QUANTIFYING STREAM BANK EROSION AND DEPOSITION RATES IN A CENTRAL U.S. URBAN WATERSHED

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by

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The undersigned, appointed by the dean of the Graduate School, have examined the thesis/dissertation entitled

QUANTIFYING STREAM BANK EROSION AND DEPOSITION

RATES IN A CENTRAL U.S. URBAN WATERSHED

Presented by Dandan Huang, a candidate for the degree of Master of Science and hereby certify that, in their opinion, it is worthy of acceptance.

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

QUANTIFYING STREAM BANK EROSION AND DEPOSITION RATES IN A CENTRAL U.S. URBAN WATERSHED

Dandan Huang

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ABSTRACT

Stream bank erosion can contribute as much as 80% of suspended sediment to streams, particularly in urbanizing watersheds. Stream bank erosion study sites were located in a lower reach of the Hinkson Creek Watershed located in Boone County, Missouri, USA. Erosion and deposition rates were quantified using the erosion pin method comparing a remnant Bottomland Hardwood Forest (BHF) stream bank to an Agricultural (Ag) stream bank (922 m apart). Ten erosion pin plots (n = 342 pins) were installed that spanned the range of bank geometry and vegetation cover variability. Results showed that during a drier (762 mm) than average (10yr avg=1077 mm) rainfall year, 15.7 and 177.8 tonnes of soil erosion occurred on the right side (facing downstream) stream banks of the BHF and Ag sites respectively (Water Year 2011). Average erosion depth measured at the BHF and Ag sites was 18 and 112 mm/yr respectively. The greatest average depth of erosion occurred during the winter season (44.7 mm), followed by summer (13.1 mm) and spring (6.3 mm) and fall with the lowest average erosion depth (1.1 mm). Results hold important implications for land-use managers wishing to reduce bank erosion and improve land-use practices, water quality and aquatic natural resource sustainability in dynamic urbanizing watersheds.

CHAPTER I

INTRODUCTION

Suspended sediment is one of the most persistent non-point source pollutants impairing water quality (Nelson and Booth, 2002). Non-point source pollutants (e.g. suspended sediment, oil, pesticides) are generally transported by precipitation and snowmelt induced surface runoff flowing over and intermittently through diffuse land surfaces and finally to water bodies (USEPA and USDA, 1998). Suspended sediment transport in streams is a natural process, however, insufficient or excessive suspended sediment in streams can cause channel hydro-geomorphic change and thus alter aquatic ecosystem status. Lane (1955) proposed an equation to illustrate relationships of four variables governing stream dynamic equilibrium.

$$Q_s \cdot D_{50} \propto Q_w \cdot S \qquad (1.1)$$

Where Q_s is sediment discharge, D_{50} is bed-sediment median size, Q_w is stream flow discharge, and S is stream slope. According to Lane's equation, insufficient suspended sediment in a stream could result in stream dynamic disequilibrium. Stream dynamic equilibrium is theoretically reached after sufficient time passes, resulting in sediment transport proportional to stream sediment transport capacity (Zaimes and Emanuel, 2006). Insufficient sediment transport can result in scouring of the stream bank and bed, which in turn can alter stream hydrogeomorphology and reduce aquatic biological integrity (Biedenharn et al., 1997). Excessive suspended sediment can reduce water clarity (Peng et al., 2002), endanger aquatic biota by blocking sunlight from submerged aquatic vegetation, and reduce habitat for aquatic organisms via siltation (Davies-Colley and Smith, 2001; Russell et al., 2001). Sediment can reduce water storage space in reservoirs through siltation, and impede navigation and water conveyance systems (Williams, 1989). Moreover, suspended sediment is a key transport vector of nutrients, heavy metals and pathogens (Bibby and Webster-Brown, 2005; Characklis and Wiesner, 1997; Gibbs, 1977; Neal et al., 1997; Tessier, 1992; Webster et al., 2000).

The 303 (d) section of the Clean Water Act (CWA) enforced by the United States Environmental Protection Agency (US EPA) requires each state, territory, and authorized tribe to develop a list of impaired water bodies, and develop total maximum daily loads (TMDLs) plans for impaired water bodies. In an attempt to mitigate the detrimental effects of suspended sediment inputs to aquatic ecosystems, many efforts have been made to investigate sources, transport and deposition of suspended sediment (Collins and Walling, 2004; Zaimes et al., 2006). Quantifying diffuse sources of channel suspended sediment load will help land managers focus on primary sources of in-stream suspended sediment, and thus implement the most effective measures to reduce sediment load in streams. In addition, understanding precipitation-runoff-stream bank erosion relationships is of vital importance to implementation of best management control strategies (i.e. TMDLs and regulations of erosion and sediment control) to effectively reduce non-point source pollution in streams (Litschert and MacDonald, 2009).

Stream bank erosion was previously identified to be a primary source of channel sediment (Mukundan et al., 2011; Simon and Rinaldi, 2006). However, there is much work that remains to be done to quantify the magnitude and rates of stream bank erosion and deposition. These quantifies are important for estimating the contribution of stream bank erosion to in-stream sediment load (Laubel et al., 1999). Hunan land use alterations can result in additional impacts to bank erosion processes and stream loading. There is therefore a great need to investigate soil and bank characteristics, climate (e.g. precipitation, temperature), and land use change (e.g. urban) on stream bank erosion processes. The following work will quantify stream bank erosion contribution to channel suspended sediment load in a central U.S. urban watershed. Results hold important implications for land-use managers wishing to improve land-use practices, water quality and aquatic natural resource sustainability in dynamic urbanizing watersheds of the Midwest and elsewhere.

BACKGROUND

Sources of In-Stream Suspended Sediment

Two primary sources of in-stream suspended sediment include hillslope sources (particularly in the form of surface runoff) and in-channel sources (i.e. bank and bed erosion) (Collins and Walling, 2004; Juracek and Ziegler, 2009; Lawler et al., 1999; Prosser et al., 2000; Simon et al., 2000) (Figure 1). The dominate sources of suspended sediment vary due to many reasons, including but not limited to geographical and climatic differences, detection (e.g. research) method differences, and varying timescales of study (Nelson and Booth, 2002). Wasson et al. (2010) used geochemical tracers to study sedimentation and alluvial bench deposits in Northern Australia and showed that 89-97 % of the suspended sediment originated from erosion by gullying and channel change, and channel widening was largely attributed to hydro-geomorphologic change with no discernible impact from land use. They argued that topography, native vegetation buffers, and floodplains create a barrier preventing topsoil delivery to water bodies. Hughes et al. (2009) used fallout radionuclides ^{137}Cs and $^{210}Pb_{ex}$, concluding that gully headcuts and sidewall erosion in the dry tropical climate of Australia contributed most sediment to total stream sediment loading. They concluded that sheetwash and rill erosion from uncultivated land (grazed pasture/woodland) was likely to contribute minor sediment to the river network. Trimble (1997) investigated 196 permanently marked cross sections at intervals along San Diego Creek, Southern California from 1983 to 1993 and found that channel incision was the source of approximately two-thirds of total sediment yield. Laubel et al. (1999) used the erosion pin method to investigate stream bank erosion over one year at 33 stream reaches of the lowland Gjern stream basin in Denmark and showed that 60-90 % of the total suspended sediment load was derived from bank erosion. Russell et al. (2001) used a composite fingerprint (comparison of geochemical, radionuclide and mineral magnetic properties of suspended sediment and potential source materials) and multivariate mixing models to investigate relative contribution of in-stream suspended sediment from the terrestrial landscape, eroding stream banks, and field drains in two small lowland agricultural catchments in the United Kingdom. They found that surface erosion was the primary source totaling 34-65 % of the sediment yield, 10 % or less was concluded to be from eroding stream banks. Nelson and Booth (2002) investigated sediment sources in an urbanizing, mixed land-used watershed in Seattle, USA, and reported that landslides contributed 50 % of fine sediment production in the watershed, 20 % was from stream bank erosion, and 15 % was from road-surface erosion. They further explicated that urbanization activities caused a nearly

50 % increase of annual watershed sediment yield. Ultimately, identifying the dominant sources of suspended sediment in rivers and streams remains confounded since sediment sources vary spatially and temporally in response to the complexity of sediment mobilization and delivery and land use change (Benda and Dunne, 1997).

Methods for identifying the sources of suspended sediment can be categorized into two primary groups: indirect methods and direct methods (Collins and Walling, 2004). Mapping, surveying (erosion pins, profilometers), photogrammetry, soil erosion tracers are considered indirect methods. Since indirect methods take little account of sediment transport and deposition dynamics and therefore the accuracy reduces when only one method is used, it is often recommended to combine two indirect methods to generate more accurate results (Collins and Walling, 2004). Hughes et al. (2009) used fallout radionuclides (^{137}Cs and $^{210}Pbex$) coupled with geochemical tracers to examine sediment sources over the last 250 years in Australia (as previously discussed). Fingerprinting (direct method) technologies are increasingly being used to identify the sources of suspended sediment in streams as the method considers sediment mobilization and delivery to be a key elements in the process of investigating the sources of suspended sediment, therefore, complementary information is not necessary (Walling et al., 1999).

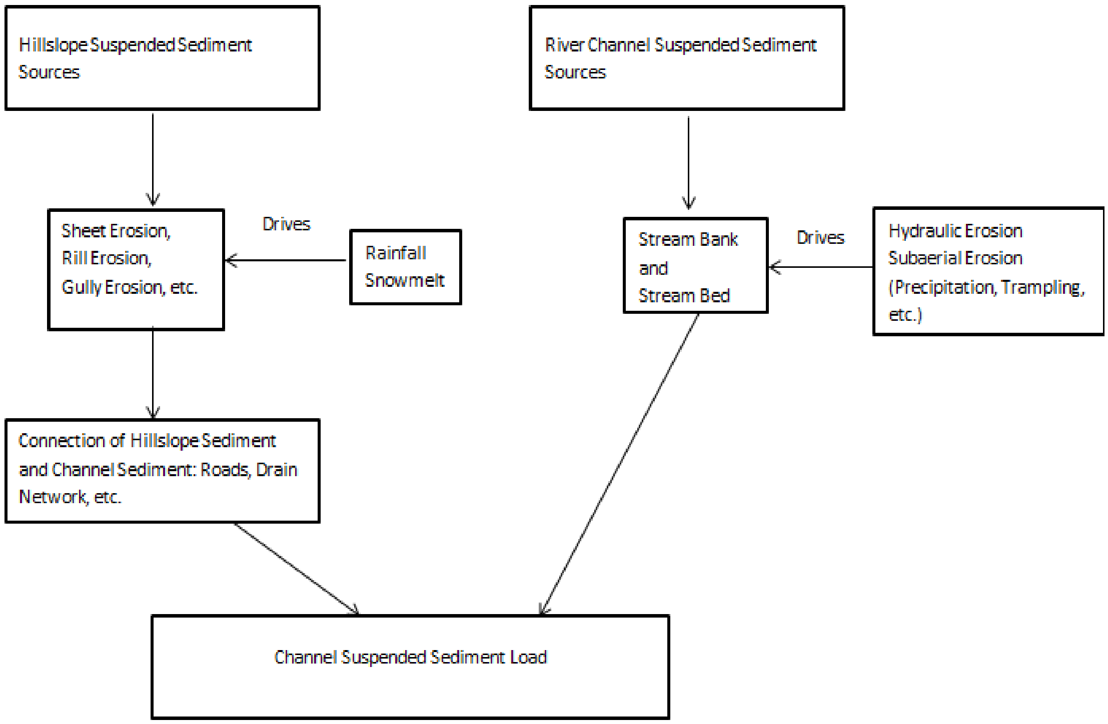

Figure 1: Framework of potential sources of channel suspended sediment load. Recreated and simplified from Collins and Walling (2004).

Stream Bank Erosion and Deposition

Stream bank erosion is considered a major source of suspended sediment loading in the United States (Mukundan et al., 2011; Simon and Rinaldi, 2006; Wynn and Mostaghimi, 2006; Zaimes et al., 2006) and worldwide (Hughes et al., 2009; Laubel et al., 1999). Stream bank erosion was shown to account for as much as 80 % of in-stream suspended sediment loading (Lawler et al., 1999; Mukundan et al., 2011; Prosser et al., 2000; Simon et al., 2000). In the U.S.A., 575,000 stream bank miles have been reported as actively eroding and of those 142,000 stream bank miles have severe erosion problems. Subsequent bank stabilization activities cost more than $1.1 billion annually

(USACE, 1981).

There are generally three processes that contribute to stream bank erosion: 1) fluvial erosion, 2) subaerial erosion, and 3) mass failure (Couper and Maddock, 2001; Hooke, 1979; Thorne, 1982). Fluvial erosion occurs when tractive forces (pushing and pulling forces) exerted by stream flow directly entrain stream bank materials and undercut the toe of stream banks (Hooke, 1979; Knighton, 1973; Wolman, 1959). Tractive forces increase with increases of flow velocity and depth, therefore, greater erosion often occurs with higher stream flow (Biedenharn et al., 1997). Precipitation is closely related to streamflow and is therefore an important indicator of stream bank erosion. Based on the observation of Wolman (1959), medium to long duration precipitation events during the winter season resulted in greater stream bank erosion than the high, short precipitation events during the summer. This was assumed to be due to longer duration precipitation creating ongoing tractive forces on saturated banks, and accompanying reduced soil shear strength due to soil saturation and possible freeze-thaw cycling during the winter. Knighton (1973) indicated that multiple closely spaced peak precipitation events resulted in higher erosion rates than single peak events. Zaimes et al. (2006) concluded similarly that stream bank erosion often occurs after many medium (20-40 mm) or/and one or two large (>40 mm) closely spaced precipitation events. This was assumed to be due to previous flows that undercut and weaken stream banks such that stream bank erosion is imminent with the next high flow. Furthermore, short time intervals of precipitation events provide little time for stream banks to dry, thereby increasing the likelihood of stream bank erosion. Julian and Torres (2006) compared the impacts of four factors (peak discharge, magnitude, variation, and duration) to stream bank erosion and found that peak discharge (30-min maximum precipitation) was one of the most important factors affecting stream bank erosion.

Subaerial erosion is climate-driven and can weather and weaken the stream bank (Thorne, 1982). It is understood to act as a "preparatory" process, weakening the bank face prior to fluvial erosion (Couper and Maddock, 2001; Wolman, 1959). Subaerial erosion is often driven by wetting-drying and freeze-thaw cycles of stream bank soils, and is affected by soil antecedent water moisture and temperature (Couper and Maddock, 2001; Wynn et al., 2008). Stream banks with high moisture content can have weakened soil inter-particle forces (Craig, 1992), reducing stream bank resistance against fluvial shear strength (Couper, 2004). Conversely, stream banks with low moisture content can cause bank shrinkage that forms desiccation cracks in the stream banks (Osman and Thorne, 1988). Stream banks become even more vulnerable to failure when cracked stream banks immediately immerse in water and generate positive pore water pressures (Osman and Thorne, 1988).

Frost heave and freeze-thaw cycling during winter seasons expand soil water and reduce grain interlocking within the soil (Wolman, 1959; Wynn and Mostaghimi, 2006; Zaimes et al., 2004). Zaimes et al. (2006) reported that soil erosion was often found on the upper portions of the cohesive stream banks, while deposition occurred on the middle and bottom extents of the stream banks in January and November, when there was little precipitation. The phenomenon may be due to freeze-thaw processes that reduce soil interlocking on upper stream banks and result in soil loss by gravity and subsequently deposited on the middle and lower portions of the bank. Cohesive (high silt-clay content) stream banks are understood to be more vulnerable to subaerial erosion than non-cohesive (high sand content) stream banks, because complicated soil structure and inter-particle attractive forces of cohesive soil can be easily changed by climate-induced factors, and usually erode as aggregates and peds (Ferrick and Gatto, 2005).

Mass failure occurs when gravity of the stream bank overrides shear strength of soils resulting in soil mass detachment from the bank. It is often caused by fluvial toe slope undercutting, increased positive soil pore-water pressure and seepage erosion (Cancienne et al., 2008; Midgley et al., 2012). Increased positive soil pore water pressure is generated by precipitation infiltration, therefore, stream bank stability reduces when stream banks are saturated (Simon et al., 2000). The likelihood of mass failure can be estimated by the factor of safety (FS) equation:

$$FS = \frac{\sum Resisting\ Forces}{\sum Driving\ Forces} \qquad (1.2)$$

The magnitude of resisting forces of stream banks is determined by several factors, including channel geometry (e.g. width, depth, and slope), bank materials (e.g. substrate type, erodibility), and bank vegetation cover (e.g. woody and herbaceous vegetation). Pauline (2003) inferred that high silt-clay content of stream bank soils tended to have high resistance from hydraulic erosion, however, cohesive stream banks are often subjected to subaerial erosion. Wynn and Mostaghimi (2006) employed an in-situ method (submerged jet test device) to demonstrate that soil bulk density was inversely related to stream bank erodibility. They indicated that higher bulk density of stream bank soils resulted in a 33 to 52 % decrease in soil erodibility and a 36 to 46 % increase in stream bank critical shear strength. Stream banks with woody root systems were reported to have higher resistance to soil erosion. The driving forces are proportional to gravitational forces (Parker et al., 2008), which are affected by fluvial entrainment (e.g. tractive force) and subaerial erosion (e.g. frost heave and freeze thaw cycling, and wetting-drying cycling), as well as gravitational force of soil, and compaction (Simon et al., 2000).

In recent decades, numerous researchers investigated land use change relationships to stream bank dynamics. Zaimes et al. (2006) compared soil erosion rates in a riparian forested buffer, row-crop agriculture, and continuous-grazed pastures in a stream reach in central Iowa and found that riparian forests had the lowest stream bank erosion (198 mm) relative to continuous-grazed pastures (594 mm) and row-crop agriculture (643 mm) for a four-year period of erosion pin measurements. They further characterized soil loss per unit of stream bank length for the three land use types and ranked them as: riparian forest buffer (75 tonnes/km), row-crop agriculture (484 tonnes/km), and continuous-grazed pastures (557 tonnes/km). Similarly, Burckhardt and Todd (1998) compared bank migration rates of forested and non-forested banks with consistent characteristics (i.e. bank height, soil type) and indicated that the bank migration rate of non-forested banks were three times greater than forested banks. Wynn and Mostaghimi (2006) inferred that riparian vegetation helps stabilize stream banks by providing large diameter roots that reinforce the stream bank, and vegetation improves local stream bank microclimate and soil moisture.

Urbanization can accelerate stream bank erosion by increasing volume and velocity of surface runoff. Arguably, increased runoff with a decreased sediment yield from urban areas can result in an imbalance between sediment transport capacity and supply (Biedenharn et al., 1997), resulting in stream flow seeking to reach dynamic equilibrium as indicated by Lane's Balance (equation 1.1) by scouring stream banks and bed. For example, channelization often results in higher peak discharges. Reduced sediment input from overland areas as a result of increased impervious surface can imbalance the four variables in Lane's equation. Increased stream velocity can scour the stream bed and banks thereby accommodating large and long duration stream flows (Biedenharn et al., 1997; Bledsoe and Watson, 2001). Previous researchers concluded that increasing impervious surfaces by 10 to 20 % can result in destabilized stream banks due to the mechanisms described above (Booth, 1990; Booth, 1991; Booth and Remelt, 1993; Schueler, 1994). Increased stream bank height and angle further accelerate stream bank failure resulting in greater quantities of sediment to streams and rivers (Simon et al., 2000).

