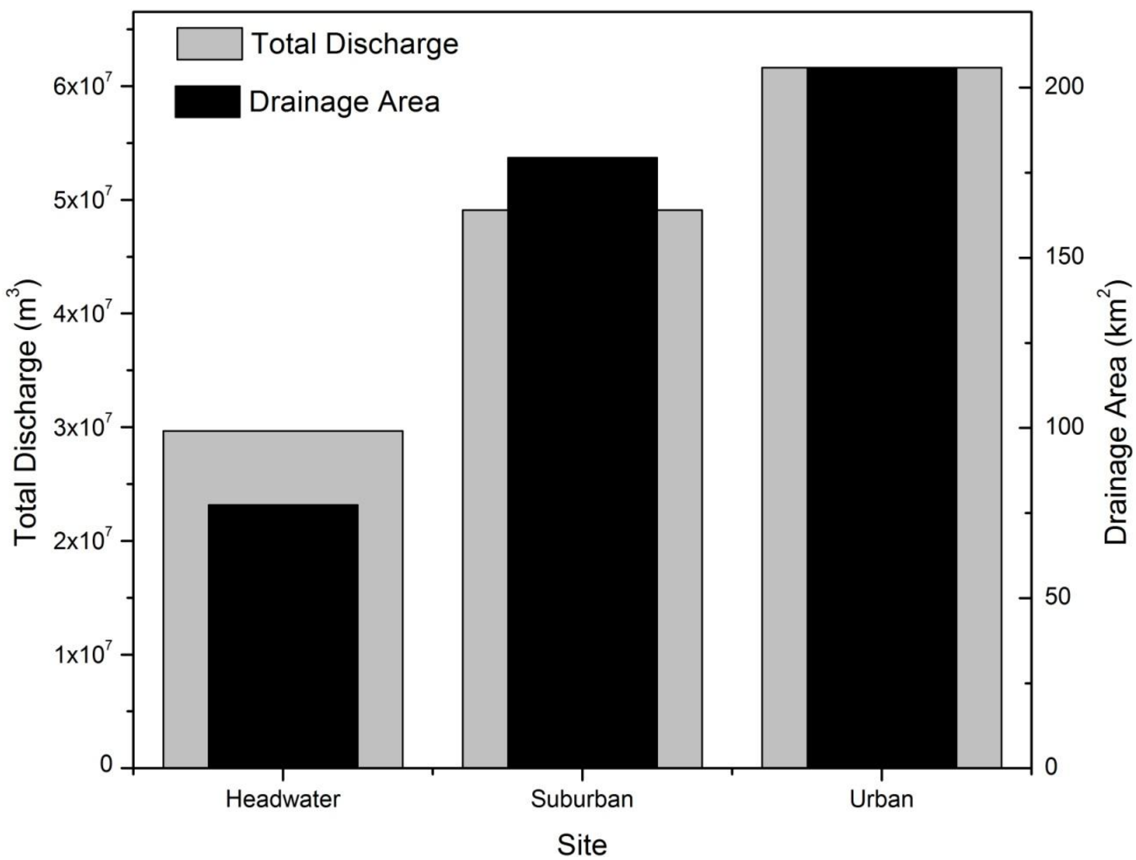

Figure 16. Drainage area and total discharge estimated from headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, Missouri.

Base Flow and Storm Flow

Figure 17 shows time series of base flow and storm flow calculated for each gauge site in this study. As expected, storm flow made up the dominant portion of the total discharge for all sites. Storm flow accounted for 76% of the total discharge at the headwater site and 68% of the total discharge at both the suburban and urban gauging stations. These results are similar to other watersheds in urban settings where storm water discharge accounted for 59 to 96 % of the total discharge (Horowitz, 2009; Lee et al., 2009). It was unexpected that storm flow would make up a larger percentage of total discharge in the headwater compared to the suburban and urban gauging stations. Intuitively, one might expect that relative to urban land-use storm water runoff would be lowest in the headwater sub-basin due to the small amount of impervious areas. However, slow to very slow infiltration rates and poor drainage classes exhibited in soils in the upper portion of the watershed (NRCS, 2003;MODNR, 2011) may cause more precipitation to run off as overland flow as opposed to infiltrating into the subsurface (Sophocleous, 2002). Further, the above average annual precipitation during the three years preceding this study may have created overly saturated soils, which can promote surface runoff (Sophocleous, 2002). The percentage of storm water discharge is 12% less in the suburban and urban sub-basins. Indicating, base flow increases in the suburban and urban sub-basins. In general, base flow is expected to decrease in watersheds with more impervious area due to decreased groundwater recharge (Myer, 2005). However, some researchers have found increasing base flows in urban areas due to decreased ground water removal (Rushton and Al-Othman, 1994). In this work, the reductions in storm water discharge in the suburban and urban basin may be attributed to increasing watershed size. The hydrograph separations performed for the suburban and urban gauging sites represent the entire drainage area above that point. Therefore, as the drainage area increases the amount of area to attenuate runoff also increases (Black, 1997). Developing strong relations between all of these interactions is beyond the scope of this study. However, there are important management implications from the base flow/storm flow separation. The current Hinkson Creek TMDL (USEPA 2011) promulgates a reduction in runoff to meet water quality standards. The objective of the current TMDL is to reduce runoff, and thus, reduce transport of solids, chemicals, and other pollutants. The current Hinkson Creek TMDL suggests a 28.7 % decrease in discharge at the outlet of the watershed. The TMDL suggests a discharge of 26.2 m^3/s to attain water quality standards (USEPA, 2011). While saying nothing of the overall implications of volume based flow reductions for unknown pollutants in the HCW, the reductions recommended by the EPA in the Hinkson Creek TMDL may in fact be an effective way to reduce the total amount of suspended sediment transported to the stream.

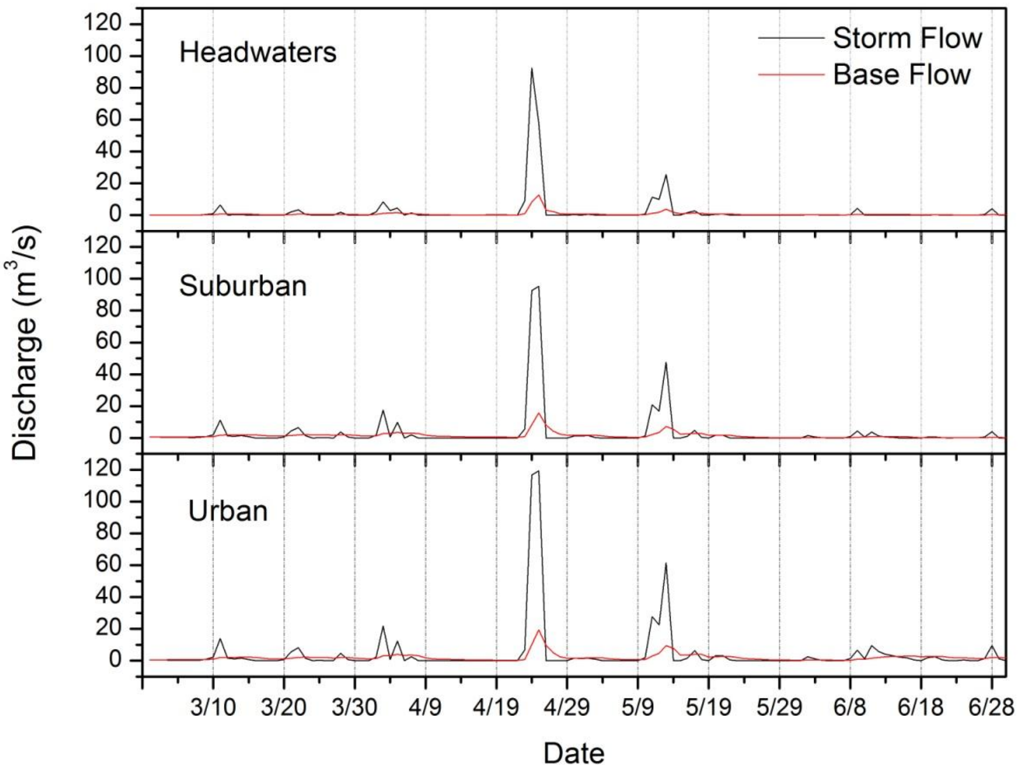

Figure 17. Time series of base flow and storm flow hydrographs for headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, central MO.

Average Daily Discharge

Figure 18 shows average daily discharge (m^3/s) and standard deviation (m^3/s) for the headwater, suburban, and urban gauging site located in HCW. Average daily discharge for the suburban and urban gauging sites are 67.9% and 128.6 % greater than average daily discharge at the headwater gauging site. In gaining streams, discharge would be expected to increase as water flows downstream and the contributing drainage area increases (Brooks et al., 2003; Schwartz and Zhang, 2002). In this study the discharge from each sub-basin increased from upstream to downstream. The standard deviation of discharge also follows this pattern. The increased urban land-use area in the suburban and urban area may explain increasing standard deviations. As the percentage of urban areas increase, impervious areas increase, which can cause stream discharge to have greater response to smaller precipitation events (Corbett et al., 1997), thus creating a broader range of flows. Hubbart and Freeman (2010) showed that 13.2 mm of precipitation increased pre-storm discharge from 1.4 m^3/s to a peak of 7 m^3/s at the suburban gauging station within HCW. Figure 19 shows precipitation and storm hydrographs for each of the land-use gauging stations located in HCW during a 13.2 mm storm event. During the same study period used by Hubbart and Freeman (2010) pre-storm discharge was 0.39 m^3/s and 1.6 m^3/s for the headwater and urban gauging station. On the day of the precipitation event discharges peaked at 3.8 m^3/s and 8.8 m^3/s for the headwater and urban gauging sites located in HCW. Clearly, there is a much larger discharge response at the suburban (1.4 to 7.0 m^3/s) and urban (1.6 to 8.84 m^3/s) gauging sites compared to the headwater (0.39 to 3.8 m^3/s) gauge site, indicating a broader range of flows during the same precipitation event. These results are consistent with previous studies, which have shown that streams located in urban areas often have higher peak flows and a quicker response to precipitation events (i.e. shorter time interval to peak discharge) compared to rural or forested streams (Burges et al., 1998; Phillips and Scatena, 2010; Walsh et al., 2005).

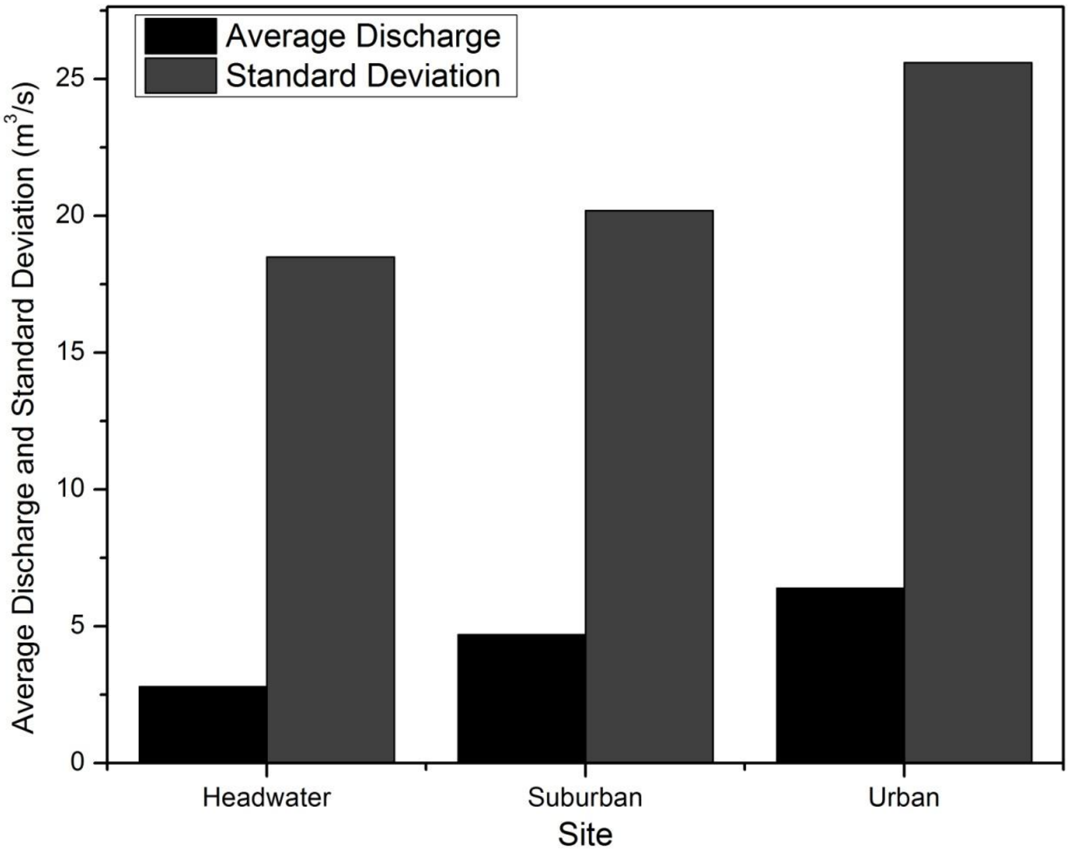

Figure 18. Average daily discharge and standard deviation for headwater, suburban, and urban land-use gauging stations located in Hinkson Creek Watershed, Missouri.

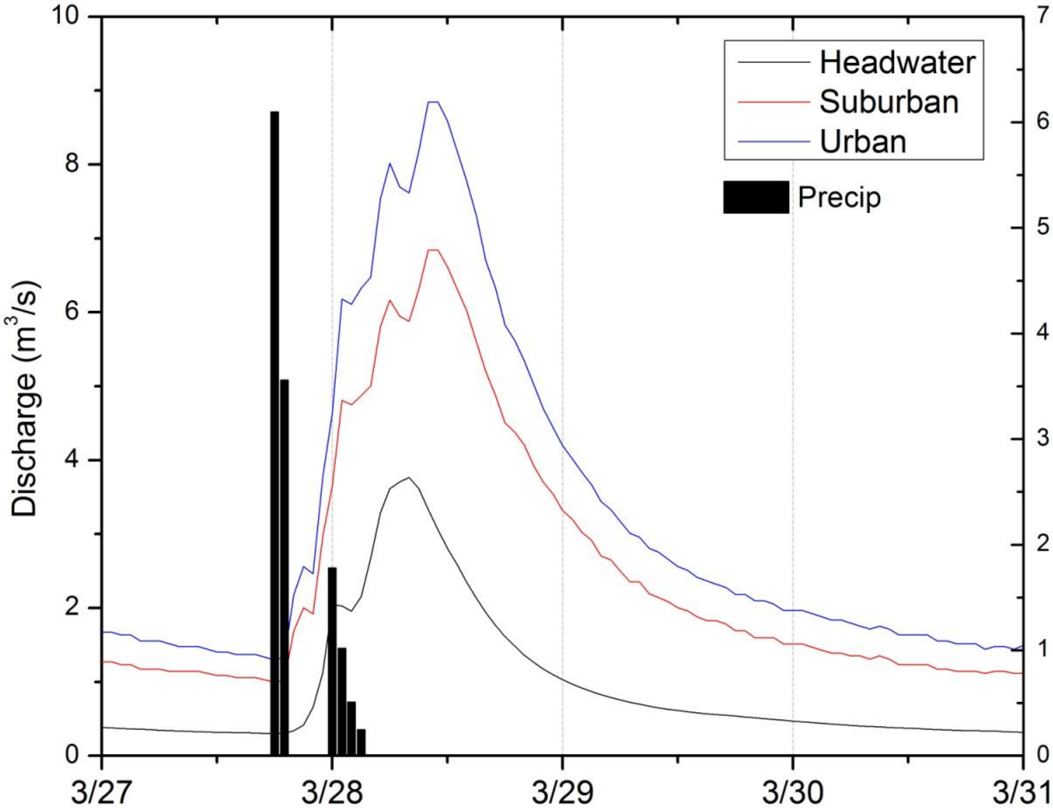

Figure 19. Precipitation and storm Hydrograph comparisons for headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed, Missouri between March 27th and April 1st 2010.