Methods for studying stream bank erosion and deposition dynamics have improved dramatically since 1863 when the first stream bank lateral change studies were catalogued (Lawler, 1993). Traditional methods for investigating stream bank erosion can be grouped into three categories based on the time period of the survey (1) long term: sedimentological evidence, botanical evidence, and historical sources; (2) intermediate term: planimetric resurvey and repeated cross profiling; and (3) short term: terrestrial photogrammetry, erosion pins, and the photo-electronic erosion pin (PEEP) system (Lawler, 1993). The erosion pin method was first used by Wolman (1959) who identified an average erosion rate of 0.5 m/year on the banks of Watts Branch, Maryland, USA. Since that time, the method has been widely used because of its simplicity, relative cheapness, and sensitivity to stream bank erosion (Laubel et al., 1999). According to Lawler (1993) the most effective methods to monitor stream bank erosion in temporal and spatial scales are PEEP and terrestrial photogrammetry respectively. The PEEP method is an advanced method rooted in the traditional erosion pin method. The improvement of this method is that it takes advantage of solar radiation theory. A solar cell is enclosed in an acrylic tube that is inserted into the stream bank, as erosion occurs, increasing exposure of the solar cell to sunlight, indicated by increased voltage, is detected by a nearby data logger (Lawler, 1993). Lawler (2005) continued to study stream bank erosion using the PEEP method and integrated Thermal Consonance Timing (TCT), which enables monitoring of stream bank erosion during the night time.

Other methods used to assess stream bank erosion rates include creating stream bank erodibility indices that include stream bank height, angle, materials, root depth, root density and percentage of stream bank protection and near bank stress (Rosgen, 2001). Methods for assessment of channel stability include the Rapid Geomorphic Assessment (RGA) (Mukundan et al., 2011; Simon, 2008). The bank stability and toe erosion model (BSTEM) used by Midgley et al. (2012) was developed to predict stream bank retreat due to fluvial erosion and geotechnical failure, this model was prone to under predict stream bank retreat on non-cohesive stream bank soils. Jia et al. (2010) presented a 3-D numerical model to simulate geomorphological changes in alluvial channels due to stream bank erosion. Notably, even though stream bank erosion models help assess stream bank erosion and stream geomorphic changes, they require field-based investigations to calibrate the models and validate the results, thus illustrating the importance of field-based stream bank dynamic studies.

OBJECTIVES

The quantitative contribution of stream bank erosion to suspended sediment load remains elusive. There are persisting questions pertaining to this issue in the central U.S. (including Missouri) and there is a global need for studies in highly managed landscapes such as urban environments and urban floodplain ecosystems. The following research was undertaken to quantify stream bank erosion and deposition rates in an urban floodplain stream reach located in central Missouri, USA. Improved understanding of stream bank stabilization processes in the built-environment will help urban land managers make improved science-based decisions to preserve and restore aquatic ecosystem health in complex urban ecosystems.

General objectives of the following work were as follows:

1) Quantify the rates of stream bank erosion and deposition over the period of one water year (WY 2011) of an urban stream in Central Missouri.
2) Quantify the rates of stream bank erosion and deposition over the period of one water year (WY 2011) between a bottomland hardwood forest (BHF) site and agricultural site of an urban stream in Central Missouri.

3) Quantify the rates of stream bank erosion and deposition seasonally over the period of one water year (WY 2011) between a bottomland hardwood forest (BHF) and agricultural land of an urban stream in Central Missouri.
4) Use results from 1 through 3 above to estimate stream bank erosion contributions to total suspended sediment load over WY 2011.

HYPOTHESIS

Specific hypotheses regarding each of the listed objectives are as follows:

H1o: There will be a significantly ($p<0.05$) higher magnitude of stream bank erosion from an agricultural stream bank than a bottomland hardwood forest (BHF) stream bank of an urban stream in central Missouri over the period of one water year (WY 2011).

H1a: There will not be a significantly ($p<0.05$) higher magnitude of stream bank erosion from an agricultural stream bank than a bottomland hardwood forest (BHF) stream bank of an urban stream in central Missouri over the period of one water year (WY 2011).

H2o: There will be higher erosion rate in an agricultural stream bank than that of a BHF stream bank of an urban stream in central Missouri over the period of one water year (WY 2011).

H2a: There will not be higher erosion rate in an agricultural stream bank than that of a BHF stream bank of an urban stream in central Missouri over the period of one water year (WY 2011).

H3o: There will be higher erosion rate from a BHF and agricultural stream bank of an urban stream in central Missouri in winter season than other seasons over the period of one water year (WY 2011).

H3a: There will not be higher erosion rate from a BHF and agricultural stream bank of an urban stream in central Missouri in winter season than other seasons over the period of one water year (WY 2011).

H4o: More than 50% of annual suspended sediment loading will originate from stream bank erosion.

H4a: Less than 50% of annual suspended sediment loading will originate from stream bank erosion.

CHAPTER II

METHODS

STUDY SITE

This research took place on a fourth order reach of an adjacent floodplain in the lower Hinkson Creek Watershed (HUC 103001020907) in Columbia, Missouri, USA. Hinkson Creek Watershed was equipped in the fall of 2008 with a nested-scale experimental watershed study design to investigate urban watershed scale physical hydrologic, land-use interactions (Figure 2). Hinkson Creek Watershed (HCW) is contained within the Lower Missouri-Moreau River Basin. The HCW is approximately 230.8 km^2 (23,080 ha) in size originating northeast of Hallsville in Boone County and flows approximately 42 km in a southwestly direction to its mouth at Perche Creek. Land use in the HCW is comprised of 25% urban area, 38% cropland and pasture, 34% forest, and 3% wetland, open, shrub and grassland area (Hubbart et al., 2010).

In the 19^{th} and 20^{th} centuries, most of the floodplain Bottomland Hardwood Forest (BHF) in Missouri was removed to develop agricultural land. Human engineered structures including ditches, levees and drainage tiles, which combined with channel alterations and soil cover changes dramatically altered the hydrology of streams, floodplains and the remnant BHF (Carter and Biagas, 2007). Two stream bank sites at a historical Bottomland Hardwood Forest (BHF) and an Agricultural (Ag) site (722 m apart) within the lower HCW floodplain were selected for intensive monitoring (Figure 2). The BHF site is characterized with a mature stand of Bottomland Hardwood Forest, including *Acer saccharinum* (silver maple), *Acer negundo* (boxelder), *Ulmus americana* (American elm), *Populus deltoids* (eastern cottonwood), and *Juglans nigra* (black walnut) surrounding an old stream meander (Hubbart et al., 2011). The site was BHF at least as far back as 1939 (the date of the earliest aerial photography). The Ag site is an abandoned agricultural field, which was cultivated by private landowners until the mid-1960s when it and the BHF site came into ownership by the University of Missouri. The University of Missouri used the Ag site for experimental crop plots until approximately 2002. The agricultural experiment station has been mowing the field approximately once per year since 2002. Study sites were previously described in Hubbart (2011), and Hubbart et al. (2011). The reader is referred to those publications for additional information.

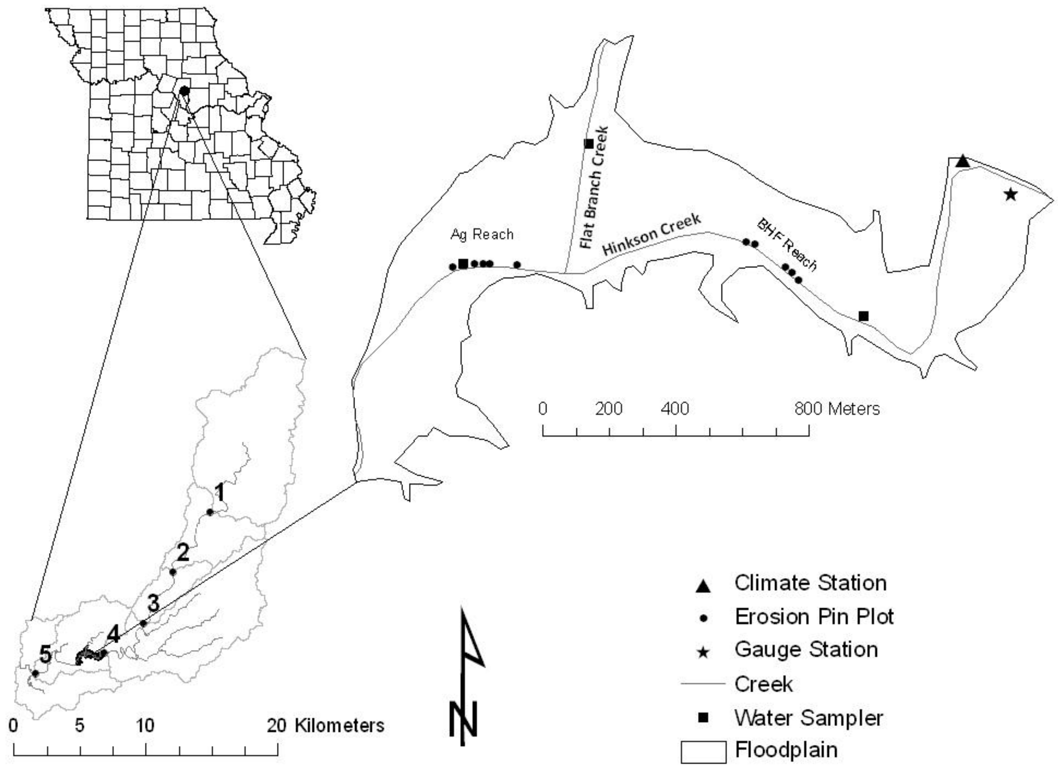

Figure 2: Map of floodplain study reach located on a fourth order reach of Hinkson Creek Watershed, located in Central Missouri, USA.

Climate

Climate in Missouri is generally influenced by continental polar air masses in winter with maritime and continental tropical air masses in summer (Nigh and Schroeder, 2002). Precipitation data collected at the University of Missouri Sanborn Field climate monitoring station from 2000 to 2011 (Calendar Year: January 1st 2000 to December 31st 2011) indicated that the highest total annual precipitation in the last decade was in 2010 (1359 mm), the lowest annual precipitation was in 2006 (733 mm) (Table 1). Average temperature in Columbia, Missouri was 13.3 ℃. The coldest month is in January (average temperature -0.7 ℃), whereas the warmest month is usually between June and August (average temperature 24.3 ℃). From 2000 to 2011, the lowest temperature in Columbia (15^{th} January in 2009) was -15.8 ℃; the hottest day in Columbia (2^{nd} August in 2011) was 33.6 ℃ (Table 2).

Table 1: Total precipitation (mm) in Columbia, Missouri from 2000 to 2011 (Calendar Year: January 1^{st} 2000 to December 31^{st} 2011) (data source: Sanborn Field, University of Missouri), USA.

Year	**Total Precipitation (mm)**
2000	971
2001	1163
2002	1071
2003	1017
2004	1104
2005	978
2006	733
2007	812
2008	1447
2009	1350
2010	1359
2011	868

Table 2: Descriptive statistics of ambient air temperature (℃) in Columbia, Missouri from 2000 to 2011 (Calendar Year: January 1^{st} 2000 to December 31^{st} 2011) (data source: Sanborn Field, University of Missouri), where min=minimum, max=maximum, and SD=Standard Deviation.

	2000	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Min	-13.4	-12.8	-11	-16.3	-14.5	-11.2	-13.5	-12.5	-14.7	-15.8	-15.3	-13
Max	30.4	30.5	30.5	31.7	29.7	32.1	32.7	32.4	30.8	29.8	31.7	33.6
Mean	13.2	13.7	13.4	13.0	13.0	13.8	14.3	13.9	12.2	12.6	13.2	13.6
SD	11.16	10.20	10.14	10.51	9.88	10.59	9.75	11.19	10.57	9.96	11.54	10.98

Topography and Soil

More than half the land area of Boone County has slopes of 2 to 35 %; the other land area has slopes either below 2% or above 35%. Elevation in the HCW ranges from 170 m at the confluence with Perche Creek to 287 m at the headwaters (Freeman, 2011; Scollan, 2011). The USGS gauging station (# 06910230) in lower Hinkson Creek drains an area of 179.5 km^2 (elevation range = 178 m to 276 m). Figure 3 shows hypsometric curves (percentage contributing area versus elevation) for contributing area draining to the USGS Gauge site and the confluence of Hinkson and Perche Creek. The HCW and USGS Gauge site encompass a similar percentage (i.e. approximately 40%) of elevation at 239 m, which indicates that precipitation falling on nearly 40% area in the Hinkson Creek Watershed at 239 m elevation, and flow of water starts at the 239 m isoline will have same time of concentration to the confluence of Hinkson and Perche Creek. The hypsometric curve also shows that approximately 40% of the total HCW area, and drainage area to the study sites of the current work is at elevations below 239 m.

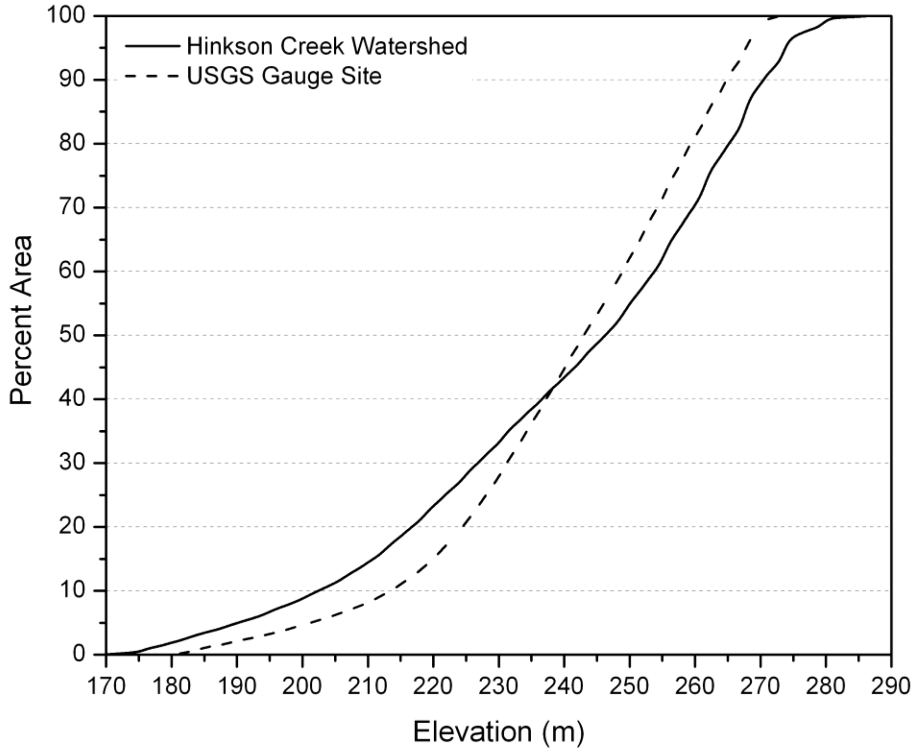

Figure 3: Hypsometric curves showing percentage contributing area versus elevation for Hinkson Creek Watershed and USGS Gauge Site.

Soil in the HCW is highly viable. The higher elevation land areas (i.e. headwaters) of the HCW are dominated by Mexico-Leonard association soil types with poorly drained and slow permeability soil characteristics. This type of soil encompasses approximately 20 % of the HCW. Soil becomes moderately to well drained with slow to moderate permeability in central to lower elevations of the HCW. Dominant soils are Keswick-Hatton-Winnegan soil association, Weller-Bardley-Clinkenbeard association, and Menfro-Winfield association. In the transition of central to lower elevations of the HCW, urban is the dominant land use (> 40 %), anthropogenic activities compact surface and near surface soil and reduce soil permeability (MODNR, 2011; USDA-NRCS, 2009). Soil types within the lower elevations of Hinkson Creek are characterized as thin cherty clay and silt to sandy clay. Mississippian and Pennsylvanian limestone, sandstone and shale with considerable bedrock exposure characterize the area (Chapman et al., 2002) (Table 3).

Floodplain areas in the HCW are dominated by alluvial soils including Moniteau silt loam and Haymond silt loam. Moniteau silt loam is characterized by 0-2 % slopes. Soils are poorly drained with moderately high infiltration rates (0.51 to 1.45 cm/hr) with occasional flooding. Haymond silt loam is characterized by 0-3 % slopes, well drained, moderately high to high infiltration rate (1.45 to 5.03 cm/hr), and frequently flooding (USDA-NRCS, 2009).

Table 3: Soil characteristics in Hinkson Creek Watershed, Boone County, Missouri, USA.

Location	Soil Series	Drainage Class	Permeability	Parent Material	Slope Range (%)
Upland Ridge to Upper Area	Mexico-Leonard Association	Poorly	Slow	Fine-Silty Loess Over Pedisediment and Glacial Till	2 to 6
Upper to Central Area	Keswick-Hatton-Winnegan Soil Association	Moderately Well	Slow to Very Slow	Loess Over Clayey Till and Fine-Silty Pedisediment	2 to 35
Central to Lower Area	Weller-Bardley-Clinkenbeard Association	Moderately Well	Slow	Loess	2 to 9
Lower Land Area near to Confluence of Perche Creek	Menfro-Winfield Association	Well	Moderate	Fine-Silty Loess	3 to 45
Bottomlands	Varied	Varied	Varied	Alluvial Soil	-

Streamflow

As presented above, a U.S. Geological Survey gauging station (#06910230, latitude 38°55'39.9", longitude 92°20'23.8" NAD83) is located on Hinkson Creek 122 m downstream of Providence Road in the city of Columbia, Missouri, approximately 10 miles downstream of the Highway 63 overpass and one mile upstream from the confluence of Flat Branch Creek. Stream flow was monitored intermittently from November 1966 to January 1982, October 1986 to September 1991, and most recently from March 2007 to the present. Average annual discharge (water year) has ranged from a low of 0.38 m^3/s in 1980 to a high of 4.53 m^3/s in 2008. Average monthly discharge measured from 1967 to 1981 ranged from a low of 0.0 m^3/s in August 1976 to a high of 10.92 m^3/s in March 1973. Average monthly discharge from 1967 to 1991 varied from a highest value of 9.44 m^3/s in May 1990 to a lowest value of 0.02 m^3/s in June 1988. 2008 to 2011 varied from a highest value 16.05 m^3/s in September 2008 to lowest value 0.087 m^3/s in September 2011. From water year 2008 to 2011, the maximum discharge was 221.15 m^3/s on September 14th 2008; minimum discharge was 0.01 m^3/s on November 4th, 2007.