Historical Flows and Land Use Change

Hinkson Creek Watershed contains the city of Columbia, MO, which had a population of 94,428 in 2000 (U.S. Census Bureau, 2000). In 2010 the population of Columbia, Missouri was 108,500 (USCB, 2011). Much of the land use change in HCW is attributed to urban development. In 1993 only 7.9% of HCW was under urban land use. By 2005, 20.7 % of the total area was in urban land use. Therefore, from 1993 to 2005 the area under urban land use increased by 160% (MODNR, 2011). Figure 20 shows: (A) a scatter plot of annual precipitation (P) versus annual water yield (Q), (B) a time series of Q/P ratios for each year, (C) average annual precipitation versus average annual precipitation for each gauging period, and (D) average Q/P ratios for each gauging period. The Q/P ratios provide an estimate of how much annual water yield changes in proportion to changes in annual precipitation. Average Q/P ratio from 1967-1981, 1987-1991, and 2007-2010 were 0.26, 0.27, and 0.43 respectively. The Q/P ratios are relatively similar from 1966-1981 gauging period to the 1987-1991gauging period. There is a large increase in average Q/P ratio from the 1987-1991 gauging period to the 2007-2010 gauging periods. The large increase indicates that there is a larger portion of precipitation is runoff from 2007- 2010 compared to 1987 - 1991. During the period of urbanization in HCW, annual water yield doubled while precipitation increased by 39%. These results are similar to a study by Walsh and Greer (2006) that showed a 200% increase in runoff with no significant increase in precipitation as impervious area of the watershed increased from 9% to 37%. Increased surface runoff is a common response to urbanization (Paul and Meyer, 2001; Walsh et al., 2005; Walsh and Greer, 2006). This simple analysis of annual water yield and annual precipitation indicates that the large increase in urban areas from 1993 to present 2005 has likely altered the rainfall/runoff relationships causing larger increases in water yield in proportion to increasing precipitation.

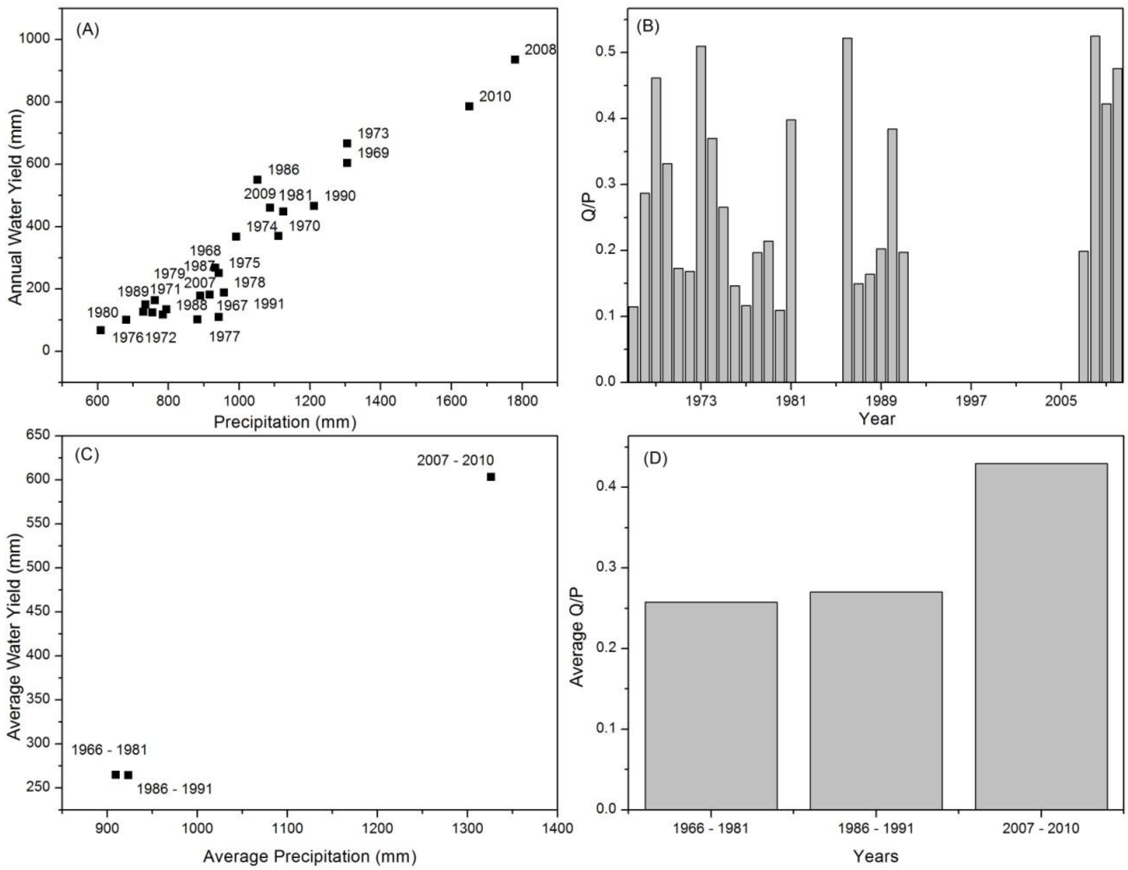

Figure 20. (A) Historical water yield (mm) and precipitation, (B) Year Q/P ratio, (C) Average water yield (mm) and precipitation for each gauging period, and (D) Average Q/P ratio for each gauging period. Discharges were recorded by a USGS gauging that is co-located with the suburban gauging station used in this study.

SUSPENDED SEDIMENT CONCENTRATION AND MEAN SIZE

Suspended Sediment Concentration

Suspended sediment concentration was sensed by laser particle diffraction on hourly intervals throughout the study period, due to data gaps hourly data was filled and averaged to create daily estimates of suspended sediment concentration. While it would be preferable to have a dataset with no missing observations, this was not achievable during this study due to equipment damage and malfunctions. Above average precipitation in the years preceding and during this study created saturated soils that promoted surface runoff and led to LARGE discharge events. Large discharge events were problematic in this study causing damage or destroying instruments located in the stream channel. The majority of large data gaps were due to pump malfunctions during high flow events and power issues. To avoid equipment failure and malfunctions researchers using the LISST-StreamSide should:

- Have replacement pumps and parts in stock in case the pump is destroyed or damaged.
- Select a sampling frequency (i.e. samples per day) that matches power supply to the particle analyzer.
- If solar panels are used to power instruments, select gauging locations that are not shaded. If sampling site is in a shaded area, use high watt solar panels or multiple solar panels.
- Regularly clean and maintain particle analyzers.

Statistical comparisons of results (ANOVA, $P < 0.05$) indicated that mean SSCs were not significantly different between the headwater, suburban and urban gauging sites (P value = 0.31). Figure 21 shows average suspended sediment concentrations and standard deviations for the headwater, suburban and urban gauging sites in this study. The concentrations from the suburban area are only 6% greater than the concentrations from the headwater. However, the concentration from the urban land-use area was 30% and 24% greater than the headwater and suburban land-use areas. These results are similar to results of Coulter et al. (2004), who used a paired watershed study design to examine suspended sediment concentrations in three watersheds. Paired watersheds were predominantly agricultural, mixed-use, and urban land uses. Results from the study indicated that mean suspended sediment concentration was lowest in the agricultural watershed (14.8 mg/l) and greatest in the mixed-land use (23.4 mg/l) and urban (21.7 mg/l) watersheds (Coulter et al. 2004). These findings are similar to results in this work where suspended sediment concentrations are higher in the suburban (mixed-use) and urban land-use areas compared to the headwater gauging site, which is dominated by agricultural land-use. In the Puget Lowland area of Washington, Packman (2004) showed mean suspended sediment concentrations to be less in agricultural (4.5 mg/l) and forested watersheds (12.0 mg/l) compared to the urban watersheds (245.0 mg/l). Results from Packman (2004) are consistent with results from HCW with higher suspended sediment concentrations observed in urban watersheds compared to agricultural sub-basin.

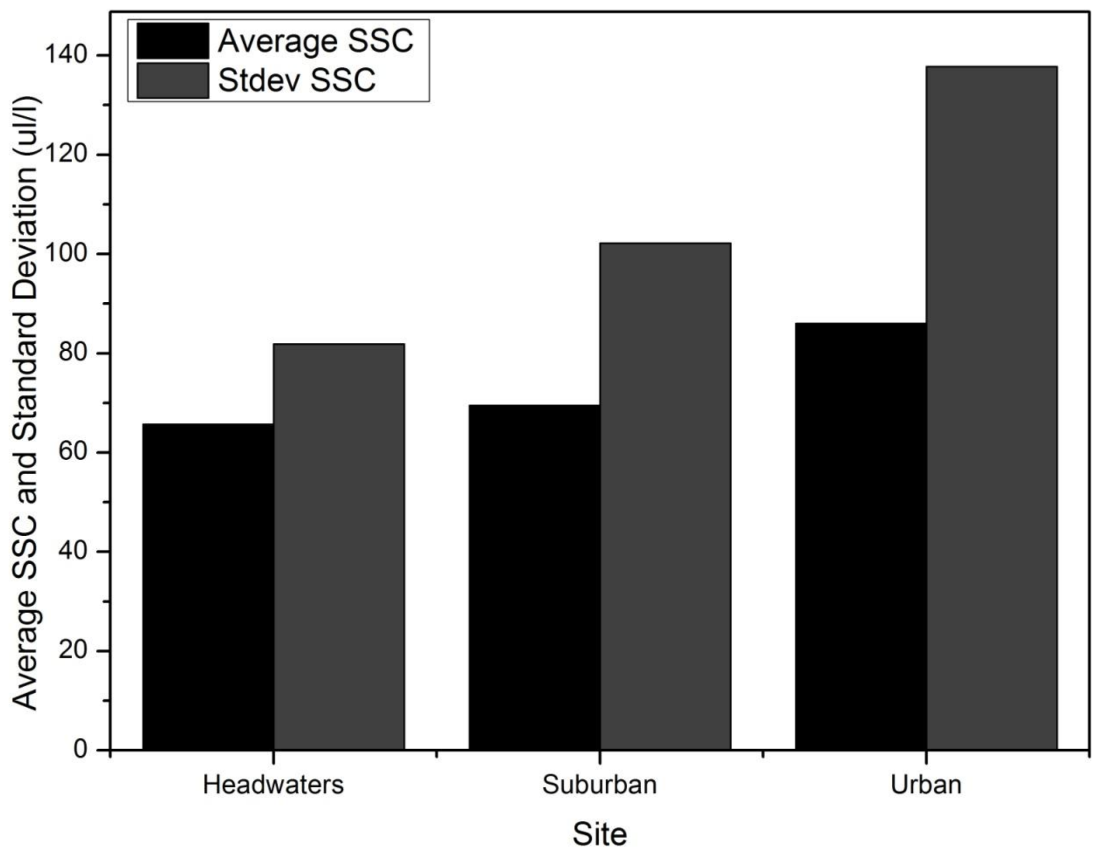

Figure 21. Average suspended sediment concentration (µl/l) and standard deviation of suspended sediment concentration (µl/l) for the headwater, suburban, and urban gauging stations used in Hinkson Creek Watershed, Missouri.

Particle density and Volumetric Conversion

Multiplying volumetric concentrations for LISSTs by particle density (Table 20) supplied corresponding gravimetric estimates of suspended sediment concentration. Average daily gravimetric concentration for the headwater, suburban, and urban land use areas was 134.1, 135.1, and 147.1 mg/l. When the average density of particles are used to convert volumetric estimates (µl/l) to gravimetric estimates (mg/l), the percent differences in average concentration decreases between sites. Differences in gravimetric suspended sediment concentrations decrease because particle densities decrease at the suburban and urban gauging station compared the headwater. Therefore, when volumetric suspended sediment concentrations are multiplied by particle densities resultant gravimetric concentrations increase by a smaller percentage at the suburban and urban gauging station.

The average particle density of suspended sediment was 2047.6, 1944.6, and 1710.6 kg/m^3 for the headwater, suburban, and urban land use gauging stations. It is difficult to compare suspended sediment particle densities observed in HCW to other studies because the majority of suspended sediment studies use gravimetric measurements of suspended sediment concentrations (Brooks et al., 2010; Horowitz, 2003; Horowitz, 2009; Lee et al., 2009) which require no density estimates. However, some researchers suggest suspended sediment particle densities are commonly between 1,660 to 2,990 km/m^3 (Allmendinger et al., 2007; Clifton et al., 1999). Particle density could be decreasing in the suburban and urban sites compared to the headwater site due increases in organic matter in the water. Several studies have shown increased nutrient concentrations in streams impacted by urbanization (Hatt et al., 2004; Lee and Bang, 2000) which can promote increased biomass growth (Walsh et al., 2008). Agrawal and Pottsmith (2000) suggest that the density of organic matter is commonly around 1,000 kg/m^3, which is considerably less than common estimates of particle density. Since suspended organic matter have densities less than sediment, the presence of organic matter could negatively skew particle density estimates. In this study the influence of organic matter on observed SSCs, particle densities, and mean particle sizes was not investigated. Further work is necessary to understand how organic matter influences laser diffraction estimates of SSCs, particle densities, and mean particles sizes.

Mean Suspended Sediment Particle Size

Mean suspended sediment particle size decreased from the headwater (151.0 µm) to the suburban (111.0 µm) and urban (79.0 µm) sites in this work. Mean suspended sediment particle size could be decreasing in suburban and urban sub-basin due to the increasing urban area. As urban area increases the smaller particles may make up a larger percentage of the particle size distribution in urban runoff (Kim and Sansalone, 2008; Hubbart and Gebo, 2010). Decreasing mean particle size may also indicate mechanical or physical weathering of particles or particle aggregates as water moves downstream. Larger particles in the headwater could be aggregates made up of finer particles (Hubbart and Freeman, 2010). As aggregates move downstream, particles could de-aggregate due to physical weathering, thus resulting in smaller mean particle sizes. However, the results from suspended sediment density analysis may indicate other processes are responsible for the decreasing mean suspended sediment particle size (impetus for future work). On average, aggregate densities are about two thirds of the density of the primary particles making up the aggregate (Young, 1980). This implies that particle densities should increases as particle aggregates weather. This is contrary to what was observed in HCW where particle sizes decreases and particle densities also decrease. Particle size may also be skewed by presence of biological material, which may increase mean particle size classes (Hubbart and Freeman, 2010). Preliminary results from a study in HCW conducted by Hubbart et al. (Spring 2011) indicate high levels of organic matter in storm water runoff. Analyzing particle size distribution from soils in different land-use areas, characterizing terrestrial runoff particle size distributions, and determining the effects of organic matter on observed particle size distributions may help explain the some of the observed phenomena.