Channel geomorphology has changed dramatically since 1939 (Figure 4). In the 1940's, the channel was manually straightened to dry the surrounding floodplain for agricultural access in the 1940's (Hubbart et al., 2011). Since that time, the channel has not changed greatly according to 1992 and 2010 aerial photographs (Figure 4).

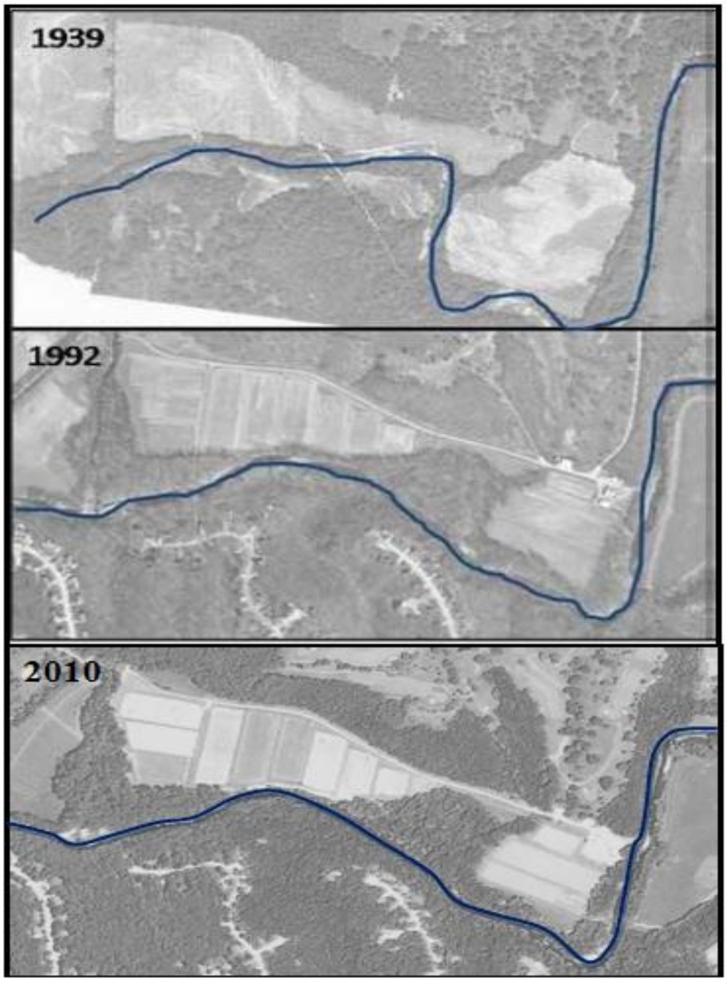

Figure 4: Comparison of aerial photos of Hinkson Creek in 1939, 1992, and 2010 flowing through the floodplain study reaches in central Missouri, USA. Reprinted with permission from Hubbart et al. 2011.

Water Quality

In 1998, Hinkson Creek was listed on the Clean Water Act (CWA) 303(d) list as impaired due to unknown pollutants (MDNR, 2011; USEPA, 2011). In the urban area, many suspected problems pertaining to water quality and hydrologic alteration drew attention of State and Federal agencies, and local residents. Suspected issues included (1) larger and more frequent floods, (2) lower base flows; (3) increased soil erosion in construction and development areas with subsequent transport of the soil to streams; (4) water contamination from urban storm water flows; (5) degradation of habitat for aquatic organisms due to the concerns listed above; and (6) degradation of aquatic habitat due to the physical alteration of stream channels and adjacent streamside (riparian) corridors (MDNR, 2009).

From 2004 to 2006, the Missouri Department of Nature Resources (MDNR) investigated the creek and found that E. coli concentration in Hinkson Creek was 1730 cfu/100 ml during non-recreational season, which far exceeded the standard of 235 cfu/100ml required by USEPA (1986). Chloride values for the Hinkson Creek in the year 2006 ranged from 25.6 mg/L to 333 mg/L (water quality standard for chloride toxicity is 230 mg/L), overall, Hinkson Creek had higher chloride concentrations than other Missouri reference streams (MDNR, 2006). Dissolved oxygen concentrations dropped below the 5 g/ml water quality criteria 2% -62% at different monitoring sites, toxicity was identified, and excessive erosion and sedimentation were noted, but the sources and periodicity of impairment was not identified (MDNR, 2006). According to the EPA and MDNR, reducing storm water runoff volume in the HCW may help improve the overall condition and water quality of Hinkson Creek (MDNR, 2011), though a recent article by Hubbart et al (2010) may suggest otherwise.

MONITORING BANK EROSION: THE EROSION PIN METHOD

The erosion pin technique was used in this work to investigate stream bank erosion and deposition rates. This method has been widely used since Wolman (1959), and has been shown to be suitable for measuring cohesive stream bank erosion and deposition rates (Haigh, 1977). Ten erosion pin plots were installed in June 2010. Sites were selected that represented the span of stream bank heterogeneity of the stream, five pin plots were installed adjacent to the bottomland hardwood forest site and five adjacent to the abandoned agricultural site (Figure 2). All pin plots were placed on the right bank of the Creek if one is facing down-stream. A total of 342 steel pins (122 cm long; 10 mm diameter) were installed. Erosion pins were comprised of re-bar installed at a 90 ° angle perpendicular to the creek-bank, 1m aerial distance from each other, as per the methods described in previously successful studies (Couper et al., 2002; Zaimes et al., 2004). Each piece of re-bar was inserted approximately 112 cm into the stream bank allowing 10 cm pin exposure (Zaimes et al., 2004; Zaimes et al., 2006). As bank erosion occurred, the length of pin exposed on the surface increased. Conversely, when deposition occurred, exposed pin length was reduced (Figure 5).

Measurement of exposed erosion pin length was conducted on a monthly basis (Gabet, 1998; Zaimes et al., 2004), during the first few days of each month (weather contingent). Soil deposition was a positive value and erosion (i.e. soil loss) was a negative value (accurate to 1 mm). If buried or completely eroded pins were replaced, the readings were recorded as “zero” or “112 cm” respectively.

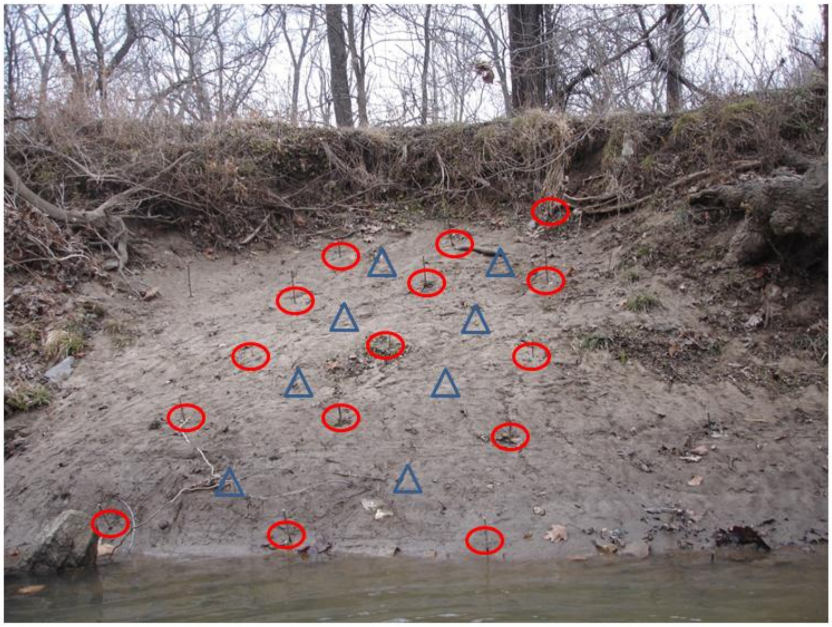

Figure 5: Erosion pin plot J at the Ag site on a fourth order reach of Hinkson Creek, Columbia, Missouri, USA. Erosion pins are circled in red, blue triangles indicates soil core extraction sites for soil characteristic analyses.

SOIL CHARACTERISTICS

Soil bulk density and soil moisture content is closely related to stream bank erodibility (Wynn and Mostaghimi, 2006; Zaimes et al., 2004). Soil cores were collected and analyzed to determine soil bulk density, soil moisture content, and other common characteristics. A total of 232 soil cores (volume= 102.97 cm^3) were collected from the ten pin plots in September 2010. Soil cores were collected from the center of every four pins (Figure 5). Soil core samples were delivered to the Interdisciplinary Hydrology Laboratory (IHL) of the University of Missouri and dried in the oven at 105 ℃ for 24 to 48 hours, or until constant weight was obtained according to the methods described by

Hillel (2004). Dry soil bulk density and volumetric water content was calculated using the following equations (Dingman, 2008):

$$\rho_b = \frac{M_m}{V_s} \tag{2.1}$$

Where ρ_b is the dry bulk density of the soil, M_m is the mass of the dry soil, V_s is the volume of the soil sample.

$$\theta = \frac{V_w}{V_s} \tag{2.2}$$

Where θ is the volumetric water content, V_w is the volume of the soil water, V_s is the volume of the soil sample.

SOIL TEXTURE

Soil texture is an important factor affecting soil erodibility (Wynn and Mostaghimi, 2006; Zaimes et al., 2006). Soil texture was determined using the hydrometer method (Bohn and Gebhardt, 1989; Grigal, 1973; Kettler et al., 2001). Ten soil samples were collected from the center of every four pins from each pin plot to capture soil heterogeneity of each plot (2 meter intervals, n=10 for each pin plot). Soil samples were returned to the IHL for analyses: A 10 g homogeneous soil subsample was dispersed thoroughly using 50 ml 5 % Sodium Hexametaphophate and shaking on a Digital Vortex Mixer (Fisher Scientific) for 30 seconds. A blank solution was made by mixing 5 % Sodium Hexametaphophate and DI water for a reference. The gravity readings from hydrometer were recorded at 40 second, and 6 hour intervals (Bohn and Gebhardt, 1989). Given that hydrometer readings are affected by room temperature, the corrected hydrometer reading was obtained by adding 0.2 units to the readings for every 0.55 °above 15.6 °; subtract 0.2 units to the readings for every 0.55 °above 15.6 °. Percentage of sand, silt and clay was calculated using the following equations (Piercy and Wynn, 2008):

$$\%\, clay = \{[(H_a - H_b) * 500\, ml]/10\} * 100\% \tag{2.3}$$

$$\%\, silt = \{[(H_c - H_b) * 500\, ml] - [(H_a - H_b) * 500\, ml]\}/10 * 100\% \tag{2.4}$$

$$\%\, sand = 1 - \%\, silt - \%\, clay \tag{2.5}$$

Where H_a is a corrected hydrometer reading at 6 hours of the soil sample after a uniform suspension of solution was obtained, H_b is blank solution density; H_c is the corrected hydrometer reading at 40 seconds of the soil sample after a uniform suspension of solution was obtained (Piercy and Wynn, 2008).

SOIL PARTICLE PARTITION

Silt-clay content of stream bank soils is critical to determine soil erodibility (Ferrick and Gatto, 2005). The silt-clay content of stream bank soil is easily suspended and transported in the water column during low precipitation or base flow conditions relative to the sand (or larger) soil component. Determination of percentage of silt-clay composition of stream bank soils helps predict soil erodibility and relative contribution of stream bank erosion to in-stream suspended sediment loading during base flow (Laubel et al., 1999). Soil samples acquired with the soil samples for the soil texture test (n=10) were analyzed for this test: 0.5 g soil sample was mixed with DI water to 1 liter solution. The sample was suspended using the Digital Vortex Mixer (Fisher Scientific company) and passed through a Nitex mesh filter with a 53 μm opening to separate out particle size >53 μm and <53 μm, and collect soil particles on filters (1.5 μm filter for particle size >53 μm, 0.7 μm filter for particle size <53 μm) (Eshel et al., 2004). Filters were dried in the oven at 105 ℃ for 1 hour and then placed in a desiccator for at least 5 hours or until the constant weight was obtained (Wyckoff, 1964).

STREAM BANK HEIGHT AND ANGLE

Stream bank height and angle are important bank geometry factors affecting stream bank stability (Osman and Thorne, 1988). Stream bank stability is inversely proportional to stream bank height and angle (Simon et al., 2000). Stream bank height and angle were determined using a clinometer (Biedenharn et al., 1997). Basic clinometer theory for measuring stream bank height and angle utilizes the right triangle theorem. The vertical height can be determined by knowing one angle and one side of right triangle (Gordon et al., 2004). The stream bank height equals the sum of H_1 and H_2 (Figure 6). H_1 was the product of the horizontal distance and the tan (Θ). H_2 was the vertical distance of a measurer's foot to his eye. For the current work, the measurer stood by the edge of the stream bank parallel to the top erosion pin (the targeted pin), and then measured the percentage and degree angle of the top erosion pin. The horizontal distance was determined by the distance of the erosion pins (erosion pins were one aerial meter apart). The measurement (accurate to 1 dm) was taken at two meter intervals along the stream bank of each of the erosion pin plots (Zaimes et al., 2006). Note that some targeted pins were not at the top of stream bank, but between the middle and top of stream bank, the actual stream bank height was determined by summing the measurement taken at the pin and the vertical distance of the pin to the top edge of the stream bank. Some erosion pins were not at the top edge of the stream bank, but some distance inside from the edge. In this case, we targeted one point at the edge of the stream bank (this point was at the same line with the top pin) with the clinometer, and measured the horizontal distance of the top pin to the stream bank top edge and deducted it from the original horizontal distance determined by the erosion pins to quantify the horizontal distance corresponding to the edge of the stream bank.

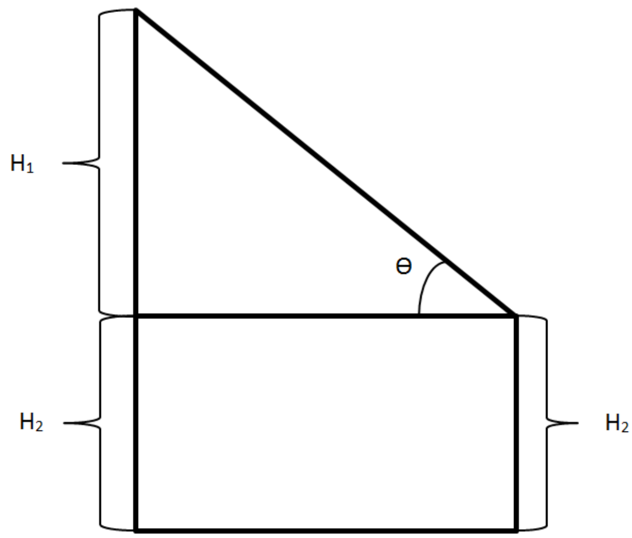

Figure 6: Right triangle theory for the stream bank height and angle measurement. H_1 and Θ is the distance and angle measured using a Suunto PM-5 clinometer. H_2 is the distance from a measurer's toe to his eye. Stream bank height is the sum of H_1 and H_2.

VEGETATION SURVEY

Vegetation species and density was identified in late June to early September 2011. A sampling frame of 1 x1 m inner dimension comprised of ½ inch polyvinylchloride (PVC) pipe was constructed for quadrat sampling (USDA, 1996). The corner of the PVC quadrat was placed on every third erosion pin (i.e. every three meters) within each erosion pin plot (Figure 7), the percentage of vegetation (vascular) around each pin was averaged to obtain the percentage of the vegetation cover for the whole pin plot (n=158). Vegetation roots that were outside the quadrat but leaning into the quadrat was not recorded (USDA, 1996). Vegetation cover was quantified in terms of percent cover as per the methods of Laubel et al. (1999).

Figure 7: Vegetation survey 1x1m quadrat in pin plot A at the BHF site of floodplain of Hinkson Creek Watershed, Boone County, Missouri, USA.

SOIL LOSS CALCULATION

The mass of eroded or deposited soil sediment was calculated using the following equation:

$$M = L \times A \times B \tag{2.6}$$

Where M is the mass of eroded or deposited soil sediment (kg) in the plot, L is the mean erosion rate in the plot (m),which is calculated by averaging the erosion rate of all the pins in the plot (Zaimes et al., 2004), A is the plot area (m^2), and B is the average site bulk density ($kg \cdot m^{-3}$) (Zaimes et al., 2004).

The mass of eroded or deposited soil sediment from each pin plot was divided by the length (m) of the plot to supply a linear erosion or deposition rate (m) for each plot (Zaimes et al., 2004; Zaimes et al., 2006). To scale to the reach, the final linear erosion or deposition rate for each site was calculated by dividing the total eroded or deposited mass by the total length of the site.

STREAM BANK EROSION AND IN-STREAM SUSPENDED SEDIMENT LOADING

Suspended Sediment Loading Estimation

Three automated water samplers (Sigma 900 MAX Portable Sampler, HACH Company) were deployed, one at the upstream of the research reach at the BHF site (306 m from the confluence of Hinkson Creek main stream and Flat Brach Creek), one at the Flat Branch site (396 m from the confluence), and one at the downstream of the research reach at the Ag site (575 m from the confluence) (Figure 2). This design enabled estimation of suspended sediment within the study reach and suspended sediment from Flat Branch Creek. Water samples were collected daily (12:00 hrs) during WY 2011. Water samples were delivered to the Interdisciplinary Hydrology Laboratory (IHL) for analysis of volume concentration of in-stream suspended sediment using Laser In-Situ Scattering and Transmissometry (LISST). The LISST instrument is a state of the art instrument for monitoring suspended sediment in shallow fresh water streams and rivers or for stormwater runoff. It categorizes suspended sediment into 32 size classes logarithmically spaced with the range of 2.5 to 500 microns and records sediment concentration. Sediment concentration is calculated in terms of the volume of sediment within each size class per unit volume of water (ul/l) (Williams et al., 2007). Additional detailed information about the LISST can be found in Hubbart and Freeman (2010), and Freeman (2011).

Suspended sediment flux was estimated by the product of daily mean discharge and suspended sediment concentration (SSC) at a single point of a cross section of the creek. Volumetric SSC (ul/l) generated by the LISST was converted to gravimetric SSC by multiplying by 1.95 g/cm^3 as per the findings of Freeman (2011) who collected grab samples four times per week from Hinkson Creek over the course of the 2010 water year, and compared volumetric SSC using the LISST and gravimetric SSC by filtration by simply dividing volumetric SSC by gravimetric SSC to obtain particle density (Hillel, 2004).

Suspended sediment flux from the BHF, FB and Ag sites as well as stream bank erosion over WY 2011 were calculated as follows:

$$S_{Ag} = S_{BHF} + S_{FB} + BE \tag{2.7}$$

Where S_{Ag} is the suspended sediment flux at the Agricultural site; S_{BHF} is the suspended sediment flux at the BHF site; S_{FB} is the suspended sediment from the Flat Branch; BE is the bank erosion from both sides of the stream banks. For much of the following analysis, it was assumed that there was equal soil loss from the both sides of the stream bank within the study reach (please see Discussion).