Suspended Sediment Concentration Comparisons

There is a general lack of suspended sediment data for the state of Missouri, which makes comparisons of results difficult, but speaks to the critical value and timing of this work. However, there are some limited data sets available from streams near Hinkson Creek. The Salt River near Santa Fe, Missouri (approximately 60 km Northeast of HCW) had a USGS (HUC 05505000) gauging station site where suspended sediment was monitored from 7/1/1980 through 6/30/1982. Average discharge and suspended sediment concentration during the monitoring period was 6.5 m^3/s and 131.63 mg/l. Those results are surprisingly similar to the results from this study. In the present study average concentration for the headwater, suburban, and urban land use areas were only 3%, 3%, and 12% greater than the average concentration from the USGS gauging station on the Salt River.

In a study conducted by Lee et al. (2009) suspended sediment concentrations and loads were estimated in Kansas City, Kansas (approximately 207 km west of HCW), using turbidity meters and grab samples to quantify suspended sediment. Lee et al. (2009)

found average suspended sediment concentration in eight urban/mixed land-use basins ranged from 200 to 730 mg/l. Averaged annual suspended sediment concentrations for all eight basins was 437.5 mg/l (Lee et al., 2009). The results from this study were considerably less compared to the findings of Lee et al. (2009). Average concentrations in HCW were 69%, 69%, and 66% smaller at the headwater, suburban, and urban gauging stations (respectively) compared to the average concentrations in Kansas City, Kansas. Sediment concentrations from Lee et al. (2009) maybe significantly higher due to the road and housing construction, low permeability soils, and erosive soils that were reported in the watersheds during the study. Suspended sediment concentration may also be significantly higher than results from Lee et al. (2009) due to differences in the size and shape of the watersheds, proximity of suspended sediment sources, and differences in vegetation.

In a study conducted by Simon et al. (2004) suspended sediment and discharge data for different eco-regions across the United States was analyzed to develop average SSCs for different eco-regions. Estimates of suspended sediment concentration from Simon et al. (2004) were based on bank full discharge scenarios with recurrence intervals of 1.5 years. HCW spans two of the eco-regions analyzed in the Simon et al. (2004) study, the Interior River Lowlands and the Central Irregular Plains. Average SSC for the Interior River Lowlands was estimated to be 222 mg/l and the average SSC for the Central Irregular Plains was estimated to be 1020 mg/l (Simon et al., 2004). The average concentrations in HCW for the headwater, suburban, and urban land use areas are 40%, 39%, and 34% smaller than the average concentration of the Interiors River Lowlands, respectively. Concentrations for the headwater, suburban, and urban land use areas were 87%, 87%, and 86% smaller than the average SSC for the Central Irregular Plains, respectively. The eco-regions used in by Simon et al. (2004) are large in comparison to the size of HCW. Due to the large size of the eco-regions, the data that was collected was influenced by cumulative effects of multiple watersheds on suspended sediment trends. Ultimately, there are a wide variety of factors that affect suspended sediment concentrations including: precipitation trends, soil types and characteristics, antecedent soil moisture, topography, land-use and watershed morphology. These factors can vary greatly spatially and temporally, which makes absolute comparisons of SSC difficult, but provides basis for future studies.

Water Quality Standard and Criteria

Water quality criteria are concentrations or levels of certain pollutants, water quality characteristics, or conditions of water of a water body that if met will protect water bodies designated uses. Section 304 of the Clean Water Act (CWA) provides water quality criteria recommendations for States in setting water quality standards. The criteria established by the USEPA provide numeric values for pollutants that should not be exceeded. However, the USEPA does not set numeric water quality criteria for suspended sediment concentrations. Instead most states, including Missouri, use narrative criteria which states, “surface waters shall be free from pollutants in amounts that cause objectionable conditions or impairment of designated uses” (USEPA, 2003). This narrative criterion is often somewhat subjective and therefore difficult for States to determine if sediment concentrations are impairing water bodies. Since no numeric suspended sediment criteria are available for the State of Missouri it is difficult to compare results of this study to the narrative criteria used in the evaluation used by the Missouri Department of Natural Resources (MODNR). The MODNR listed suspended sediment as a possible source of impairment in the HCW through visual observation of turbidity (USEPA, 2011). Findings from this study indicate that average suspended sediment concentrations are generally lower than results from other studies in the region (Simon et al., 2004; Lee et al., 2009). Analysis of historical data from the Salt River located approximately 60 km Northeast of HCW indicated that average SSCs were only slightly larger (3 to 12%) than concentrations from the Salt River, which has been used as a reference stream in the current TMDL for Hinkson Creek (USEPA, 2011). It is worth pointing out that the upper portion of the Salt River Watershed is approximately nine times larger than the HCW with a variety of land-use and morphological differences, which make the watershed suspect for comparisons to the HCW. Further, Salt River suspended sediment data was from a historical archive (7/1/1980 to 6/30/1982) and may not be representative of current water quality conditions almost 30 years later. Most of the comprehensive suspended sediment data sets for Missouri are from much larger rivers and in general are not useful for comparisons of smaller watersheds. Horowitz (2003) indicated the 20-year mean suspended sediment concentrations of the Missouri River at Herman, Missouri was 696 mg/l. The mean SSC from the Missouri river is approximately four times higher than SSCs observed in HCW and the Salt River. Lack of sediment data may pose future problems for natural resources managers, policy makers, and scientist who are attempting to protect water quality and biota. There is obviously a great need for continued research that characterizes and quantifies suspended sediment in central Missouri streams which could serve as reference streams for impaired water bodies.

Storm Flow and Base Flow Suspended Sediment Concentration

Average suspended sediment concentrations were calculated for periods when the stream's only contribution was from base flow and when the stream was receiving water from over land flow. During base flow conditions average SSC was 38 µl/l, 44.5 µl/l, and 37.8 µl/l for the headwater, suburban and urban land-use area, respectively. Average suspended sediment concentration under base flow conditions was 58%, 57%, and 70% less than average SSC under storm flow conditions for the headwater, suburban and urban land-use gauging station respectively. In a study by Allan et al. (1997) SSCs were found to be higher in areas of greater agriculture and cultivation during base flow conditions. In this study, average concentration during base flow conditions was higher in sub-basins with the largest amount of area under agricultural land-use. Results from this study are similar to results presented by Allan et al. (1997) with higher base flow concentrations in the sub- basins with larger percentages of agricultural land-use area. In Atlanta Georgia, a study conducted to quantify suspended sediment in an urban stream, identified sediment concentrations below 10 mg/l during base flow conditions (Horowitz, 2009). In this study suspended sediment concentrations for the headwater, suburban and urban land-use areas was 280% (38.0 mg/l), 345% (44.5 mg/l), and 278% (37.8 mg/l) higher (respectively) than the results presented by Horowitz (2009). These differences could be attributable to the fact that much of the HCW is not urbanized and the watershed studied by Horowitz (2009) (inside Atlanta, Georgia) is largely urbanized. In a largely forested watershed in North Carolina observed SSCs ranged from 120 to 200 mg/l in storm events. During lower flows SSC was ~5 mg/l (Chen et al., 2004). In comparison to a watershed that is largely unaffected by urban development (Chen et al., 2004) base flow concentrations from the HCW are at least five times larger than results presented by Chen et al. (2004). During higher flows average concentrations reported by Chen et al. (2004) were 25 to 77 % greater than average storm flow SSCs observed in HCW. Mean base flow SSCs observed in HCW are higher than previously published results (Chen et al., 2004; Horowitz, 2009) which indicates more suspended sediment may be transported during lower flows in HCW compared to other studies.

SEDIMENT LOADS AND YIELDS

In this section results will be presented in two different ways. The first method presented will be cumulative sediment loads and yields. This method examines the cumulative effects of land-use and watershed size. The entire drainage area above particular gauging stations influences the cumulative sediment loads and yields results. The second method examines sub-basin sediment loads and yields which provides a way to examine how characteristics of individual sub-basins affected observed sediment trends.

Cumulative Sediment Load and Yields

Total sediment loads (m^3, tonne) for each gauging station was calculated by multiplying the average suspended sediment concentrations (µl/l) by the average daily discharge (m^3/day) and a unit conversion factor (unit conversions factor converts SSCs from µl/l to m^3/m^3). Figure 22 shows total sediment loads for headwater (site 1), suburban (site 2), and urban (site 3) land-use gauging stations located in HCW. Sediment load increases continually as Hinkson Creek flows from the headwater, through the suburban, and finally to the urban gauging station. This pattern is expected since suspended sediment load is conveyed downstream and additional land-use areas contribute sediment to the total load. Further, a significant amount of suspended sediment can be stored in stream channels (Asselman, 1999; Asselman et al., 2003; Collins and Walling, 2006) which can be remobilized during high discharge events or floods (Asselman, 1999). The current work showed that the total sediment load at the suburban and urban land-use gauging stations was 108% and 225% larger than the sediment load at the headwater gauging station. The sediment load at the suburban gauging stations was 36% smaller than urban gauging station (Figure 22).

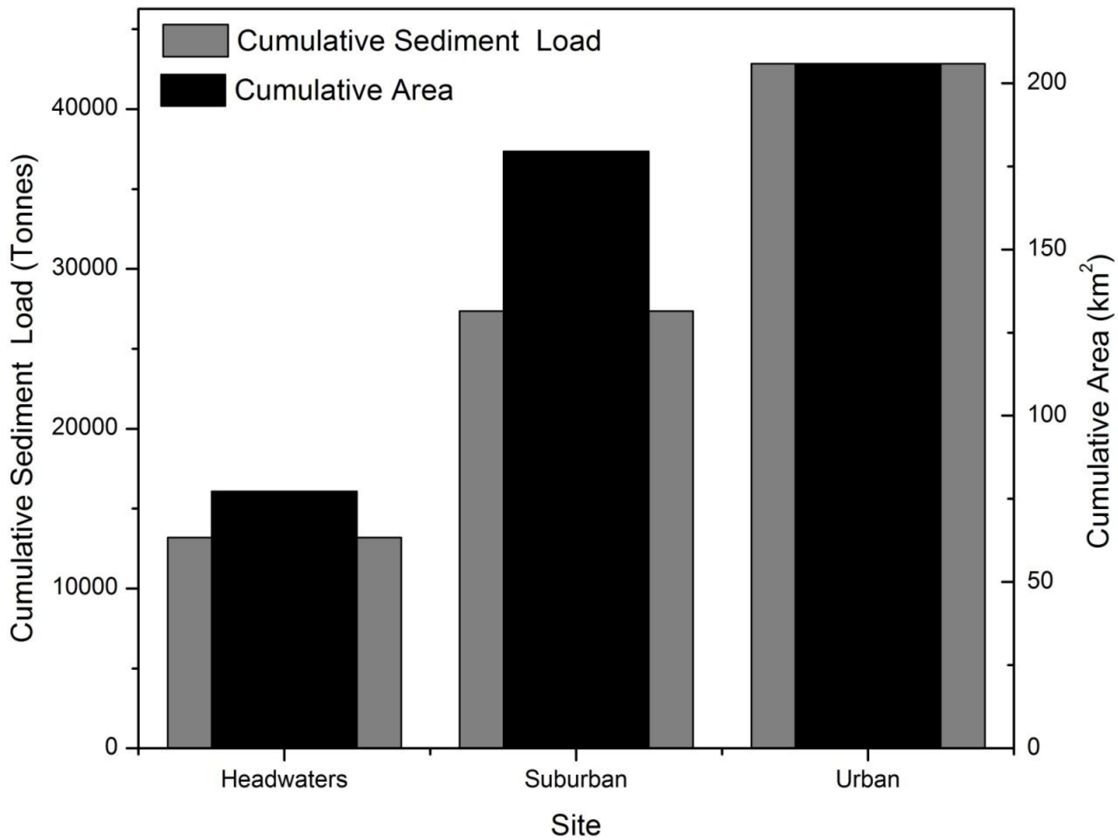

Figure 22. Total suspended sediment load (tonnes) transported through the headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed, Missouri.

Figure 23 shows daily averages and standard deviations for sediment loads at each gauging site located in HCW. The observed daily average suspended sediment load and standard deviation follows the same trend as total sediment loads for each gauging site, with values increasing as Hinkson Creeks flows from the headwater towards the urban gauging site. The increasing standard deviation values (Table 25) indicate there is a greater range of sediment loads occurring in the suburban and urban gauging sites compared to the headwater gauging site. Standard deviations for daily sediment loads were similar to the observed discharge standard deviations presented earlier (Figure 18). This is reasonable since sediment load is correlated to discharge regimes (Asselman, 2000; Horowitz, 2003; Lee et al., 2009; Horowitz, 2009; Walling, 1977). As mentioned earlier, the suburban and urban sub-basin exhibit larger discharge response to the same precipitation event compared to the headwater sub-basin. The larger discharge response in the suburban and urban sub-basins is likely attributed to the increased impervious areas. Higher peak flow events create a higher range of sediment loads in the suburban and urban sub-basin (similar to water flow) compared to the headwater, thus illustrating impervious land-use effects on suspended sediment trends.