Flat Branch Stream Discharge Estimation

The Velocity-Area (V-A) method (Dingman, 2008) was used to create rating curves to estimate the stream discharge from stage data collected at Missouri-Kansas-Texas (MKT) trail bridge. Stream discharge is determined by the equation:

$$Discharge = Area \times Velocity \tag{2.8}$$

The basic principle is that a cross section of a stream is divided into numerous subsections (normally n≥25) (Figure 8). In each subsection, the length and width of subsection are measured to determine the area. Flow velocity is measured at the center of the subsection, to obtain an accurate measurement of average velocity at each section. It is recommended to average two measurements taken at the 0.2 and 0.8 of the vertical depth to produce an average that is within 1% of the true value. However, given that it is often unattainable to measure velocity at 0.8 depth of the stream section if stream depth is shallow, velocity at 0.6 depth of the stream section was used (USGS 1982). Incremental discharge for each subsection is computed

$$q_i = v_i \left(\frac{b_{i+1}-b_i}{2} + \frac{b_i-b_{i-1}}{2}\right) d_i = v_i \left(\frac{b_{i+1}-b_{i-1}}{2}\right) d_i \tag{2.9}$$

and total discharge is obtained by summing the incremental discharges for all segments.

$$Q = q_1 + q_2 + q_3 + \cdots + q_n \qquad (2.10)$$

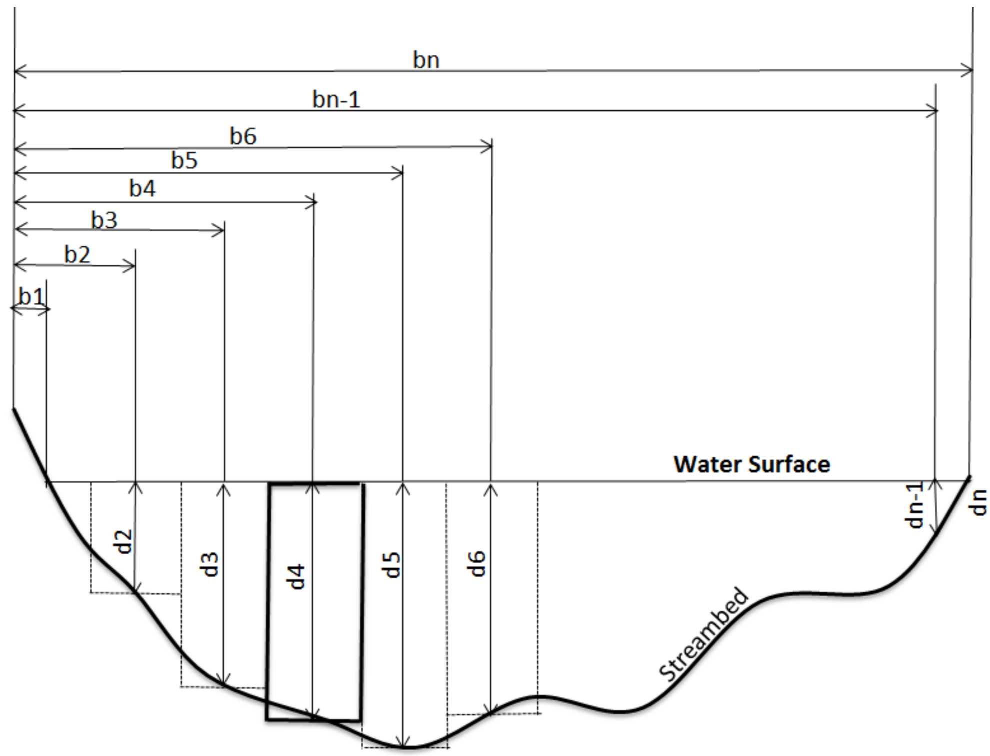

Figure 8: Delineation of a cross section for measurement of discharge by the velocity-area method. Simplified from Dingman (2008).

DATA ANALYSIS

The Analysis of Variance (ANOVA) test is used to test if there are significant mean differences among multiple experimental groups, while the t-test can only examine two groups at a time (McHugh, 2011). The ANOVA test is a better method than repeated t-tests between each of the pairs of interest because it reduces Type I errors due to alpha inflation introduced by the t-test (McHugh, 2011).

Basic logic of ANOVA is to analyze mean variations between different groups and variations due to error (e.g. chance or sampling error) (Table 4). If the ratio of mean variations between different groups and variations due to error equals to 1, there are no differences between the groups, if the ratio is greater than one, there are differences between the groups. The variance (the mean of the squared deviations about the mean, MS) is determined by the sum of the squared deviations about the mean (SS) divided by the degrees of freedom (DF). If F estimated value (MS_B/MS_w) is greater than F critical value at α=0.05, we consider the means of the groups to be significantly different. The P value is the probability of the obtained result occurring due to the error, if the P value is less than 0.05, we consider the means of the groups to be significantly different (Plonsky, 2007).

Table 4: The Analysis of Variance (ANOVA) method**.**

Source of Variation	**SS**	**DF**	**MS**	**F**
Between	SS_B	k-1	MS_B	$\frac{MS_B}{MS_w}$
Within	SSw	N-k	MS_W	-
Total	SS_T	N-1	-	-

Note: SS: Sums of Squares, DF: Degrees of Freedom, MS: Mean Squares.

Analysis of variance (ANOVA) was performed for this work using Origin 8.5: Data Analysis and Graphing Software (Origin Corporation, Northampton, MA, USA).

One-way ANOVA test is often used when comparison of variance of test groups with only one treatment factor. One-way ANOVA was used to analyze whether there are significant differences among the ten erosion pin plots, the BHF and Ag sites pertaining to soil texture, soil characteristics (i.e. dry bulk density, porosity), stream bank height and angle, and vegetation cover respectively (Zaimes et al., 2004).

A two-way ANOVA test is used to test two independent treatment factors and their interactions (Tusell, 1990), and was therefore used to test spatial (BHF site and Ag site) and temporal (monthly and seasonal) soil loss/gain, erosion/deposition per unit length, and erosion/deposition rates over WY 2011, similar to the methods of Willett (2010).

Linear Regression analysis was used to determine the strength of the relationship between two variables (i.e. vegetation cover/stream bank erosion and deposition rates), using a least square regression line to determine the relationship between the two variables (Wynn and Mostaghimi, 2006).

CHAPTER III

RESULTS

HISTORIC HYDROCLIMATE

Historic precipitation and temperature data provide insights pertaining to stream bank antecedent (pre-existing) soil water trends, and is therefore best interpreted in terms of Water Year (WY). Use of water year as a standard time interval is often used in hydrological studies because hydrological systems in the northern hemisphere are typically at their lowest levels near October 1, and increased temperatures and generally drier weather patterns of summer give way to cooler temperatures, which decreases evaporation rates. From 2001 to 2011, WY 2006 was the driest year in Columbia with annual precipitation of 677 mm, while WY 2010 was the wettest year with annual precipitation of 1651 mm. Average daily temperature from WY 2001 to 2011 was 13.2 ℃. The hottest water year was 2002 with average daily temperature of 14.1 ℃, whereas the coldest water year was 2001 with average daily temperature of 12.4 ℃. Due to data gaps of stream discharge measured at the USGS gauging station, only average daily stream discharge from WY 2007 to 2011 was available. WY 2007 had the lowest average daily discharge of 1.33 m^3/s. In contrast, WY 2008 had highest average daily discharge (4.53 m^3/s). Table 5 shows descriptive statistics of climate and stream discharge data collected at the Sanborn Field weather station and the USGS gauging station (#06910230) respectively in Columbia, Missouri, USA.

Table 5: Annual precipitation and average daily temperature from Water Year 2001 to 2011(e.g. Water Year 2001: October 1st 2000 to September 31st 2001), and average daily stream discharge from WY 2007 to 2011. Precipitation and temperature data collected from Sanborn Field weather station on the University of Missouri Campus, average daily stream discharge data collected from USGS gauging station (# 06910230) in Columbia, Missouri, USA.

	Annual Precipitation (mm)	**Average Daily Temperature (℃)**	**Average Daily Stream Discharge (m^3/s)**
Min	677	12.39	1.33
Max	1651	14.14	4.53
Average	1077	13.19	2.91
Median	1088	13.01	2.63
SD	298	0.70	1.55

Figure 9 shows historic average daily discharge of Hinkson Creek from WY 1967 to 2011. The highest average daily discharge occurred in WY 1986 at a rate of 4.69 m^3/s, the lowest average daily discharge occurred in WY 1980 with a rate of 0.38 m^3/s. To provide a more recent historical perspective, Hinkson Creek average daily discharge in WY 2008 (4.53 m^3/s) and 2010 (4.51 m^3/s) were higher than WY 2007 (1.33 m^3/s), 2009 (2.63 m^3/s), and 2011 (1.55 m^3/s). Analysis of average daily discharge for the most recent years of data (i.e. WY 2007-2011) shows that stream discharge fluctuates year to year depending on various factors including: precipitation, land use/land cover change, topography and antecedent soil water characteristics.

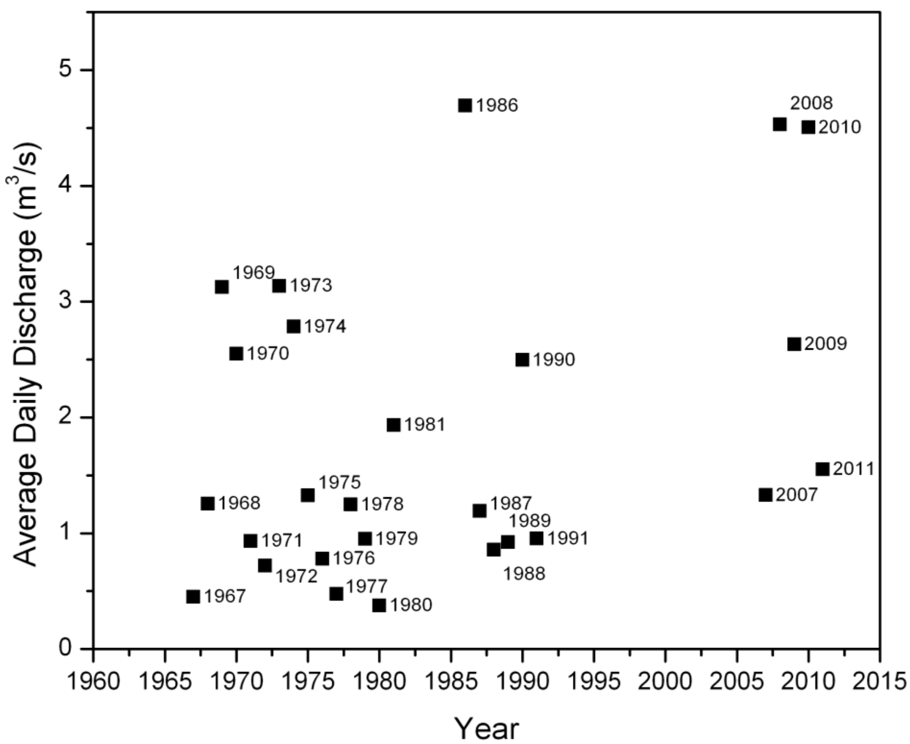

Figure 9: Historic average daily discharge (m^3/s) of Hinkson Creek in Boone County, Missouri, USA from Water Year 1967 to 2011.(e.g. Water Year 2001: October 1st 2000 to September 31st 2001) as monitored at the Hinkson Creek USGS gauging station (# 06910230).

HYDROCLIMATE OF WATER YEAR 2011

WY 2011(October 1st 2010 to September 31st 2011) was generally drier than the average previous 10 years (Table 7). Total precipitation in WY 2011 was 762 mm, which is 46 % lower than the 10-yr average. Daily air temperature reached its peak on August 2nd (33.6 ℃) and dropped to the lowest value of -13 ℃ on February 3rd. Average daily temperature during the period of this work was 13.2 ℃ (Table 6), which is nearly identical to the average past 10 years value (0.0 % difference) (Table 7).

In agreement with historic seasonal precipitation distributions, the spring season was the wettest season of the year. During WY 2011, 414 mm precipitation fell in Columbia during March 2011 and June 2011 totaling 54.4 % of the total precipitation of WY 2011 (762 mm). For comparison, in WY 2010, Columbia received 583 mm precipitation during the same time period (35.6 % of the total precipitation of the WY 2010 (1651 mm), Freeman (2011)).

Table 6: Annual precipitation and daily temperature descriptive statistics for WY 2011 (October 1st 2010-September 31st 2011) in Columbia, Missouri, USA.

	Annual Precipitation (mm)	**Average Daily Temperature (℃)**
Total	762	-
Min	-	-13.00
Max	-	33.61
Average	-	13.15
SD	-	11.47

Table 7: Comparison of annual precipitation and mean daily temperature between previous 10 years (WY2001-2010) and WY2011 (October 1st 2010-September 31st 2011) in Columbia, Missouri, USA.

	Annual Precipitation (mm)	**Average Daily Temperature (℃)**
10 Year Average	1109	13.2
WY 2011	762	13.15
% difference	46.0	0.0

STREAM BANK SOIL CHARACTERISTICS

Table 8 shows descriptive statistics for stream bank soil characteristics for the ten erosion pin plots (n=232) located in the floodplain of the HCW (Figure 2). Average bulk density was 1.32 g/cm^3, average porosity was 0.5, average volumetric water content was 0.32, average degree of saturation was 0.64, and void ratio was 1.02.

Table 9 shows the comparison of mean soil characteristics for the overall study, the BHF and Ag site. ANOVA tests indicated that there were not significant differences in terms of dry bulk density, porosity, and void ratio between the BHF and Ag site. However, there were significant differences of volumetric water content and degree of saturation between the sites ($P<0.05$).

Table 8: Soil characteristics (bulk density, porosity, volumetric water content, degree of saturation, and void ratio) for erosion pin plots in WY 2011, Columbia, Missouri, USA (n=232).

	Bulk Density (g/cm3)	**Porosity**	**Volumetric Water Content**	**Degree of Saturation**	**Void Ratio**
Max	1.61	0.63	0.47	0.92	1.70
Min	0.98	0.39	0.10	0.19	0.64
Average	1.32	0.50	0.32	0.64	1.02
Median	1.33	0.50	0.34	0.70	1.00
SD	0.11	0.04	0.09	0.18	0.17

Table 9: Mean soil characteristics (dry bulk density, porosity, volumetric water content, degree of saturation, and void ratio) for overall study site, Bottomland Hardwood Forest, and Agricultural site in WY 2011, Columbia, Missouri, USA.

	Sample Size (n)	**Bulk Density (g/cm^3)**	**Porosity**	**Volumetric Water Content**	**Degree of Saturation**	**Void Ratio**
Overall	232	1.32	0.50	0.32	0.64	1.02
BHF	113	1.33	0.50	0.28	0.57	1.01
Ag	119	1.32	0.50	0.35	0.70	1.02
P (BHF vs. Ag)	-	0.77	0.77	5.6E-8	3.8E-8	0.56

SOIL TEXTURE

Table 10 shows descriptive statistics for stream bank soil texture (percent silt, clay and sand). Average percent clay was 6.6, average percent silt was 27.9, and average percent sand was 65.5.

Table 11 shows mean percentage of clay, silt and sand of the stream banks for the overall study area, the Bottomland Hardwood Forest, and the Agricultural site. ANOVA results indicated that there was a significant difference in percent clay between the BHF and Ag site ($P<0.05$), whereas, there were no significant differences of silt and sand composition between the two sites ($P>0.05$).

Table 10: Percentage of clay, silt, sand and soil texture for ten stream bank erosion pin plots for Water Year 2011 in Columbia, Missouri, USA (n=100).

	%clay	**%silt**	**%sand**
Max	13.8	55.0	91.2
Min	1.3	5.0	41.2
Average	6.6	27.9	65.5
Median	6.3	27.5	66.2
SD	3.2	10.7	11.2

Table 11: Mean percentage of clay, silt, and sand for overall study site, Bottomland Hardwood Forest, and Agricultural site for Water Year 2011, Columbia, Missouri, USA.

Study Site	**Sample Size (n)**	**%clay**	**%silt**	**%sand**
Overall	100	6.6	27.9	65.5
BHF	50	8.1	26.2	65.8
Ag	50	5.2	29.6	65.2
P-value (BHF vs. Ag)	-	3.9E-6	0.1	0.8

Table 12 shows descriptive statistics for the stream bank soil with particle size >53 µm and <53 µm. The 53 µm cutoff represents the threshold of silt-clay and sand, which also separates cohesive and non-cohesive sediment (Eshel et al., 2004). Average percent of soil particles <53 µm was 34, average percent of soil particle >53 µm was 66. Percent of soil particles >53 µm and < 53 µm for the BHF and Ag were significantly different ($p<0.1$) (Table 13).

Table 12: Percent of soil with particle size >53 µm and particle size <53 µm for ten erosion pin plots (n=100) in floodplain area in Hinkson Creek Watershed, Central Missouri, USA (WY 2011).

	Particle size <53 µm (%)	**Particle size >53 µm (%)**
Max	73.6	90.7
Min	9.3	26.4
Average	34.0	66.0
Median	32.5	67.5
SD	14.2	14.2

Table 13: Average percent of soil with particle size >53 µm and particle size <53 µm for overall study site, Bottomland Hardwood Forest, and Agricultural site, Columbia, Missouri, USA (WY 2011).

Study Site	**Sample Size (n)**	**Particle Size <53 µm (%)**	**Particle Size >53 µm (%)**
Overall	100	34.0	66.0
BHF	50	31.6	68.4
Ag	50	36.4	63.6
P-value (BHF vs. Ag)	-	0.091	0.0012

STREAM BANK HEIGHT AND ANGLE

Table 14 shows descriptive statistics for the stream bank height and angle of the ten erosion pin plots (n=34). The highest stream bank was at plot I (averaged height: 4.9 m), whereas the shortest stream bank height was at pin plot E (averaged height: 2.7 m). The most vertical stream bank was plot E (we treated this stream bank as vertical with angle of 90 °), and plot A had the smallest stream bank angle with averaged value of 15.5 °.

Results of ANOVA indicated that the stream bank at the Ag site were significantly higher than the BHF site (P=0.01, α=0.05), however, the stream bank at the Ag site were not significantly steeper than the BHF site (P=0.21, α=0.05) (Table 15).

Table 14: Stream bank height and angle of ten erosion pin plots (n=34), Columbia, Missouri, USA (WY 2011).

Plot	Stream Bank Height (m)	Stream Bank Angle (°)
Max	4.9	90.0
Min	2.7	15.5
Average	3.5	32.2
Median	3.4	26.8
SD	0.6	21.5

Table 15: Average stream bank height and angle of overall study site, Bottomland Hardwood Forest, and Agricultural site, Columbia, Missouri, USA (WY 2011).

Plot	Sample Size (n)	Stream Bank Height (m)	Stream Bank Angle (°)
Overall	34	3.5	32.2
BHF	19	3.3	37.1
Ag	15	3.8	27.3
P-value (BHF vs. Ag)	-	0.01	0.21

VEGETATION COVER

Table 16 shows that erosion pin plot B (BHF) had the greatest herbaceous vegetation cover (82.6 %), the most sparse herbaceous vegetation cover was at erosion pin plot E (Ag) with vegetation cover of 21.8 %. The dominant herbaceous vegetation of the stream bank was *Glechoma hederacea* (ground ivy) at pin plot A, B, C, E, F, and J, while the dominant herbaceous vegetation cover was *Humulus japonicus* (japanese hop) at pin plot D, G, H, and I.

Results of ANOVA indicated that there were no significant differences in herbaceous vegetation cover between the BHF and Ag site (P = 0.61). The dominant herbaceous vegetation for the overall study site was *Glechoma hederacea* (ground ivy), taking up 25.1 % of the studied stream bank area, closely followed by *Humulus japonicus* (japanese hop) (22.59 %). The dominant herbaceous vegetation species covering the stream bank at the BHF site was *Glechoma hederacea* (ground ivy) (34.8 %), the second dominant species was *Humulus japonicus* (japanese hop) (10.1 %). Whereas, the dominant herbaceous vegetation species at the Ag site was *Humulus japonicus* (japanese hop) (35.1 %), the second dominant species was *Glechoma hederacea* (ground ivy) (15.4 %) (Table 17).

Table 16: Vegetation species and percentage of vegetation cover for ten erosion pin plots, Columbia, Missouri, USA (WY 2011).

Plot	Sample Size (n)	Top Three Vegetation Species	Percentage of Vegetation Cover in the plot (%)
A	14	Average Total Cover	46.57
		Glechoma hederacea (ground ivy)	43.36
		Polygonum hydropiperoides (swamp smartweed)	3.95
		Boehmeria cylindrica (smallspike false nettle)	2.36
B	14	Average Total Cover	82.64
		Glechoma hederacea (ground ivy)	53.21
		Urtica dioica (stinging nettle)	7.11
		Elymus viginicus (wild rye)	6.89
C	15	Average Total Cover	63.57
		Glechoma hederacea (ground ivy)	34.97
		Verbesina alternifolia (yellow ironweed)	7.00
		Polygonum hydropiperoides (swamp smartweed)	6.23
D	14	Average Total Cover	78.14
		Humulus japonicus (japanese hop)	47.50
		Glechoma hederacea (ground ivy)	33.43
		Polygonum hydropiperoides (swamp smartweed)	4.50
E	14	Average Total Cover	21.79
		Glechoma hederacea (ground ivy)	9.21
		Parthenocissus quinquefolia (virginia creeper)	3.14
		Humulus japonicus (japanese hop)	3.00
F	18	Average Total Cover	56.61
		Glechoma hederacea (ground ivy)	35.83
		Chasmanthiunm latifolium (river oats)	5.33
		Humulus japonicus (japanese hop)	4.06
G	15	Average Total Cover	55.00
		Humulus japonicus (japanese hop)	42.13
		Ambrosia trifida (giant ragweed)	5.67
		Sorghum halepense (johnson grass)	4.53
H	18	Average Total Cover	88.31
		Humulus japonicus (japanese hop)	79.58
		Glechoma hederacea (ground ivy)	9.72
		Polygonum virginianum (jumpseed)	0.72
I	18	Average Total Cover	68.42
		Humulus japonicus (japanese hop)	49.64
		Muhlenbergia spp. (muhly spp.)	3.17
		Sorghum halepense (johnson grass)	2.39
J	18	Average Total Cover	60.56
		Glechoma hederacea (ground ivy)	31.25
		Lonicera maackii (bush honeysuckle)	4.78
		Polygonum hydropiperoides (swamp smartweed)	3.78

Table 17: Vegetation species and percentage of vegetation cover for Bottomland Hardwood Forest, and Agricultural site, Columbia, Missouri, USA (WY2011).

Study Site	**Sample Size (n)**	**Top Three Vegetation Species**	**Percentage of Vegetation Cover (%)**
Overall	158	Average Total Cover	62.16
		Glechoma hederacea (ground ivy)	25.10
		Humulus japonicus (japanese hop)	22.59
		Polygonum hydropiperoides (swamp smartweed)	1.92
BHF	71	Average Total Cover	58.54
		Glechoma hederacea (ground ivy)	34.84
		Humulus japonicus (japanese hop)	10.10
		Polygonum hydropiperoides (swamp smartweed)	2.94
Ag	87	Average Total Cover	62.60
		Humulus japonicus (japanese hop)	35.08
		Glechoma hederacea (ground ivy)	15.36
		Sorghum halepense (johnson grass)	1.38

SOIL EROSION AND DEPOSITION RESULTS

Erosion Pin Plot Soil Loss and Gain Comparison

The maximum cumulative soil deposition occurred at pin plot J (1655 kg), whereas the maximum cumulative soil erosion occurred at pin plot I (8307 kg) over WY 2011 (Table 18). Total soil erosion from the ten erosion pin plots was estimated to be 17.88 tonnes, calculated using equation 2.6.

The maximum erosion rate (in depth) was 280 mm/WY at plot I, the maximum deposition rate (in depth) was 50 mm/WY at plot J, the average erosion rate for the ten erosion pin plots was 65 mm/WY. Stream bank erosion (i.e. soil loss) dominated over all study plots.

Table 18: Total magnitude of soil erosion/deposition, erosion/deposition per unit length, and erosion/deposition rate (in depth) of ten erosion pin plots in Columbia, Missouri, USA. Data collected from October 2010 to September 2011. Where (-) indicates soil loss.

Pin Plot	Mean Erosion/Deposition Rates* (mm/WY)	Total Soil Loss/Gain** (kg)
A	-8	-347
B	-14	-571
C	7	114
D	-1	-43
E	-74	-1165
F	-10	-347
G	-234	-6292
H	-87	-2577
I	-280	-8308
J	50	1655
Max	50	1655
Min	-280	-8308
Mean	-65	-1788
Median	-12	-459
SD	109	3126
Total	-	-17881

Note: * Mean erosion/deposition rates were calculated by averaging all the pin measurements (depth) in the plot. Mean erosion/deposition rate for a year was calculated by averaging monthly erosion/deposition rate for each pin plot.
** Total soil loss is cumulative soil loss over one year period of WY 2011.

BHF and Ag Soil Loss Comparison

The average erosion rate (in depth) was 18 mm/WY at the BHF site and 112 mm/WY at the Ag site (WY 2011). The magnitude of soil erosion from the stream banks (both sides of the stream banks within the study reach) at the Ag site was nearly 11 times greater than the BHF site (31.3 tonnes vs. 355.5 tonnes) over WY 2011. Considering all available data, the total magnitude of soil erosion from the stream bank within the study site was approximately 8049.1 tonnes for WY 2011 (Table 19). The stream bank soil erosion per unit length (i.e. per linear meter) at the BHF site was 65 kg/m, whereas it was 635 kg/m at the Ag site.

Table 19: Area, stream length, and total soil loss from the stream banks of Hinkson Creek Watershed, Floodplain area, Bottomland Hardwood Forest, and Agricultural site, Columbia, Missouri, USA.

	Area (km^2)	**Stream Length (km)**	**Mean Erosion Rate* (mm/WY)**	**Total Soil Loss** (tonnes/WY)**	**Erosion Per Unit Length*** (kg/m/WY)**
HCW	231	42	-	-	-
Floodplain	0.89	1.15	65	8049.1	-
BHF	-	0.24	18	31.3	65
Ag	-	0.28	112	355.5	635

Note: * Mean erosion/deposition rate for the plot was calculated by averaging all the pins reading (depth) in the plot. Mean erosion/deposition rate for a year was calculated by averaging monthly erosion/deposition rate for each pin plot.
** Total soil loss is cumulative soil loss over one year period of WY 2011.
*** Erosion per unit length was calculated by dividing total soil erosion from the stream banks of the each sub reach by its total stream bank length as per the methods of Zaimes et al. (2006).

Monthly Soil Loss Comparison

Table 20 shows that the maximum monthly deposition for the overall study reach occurred in March 2011 (845 kg), with deposition per unit length of 14 kg/m, and deposition rate of 3 mm. The maximum erosion occurred in January 2011 (4980 kg), with erosion per unit length of 95 kg/m, and erosion rate of 19 mm. The mean monthly soil loss was 1490 kg from the ten erosion pin plots. The mean monthly erosion per unit length was 29 kg/m, and mean monthly erosion rate was 5 mm.

The maximum monthly deposition for the BHF site occurred in March 2011 (661 kg), with deposition per unit length of 21 kg/m, and deposition rate of 5 mm. The maximum erosion occurred in February 2011 (1415 kg), with erosion per unit length of 50 kg/m, and erosion rate of 14 mm. The mean monthly soil loss was 168 kg from the ten erosion pin plots. The mean monthly erosion per unit length was 5 kg/m, and mean monthly erosion rate was 2 mm.

The maximum monthly deposition for the Ag site occurred in September 2011 (393 kg), with deposition per unit length of 16 kg/m, and deposition rate of 3 mm. The maximum erosion occurred in January 2011 (3980 kg), with erosion per unit length of 159 kg/m, and erosion rate of 27 mm. The mean monthly soil loss was 1322 kg from the ten erosion pin plots. The mean monthly erosion per unit length was 53 kg/m, and mean monthly erosion rate was 9 mm.

Two-way ANOVA tests indicated that there were significant differences of the monthly magnitude of erosion/deposition among all pin plots, and between the BHF and Ag site ($p<0.01$). Similarly, erosion/deposition per unit length and erosion/deposition rate varied significantly ($P<0.01$) monthly and spatially (differences among overall, BHF, and Ag).

Table 20: Monthly comparison of magnitude of erosion/deposition, erosion/deposition per unit length, and erosion/deposition rates from ten erosion pin plots in Hinkson Creek Watershed, central Missouri, USA. Data collected from October 2010 to September 2011.

	Magnitude of Erosion/Deposition* (kg)			**Erosion/Deposition Per Unit Length** (kg/m)**			**Erosion/Deposition Rates*** (mm)**		
	Overall	BHF	Ag	Overall	BHF	Ag	Overall	BHF	Ag
October-10	-289	-96	-192	-6	-4	-8	-1	0	-1
November-10	-444	-286	-158	-9	-11	-6	-2	-3	-1
December-10	-3195	562	-3756	-65	21	-150	-11	5	-27
January-11	-4980	-1000	-3980	-95	-31	-159	-15	-3	-27
February-11	-4666	-1415	-3251	-90	-50	-130	-19	-14	-23
March-11	845	661	184	14	21	7	3	5	1
April-11	-106	14	-121	-2	0	-5	-1	-2	-1
May-11	-2230	-182	-2048	-43	-3	-82	-8	-2	-15
June-11	-190	20	-210	-3	1	-8	-1	0	-2
July-11	-1952	-713	-1239	-37	-24	-50	-9	-9	-9
August-11	-1125	367	-1492	-24	12	-60	-3	3	-10
September-11	450	57	393	9	1	16	2	1	3
Max	845	661	393	14	21	16	3	5	3
Min	-4980	-1415	-3980	-95	-50	-159	-19	-14	-27
Average	-1490	-168	-1322	-29	-5	-53	-5	-2	-9
Median	-784	-41	-724	-16	-1	-29	-3	-1	-5
SD	1858	591	1522	36	20	61	7	5	11

Note: * The sum of soil loss from the ten erosion pin plots for each month.
** Monthly erosion/deposition per unit length was calculated by total mass of soil loss/gain divided by length of stream bank for each pin plot. Averaged pin plot monthly value to get mean monthly value for each site.
*** Mean erosion/deposition rate was calculated by averaging data from all pins.

Seasonal Soil Loss Comparison

Table 21 shows seasonal cumulative magnitude of erosion/deposition, seasonal average erosion/deposition per unit length, seasonal cumulative erosion/deposition rate. Considering the entire study reach (analysis for the ten erosion pin plots), winter (December, January, and February) had largest cumulative erosion (12.841 tonnes), with erosion per unit length of 83 kg/m, and erosion rate of 45 mm, followed by summer (June, July, and August) (3.266 tonnes, 21 kg/m, 13 mm) and spring (March, April, and May) (1.491 tonnes, 10 kg/m, 6 mm), fall (September, October, and November) season had lowest cumulative erosion (0.283 tonnes, 2 kg/m, 1 mm) over the WY 2011.

For the BHF site (analysis of the erosion pin plots A, B, C, D, E), winter (December, January, and February) had largest cumulative erosion (1.854 tonnes), with erosion per unit length of 20 kg/m, and erosion rate of 12 mm, followed by summer (June, July, and August) (0.326 tonnes, 4 kg/m, 6 mm) and fall (March, April, and May) (0.326 tonnes, 4 kg/m, 2 mm), fall (September, October, and November) season had cumulative deposition (0.494 tonnes, 6 kg/m, 2 mm) over the WY 2011.

For the Ag site (analysis of the erosion pin plots F, G, H, I, J), winter (December, January, and February) had largest cumulative erosion (10.987 tonnes), with erosion per unit length of 146 kg/m, and erosion rate of 78 mm, followed by summer (June, July, and August) (2.94 tonnes, 39 kg/m, 20 mm) and spring (March, April, and May) (1.985 tonnes, 26 kg/m, 15 mm), fall (September, October, and November) season had cumulative deposition (0.043 tonnes, 1 kg/m, 0 mm) over the WY 2011.

Two-way ANOVA tests indicated that there are significant differences of seasonal mass of erosion/deposition among overall, BHF and Ag site ($p<0.01$). Similarly, erosion/deposition per unit length and erosion/deposition rates varied seasonally and spatially (differences among overall, BHF, and Ag).

Table 21: Seasonal comparison of magnitude of erosion/deposition, and average erosion/deposition per unit length, and average erosion/deposition rate of the stream banks in the floodplain of Hinkson Creek Watershed, central Missouri, USA.

	Total Mass of Erosion/Deposition* (kg)			**Average Erosion/Deposition Per Unit Length** (kg/m)**			**Seasonally Erosion/Deposition Rate*** (mm/season)**		
	Overall	BHF	**Ag**	Overall	BHF	**Ag**	Overall	BHF	**Ag**
Spring	-1491	494	-1985	-10	6	-26	-6	2	-15
Summer	-3266	-326	-2940	-21	-4	-39	-13	-6	-20
Fall	-283	-326	43	-2	-4	1	-1	-2	0
Winter	-12841	-1854	-10987	-83	-20	-146	-45	-12	-78

Note: * Total mass of erosion was estimated by summing the monthly erosion from the ten erosion pin plots.
** Average erosion/deposition per unit length was calculated by averaging the monthly erosion/deposition per unit length for the ten erosion pin plot.
*** Seasonal erosion/deposition rate was calculated by summing the mean monthly erosion rate from the ten erosion pin plots.

SUSPENDED SEDIMENT FLUX ESTIMATION

Total suspended sediment load calculated from daily samples obtained (306 m upstream from the confluence of Hinkson Creek and Flat Branch Creek) at the BHF site was 45817 tonnes for the WY 2011. Suspended sediment totaled 65461 tonnes (575 m downstream from the confluence of Hinkson Creek and Flat Branch Creek) at the Ag site. Total suspended sediment contribution from Flat Branch (FB) creek during WY2011 was 7606 tonnes. Total erosion (i.e. both stream banks) was estimated to be 8049 tonnes in WY 2011. Based on this computation, there was a 12037 tonnes suspended sediment difference between suspended sediment loading from the BHF site (upstream) and contributions of Flat Branch creek and the Ag site. There was therefore 3989 tonnes of in-stream suspended sediment that must have come from other sources, such as channel bed erosion and terrestrial surface runoff.

Suspended sediment loading was correlated to stream discharge (r^2=0.84 for the BHF; r^2=80 for the Ag site) (Figure 11), stream sediment loading was proportional to stream discharge, and stream discharge and suspended sediment reached their peaks on January and May (Figure 10).

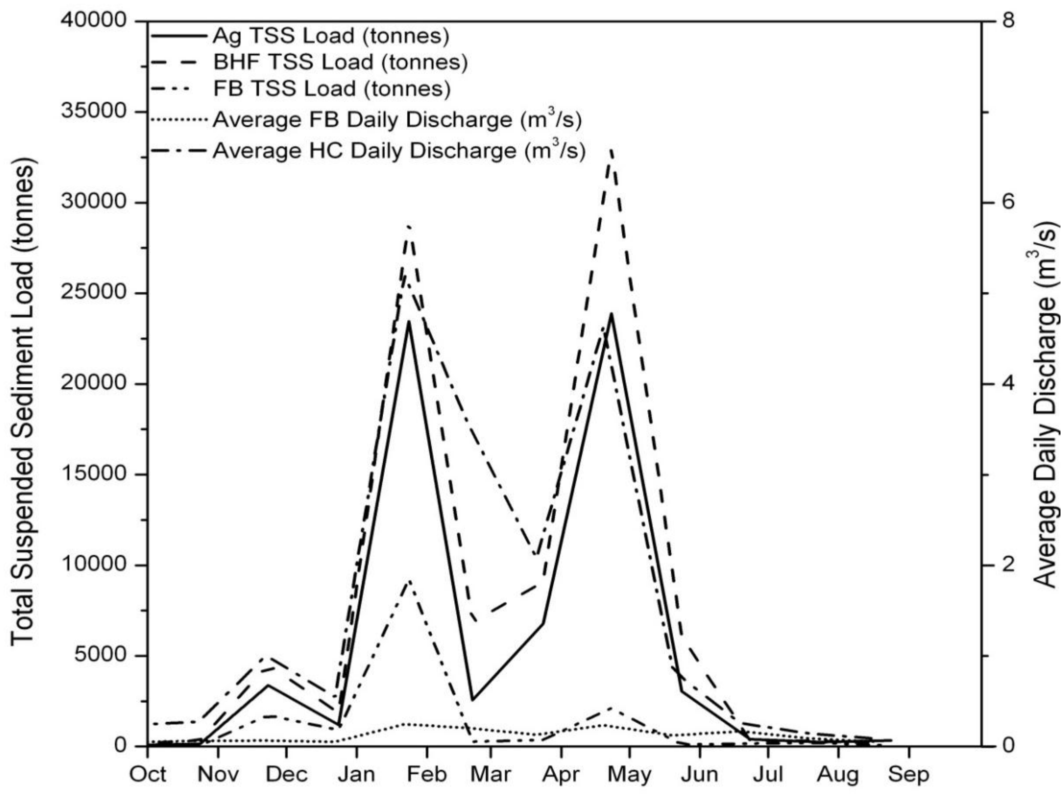

Figure 10: Total suspended sediment (TSS) (tonnes) from the Bottomland Hardwood Forest, Agricultural site, and Flat Branch Creek. Average daily discharge (m^3/s) from the Hinkson Creek and Flat Branch Creek, Columbia, Missouri, USA.