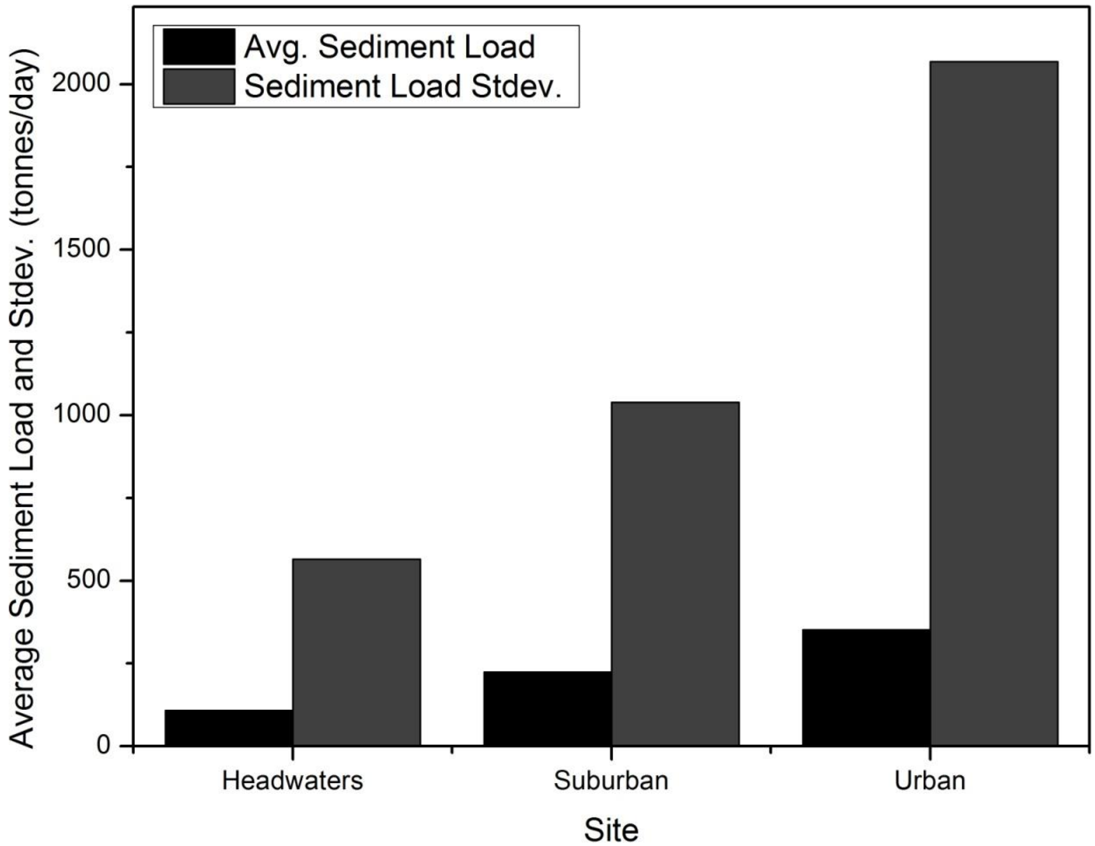

Figure 23. Daily average sediment load and standard deviation for headwater, suburban, and urban gauging sites located in Hinkson Creek Watershed, Missouri

Figure 24 shows daily average and median daily suspended sediment measured at the headwater, suburban, and urban gauging sites. The daily average suspended sediment loads are large in comparison to daily median sediment loads. The median suspended sediment loads are likely more representative of the central tendencies of daily sediment load (Simon et al., 2004). Daily averages sediment loads are likely positively skewed due to large discharge events that create very large sediment loads.

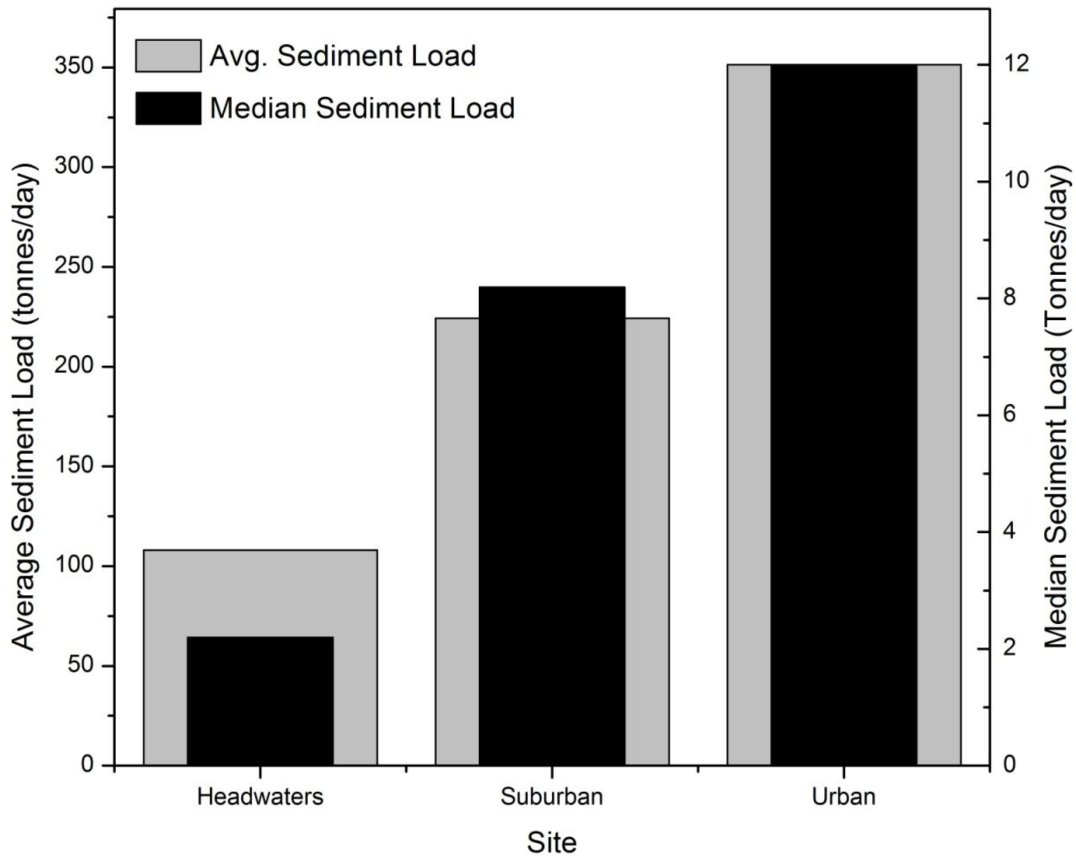

Figure 24. Average and median daily suspended sediment load for the headwater, suburban, and urban gauging station in Hinkson Creek Watershed, Missouri.

Statistical tests (P < 0.05) indicated that median daily sediment loads were statistically different (P value <0.001) between gauging sites in HCW. This is interesting because mean SSCs were not statistically different between gauging sites in HCW. This may indicate that land-use type does not influence SSCs as much as it influences sediment loads. Sediment load is a product of SSC and discharge. Theoretically, sediment load will increase with any increase in discharge even if the SSC remains constant.

Therefore, suspended sediment loads are likely statistically different in part due to large differences in discharge between the sub-basins. Changes in land-use in the watershed (i.e. increased impervious area) indirectly affect suspended sediment loads by increasing the frequency of large, flashy discharge events.

Storm Flow and Base Flow Sediment Loads

In this study total sediment load generated by storm flow amounted to over 97% of the total sediment load for each site. These results agree favorably with other studies that have shown as much as 99% of streams total sediment load is transported during storm event generated runoff (Walling and Web, 1982; Horowitz, 2009). The current Hinkson Creek TMDL calls for volume based surface runoff reduction to meet water quality standards. If storm water runoff was significantly reduced, sediment loads in HCW may also be significantly reduced. Sediment particles eroded from stream channels were shown to be a significant source in agricultural watersheds (Willet, 2010) and in urban watersheds (Fraley et al., 2009; Nelson and Booth, 2002; Trimble, 2000). Reducing the frequency and magnitude of peak flows in the HCW may also therefore significantly reduce the amount channel erosion in the urban sub-basin.

Cumulative Sediment Yield

Table 29 shows observed suspended sediment yields for different land-use types from various authors. Figure 25 shows CSY and total drainage area for each gauging site. CSYs for the headwater, suburban, and urban land use areas are 170.3 tonnes/km^2, 152.4

tonnes/km^2, and 208.1 tonnes/km^2 respectively. CSY decreased from the headwater site the urban site and then increased from the suburban site to the urban site. Dedkov and Moszherin (1992) suggested that stream systems are characterized by positive or negative relationships between sediment yields and drainage area according the relative importance of channel erosion or slope erosion (i.e. sheet and gully erosion). In streams dominated by channel erosion, erosion rates will increase downstream in response to more entrainment and transport of sediment particles, thus creating a positive relationship between sediment yield and downstream drainage area (Asselman et al., 2003; Dedkov and Moszherin, 1992; Walling and Webb, 1996). In areas where hillslope erosion makes up the dominant sediment sources, much of the erosion may be concentrated in the headwater and a larger percentage of mobilized sediment will be deposited in the stream system. This process thus creates an inverse relationship between sediment yield and drainage area, with sediment yield decreasing as drainage area increases (Dedkov and Mozzherin, 1992). The positive and negative relationship between sediment yield and increasing drainage area may partly explain the observed CSYs in HCW. The CSY decreases from the headwater site to the suburban site, which could indicate the erosion processes in the headwater gauging site are dominated by slope erosion (gully and sheet erosion). The decreased CSY at the suburban site may also be due to storage of eroded material in the upper portion of the watershed (Asselman et al., 2003). Another explanation for the decreased CSY at the suburban sub-basin is due to the large increase in drainage area. Since this study uses a nested study design, changes in CSYs between the basins are strongly influenced by the total drainage area of the gauging site. In a nested study design watershed, a small increase in downstream sediment production in proportion to the increase in total drainage area will cause the CSY of the downstream gauging site to decrease. The large increase in total drainage area between the headwater and suburban area decreases the suburban CSY compared to the headwater CSY. CSY increased from the suburban site to the urban gauging site which may indicate the dominant source of eroded material comes from stream-bank erosion (Asselman et al., 2003). This observation is consistent with other studies that have noted increased streambank erosion in urban environments (Nelson and Booth, 2002; Trimble, 1997).

Table 29. Reported global suspended sediment yields (tonnes/km^2/year) for different land use types.

Land-Use Type	Sediment Yield (tonnes/km^2/year)	Author
Urban	135	Allmendinger et al , 2007
Urban	96	Fraley et al, 2009
Urban	35	Fraley et al, 2009
Urban	47	Fraley et al, 2009
Urban	3220	Leopld, 1968
Urban	151	Lee et al., 2009
Urban	140	Lee et al., 2009
Urban	175	Lee et al., 2009
Urban	266	Lee et al., 2009
Urban	182	Lee et al., 2009
Urban	210	Lee et al., 2009
Urban Average	423	-
Ag	257	Wolman, 1967
Ag	74	Wolman, 1967
Ag	102	Wolman, 1967
Ag	25	Walling et al., 2002
Ag	58	Walling et al., 2002
Ag	22	Walling et al., 2002
Ag	27	Walling et al., 2002
Ag	26	Walling et al., 2002
Ag	29	Walling et al., 2002
Ag	39	Walling et al., 2002
Ag Average	66	-
Forest	3	Wolman, 1967
Forest	5	Wolman, 1967
Forest	2	Wolman, 1967
Forest	1	Birkinshaw et al., 2010
Forest	3	Birkinshaw et al., 2010
Forest Average	3	-
Construction	44468	Wolman, 1967
Construction	737	Wolman, 1967
Construction Average	22602	-
Grasland	108	Garbecht and Starks, 2009
Grassland Average	108	-

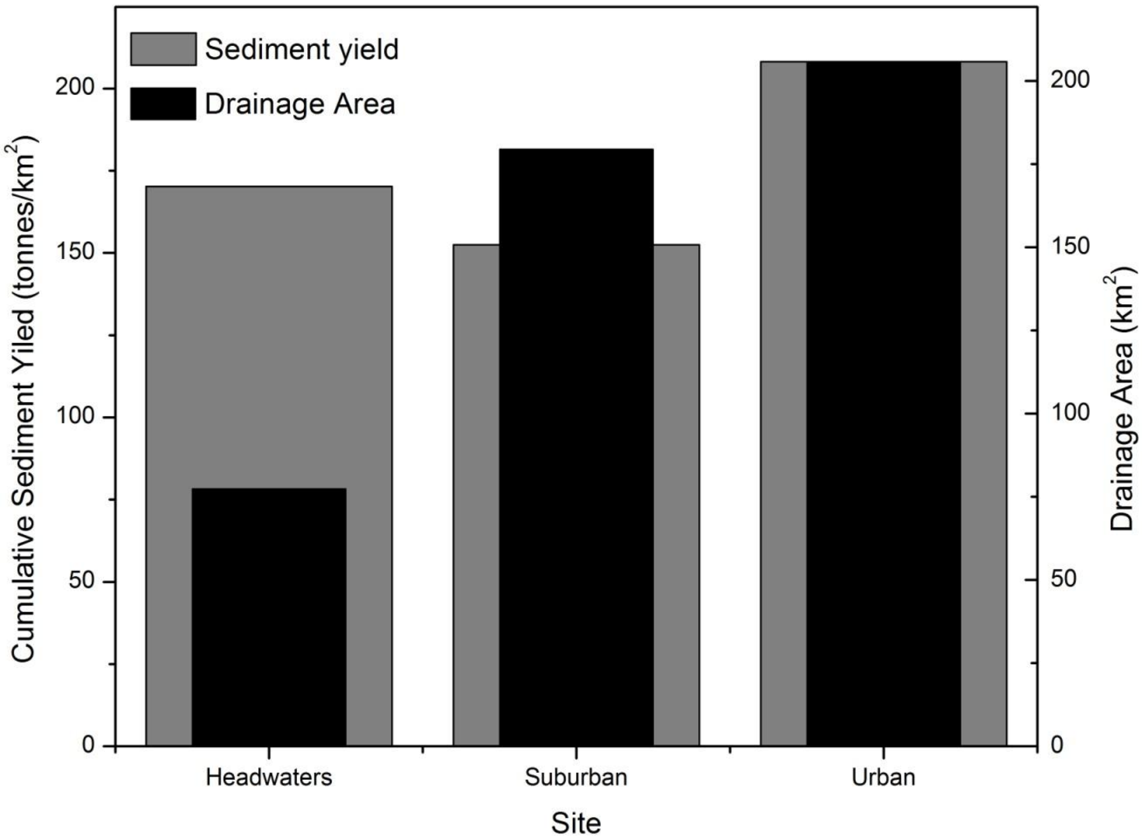

Figure 25. Cumulative Sediment Yield (CSY) (tonnes/km^2) and drainage area (km^2) for headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed. Sediment yields reflect total area draining to each gauging location.

Suspended sediment yields can be highly variable from one watershed to another even when the dominant land-uses are the same (Nelson and Booth, 2002). Table 29 illustrates the wide range of sediment loads under different land-uses. Sediment yields are highly variable from one watershed to another due to in differences in watershed characteristics. The sediment yields presented in this study are from a four month period which makes comparisons difficult. Most sediment yields presented in other studies are calculated for a full year. However, it is common for the majority of suspended sediment to be transported during the spring runoff season (Gray and Gartner, 2009). For this reason it may be acceptable to compare sediment yields from this study to annual yields from other studies. In Kansas City, Kansas, Lee et al. (2009) reported sediment yield near the outlet of an urban/urbanizing watershed of 157 tonnes/km^2/year. The suspended sediment yield at the urban gauging station which is near the outlet of HCW was 208 tonnes/km^2. Thus, sediment yields from the HCW were 32% greater than annual sediment yields reported by Lee et al. (2009). The sediment yields in HCW are likely larger than yields in Lee et al. (2009) because of the difference in total discharge. As mentioned earlier mean SSCs from HCW were approximately 66 - 69% smaller than mean SSCs presented by Lee et al. (2009). This indicates that sediment loads observed in HCW are larger compared to results from Lee et al. (2009) due differences in total discharge or to high frequency of large discharge events in HCW. Trimble (1997) conducted a study in San Diego Creek Watershed (288 km^2), southern California evaluating the effect of urbanization on suspended sediment trends and channel erosion. Total sediment yield was 521 tonnes/km^2/year. In comparison, sediment yields in HCW were 60% smaller than sediment yields presented by Trimble (1997). Trimble (1997) found that up to two thirds of the total sediment load in San Diego Creek Watershed was from channel erosion, which may account for the large difference in sediment yields compared to the HCW. Horowitz (2009) showed sediment yields from urbanized watershed within the City of Atlanta Georgia ranging from 80 to 800 tonnes/km^2/year. The sediment yields observed at the urban gauging station in HCW fall within the range of sediment yields presented by other researchers (Horowitz, 2009; Lee et al., 2009; Trimble, 1997). The above average precipitation during years preceding this study and subsequent high antecedent soil moisture conditions likely caused above average sediment yields. Sediment yields presented in this case study may not represent historical sediment yields in HCW. Therefore, comparisons between this case study and other studies should be interpreted with caution. Ongoing investigations in the HCW will better determine annual sediment yields and partition the amount of sediment origination from channel erosion.