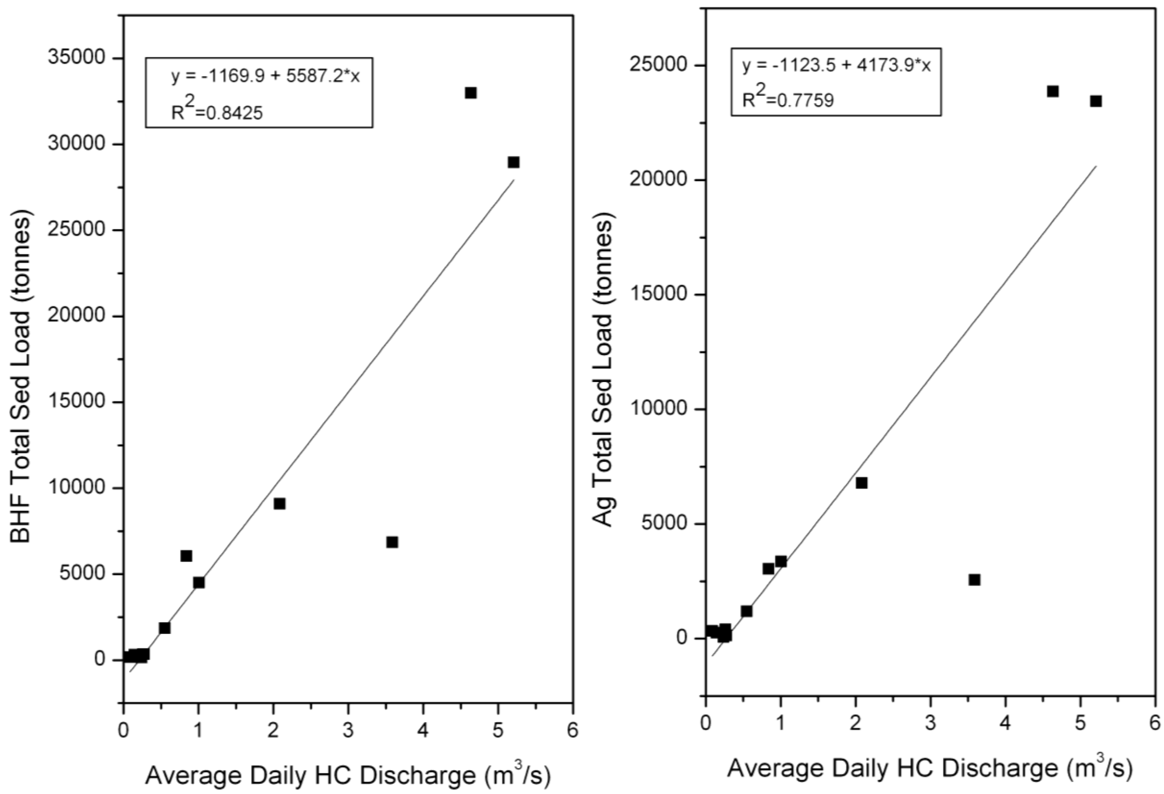

Figure 11: Regression plots of total suspended sediment load at the Bottomland Hardwood Forest and Agricultural site vs. Hinkson Creek daily mean discharge in Columbia, Missouri, USA.

CHAPTER IV

DISCUSSION

HISTORICAL HYDROCLIMATE

May, June and July were the wettest months in the City of Columbia from Water Year 2001 to 2011. Precipitation during spring, summer and early fall months is characterized by showers and thunderstorms. November, December, and February were the driest months (Figure 12), with most precipitation in the form of snow or rain or freezing rain (less frequent) (MCC, 2011).

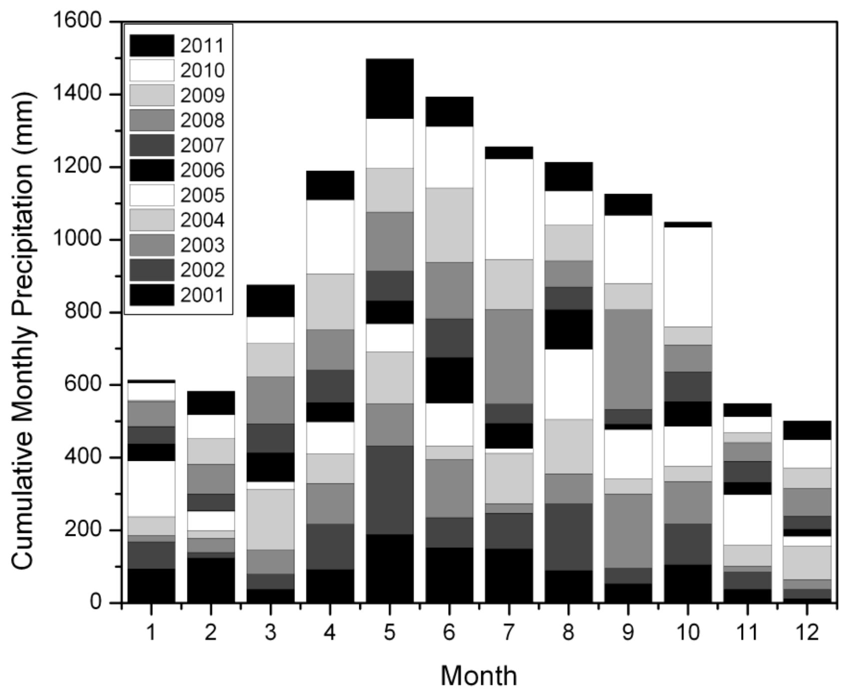

Figure 12: Cumulative monthly precipitation from Water Year 2001 to 2011(e.g. Water Year 2001: October 1st 2000 to September 31st 2001), Columbia, Missouri, USA.

Annual water yield and annual precipitation were monitored at the USGS gauging station and Sanborn field weather station at the University of Missouri respectively. Annual water yield is closely related to annual precipitation (Calendar Year: January 1st to December 31st) (A in Figure 13). 1980 was the driest year in Columbia with annual water yield of 67.1 mm. 2008 was the wettest year with annual water yield of 824.4 mm (note: years with missing stream discharge data are not considered in this comparison).

The ratio of annual precipitation and annual water yield varied year to year (B in Figure 13). The largest difference of annual precipitation and annual water yield occurred in 1980 (Q/P= 9.2), the smallest difference occurred in 2008 (Q/P= 1.8), indicating that the water loss (the disparity between precipitation and water yield) in 1980 was greater than that in 2008. There are many mechanisms that contribute to water loss, including evaporation, transpiration by plants, sublimation of snow, water storage in various locations, including lakes, wetlands, soil depressions, and the soil saturated or unsaturated zones (Zaimes and Emanuel, 2006). The difference between annual precipitation and annual water yield also varies with temperature; climate, land use/ land cover change, and topography as well as antecedent soil water content. Few data are available pertaining to collective historical temperature, topography and soil water content in Columbia. By analyzing urban land use trends, urban land use in Hinkson Creek Watershed has increased dramatically in recent years (Hubbart et al., 2011). There was only 7.9 % urban area in the HCW in 1993, it increased by 12.8 % and reached 20.7 % by 2005. By 2010, the urban area occupied 25 % of the HCW (Hubbart et al., 2011). The increase of impervious surface in Hinkson Creek Watershed can reduce the water infiltration rate and groundwater storage, and increase peak stream discharge and annual water yield (B in figure 13). These relationships may therefore be reflected in the ratios of annual precipitation and annual water yield in the most recent years (2008-2011) where they are smaller than most other years (B in Figure 13).

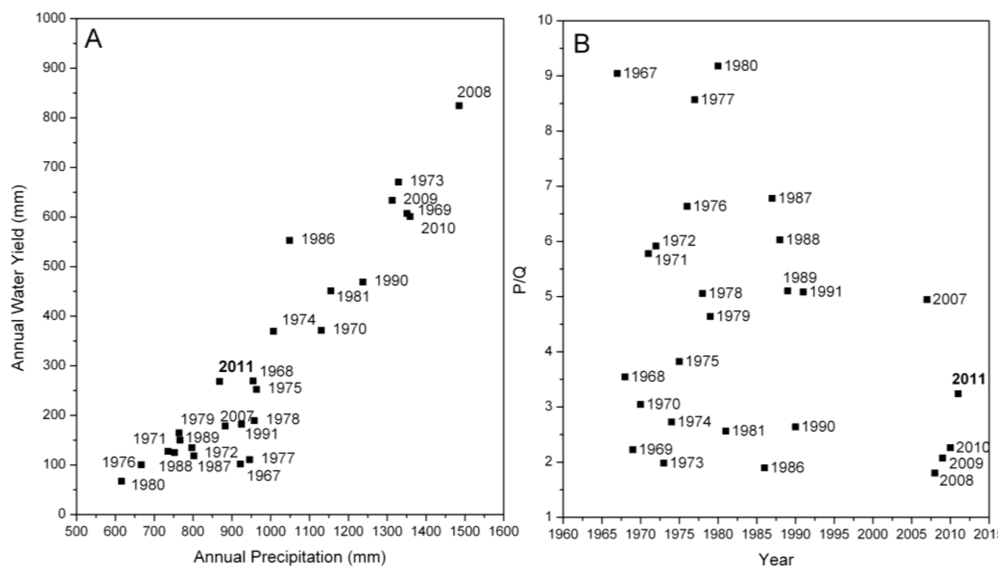

Figure 13: A) historical annual water yield and annual precipitation, B) ratio of annual precipitation (P) and annual water yield (Q) (Calendar Year 1967 - 2011).

HYDROCLIMATE OF WATER YEAR 2011

The city of Columbia, Missouri received total precipitation of 762 mm in WY2011, which was 54 % less than WY 2010 (1651 mm), and 46 % less than the average total precipitation of the past 10 water years (1109 mm). This observation is important because antecedent soil water content is a principal factor in stream bank erodibility since it affects the capacity of a stream bank to absorb overland flow thereby influencing soil infiltration rates (Wynn and Mostaghimi, 2006). Since there was relatively high rainfall in Water Year 2010 (total precipitation = 1651 mm), the antecedent water content of the stream bank soils of this study may have maintained a relatively high water content compared to previous years.

Figure 14 shows average daily precipitation, average daily discharge, and average daily temperature in Hinkson Creek Watershed. There were four relatively large precipitation events during the 2011 water year. Those events were on 12/31/2010 (37.1 mm), 5/12/2011 (30.7 mm), 5/25/2011 (43.2 mm), and 6/27/2011 (51.8 mm). Stream discharge had three peaks on 12/31/2010 (26.1 m^3/s), 2/28/2011 (25 m^3/s), and 5/25/2011 (35 m^3/s) respectively. The high stream discharge on 12/31/2010 and 5/25/2011 was likely due to high precipitation events; however, the stream discharge peak on 2/28/2011 may be due to snowmelt of approximately 46 cm of snowfall two days before 2/28/2011. The rise of temperature from below 0 ℃ in early February 2011 to a peak in mid-February (18 ℃) and stayed above 0 ℃ through the rest of the February resulted in rapid snowmelt, thus contributing to peak flows in February 2011.

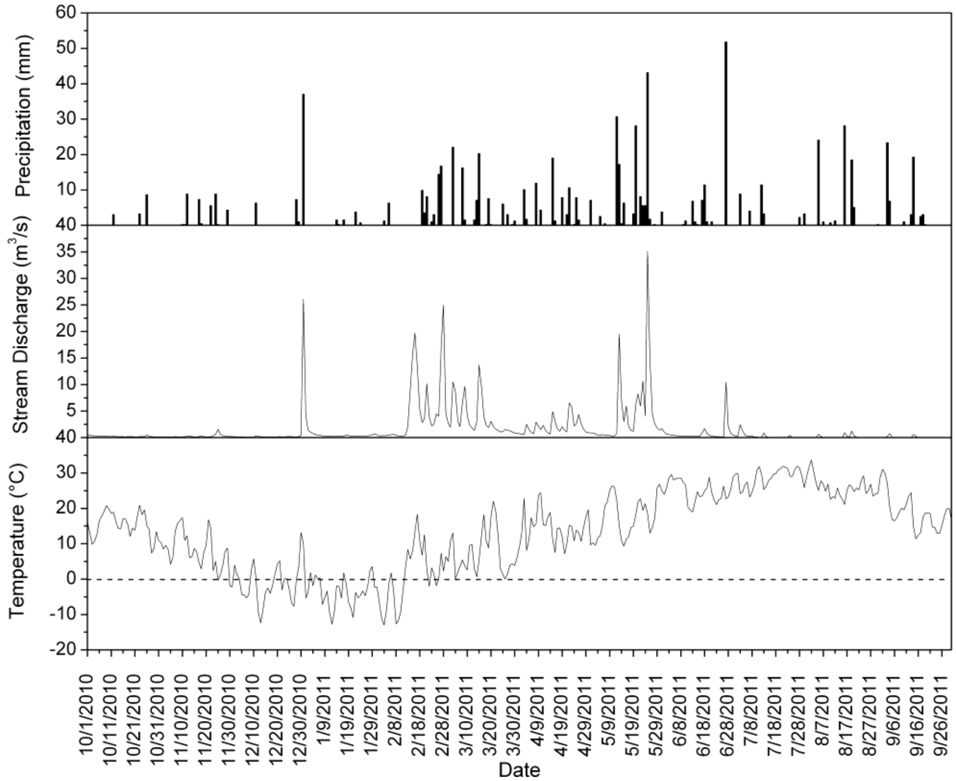

Figure 14: Mean daily precipitation, stream discharge, and air temperature for WY 2011. Discharge data collected from USGS gauging station (#06910230). Precipitation and temperature data collected from Sanborn Field on the University of Missouri Campus in Columbia, Missouri, USA.

STREAM BANK SOIL CHARACTERISTICS

Bulk Density

Bulk density is an indicator of infiltration and erodibility of soil (Wynn and Mostaghimi, 2006). Increases in soil bulk density can result in decreases of soil erodibility and increases of soil critical shear strength (Wynn and Mostaghimi, 2006). There was no significant difference of soil bulk density between the BHF and Ag site (A in Figure 15). This finding is consistent with the findings of Hubbart et al. (2011), who conducted a study that included soil bulk density on the floodplain area at the BHF and the Ag site (n=150 for BHF site; n=150 for Ag site) concluding it was not significantly different ($P>0.05$) in terms of soil bulk density between the sites. In the current study, this finding implies that soil bulk density may not be a principle factor contributing variations of stream bank erosion between these two sites.

Volumetric water content between the BHF and Ag sites was significantly different ($p< 0.05$) (B in Figure 15). Stream bank surface volumetric water content at the Ag site (0.35) was 7 % higher than the stream bank soil at the BHF site (0.28). Soil cores were collected in September 2010, when vegetation was mature and theoretically transpiring large amounts of water. Reduced surface soil water content was therefore likely due to increased surface evaporation and transpiration by woody vegetation adjacent to the stream banks. This is corroborated by the findings of Zaimes et al. (2006), who found that higher precipitation in September did not result in a large magnitude of stream bank erosion when row crops and other vegetation were mature. High relative transpiration of mature vegetation results in reduced soil water content, and increasing infiltration rate of ground soils. Hubbart et al. (2011) conducted a study of soil characteristics at the BHF site and Ag site (same study site with this research) at the floodplain area of Hinkson Creek Watershed, they calculated soil water content at depths of 0, 15, 30, 50, 75, and 100 cm (n=150) finding that volumetric water content over 1 m depths at the BHF site was 11% higher than the Ag site, concluding that woody vegetation helps increase infiltration rates and increases soil porosity and therefore soil water holding capacity.

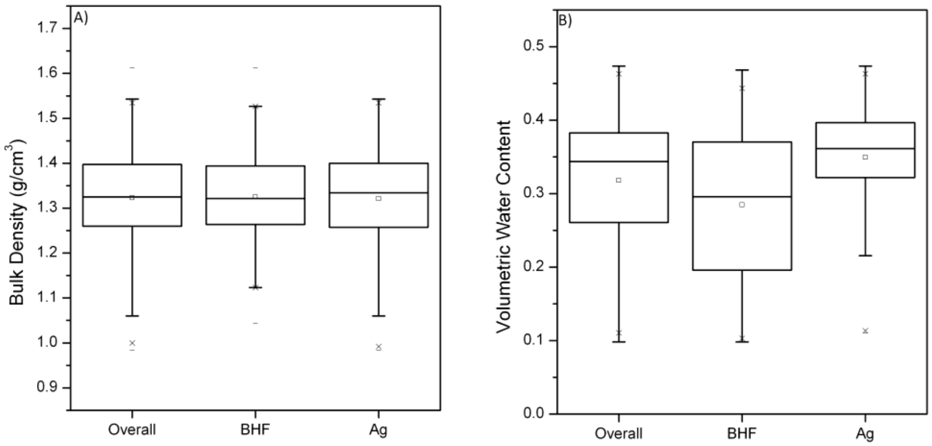

Figure 15: Box plot for soil bulk density (A) and volumetric water content (B) averaged between Bottomland Hardwood Forest, and Agricultural streambank study sites in Columbia, Missouri, USA.

Soil Texture

There was a significant difference detected ($P<0.05$) between clay contents of the stream banks of BHF and Ag site. Clay content of the stream bank at the BHF site was 54 % higher than the Ag site (8.1 % vs. 5.2 %). There was no significant difference detected between the BHF and Ag site in terms of silt and sand content ($p_{silt}=0.11$, $P_{sand}=0.79$, $\alpha= 0.05$) (Figure 16). Silt-clay content (particle size <53 μm) at the Ag site was significantly higher than the BHF site ($P= 0.091$, $\alpha= 0.1$) (Figure 17), sand content (particle size > 53 μm) at the BHF site was significantly higher than the Ag site. Stream banks with high silt-clay contents are known to be more vulnerable to subaerial erosion, which is primarily affected by soil water content (Couper et al., 2002). The stream bank at the Ag site had higher average silt-clay content. Therefore, it is possible that the stream bank at the Ag site has higher resistance to fluvial erosion relative to the BHF, but may be more susceptible to subaerial erosion. In contrast, there was higher percentage of sand content in the stream bank at the BHF site than the Ag site. This difference may be due to suspended sediment with larger particle size (e.g. > 53 μm) are more likely to settle out of suspension due to increased stream bank surface roughness provided by woody and herbaceous vegetation.

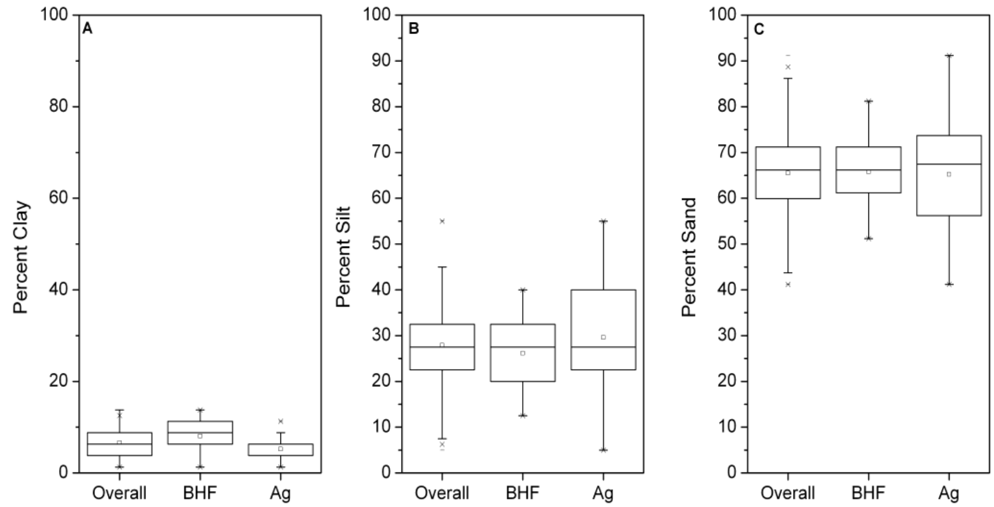

Figure 16: Percentage of clay, silt, and sand content of the stream bank soil for overall study site, Bottomland Hardwood Forest, and Agricultural site, Columbia, Missouri, USA (WY 2011).

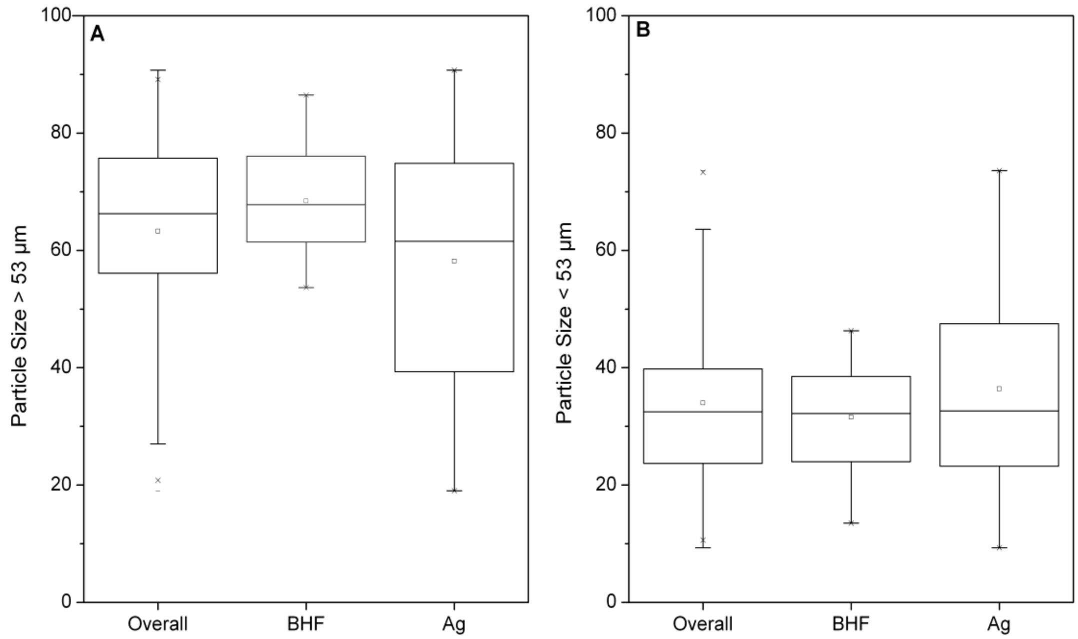

Figure 17: Mean percentage of soil with particle size >53 µm and particle size <53 µm for overall study site, Bottomland Hardwood Forest, and Agricultural site, Columbia, Missouri, USA (WY 2011).

STREAMBANK HEIGHT AND ANGLE

The stream bank heights ranged from 4.9 m to 2.7 m over the ten erosion pin plots. The stream banks at the Ag site were on average significantly higher than the BHF site ($P<0.05$) (Figure 18). The average stream bank height at the Ag site was 15.9 % higher than the BHF site (3.8 m vs. 3.3 m). Linear regression tests showed that there was no correlation between stream bank height and angle and erosion rate ($r^2 = 0.44$ for height; $r^2 = 0.14$ for angle). This finding is consistent with Laubel et al. (1999) who estimated erosion rates of stream banks at 33 stream reaches over one year and reported no significant relationships between stream bank erosion with stream bank height, bank angle, stream slope, and vegetation cover.

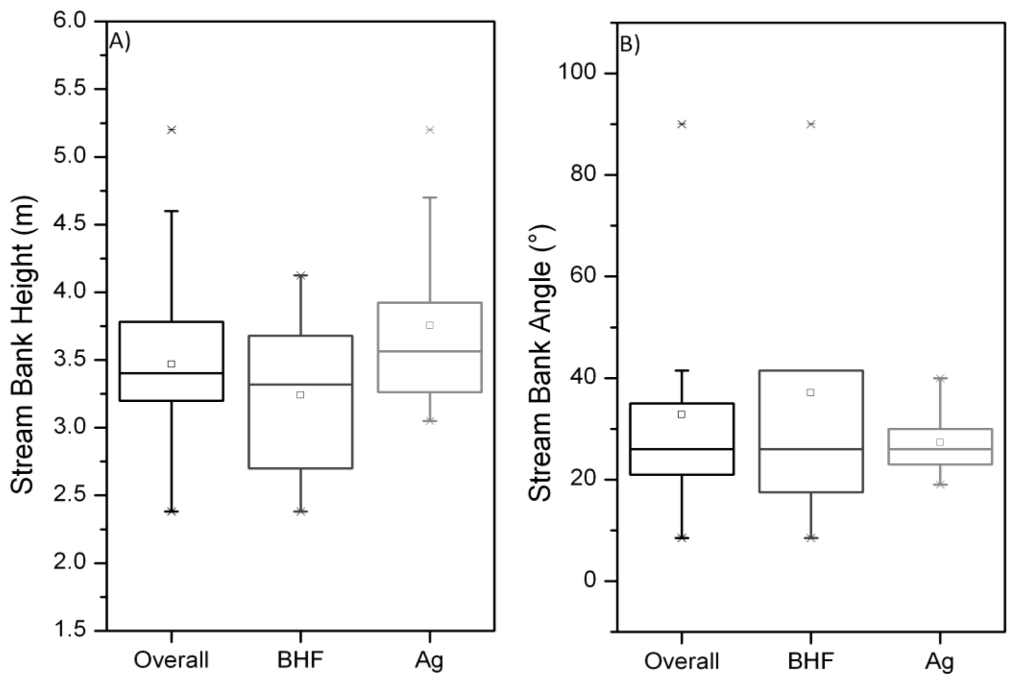

Figure 18: Box Plots showing stream bank height (m) and stream bank angle (°) of entire study reach, Bottomland Hardwood Forest, and Agricultural site in the floodplain of the Hinkson Creek Watershed, Columbia, Missouri, USA.

VEGETATION SURVEY AND COVERAGE

The dominant herbaceous vegetation covering the stream bank at the BHF site was *Glechoma hederacea* (ground ivy). The dominant herbaceous vegetation covering the stream bank at the Ag site was *Humulus japonicus* (japanese hop). The dominant woody vegetation at the BHF site included *Acer saccharinum* (silver maple), *Acer negundo* (boxelder), *Ulmus americana* (American elm), *Populus deltoids* (eastern cottonwood), and *Juglans nigra* (black walnut) (Hubbart et al., 2011). The woody vegetation adjacent to the stream bank of most erosion pin plots at the BHF site helped retain soil particles by virtue of extensive and expansive root systems. Presumably, the woody vegetation also provided favorable microclimate conditions around the stream bank thus maintaining soil water content that prevents stream bank drying (Wynn and Mostaghimi, 2006; Zaimes et al., 2006). However, there was not a linear relationship detected between vegetation cover and erosion rate in this work. Therefore, erosion rates were more likely affected by a combination of several factors, including precipitation, temperature, soil and bank characteristics and vegetation cover (Julian and Torres, 2006).

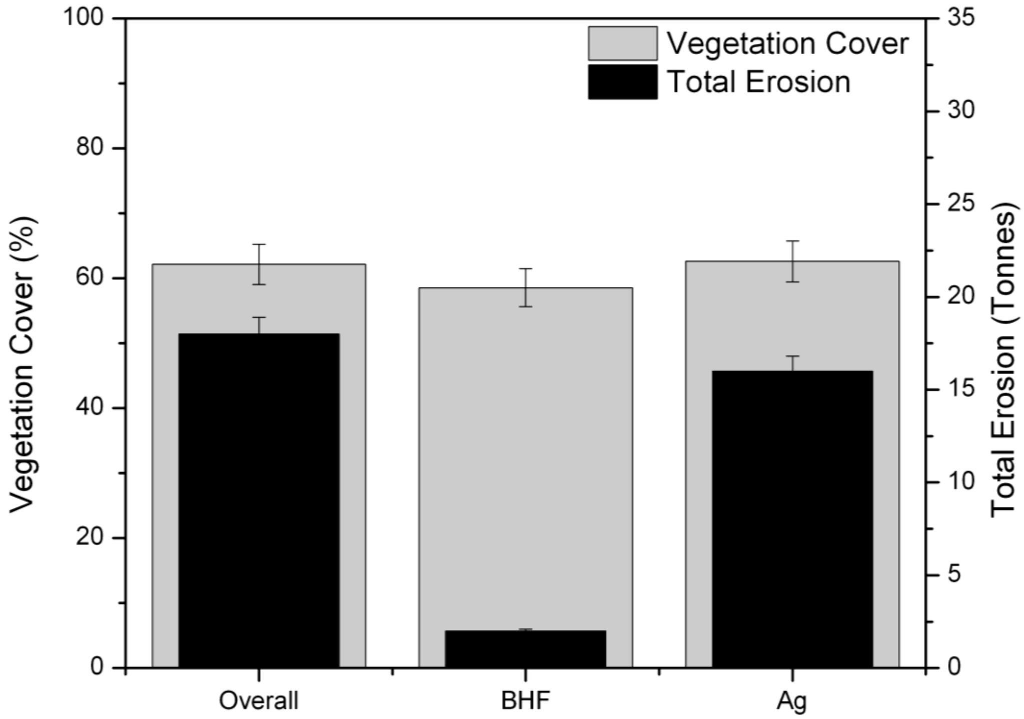

Figure 19: Percent herbaceous vegetation covering the stream banks and total soil erosion from entire study reach, Bottomland Hardwood Forest, and Agriculture site, Lower Hinkson Creek Watershed, Central Missouri, USA.

STREAM BANK EROSION AND DEPOSITION

Precipitation vs. Stream Bank Erosion and Deposition

Figure 20 shows that the significant erosion events were not coincident with high precipitation events or associated stream flow events in this study, but were more likely affected by a combination of several factors. The magnitude of bank erosion in December (3195 kg) was approximately seven times greater than in November (444 kg). There were nine small-sized (< 20 mm) precipitation events in November 2010, however, the temperature stayed above 0 ℃. There were three small sized (< 20 mm) and one medium sized (20-40 mm) precipitation event in December, and the temperature dropped to -12 ℃ in mid-December, freeze-thaw processes in December were likely to weaken the stream banks, reducing the stream bank shear strength prior to the medium size precipitation event (37 mm) occurring on December 31st 2010, causing much larger soil erosion comparing to the magnitude of soil erosion in November 2010. January had the highest magnitude of erosion (4980 kg), there were five small size precipitation events in January after the medium size precipitation on December 31st 2010. Stream banks may have been more susceptible to low stream flow erosion after freeze-thaw cycles (Zaimes et al., 2006). Stream discharge reached its peak on February 28th 2011, which contributed by snowmelt, may have prompted another high stream bank erosion event on the already weakened stream banks.

There were 40 medium (20-40 mm) to small (<20 mm) precipitation events during the spring months. High frequency of smaller precipitation events conceivably puts little hydraulic stress on stream banks (relative to larger events), and could lead to accumulation of sediment on stream banks. This may also be attributable to root systems of woody and herbaceous vegetation that increase stream bank surface roughness. Sediment may thus settle out of suspension and deposit on the stream banks. Relatively low precipitation was therefore adequate for vegetation growth, but not sufficient for soil erosion (Zaimes et al., 2006). The peak precipitation events did impact stream bank erosion in this study. For example, a great deal of erosion in May 2011 was likely due to high peak discharge associated with high precipitation. Rapid drawdown of the water table in the banks during the recessional limb of hydrographs may also cause substantial bank erosion (Lawler et al., 1999; Simon et al., 2000). Similar studies conducted by Hooke (1979), Knighton (1973), Zaimes et al. (2006), and Julian and Torres (2006) showed that peak flow intensity is one of the most significant factors causing stream bank erosion. Several small precipitation events (<30 mm) in August and September 2011, were not high enough to maintain higher flows. This coupled with high surface evaporation and plant transpiration (ET) and soil infiltration (Zaimes et al., 2006) can effectively reduce surface runoff leading to reduced streamflow.

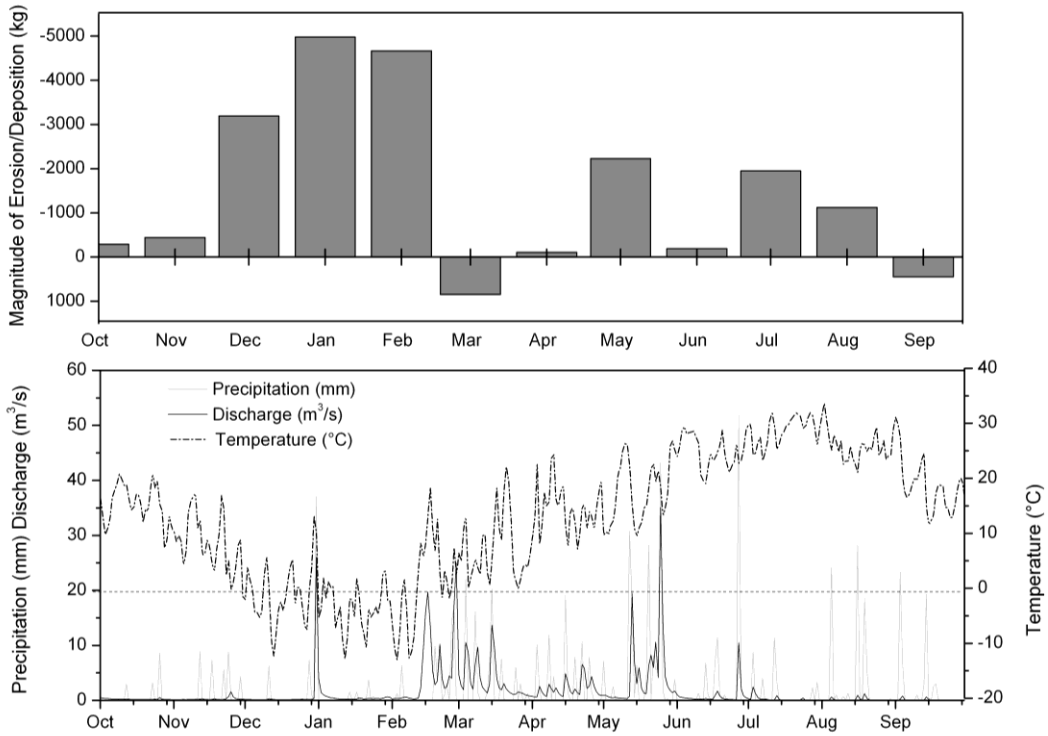

Figure 20: Cumulative monthly magnitude of erosion/deposition of stream banks and daily mean precipitation, daily mean stream discharge, and daily mean temperature in Hinkson Creek Watershed, Missouri, USA (WY 2011).

Erosion/Deposition among Erosion Pin Plots

The maximum total soil deposition occurred at pin plot J (1655 kg), while the maximum total soil loss (erosion) occurred at pin plot I (8308 kg) over WY 2011. Comparison of the soil bulk density of the stream banks at plot I and Plot J indicated that the bulk density at Plot I was 3.7 % higher than plot J. Previous research showed that higher soil bulk density results in greater soil critical shear strength (Asare et al., 1997; Wynn and Mostaghimi, 2006). The water moisture content and vegetation cover at Plot I was 10 % and 12 % less than plot J respectively. Wynn and Mostaghimi (2006) stated that maintaining at least 10 % pore water in the soil profile can improve soil strength by improving cohesion among soil particles. Silt-clay content of the stream bank soil at pin plot I was 65 % higher than pin plot J, stream banks with high silt-clay content may have been susceptible to sub-aerial erosion but had high resistance against fluvial entrainment (Couper, 2004). Therefore, pin plot I was probably more susceptible to sub-aerial erosion. Furthermore, the average bank height and angle of plot I was 49 % and 84 % higher than that of plot J. Due to a relatively high and steep stream bank at pin plot I, the stream bank was thus physically more prone to failure. In May 2011, the stream bank collapsed due to high rainfall thus contributing greatly to total erosion.

Table 22: Comparison of stream bank soil and bank characteristics, soil loss/gain, and erosion/deposition rate between pin plot I and J at the Floodplain study reach of Hinkson Creek Watershed, Central Missouri, USA.

Pin Plot	**BD (g/cm^3)**	**SWC**	**PS<53 µm (%)**	**VC (%)**	**ABH (m)**	**ABA (°)**	**TSLG (kg)**	**EDR (mm/WY)**
I	1.39	37	53	68	4.9	74.7	-8308	-280
J	1.34	28	32	61	3.3	40.7	1655	50
%diff	3.7	-10	65	-12	49	84	-	-

Note: BD: Bulk Density; SWC: Soil Water Content; PS: Particle Size; VC: Vegetation Cover; ABH: Average Bank Height; ABA: Average Bank Angle; TSLG: Total Soil Loss/Gain; EDR: Erosion/Deposition Rate.

As previously discussed, woody vegetation can help improve microclimate around stream banks by providing shading in summer time thus reducing dryness of stream banks (Wynn and Mostaghimi, 2006). In addition, strong root systems can increase soil cohesion and tensile strength in the near surface soil, thus supporting soil aggregation that prevents soil sub-aerial erosion (Wynn and Mostaghimi, 2006). There was a lack of woody vegetation at or adjacent to pin plot I at the Ag site (Figure 21). At the Ag site, the upper stream bank was covered by herbaceous vegetation, including the dominant plant *Humulus japonicus* (japanese hop), *Glechoma hederacea* (ground ivy), and *Sorghum halepense* (johnson grass). Even though herbaceous species can provide some stream bank protection against erosion, the contribution was less obvious since the stream bank was observed to dry much more quickly under herbaceous vegetation cover due to high surface evapotranspiration and corresponding shallow root systems. The exposed lower portions of the stream bank were frequently immersed in water and impacted by hydraulic erosion, causing the stream bank toe undercutting that reduced stream bank stability. Zaimes et al. (2006) corroborated this finding concluding that upper parts of the stream bank protected by perennial vegetation had less erosion than lower exposed parts of the stream bank that were susceptible to fluvial entrainment. Pin plot J was covered by herbaceous vegetation as well as woody vegetation, with short and gradual slope stream bank relative to pin plot I. It was more likely that the sediment settled out of the flow and deposited on the stream bank at pin plot J, soil erosion reduced due to the surrounding trees and herbaceous vegetation cover (Figure 21).