Sub-Basin Sediment Loads and Yields

Sub-basin sediment yields (SBSY) were calculated using methods presented in Table 7. SBSYs were calculated by subtracting the upstream sub-basin's total sediment load from the lower sub-basins sediment load and dividing by the drainage area of the lower sub-basin (Lee et al., 2009; Walling and Web, 1996). SBSYs do not represent the total amount of sediment originating from that sub-basin. However, the method provides a preliminary way to assess the impact of land-use on suspended sediment loads in each sub catchment (e.g. Lee et al, 2009; Walling and Web, 1996). Figure 26 shows contribution of sediment from each sub-basin draining to each gauging station. The sediment load (Tonnes) produced by each sub-basin is relatively similar to each other even though sub catchment areas are quite different (headwater = 77.4 km^2, suburban = 102.2 km^2, and urban 26.3 km^2). The headwater, suburban, and urban land-use areas contributed 13,180, 14,189, and 15,384 tonnes to the total load respectively. These results have important implications for land-use and sediment yields. The total area of each land-use type increased (except agricultural land-use) as the stream flows from the headwater to the suburban catchment. However, the sediment load production for the suburban catchment was only 7.7% greater than the contribution from the headwater catchment. As the stream flows through the suburban catchment to the urban catchment the area of each land-use type decreases. While the area (km^2) of each land-use type decreases from the suburban sub-basin to the urban catchment, the sediment load (tonnes) contribution from the urban sub-basin is 8.4% greater than the suburban contribution. These small differences in sediment loads between each sub-basin indicate that suspended sediment loads do not vary greatly as the amount of land-use areas changes between sub-basins. This result may indicate that suspended sediment yields for the same land-use type are highly variable between sub-basins or stream-bank erosion is contributing very large proportions of sediment to the sub-basin sediment loads. There are however some limitations to this analysis. This type of analysis cannot account for suspended sediment being deposited in the stream. However, suspended sediment is generally transported conservatively (Hooke, 2003). Future research that characterizes suspended sediment deposition (or lack thereof) will improve estimates of sediment originating for individual sub-basins.

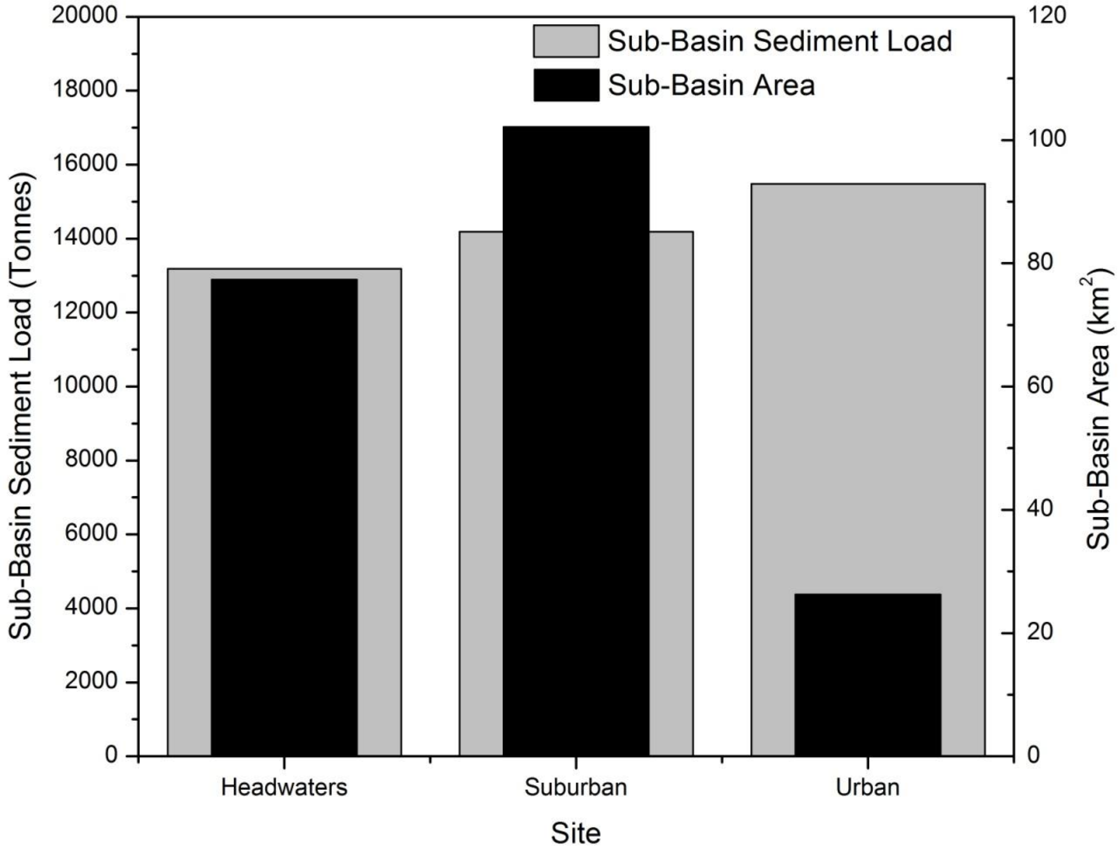

Figure 26. Sub-basin sediment load (tonnes) for headwater, suburban, and urban sub-basin in Hinkson Creek Watershed, Missouri. Assumes all sediment from each gauging site exits the outlet of the watershed.

To quantify the influence of land-use on suspended sediment trends, sediment yield was calculated for each sub-basin in HCW by using only the sediment load produced from each individual catchment and the drainage area of that catchment (Lee et al., 2009; Walling and Web, 1996). Figure 27 shows sub-basin sediment yields (SBSY) (tonnes/km^2) and drainage area (km^2) for individual catchments draining to each gauging station. As shown, sediment yield decreased at the suburban gauging station compared to the headwater gauging station even though the total area of the suburban catchment is larger than the headwater catchment. The lower sediment yield at the suburban gauging station could be due to the sediment buffering capacity of the catchment and the location of sediment sources (Walling, 1999). Golosov et al. (1992) showed that for small drainage basins the sediment delivery ratio ranged from zero to 89%. If the suburban catchment has a low sediment delivery ratio, much of the sediment that is eroded may never reach the stream, thus, not affecting the sediment yield of the catchment (Walling, 1999). There is a large increase in sediment yield at the urban gauging site compared to the suburban gauging site (Figure 27). The urban site contains the largest percentage of impervious surface, which may contribute to the large increase in sediment yield. Further, stream channels surrounded by urban areas are extremely susceptible to channel erosion and incision. Studies have shown that a significant proportion of urbanizing steam's total sediment load can come from channel erosion (Trimble, 1997; Nelson and Booth, 2002). Large contributions of suspended sediment from stream banks in the urbanized area may explain the high sediment yield observed at the urban gauging site in this study.

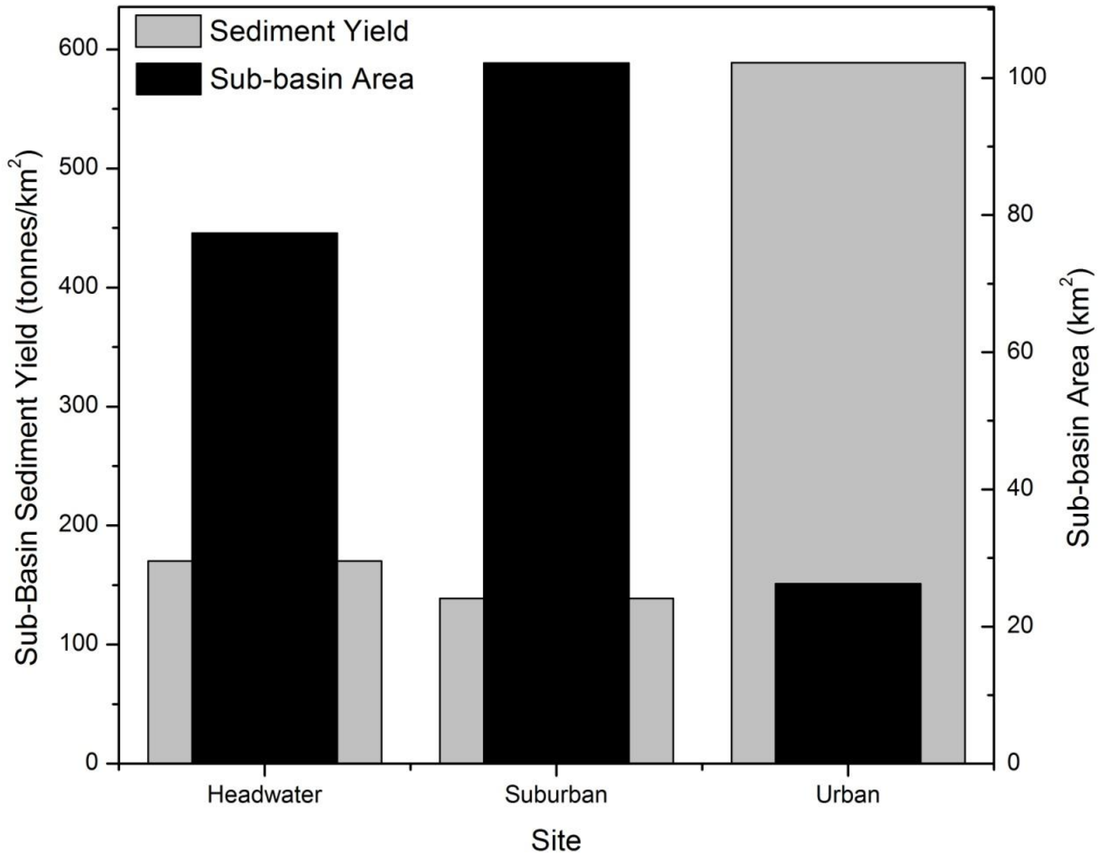

Figure 27. Sub-Basin Sediment yield (tonnes/km^2) and drainage area (km^2) for headwater, suburban, and urban sub-basins draining to each gauging station located in Hinkson Creek Watershed.

Summary of Sediment Yields

Sediment yield (tonnes/km^2) in sub-basins of HCW were analyzed two ways. The first method (Figure 25) calculated cumulative sediment yield at each gauging station. The second method (Figure 27) calculated sub-basin sediment yields by using sediment loads and drainage areas of the individual sub-basin. Results from both methods indicated that sediment yields were lowest in the suburban drainage area and highest in the urban drainage area. Results from cumulative sediment yield analyses indicated that overland erosion may be the dominant source of in-stream sediment in the upper portions of the watershed. Cumulative sediment yield estimations also indicated that as the watershed transitions from the suburban catchment to the urban catchment sediment sources may be dominated by stream bank erosion or other in-stream hydrogeomorphic erosion processes. Sub-basin sediment yield in the urban sub-basin was 246% and 324% higher compared the headwater and suburban sub-basins. The large sub-basin sediment yield likely confirms results derived from the cumulative sediment yield computations that indicated channel erosion may be the dominant source of erosion transported through the urban sub-basin.

SEDIMENT RATING CURVES

Suspended sediment rating curves were constructed for the headwater, suburban and urban land use monitoring sites by log-transforming the discharge and SSC data and fitting a linear line to the log-transformed observed data (Table 30). The rating curves developed in this study had seemingly low r^2 values (i.e. r^2 < than 0.50). Horowitz (2003) presented suspended sediment rating curves, which were developed in similar methods as the rating curves in this study; with $r^2 < 0.40$ estimated total suspended sediment flux with approximately 8 to 11% accuracy. Suspended sediment rating curves for different streams and rivers have a large range of r^2 values (0.15 to 0.93) (Asselman, 2000; Horowitz, 2003; Horowitz, 2009; Lee et al., 2009; Walling, 1977). Low correlations between discharge and SSC are not uncommon (Tramblay et al., 2010). Tramblay et al.

(2008) showed that correlations between maximum SSC and corresponding discharge was significant in only 92 of the 208 rivers analyzed in North America. This indicates that in many rivers, suspended sediment loads are supply limited as opposed to discharge limited (Tramblay et al., 2010). This implies that discharge alone cannot account for all of the variability observed in sediment loads.

The rating curves for site 1, 2, and 3 estimates were +28.2, -48.4, and +11.3 % different from measured sediment loads at each site (Figure 30). However, Nash-Sutcliffe analysis indicated that there was good agreement between the modeled and measured sediment loads for the suburban (NS =0.85) and urban (NS=0.83) rating curves. Modeled sediment loads did not compare as well with measured loads at the headwater gauging site (NS= 0.43). Suspended sediment rating curves were fairly accurate for the short duration of monitoring time. However, high accuracy should be expected given the sampling frequency and high (i.e. hourly) sample size. The rating curve for the urban gauging site, which is nearest the HCW outlet, has the lowest percent error and highest NS (0.83) and is likely the most useful for developing and implementing sediment TMDLs due to its proximity to the watershed outlet.

Suspended sediment concentration can often vary over several orders of magnitude for a given discharge level (Walling and Webb, 1982). Thus, deriving rating curves from longer periods of time could improve errors associated with rating curve estimates of suspended sediment load. Figure 29 shows time series of estimated suspended sediment load, measured suspended sediment loads, and average daily discharge for the headwater, suburban, and urban sites. The estimated sediment loads for the headwater, suburban, and urban land use areas track the measured suspended sediment load well. However, during the largest discharge event, the rating estimates tend to diverge from the measured sediment load suggesting rating curves do not estimate sediment load well during large discharge events. Estimated suspended sediment load likely diverges from the measured load due to the lack of measurements during large, high flow events causing the model to overestimate sediment loads at the headwater and urban gauging sites and underestimate at the suburban site. Sediment rating curves produced in this study provide a valuable tool for estimating sediment loads where suspended sediment sensing instrumentation or rigorous suspended sediment sampling regimes are not available.

Table 30. Rating equations and R^2 values for suspended sediment rating curves for the headwater, suburban, and urban gauging stations located in Hinkson Creek Watershed, Missouri.

Site	Sediment Rating Equation	R^2 Value	Nash-Sutcliffe
Headwater	y=0.4973x+0.9328	0.42	0.44
Suburban	y=0.4812x+0.7974	0.43	0.85
Urban	y=0.7748x+0.0993	0.49	0.83

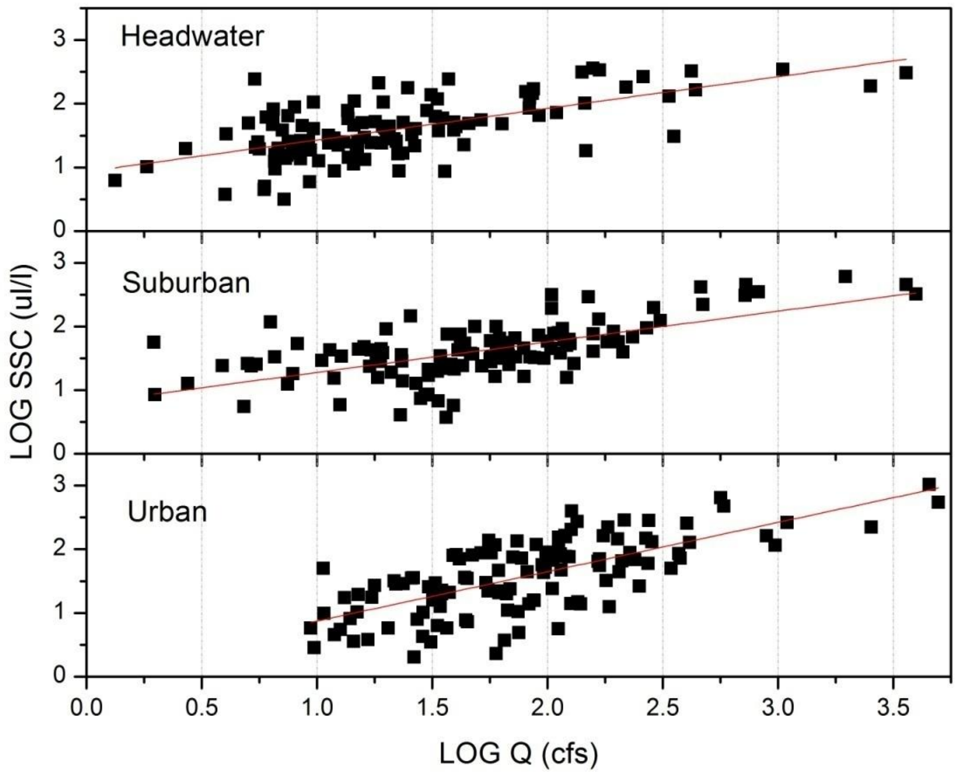

Figure 28. Suspended sediment rating curve for the headwater, suburban, and urban land-use areas draining to each gauging site in Hinkson Creek Watershed, Central Missouri.

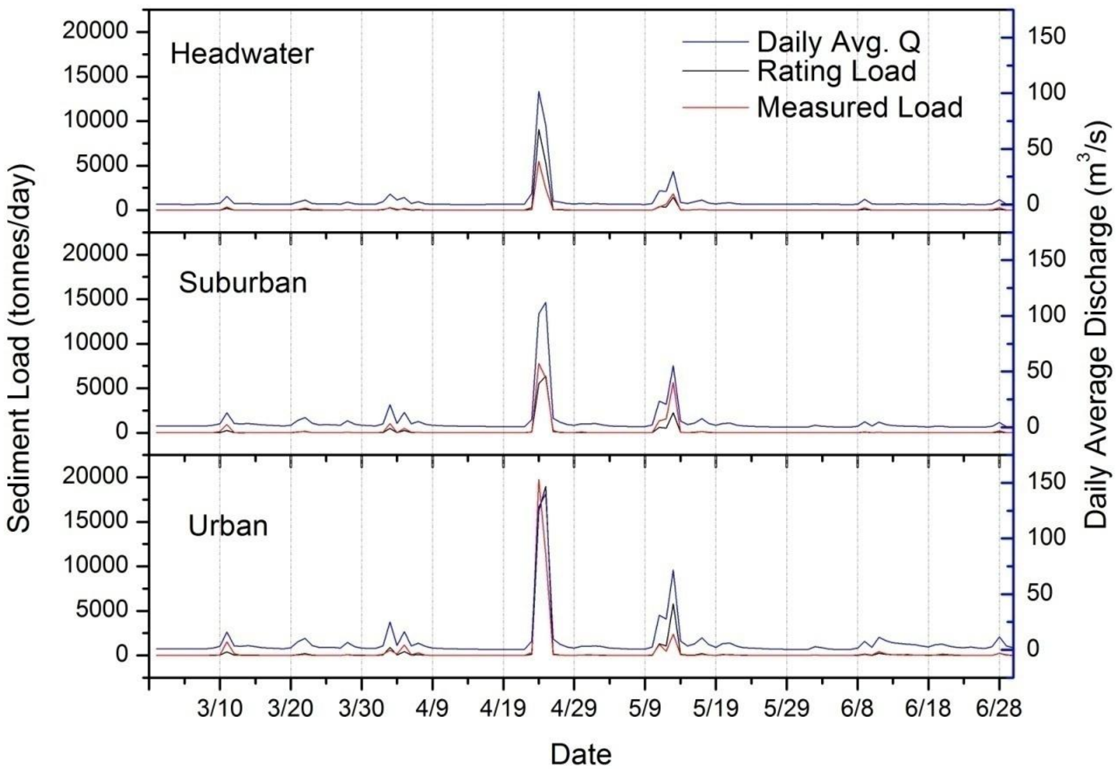

Figure 29. Time series of measured suspended sediment load and estimated suspended load for the headwater, suburban, and urban land use gauging stations in Hinkson Creek Watershed in Central Missouri.

CHAPTER V

CONCLUSIONS

The work presented in this study is some of the first of its kind focusing on suspended sediment trends in a contemporary Midwestern multi-use urbanizing watershed. The objectives of this study was to characterize and quantify suspended sediment concentrations, loads, and mean particles sizes, develop relationships between sediment yields and land-use type, and construct sediment rating curves useful to land managers and scientists.

Mean SSCs were 65.7, 69.5, and 86.0 µl/l at the headwater, suburban and urban gauging stations. Statistical analysis ($P < 0.05$) indicated there was not a significant difference in daily mean SSCs observed at the headwater, suburban, and urban gauging site. Mean SSCs were found to be lowest in the headwater (65.7 µl/l), which is dominated by agricultural land use and only slightly higher in the suburban sub-basin (69.5 µl/l). Mean SSC was the highest in the urban sub-basin (86.0 µl/l). These results were found to be similar in previous studies (Coulter et al., 2004; Packman, 2004; Wolman and Schick, 1967) showing higher SSCs in urban and mixed land use watersheds. Based on results of this study, mean suspended sediment concentration results from Hinkson Creek were lower than results from other studies done in nearby regions (Simon et al., 2004; Lee et al., 2009). The Salt River, which has been selected as a reference stream in the current Hinkson Creek TMDL (USEPA, 2011), had suspended sediment concentrations that were only slightly lower than concentrations from the Hinkson Creek. However, there are many notable differences (watershed size, soils, land-use type, and channel morphology) between the Salt River Basin and HCW.

Mean suspended sediment particle size was 151.1 µm, 111.0 µm, and 79.4 µm at the headwater, suburban, and urban gauging site respectively. According to ANOVA ($P < 0.05$) results are significantly different (P value < 0.001) between the sites. The decreasing mean particle size in the suburban and urban sub-basin may indicate as suspended sediment particles are transported through the watershed sediment particles are weathered and thus decrease in size. If larger particles in the headwater are aggregates made up of smaller particles, physical weathering of particles may cause aggregates to break down as they move from upper reaches of the watershed to lower reaches. Average particle size could also be decreasing in the lower catchments of the watershed because of the increase in urban areas. As urban area increase smaller particles may comprise larger percentages of the particle size distribution in urban runoff (Kim and Sansalone, 2008, Hubbart and Gebo, 2010).

The laser particle analyzers, such as those used in this study, provide estimates of volumetric suspended sediment concentrations. To compare volumetric SSCs to gravimetric SSCs a particle density of sediment must be assumed or estimated. Suspended sediment particle densities were estimated by using results from gravimetric (i.e. filtration) and volumetric analysis (i.e. laser diffraction) of SSCs. The sample particle density was estimated by dividing the gravimetric SSC (mg/l) by the volumetric concentrations (µl/l). The average particle density was 2,048, 1,945, and 1,711 kg/m^3. This indicates that suspended sediment particle densities were highest in the headwater and lowest at the urban gauging station. The decreasing density observed in the HCW may have also been influenced by the presence of organic matter in the more urban areas. The influence of organic matter on observed SSCs and mean particle size were not examined in this study, which provided impetus for further work.

The Kruskal-Wallis analysis of medians test ($P < 0.05$) indicated that daily median sediment loads were statistically (P value < 0.001) different between the headwater, suburban, and urban gauging stations. This is interesting to note because mean suspended sediment concentrations between the gauging stations were not statistically different using ANOVA. This indicates that land-use may have little effect on suspended sediment concentrations. However, differences in land-use alters the hydrology of HCW and promotes relatively high peak flow events in the suburban and urban portions of the watershed compared to the headwater. The statistical differences in mean suspended sediment loads are likely due to the larger discharge response exhibited in the suburban and urban portions of the watershed .

Cumulative suspended sediment load passing measured at the headwater, suburban, and urban gauging station was 13,183, 27,369, and 42,853.5 tonnes. Sub-basin sediment load contributions for the headwater, suburban, and urban sub-basins were 13,180, 14,1889, and 15,484 tonnes. These loads may not represent the total sediment entering the streams but provide a mode of comparing sediment loads between sub-basins. Sub-Basin Sediment Yields (SBSY) (tonnes/km^2) were calculated for headwater, suburban, and urban sub-basin. The suburban catchment (139.0 tonnes/km^2) had lower sediment yields compared to the headwater (170.3 tonnes/km^2) and urban catchment by

18%. The urban catchment (588.7 tonnes/km^2) had a significantly higher sediment yield compared to the other two catchments. The sediment yield from the urban catchment was 246% greater than the headwater catchment and 300% greater than the suburban catchment. These results indicate that suspended sediment yield may be strongly influenced by the percentage of urban land-use area in the catchment, and/or erosion of stream banks. Sediment yield was lowest in the suburban land-use catchment. This result was somewhat unexpected. Generally, as the watershed size increases the sediment yield also increases (Lee et al., 2009). The decreased sediment yield observed at the suburban gauging site may be due to the catchment's ability to buffer sediment from entering the stream or to suspended sediment being stored in the channel. The sediment loads calculated from the headwater (13,180 tonnes), suburban (14,189 tonnes) and urban (15,484 tonnes) watershed indicated that land-use types may influence suspended sediment trends but there are host of other variables that also influence sediment yields, including soil characteristics, antecedent soil moisture, topography, and precipitation patterns. Those confounding variables provide basis for future investigation.

Base flow and storm flow suspended sediment concentrations and loads were calculated in this study by using hydrograph separation techniques. Suspended Sediment Concentrations (SSC’s) during periods of storm flow events were over two times the concentration during base flow events. As expected, the vast majority of sediment was transported when overland flow was contributing to the total flow of the stream. Over 97% of the total sediment load, at all gauging stations, was transported during periods of storm flow events. If suspended sediment is determined to be a source of impairment in the HCW, sediment loads may be reduced by increasing base flow and decreasing total discharge. This possible scenario avoids a multitude of potential reciprocal impacts from such measures however, including high concentration flushing events and increased loss and/or alteration of aquatic habitat and biota.

Suspended sediment rating curves were developed using daily SSC data estimated by laser particle diffraction analyzers deployed in the field. Even though the r^2 values for the suspended sediment rating curves did not provide a strong correlation between suspended sediment concentration and discharge, the Nash-Sutcliffe efficiency parameters indicated there was good agreement between modeled sediment loads and measured load for the headwater (NS = 0.44), suburban (NS = 0.85), and urban (NS=0.83) sites. The urban sediment rating curve also estimated total suspended sediment load within 11% of the measured load. The urban sediment rating curve is possibly the most important rating curve because of its proximity to the watershed outlet and thus a close estimate of total watershed loading. Suspended sediment rating curves developed in this study provide a useful tool for estimating suspended sediment loads absent of suspended sediment sensing instrumentation or suspended sediment sampling programs.

Using laser diffraction particle analyzers to characterize sediment flux provided many interesting results in this work. As stated, results indicated that mean SSCs were not statistically different between gauging stations. However, median sediment loads were found to be significantly different. This implies that statistical differences of mean sediment loads may be more influenced by differences in discharge as opposed to differences in SSC. It was also shown that the majority of total suspended sediment load (i.e. greater than 97 %) is transported during high flow events. Reducing the frequency and magnitude of high flow events may significantly decrease total sediment load transported in HCW. Mean particle size decreased from the headwater to the urban gauging site. However, future work is needed to determine the cause of the decreasing mean particle sizes observed in HCW and how the presence organic material affects observed SSCs and mean sediment particle size. Analysis of sediment yields indicated that the dominant source of suspended sediment in the headwater may be from soil surface erosion and the dominant source suspended sediment in urban sub-basin is likely from channel erosion.

Study Results on Management Implications and Future Directions

These results have important management implications for suspended sediment flux in the HCW and the central U.S. Suspended sediment yields in the upper portion of HCW may be reduced by traditional erosion control methods, which decrease surface erosion and subsequent transport of sediment to the stream channel. In the urban portion of the watershed sediment loads may be reduced by reducing the magnitude and frequency of peak discharges or increasing or improving riparian corridors, increase evapotraspiration, and stabilize urban stream banks. Further work is needed to quantify the amount of suspended sediment origination from in-stream processes. Suspended sediment rating curves produced via laser diffraction instruments are the first of its kind and provided relatively accurate estimates of total load. These rating curves were developed from short data periods (i.e. 4 months) and further support the potential of laser diffraction instruments in freshwater suspended sediment studies. Future work is needed to determine if suspended sediment is a source of impairment in Hinkson Creek. If suspended sediment is determined to be a source of impairment, rating curves developed in this study will provide a useful tool for estimating total suspended sediment load and developing waste load allocations for TMDLs in HCW. Research is needed that quantifies suspended sediment trends of a stream that is not impacted by land-use change and urbanization (i.e. reference stream) in central Missouri. Suspended sediment data collected from unimpaired streams will provide a reference to results from this study and will help determine if suspended sediment is a source of water impairment in Hinkson Creek.

LITERATURE CITED

Agrawal, Y.C., and H.C. Pottsmith. 2000. Instruments for Particle Size and Settling Velocity Observations in Sediment Transport. Marine Geology 168: 89-114.

Allan, J.D., D.L. Donna, L. Erickson, and J. Fay. 1997. The Influence of Catchment Land Use on Stream Integrity Across Multiple Spatial Scales. Freshwater Biology 37: 149-161.

Allmendiger, N.E., J.E. Pizzuto, G.E. Moglen, and M. Lewicki. 2007. A Sediment Budget for an Urbanizing Watershed 1951-1996, Montgomery County, Maryland, U.S.A. Journal of the American Water Resources Association 43: 1483-1496.

American Society for Testing and Materials (ASTM). 2007. D 3977 – 97 Standard Methods for Determining Sediment Concentrations in Water Samples.

American Society for Testing and Materials (ASTM). 2008a. D4411-03. Standard Guide for Sampling Fluvial Sediment in Motion.

American Society for Testing and Materials (ASTM) 2008b.D3858-95. Standard Test Method for Open-Channel Flow Measurement of Water by Velocity-Area Method.

American Society for Testing and Materials (ASTM) 2008c. D5541-94. Standard Practice for Developing a Stage-Discharge Relation for Open Channel Flow.

Arnold, J.G., and P.M. Allen. 1999. Validation of Automated Methods for Estimating Baseflow and Groundwater Recharge From Stream Flow Records. Journal of American Water Resources 35(2):411-424.

Arnold, J.G., P.M Allen, R. Muttiah, R. Srinivasan, and G. Bernhard. 1995. Automated Baseflow Separation and Recession Analysis Techniques. Groundwater 33(6):1010-1018.

Arnold, C.L., Jr., and C.J. Gibbons.1996. Impervious Surface Coverage. Journal of American Planning Association 62:243-259.

Asselman, N.E.M. 1999. Suspended Sediment Dynamics in a Large Drainage Basin: the River Rhine. Hydrological Processes 13(10):1437-1450.

Asselman, N.E.M. 2000. Fitting and Interpretation of Sediment Rating Curves. Journal of Hydrology 234:228-248.

Asselman, N.E.M., H. Middelkoop, and P.M. van Dijk. 2003. The Impact of Changes in Climate and Land Use on Soil Erosion, Transport and Deposition of Suspended Sediment in the River Rhine. Hydrological Processes 17:3225-3244.

Bales, J.D., J.C. Weaver, and J.B Robison. 1999. Relation of Land Use to Streamflow and Water Quality at Selected Sites in the City of Charlotte and Mecklenburg County, North Carolina, 1993-98. United States Geological Survey Water-Resources Investigations Report 99-4180: 95.

Birkinshaw, S.J., J.C. Bathurst, A. Iroume, and H. Palacios. 2010. The Effect of Forest Cover on Peak Flow and Sediment Discharge- an Integrated and Modeling Study in Central-Southern Chile. Hydrological Processes: 0-00.

Black, P.E. 1997. Watershed Functions. Journal of the American Water Resources Association 33(1):1-11.

Booth, D.B. 1990. Stream-Channel Incision Following Drainage-Basin Urbanization. American Water Resources Bulletin 26:407-417.

Booth, D.B., and P.C. Henshaw. 2001. Rates of Channel Erosion in Small Urban Streams. In The Influence of Land Use on the Hydrologic-Geomorphic Responses of Watersheds (M.S. Wigmosta, ed.) American Geophysical Union Monograph Series 2:17-38.

Born, M., and E. Wolf 1975. Principles of Optics, Peragon Press, New York.

Brooks, K.N., P.F. Ffolliott, H.M. Gregersen, and L.F. DeBano. 2003. Hydrology and the Management of Watershed, third edition. Blackwell Publishing Professional, Ames, Iowa.

Burges, S.J., M.S. Wigmosta, and J.M. Meena. 1998. Hydrological Effects of Land-Use Change in a Zero-Order Catchment. Journal of Hydrologic Engineering 3:86-97.

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 poser with map, descriptive test, summary tables, and photographs): Reston Virginia, United States Geological Survey (map scale 1:1,800,000).

Chapman, T.G. 1999. A Comparison of Algorithms for Stream Flow Recession and Basflow Separation. Hydrological Process 13(5):750-714.

Chen, C.W., L. Weintraub, L. Olmsted, and R.A. Goldstein. 2004. Decisions Framework for Sediment Control in Muddy Creek Watershed. Journal of the American Water Resources Association 40(6):1553-1562.

Chow, V.T., D.R. Maidment, and L.W. Mays. 1988. Applied Hydrology. McGraw-Hill, New York, New York.

Clark, E. H., J. A. Haverkamp, and W. Chapman, 1985. Eroding Soils: The Off-Farm Impacts. The Conservation Foundation, Washington D.C., 252.

Clifton, J., P. MacDonald, A. Plater, and F. Oldfield. 1999. An Investigation Into the Efficiency of Particle Size Separation Using Stoke's Law. Earth Surface Processes and Landforms 24:725-730.

Collins, A.L., and D.E. Walling. 2006. Fine-Grained Bed Sediment Storage Within the Main Channel Systems of the Frome and Piddle Catchments, Dorset, UK. Hydrological Processes 21(11):1148-1459.

Collins, A.L., D.E Walling, and G.L.J. Leeks. 1997. Fingerprinting the Origin of Fluvial Suspended Sediment in Larger River Basins: Combing Assessment of Spatial Provenance and Source Type. Geografiska Annaler 79:239-254.

Corbett, C.W., M. Wahl, D.E. Porter, D. Edwards, and C. Moise. 1997. Nonpoint Source of Runoff Modeling: A Comparison of a Forested Watershed and an Urban Watershed on the South Carolina Coast. Journal of Experimental Marine Biology and Ecology 213:133-149.

Coulter, C.B., R.K. Kolka, J.A. Thompson. 2007. Water Quality In Agriculture, Urban, and Mixed Land Use Watersheds. Journal of The American Water Resources Association 40(6):1593-1601.

Davis, B.E. 2005. A Guide to Proper Selection of Federally Approved Sediment and Water-Quality Samplers. Reston Virginia, United States Geological Survey, Accessed December 10, 2010. Available at: http://pubs.usgs.gov/of/2005/1087

De Vries, A., and H.C. Clavers. 1994. Riverine Fluxes of Pollutants: Monitoring Strategy First, Calculation Methods Second. European Journal of Water Pollution Control 4:12-17.

Dedkov, A.P., and V.P. Moszherin. 1992. Erosion and Sediment yield in Mountain Areas of the World. In: Erosion, Debris Flows and Environmental Management in Mountain Regions. (D.E. Walling, T.R. Davies, and B. Hasholt, eds.). International Association of Hydrological Sciences 209:29-36.

Devereaux, O.H., K.L. Prestegaard, B.A. Needelman, and A.C. Gellis. 2010. Suspended-Sediment Sources in an Urban Watershed., Northeast Branch Anacostia River, Maryland. Hydrological Processes 24:1391-1403.

Dingman, S.L. 2008. Physical Hydrology, 2nd Edition. Waverly Press, Unites States.

Dodds, W.K., and M.R. Whiles. 2004. Quality and Quantity of Suspended Particles in Rivers: Continent-Scale Patters in the United States. Environmental Management 33:355-367.

Dottori, F., M.L.V. Martina, and E. Todini. A Dynamic Rating Curve Approach to Indirect Discharge Measurement. Hydrology Earth System Sciences 13:847-863.

Eckhardt, K. 2005. How to Construct Recursive Digital Filters for Baseflow Separation. Hydrological Processes 19 (2):507-515.

Edwards, T.K., and C.D Glysson. 1970. Field Methods for Measurement of Fluvial Sediment. Techniques of Water-Resources Investigations of the United States. Geological Survey. Book 3, Chapter C2.

Edwards, T.E., and G.D. Glysson. 1999. Field Methods for Collection of Fluvial Sediment. Techniques of Water-Resources Investigations 3:89. Reston Virginia, United States Geological Survey.

Eshel, G., G.J. Levy, U. Mingelgrin, and M.J. Singer. 2004. Critical Evaluation of the Use of Laser Diffraction for Particle-Size Distribution Analysis. Soil Science Society of America Journal 68:736-743.

Ferguson, R.I. 1986. River Loads Underestimated by Rating Curves. Water Resources Research 22:74-76.

Foster, I.D.L., and S.M. Charlesworth. 1996. Heavy Metals in the Hydrological Cycle: Trends and Explanation. Hydrologic Processes 10:227–261.

Federal Interagency Sedimentation Project (FISP). Operators Manual for the US DH-48 Depth-Integrating Suspended-Sediment Sampler, Accessed January 10, 2010. Available at: http://fisp.wes.army.mil

Fraley, L.M., J.M. Miller, and C. Welty. 2009. Contribution of in –Channel Processes to Sediment Yield of an Urbanizing Watershed. Journal of the American Water Resource Association 45:749-766.

Freeze, R.A., and P.A. Witherspoon. 1967. Theoretical Analysis of Regional Groundwater Flow, II: Effect of Water Table Configuration sand Subsurface Permeability Variations. Water Resources Research 3(2):623-634.

Frankenberger, J.R., E.S. Brooks, M.T. Walter, M.F. Walter, and T.S. Steenhuis. 1999. A GIS-Based Variable Source Area Hydrology Model. Hydrological Processes, 13:805-822.

Garbretch, J.D., And P.J. Starks. 2009. Watershed Sediment Yield Reduction Through Soil Conservation in a West-Central Oklahoma Watershed. Journal of Ecohydrology 2(3):313-320.

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.

Gavin, Yu. S. 1982. About Daily Discharge Calculation with Computer. Proceedings of the State Hydrological Institute 176:49-64.

Glysson, G.D., J.R. Gray, L.M. Conge. 2000. Adjustment of Total Suspended Solids Data for Use in Sediment Studies. Proceedings, ASCE's 2000 Joint Conference of Water Resources Engineering and Water Resources Planning and Management, July 30 – August 2, 200, Minneapolis, MN.

Golosov, V.N., N.N. Ivanova, L.F. Litvin, and A.Y. Sidorchuk. 1992. Sediment Budgets of River Catchments and River Channel Aggradation on the Russian Plain. Geomorphology 4:62-71.

Grigorjev, V.I., V.N. Desnyansky, Zaimsky, G.A., and E.I. Kaganov. 1977. Algorithms and Software for Computations of Daily Discharge Values. Proceedings of VNIIGMI 32:52-64.

Gray, J.R., and G.D. Glysson. 2002. Introduction to the Proceeding of the Federal Interagency Workshop on Turbidity and Other Sediment Surrogates. Proceeding of Fifth Interagency Workshop on Turbidity and Other sediment Surrogates (30-April-2 May 2002, Reno, USA). United States Geological Survey, USA.

Gray, J.R., G.D. Glysson, L.M. Turcious, and G.E. Schwarz. 2000. Comparability of Suspended-Sediment Concentration and Total suspended Solids Data. Water-Resources Investigations 00-4191. Reston Virginia, United States Geological Survey.

Gray, J.R., and Gartner, G.W. 2009. Technological Advances in Suspended-Sediment Surrogate Monitoring. Water Resources 45:1-20.

Hammer, T.R. 1972. Stream Channel Enlargement Due to Urbanization. Water Resources Research 8:1530-1540.

Hatt, B.E., T.D. Fletcher, C.J. Walsh, and S.L. Taylor. 2004. The Influence of Urban Density and Drainage Infrastructure on the Concentrations and Loads of Pollutants in Small Streams. Environmental Management 34:112-124.

Herschy, R.W. 1985. Accuracy. In. Streamflow Measurements. Elsevier, Amsterdam.

Herschy, R.W. 1999. Hydrometry Principles and Practices second edition. (R.W. Herschy, ed.). Wiley Publishing, England.

Holmes, T.P. 1988. The Offsite Impact of Soil Erosion on the Water Treatment Industry. Land Economics 64:356-366.

Hooke, J. 2003. Coarse Sediment Connectivity in River Channel Systems: A Conceptual Framework and Methodology. Geomorphology 56:79-94.

Horowitz, A.J. 1995. The Use of Suspended Sediment and Associated Trace Elements in Water Quality Studies. International Association of Hydrological Science Special Publication 4. International Association of Hydrological Science Press, Wallingford.

Horowitz, A.J. 2003. An Evaluation of Sediment Rating Curves for Estimating Suspended Sediment Concentrations for Subsequent Flux Calculations. Hydrological Processes 17:3387-3409.

Horowitz, A.J., K.A. Elrick, and J.J. Smith. 2001. Estimating Suspended Sediment and Trace Element Fluxes in Large River Basins: Methodological Considerations as Applied to the NASQAN Programme. Hydrological Processes 15:1107-1132.

Horowitz, A.J. 2009 Monitoring Suspended Sediment and Associated Chemical Constituents' in Urban Environments: Lessons From the City of Atlanta, Georgia, USA Water Quality Monitoring Program. Journal of Soils Sediments 9:342-363.

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.

Hubbart, J.A., and N.A. Gebo. 2010. Quantifying the Effects of Land-Use and Erosion by Particle Size Class Analysis in the Central U.S. Erosion Control Journal, 17(7):1-4.

Hubbart, J.A., and G.W. Freeman. 2010. Sediment Laser Diffraction: A New Approach to an Old Problem in the Central U.S. Stormwater Journal, 11(7):36-44.

Hubbart, J.A., J. Holmes, and G. Bowman. 2010. Integrating Science Based Decision Making and TMDL Allocations in Urbanizing Watersheds. The Watershed Science Bulletin, 01:19-24.

Intergovernmental Panel on Climate Change (IPCC). 2007. Fourth Assessment report, Climate Change 2007: The Physical Science Basis. United Kingdom: Cambridge Press.

Jennings, D., and T.S. Jarnagin. 2002. Changes in Anthropogenic Impervious Surfaces, Precipitation, and Daily Stream Flow Discharge: A Historical Perspective in a Mid-Atlantic Subwatershed. Landscape Ecology 14(5):471-489.

Jonasz, M. 1991. Size, Shape Composition and Structure of Microparticles From Light Scattering. (J.P.M Syvitiski, ed.) Principles, methods and applications of particle size analysis. Cambridge University Press. Cambridge.

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.

Kennedy, E.J. 1984. Discharge Ratings at Gauging Stations. Techniques of Water-Resources Investigations of the United States Geological Survey, Book 3, chap. A10, 59 pp., United States Geological Survey., Reston, VA., Accessed February 17, 2011. Available at: http://pubs.usgs.gov/twri/twri3-a10/pdf/TWRI_3-A10.pdf

Keyes, A.M., and D. Radcliffe. 2002. A Protocol for Establishing Sediment TMDLs. The Georgia Conservancy: Atlanta, GA; 31 pp.

Kim. J.Y., and J. Sansalone. 2008. Particulate Matter Particle Size Distribution Transported in Urban Runoff. World Environmental and Water Resources Congress: Ahupua's:1-10.

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.

Krashnikikov, S.A. 1987. About Optimal Approximation for Stage-Discharge Relationship. Proceedings of the State Hydrological Institute 328:58-69.

Kruskal, W.H., and A. Wallis. Use of Ranks in One-Criterion Variance Analysis. Journal of the American Statistical Association 47 (260):583-621.

Lambie, J.C. 1978. Hydrometry: Principles and Practices first edition. (R.W. Herschy, ed.). Wiley Publishing, England.

Lee, C.J., P.P. Rasmussen, A.C. Ziegler, and C.C. Fuller. 2009. Transport and Sources of Suspended Sediment in the Mill Creek Watershed, Johnson County, Northeast Kansas, 2006-07. United State Geological Survey. Scientific Investigations Report 2009-5001.

Lee, J.H., and K.W. bang. 2000. Characterization of Urban Stormwater Runoff. Water Research 34:1773-1780.

Leopold, L.B. 1968. Hydrology for Urban Planning- a Guide Book on the Hydrologic Effects of Urban Land Use. United States Geological Survey Circular 554.

Lesnikova, G.V. 1973. To the Issue about Analytical Expression of Stage-Discharge Relationships and Their Use in Discharge Calculations By Computer. Proceeding of NIIAK 87:32-37.

Lim, K.J., B.A. Engel, Z. Tang, J. Choi, K.J. Kim, S. Muthukrishnan, and D. Tripathy. 2005. Automated Web GIS Based Hydrograph Analysis Tool, WHAT. Journal of the American Water Resources Association 41 (6):1407-1416.

Lyne, K.J., and M. Hollick. 1979. Stochastic Time Variable Rainfall-Runoff Modeling. Hydro and Water Resource Symposium. Institute of Engineers Australia, Perth, Australia:82-92.

Melis, T.S., Topping, D.J., Rubin, and D.M. 2003. Testing Laser-Based Sensors for Continuous In Situ Monitoring of Suspended Sediment in the Colorado River, Arizona. In Erosion and Sediment Transport Measurements in Rivers, Technological and Methodological Advances. International Association of Hydrologic Science 203:21-27.

Meybeck, R.J., L. Laroche, H.H. Durr, and J.P.M Syvitiski. 2003. Global Variability of Total Suspended Solids and Their Fluxes in Rivers. Global Planetary Change 39:65-93.

Missouri Department of Natural Resources (MDNR). 2011. Total Maximum Daily Load for Hinkson Creek Boone County, Missouri. Prepared by the Missouri Department of Natural Resources Water Protection Program.

Missouri Resource Assessment Program (MORAP). 2005. Landuse/Land Cover Data.

Mohta, J.A., P.J. Wallbring, P.B Hairsine, and R.B. Grayson. 2003. Determining Sources of Suspending Sediment in a Frosted Catchment in South Eastern Australia. Water Resources Research 39:1056.

Mukundan, R., D.E. Radcliffe, and J.C. Ritchie. 2010. Channel Stability and Sediment Source Assessment in Streams Draining a Piedmont Watershed in Georgia, USA.

Morgan, R.P.C. 1995. Soil Erosion and Conservation, 2nd edition. Longman, London.

Meyer, S.C. 2005. Analysis of Base Flow Trends in Urban Streams, Northeastern Illinois, USA. Hydrogeology Journal 13: 871-885.

Neller, R.J. 1988. A Comparison of Channel Erosion in Small Urban and Rural Catchments, Armidale, New South Wales. Earth Surface Processes and Landforms 13(1):1-7.

Nelson, E.J., and D.B. Booth. 2002. Sediment Sources in an Urbanizing, Mixed Land-Use Watershed. Journal of Hydrology 264:51-68.

Nigh, T. A., and W. A. Schroeder. 2002. Atlas of Missouri Ecological Sections. Missouri Department of Conservation.

Novotny, V., and H. Olem. 1994. Water Quality. Prevention, Identification, and Management of Diffuse Pollution. New York: Van Nostrand Reinhold.

Oschwald, W.R. 1972. Sediment-Water Interactions. Journal of Environmental Quality 1:360-365.

Oskerkamp, W.R., P. Heilman, and L.J. Lane. 1998. Economic Considerations of a Continental Sediment Monitoring Program. International Journal of Sediment Research 13:12-24

Overleir, A.P., and T. Teitan. 2005. Objective Segmentation in Compound Rating Curves. Journal of Hydrology 311:181-201.

Owens, P.N. 2005. Soil Erosion and Sediment Fluxes in River Basins: The Influence of Anthropogenic Activities and Climate Change. Soil and Remediation. (Lens, P., T. Grotenhuis, G. Malina, H. Tabak, eds.). IWA Publishing, London.

Owens, P.N., R.J. Batalla, A.J. Collins, B. Gomex, D.M. Hicks, A.J. Horowitz, G.M. Kondolf, M. Marden, M.J. Page, D.H. Peacock, E.L. Petticrew, W. Salomons, and N.A. Trustrum. 2005. Fine Grained Sediment in River Systems: Environmental Significance and Management Issues. River Research and Applications 21:693-71

Owens, P.N., D.E Walling, and G.J.L Leeks. 2000. Tracing Fluvial Suspended Sediment Sources in the Catchment of the River Tweed, Scotland, Using Composite Fingerprints and Numerical Mixing Model. Tracers in Geomorphology (I.D.L Foster, ed.). Wiley, Chichester.

Packman, J.J. 2004. Land-Use Effects on Suspended Sediment in Puget Lowland Salmonid Streams. Master's Thesis, Graduate School, University of Washington.

Pedocchi, F., and M.G. Garcia. 2006. Evaluation of the LISST-ST Instrument for Suspended Particle Size Distribution and Settling Velocity Measurements. Continental Shelf Research 26:943-958.

Perkins, B. 1995. Temporal Variability of a Midwestern Stream During Spring. Master’s Thesis, Graduate School, University of Missouri-Columbia.

Pflieger, W.L. 1989. Aquatic Community Classification System for Missouri. Missouri Department of Conservation. Jefferson City, Missouri. Aquatic Series 19:70.

Phillips, S.B., and F.N Scatena. 2010. Flashiness Indices for Urban and Rural Streams in Puerto Rico. American Water Resource Association. American Water Resource Association Summer Specialty Conference, Sam Juan, Puerto Rico, August 30-September 1, 2010.

Phillips, J.M., B.W. Webb, D.E. Walling, and G.J.L Leeks. 1999. Estimating the Suspended Sediment Load of Rivers in the LOIS Study Area Using Infrequent SF Samples. Hydrological Processes 13:1035-1050.

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.

Pickett, S.T.A., M.L. Cadenasso, J.M. Grove, C.H. Nilon, R.V. Pouyat, W.C. Zipperer, and R. Costanza. 2001. Urban Ecological Systems: Linking Terrestrial, Ecological, Physical, and Socioeconomic Components of Metropolitan Areas. Annual Review of Ecology and Systematics 32:127-157.

Porterfield, G. 1972. Computation of Fluvial Sediment Discharge. Techniques of Water-Resource Investigations, Book 3, chap. C3, 55 pp., United States Geological Survey., Reston, Va., accessed December 10, 2010. Available at: http://water.usgs.gov/pubs/twri/twri3-c3/

Reichenberger, S., M. Bach, A. Skitchak, and H.G. Frede. 2007. Mitigation Strategies to Reduce Pesticide Inputs in Ground- and Surface Water and their Effectiveness: a Review. Science of the Total Environment 384:1-35.

Rose, P., and N.E. Peters. 2001. Effects of Urbanization in the Atlanta Area (Georgia, USA: A Comparative Hydrological Approach. Hydrological Processes 15:141-1457.

Rushton, K.R., and A.A.R. Al-Othman. 1994. Control of Rising Ground-Water Levels in Riyadh, Saudi Arabia. (W.B. Wilkinson, ed.) Groundwater Problems in Urban Areas. Thomas Telford, London.

Russell, M.A., D.E. Walling, B.W. Webb, and R. Bearne. 1998. The Composition of Nutrient Fluxes From Contrasting UK River Basins. Hydrologic Processes 12:1461–1482.

Schmidt, A.R., and B.C. Yen. 2002. Stage-Discharge Rating Revisited. (Wahl, T.L., Pugh, C.A., Oberg, K.A., Vermeyen, T.B., Eds.). Hydraulic Measurements and Experimental Methods. Proceedings of the EWRI and IAHR Joint Conference, Estes Park, CO, July 28- August 1, 2002

Shiklomanov, A.I., T.I. Yakovleva, R.B. Lammers, I.P. Karasev, C.J. Vorosmarty, and E. Linders. 2005. Cold Region River Discharge Uncertainty-Estimates From Large Russian River. Journal of Hydrology 326:231-256.

Simon, A., A. Curini, S.E. Darby, E.J. Langedon. 2000. Bank and Near Bank Processes in an Incised Channel. Geomorphology 35:193-217.

Simon, A., W. Dickerson, and A. Hiens. 2004. Suspended-Sediment Transport Rates at the 1.5- year Recurrence Interval for Ecoregions of the United States: Transport Conditions at the Bankfull and Effective Discharge. Geomorphology: 58:243-262.

Singh, K.P., and A. Durgunoglu. 1989. Developing Accurate and Reliable Stream Sediment Yields. Sediment and the Environment. International Association of Hydrologic Science 184:193-199.

NRCS. 2003. Soil Survey for Boone County, Missouri. Natural Resource Conservation Service. United States Department of Agriculture, Soil Conservation Service.

Sophocleous, M. 2002. interactions Between Groundwater and Surface Water: the State of the Science. Hydrogeology Journal 10:52-67.

Swithenbank, J., J.M. Beer, D.S. Taylor, D. Abbot, and G.C. McCreath. 1976. A Laser Diagnostic Technique for Measurement of Droplet and Particle Size Distribution. AIAA, New York.

Thom, R.H., and J.H. Wilson. 1980. The Natural Division of Missouri. Transactions, Missouri Academy of Sciences 14:23.

Tim, U.S., and R. Jolly. 1994. Evaluating Agricultural Nonpoint Source Pollution Using Integrated Geographic Information Systems and Hydrologic/Water Quality Model. Journal of Environmental Quality 23:25-35.

Tramblay, Y., S, A. St-Hilaire, and T.B.M.J. Ouarda. 2008. Frequency Analysis of Maximum Annual Suspended Sediment Concentrations in North America. Journal of Hydrological Science 53(1):236-252.

Tramblay, Y., T.B.M.J. Ouarda, A. St-Hilaire, and J. Poulin. 2010. Journal of Hydrology 380:305-317.

Trimble, S.W. 1997. Contribution of Stream Channel Erosion to Sediment Yield From and Urbanizing Watershed. Science 278:1442-1444.

Uri, N, D. 1999. The Environmental Implication of Soil Erosion in the United States. Environmental monitoring and Assessments 66:293-312

Urick, R.J. 1975. Principles of Underwater Sound 2nd edition. McGraw Hill, New York.

United States Census Bureau (USCB). 2011. U.S. Census Bureau Delivers Missouri's 2010 Census Population Totals, including First Look at Race and Hispanic Origin Data for Legislative Redistricting, Accessed March 22, 2011. Available on line at: http://2010.census.gov/news/releases/operations/cb11-cn49.html

USEPA (U.S. Environmental Protection Agency). 1981. Process Design Manual: Land Treatment of Municipal Wastewater. United States Environmental Protection Agency 6125/1-81-018.

USEPA (U.S. Environmental Protection Agency). 2003. Developing Water Quality Criteria for Suspended and Bedded Sediments (SABS). U.S. EPA Science Advisory Board Consultation. United States Environmental Protection Agency.

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.

USEPA (U.S. Environmental Protection Agency). 2010. Stay of Correction of the Numeric Limit for Construction and Development ELGs. EPA.821010-003. Office of Water, United States Environmental Protection Agency.

USEPA (U.S. Environmental Protection Agency). 2011. Total Maximum Daily Load (TMDL) for Hinkson Creek. United States Environmental Protection Agency Region 7 Total Maximum Daily Load.

Waananen, A.A. 1969. Urban Effects on Water Yield. Water Resource Symposium 2. University of Texas Press, Austin, Texas.

Walling, D.E. 1977. Assessing the Accuracy of Suspended Sediment Rating Curves for a Small Basin. Water Resources Research 13:531-538.

Walling, D.E. 1983. The Sediment Delivery Problem. Journal of Hydrology 69:209-237.

Walling, D.E. 1999. Linking Land Use, Erosion and Sediment Yield in River Basins. Hydrobiologia 410:223-240.

Walling, D.E., and B.W. Webb. 1982. Sediment Availability and the Prediction of Storm-Period Sediment Yields. International Association of Hydrological Science 137:327-337.

Walling, D.E., and B.W. Webb. 1988. The Reliability of Rating Curve Estimates of Suspended Sediment Yield: Some Further Comments. Sediment Budgets. International Association of Hydrological Sciences 174:337-350.

Walling, D.E., and B.W. Webb. 1996. Erosion and Sediment Yield: Global and Regional Perspectives. International Association of Hydrological Science 236:1-81.

Walling, D.E, N.O. Owens, and J.L Leeks. 1999. Fingerprinting Suspended Sediment Sources in the Catchment of the River Ouse, Yorkshire, UK. Hydrologic Processes 13:995-975.

Walling, D.E., and D. Fang. 2003. Recent Trends in Suspended Sediment Loads of the World's Rivers. Global Planetary Change 39:169-190.

Walling, D.E., M.A. Russell, R.A. Hodgkinson, and Y. Zhang. 2002. Establishing Sediment Budgets for Two Small Lowland Agricultural Catchments in the UK. Catena 47:323-353.

Walsh, C.J., A.H. Roy, J.W. Feminella, P.D. Cottingham, P.M. Groffman, and R.P. Morgan, II. 2008. The Urban Stream Syndrome: Current Knowledge and the Search for a Cure. Journal of North American Benthological Society 24(3):706-723.

Ward, A.D., and S.W. Trimble. 2004. Environmental Hydrology. Lewis Publishers, United States.

Wei, L., B. Zhang, and M. Wang. 2007. Effects of Antecedent Soil Moisture on Runoff and Soil Erosion in Alley Cropping Systems. Agriculture Water Management 94:54-62.

White, M.D., and K.A. Greer. 2006. The Effects of Watershed Urbanization on the Stream Hydrology and Riparian Vegetation of Los Penasquitos Creek California. Landscape and Urban Planning 74:125-138.

Willet, C.D. 2010. Streambank Erosion and Risk Assessment of Contaminated Transport in Missouri Watersheds. Master's Thesis, Graduate School, University of Missouri-Columbia.

Williams, G.P. 1989. Sediment Concentration Versus Water Discharge During Single Hydrologic Events in Rivers. Journal of Hydrology 111:89-106.

Williams, N.D., D.E. Walling, and G.J.L. Leeks. 2007. High Temporal Resolution In Situ Measurement of Effective Particle Size Characteristics of Fluvial Suspended Sediment. Water Research 41:1081-1093.

Wolman, M.G. 1967. A Cycle of Sedimentation and Erosion in Urban River Channels. Geografiska Annaler 49(A):385-395.

Wolman, M.G., and A.P Schick. 1967. Effects of Construction on Fluvial Sediment, Urban and Suburban Areas of Maryland. Water Resources Research 3:451-464.

Wood, P.J., and P.D. Aarmitage. 1997. Biological Effects of Fine Sediment in the Lotic Environment. Environmental Management 21:203-217.

Young, R.A. 1980. Characteristics of Eroded Sediment. Transactions of the American Society of Agriculture 23(5):1139-1142.

Yu, B. 2000. A Systematic Over-Estimation of Flows. Journal of Hydrology 233:258-262.