Figure 21: Comparison of erosion pin plot I and J at the floodplain study reach of Hinkson Creek Watershed, Central Missouri, USA. Photos taken August 1st 2011.

BHF vs. Ag Soil Loss

The soil loss from the BHF site (both sides of the stream banks within the study reach) (31.3 tonnes) was approximately 11 times less than the Ag site (355.5 tonnes). There were no statistically significant ($P<0.05$) differences between bulk density, herbaceous vegetation cover and stream bank slope between the BHF site and Ag sites, however, volumetric water content, silt-clay component (particle size <53 µm), and stream bank height were significant different between the BHF and Ag site ($P<0.05$) (Table 23). It was observed that woody vegetation at the BHF site adjacent to the stream bank had strong root systems to support the stream bank and retain soil particles in place, thus helping prevent stream bank erosion. Other authors have likewise made these connections (Burckhardt and Todd, 1998; Zaimes et al., 2004). Smith (1976) reported that erosion rates were inversely proportional to root volume in bank soils. The stream bank soils composed of silt without roots had erosion rate of 264.5 kg/hr, while the stream banks consisting of silt and 16 to 18 % root reinforcement had erosion rates of only 0.55 kg/hr. Erosion rates reduced to 0.01 kg/hr when the stream bank consisted with silt and 16 to 18 % root reinforcement and 5 cm of root riprap. Burckhardt and Todd (1998) indicated that non-forested stream banks suffered from five times greater erosion than their forested counterparts during high flow events. As mentioned earlier, woody vegetation also provides shading in the summer time, thus reducing soil temperature and maintaining higher soil moisture relative to non-forested banks. Wynn and Mostaghimi (2006) reported that soil water stress was 13 to 57 % lower in a woody vegetation dominated environment than herbaceous vegetation dominated environments, because large volume of roots of woody vegetation has wider and deeper extension in soil profiles than herbaceous vegetation to satisfy evapotranspiration demands and still maintain relatively high level of water in near surface soils. Conversely, stream banks covered with herbaceous vegetation may have lower capacity of maintaining soil water content during the summer time due to high rates of water consumption by relatively shallow rooted and low-lying herbaceous plant species.

Table 23: Comparison of stream bank soil parameters and stream bank characteristics of the BHF and Ag site in Hinkson Creek, Columbia, Missouri, USA.

Study Site	**Bulk Density (g/cm^3)**	**Vegetation Cover (%)**	**Volumetric Water Content**	**Particle Size <53 µm (%)**	**Particle Size >53 µm (%)**	**Average Bank Height (m)**	**Averaged Bank Angle (%)**
BHF	1.32	58.54	0.29	31.59	68.41	3.27	54.36
Ag	1.32	65.78	0.35	36.39	63.61	3.79	51.8
P-value	0.77	0.74	5.6E-8	0.091	0.0012	0.00888	0.67

Comparison of Erosion Rates with Other Studies

Erosion rates in this study varied with land use. The Bottomland Hardwood Forest had less stream bank erosion than the Agricultural land (18 mm/year vs. 112 mm/year). Other studies with comparable drainage area sizes show similar results ranging from 4 mm/year (Willett, 2010; Zaimes et al., 2006) to 580 mm/year (Twidale, 1964) in different land uses and soil types (Table 24).

Table 24: Erosion rate comparisons of streams of comparable drainage area size (0-200 km^2) using the erosion pin method.

Reference	**Location**	**Drainage Area (km^2)**	**Erosion Rate (mm/WY)**
Current study (HCW)	Central Missouri, USA	179.5	-
Bottomland Hardwood Forest		-	18
Agricultural land		-	112
Willett (2010)	Northeastern Missouri, USA	284	4-387
Zaimes et al. (2006)	Iowa, USA	52	4-295
Gardiner (1983)	Lagan, North Ireland, UK	85	80-140
Twidale (1964)	R. Torrens, Australia	77.8	580

SEASONAL EFFECTS ON BANK EROSION

This work showed that the greatest stream bank erosion occurred during the winter time of WY 2011 (12.8 tonnes). This figure is four times higher than the erosion during the summer of WY 2011 (3.3 tonnes, the second greatest stream bank erosion) for the whole study reach (Figure 22). These findings are consistent with previous research. Wolman (1959) and Lawler et al. (1999) indicated that the greatest magnitude of stream bank erosion occurred in the winter season (December- March) due to high precipitation events and freeze-thaw mechanisms. During the winter season of WY 2011, there was a total of 18 precipitation events (one medium size (20-40 mm) and 17 smaller events (<20 mm). This was the fewest precipitation events occurring among the four seasons (Table 25). However, freeze and thaw cycling occurred in the stream bank may have weaken the stream bank. Thus, soil cohesion was reduced and the stream bank was more vulnerable to fluvial entrainment (Hooke, 1979), thus resulted in greater magnitude of bank erosion. In addition, in winter time, stream banks are generally wet and near saturated. With relatively high water content in stream bank soils, the stream banks are not able to absorb large volumes of rainfall or overland flow, thus resulting in higher peak discharge and higher potential bank erosion. These findings are corroborated in the results of multiple previous studies (Willett, 2010; Wolman, 1959; Zaimes et al., 2006).

There were a higher number of medium to high precipitation events in the spring and summer seasons (Table 25) than the winter and fall seasons. The high erosion events likely occurred after each high precipitation event coupled to high peak discharge in the study reach (the urban area of Hinkson Creek Watershed) as discussed earlier. The fall season had lowest erosion (283 tonnes). This was assumed due to less frequency and intensity of precipitation events, and high water absorption and high soil erosion prevention by vegetation.

Table 25: Low, medium and high precipitation events in Spring, Summer, Fall, and Winter of WY 2011 in Columbia, Missouri, USA.

Season	Low (< 20 mm)Daily Precipitation Events	Medium (20-40 mm) Daily Precipitation Events	High (>40 mm) Daily Precipitation Events
Spring	36	4	1
Summer	21	2	1
Fall	19	1	0
Winter	17	1	0

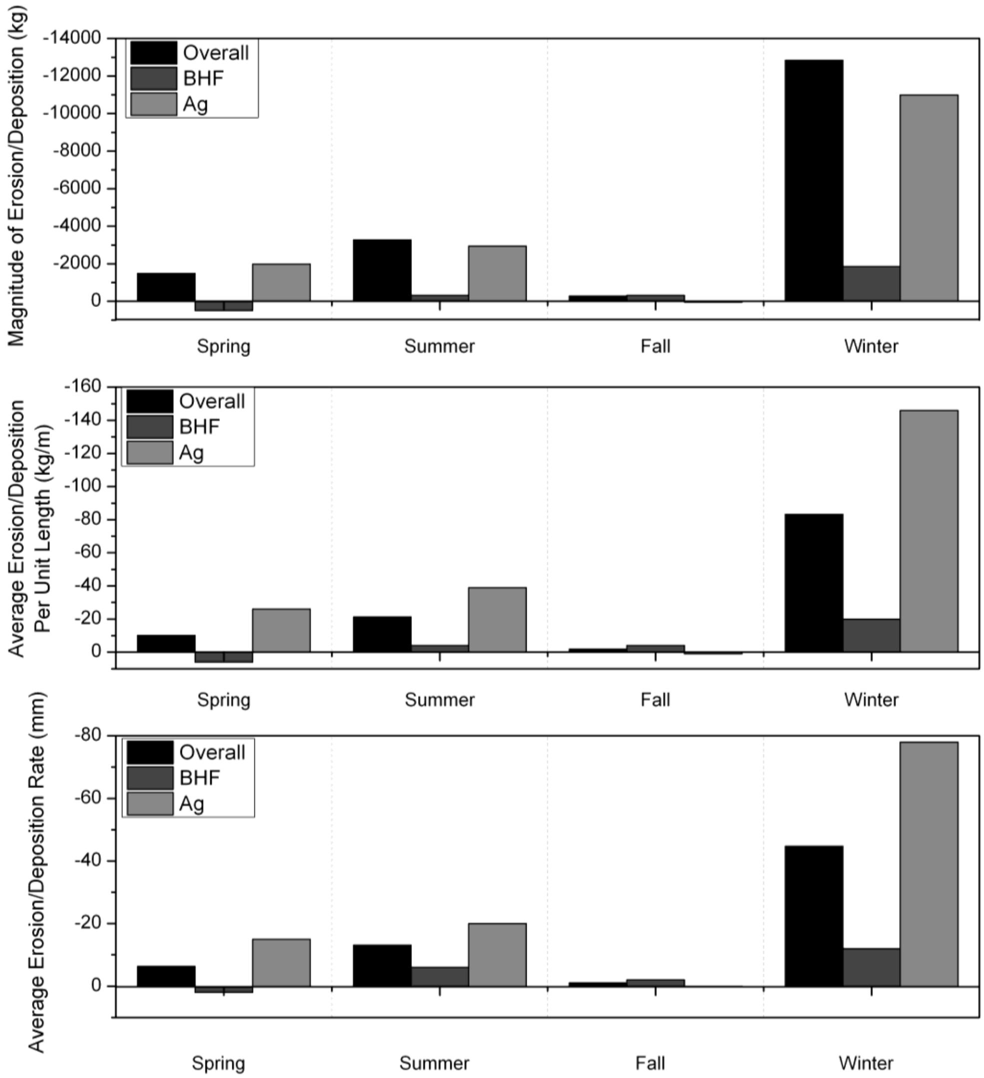

Figure 22: Seasonal erosion rates of stream banks at the floodplain of Hinkson Creek Watershed, Central Missouri, USA (WY 2011). Spring: March, April, and May: Summer: June, July, and August; Fall: September, October, and November; Winter: December, January, and February. Where erosion (i.e. soil loss) is negative (-).

IN-STREAM SUSPENDED SEDIMENT FLUX

Analyses of bank erosion rates and mass supplied information necessary to estimate the difference between suspended sediment at the upstream and 1.15 km downstream of the study reach during WY 2011. Results indicated that Flat Branch Creek (the tributary of the HCW), contributed 7606 tonnes of suspended sediment to Hinkson Creek. There was 8049 tonnes of soil erosion estimated from the stream banks (both sides of the stream banks) within this 1.15 km study reach. There was thus (by residual) 3989 tonnes of suspended sediment left over, either originating from other potential terrestrial diffuse sources, channel bed erosion, or measurement error. If it is assumed that the major sources of in-stream suspended sediment originate from stream in-stream processes (e.g. bank erosion, channel bed incision and surface runoff), stream bank erosion comprised as much as 67 % of in-stream suspended sediment loading during this study. Other sources (e.g. surface runoff, stream bed erosion) comprised the remaining 33% of in-stream suspended sediment loading during WY 2011. The results of the current study are generally consistent with previous study findings with similar watershed characteristics. Trimble (1997) investigated 196 permanent marked cross sections at intervals along San Diego Creek, Southern California from 1983 to 1993 and found that channel incision was responsible for approximately two thirds of the sediment yield. Willett (2010) indicated that 58 % of suspended sediment originated from bank erosion, and 42 % of suspended sediment was from overland areas in Crooked and Otter Creek Watersheds located in northeastern Missouri within the Salt River Basin. Mukundan et al. (2011) reported that stream bank erosion contributed as much as 90 % of the total sediment load in the North Fork Broad River watershed in the Piedmont region of Georgia that drains an area of 182 km^2. Laubel et al. (1999) conducted a stream bank erosion survey in a basin located in central Jutland, Denmark and found that 60 to 90 % of suspended sediment load was derived from stream bank erosion. Given the results of previous studies, the results generated here are reasonable. It is arguable that much of the remaining 33 % of sediment load yet unaccounted for, may come from bed incision processes, given urbanization associated channel straightening, and related hydro-geomorphological alterations.

The in-stream suspended sediment flux estimation of this work was based on the following assumptions: (1) particle density was 1.95 g/cm^3. This value was derived from Freeman (2011), who conducted an analysis comparing the ratio of gravimetric analysis and volumetric analysis of suspended sediment in the Hinkson Creek Watershed during water year 2010 and concluded 1.95 g/cm^3 as the mean suspended sediment particle size in the current study segment of the Hinkson Creek; (2) there is an equal magnitude of erosion from the opposite side (left side when facing downstream) of the stream bank. Since the stream channel is meandering, stream flow scours the right bank side and deposits sediment on the left bank side, as stream flow goes further downstream, it scours the left bank side and deposits sediment on the right bank side, therefore, estimation of total soil erosion from both stream banks within the study site by doubling erosion from one single side is a reasonable approach; (3) suspended sediment is distributed in the stream homogenously. This is understood to be the case particularly during high flow events which are common in flashy hydrocliamte on the Midwest, USA (Edwards and Glysson, 1970; Porterfield, 1972). Previous authors used employing point-based, or grab-sample based sampling methods to investigate suspended sediment loading (Horowitz, 2003; Lee et al., 2009), and found it an appropriate method to estimate suspended sediment load.

ANTHROPOGENIC INFLUENCES ON BANK EROSION

Human activities can have significant impacts on stream bank stabilization, especially in urbanizing watersheds. Increased impervious surface area, including buildings, parking lots, and pavement enhances surface runoff. Increased stream discharge scours stream banks and causes increased suspended sediment load. These impacts have been observed by other researchers. For example, Bledsoe and Watson (2001) claimed that 10 to 20 % impervious surface can destabilize stream banks and abruptly degrade indices of aquatic ecosystem integrity. The city of Columbia has developed and expanded quickly. In 1993, there was only 7.9 % of urban area; by 2005, it was 20.7 % of urban area; it was 25 % urban area in 2010 (Hubbart et al., 2010). In June 2011, the city of Columbia started constructing a sewage line across the Ag site approximately 40 m away from the stream. A large volume of groundwater was pumped to the creek. The process of pumping water from the inland area to the creek created an artificial waterfall that further eroded the stream bank surface. By the authors' observation, it is estimated that the magnitude of stream bank erosion due to the artificial waterfall amounted to approximately 0.2 % of the total erosion (~8 tonnes).

METHODOLOGICAL DISCUSSION

The erosion pin method has been widely used and has been demonstrated to be an effective way to estimate stream bank erosion at smaller scales. The method provides relatively accurate estimations of magnitude of stream bank erosion relative to stream bank erosion models and satellite imagery analysis. However, the erosion pin method does have some disadvantages, including (but not limited to):

(1) Stream bank disturbance by human access to the stream bank and animal crossing can affect erosion/deposition measurements (i.e. compaction).

(2) Climate conditions such as frozen heave, stream bank swelling-shrinking may affect erosion pin readings in ways unrelated to stream hydro-geomorphological processes.

(3) Erosion pins that become buried or washed away could cause data gaps or overestimate or underestimate actual values.

The PEEP method may supply a viable alternative to the tradition erosion pin method. As mentioned in Lawler (2005), the PEEP allows measurement of magnitude, frequency, and timing of stream bank erosion more precisely than the conventional erosion pin method since the traditional method requires manual measurement of erosion pin length, which is labor intensive, costly, and difficult to complete in a timely manner (i.e. equal interval, event based, etc.), whereas the PEEP monitors erosion and erosion process with a accuracy to hours since it applies solar radiation sensors in the stream banks like the traditional pins, as erosion occurs, increased solar energy is sensed corresponding to erosion. With the aid of Thermal Consonance Timing, soil erosion can be monitored at night (Lawler, 2005). These two techniques enable monitoring stream bank erosion at a fine temporal scales resulting in higher resolution data.

Finally, the estimates of contributions of stream bank erosion and surface runoff to in-stream suspended sediment load calculated in this work were based on several assumptions discussed earlier. Improved accuracy may be achieved by refinement of rating curves, quantifying bed load, bed incision processes, validation of particle density estimations, stream bank erosion surveys on both sides of the stream channel, and evaluation of stream cross section sediment distribution. The fingerprinting isotope tracer method (Collins et al., 2001) may provide yet another method to estimate sources of in-stream suspended sediment.

FUTURE DIRECTIONS

One year data is obviously insufficient to estimate inter-annual variations of stream bank erosion and deposition dynamics. Therefore, additional years of stream bank erosion and deposition data collection are necessary to detect annual statistical annual trends of stream bank erosion/deposition rates and response to variable climate and disturbances (Laubel et al., 1999). Zaimes et al. (2006) conducted a stream bank erosion survey from June 1998 to July 2002, four years of stream bank erosion data provided an improved evaluation of the temporal variation of stream bank dynamics. In the current study, the winter in WY 2011 was cold, while the winter in WY 2012 was warmer. Climate differences such as these will provide useful comparisons of stream bank erosion under different climate scenarios.

CHAPTER V

CONCLUSIONS

The work presented in this study quantifies stream bank erosion and deposition rates in a floodplain stream of an urbanizing watershed in central Missouri. Study objectives were to quantify annual and seasonal stream bank erosion and deposition rates in a lower reach of the Hinkson Creek Watershed, in central Missouri, USA. An additional objective was to examine land-use impacts on stream bank erosion/deposition rates in urban conditions, and bank erosion contributions to in-stream suspended sediment load. New information generated in this research will improve stream ecosystem health evaluations and water quality management in complex urban ecosystems by quantitatively identifying the primary sources of in-stream suspended sediment loading, thus allowing implementation of the most cost effective measures to reduce suspended sediment load in streams.

WY 2011 was relatively dry and cold compared to the ten year average. Soil bulk density was not significantly different between the stream banks at the BHF and Ag sites, while volumetric water content at the Ag site was 7 % higher than the BHF site. Silt-clay percentage of the stream banks at the BHF site was significantly higher than the Ag site ($P=0.09$, $\alpha=0.1$). Stream bank height at the Ag site was significantly higher than the BHF site ($P=0.01$, $\alpha=0.05$). However, no significant difference of the stream bank angles between the two sites was detected ($P=0.21$, $\alpha=0.05$). There was no significant difference detected between herbaceous vegetation covering the stream banks between the BHF and

Ag site. Stream bank erosion and deposition rates varied spatially and temporally, and were affected by several factors including (precipitation, soil texture, vegetation cover, stream bank geometry). These findings are consistent with previous studies (Julian and Torres, 2006).

In WY2011, the magnitude of erosion from the BHF site was 31.3 tonnes as opposed to 355.5 tonnes in the Ag site (two sides of the stream banks). The erosion per unit length was 65 kg/m at the BHF site and 635 kg/m at the Ag site. The erosion rate was 18 mm/year at the BHF site and 112 mm/year at the Ag site. Stream bank erosion was affected by factors including precipitation, peak discharge, and land use types. Erosion rates varied seasonally and yearly. The erosion rate in the winter (45 mm) was 3.4 times greater than the summer season (13 mm). The fall season had smallest erosion rate (1 mm). During the winter season, when evaporation and temperatures were low, stream bank soil was nearly saturated; the stream banks were therefore vulnerable to fluvial entrainment and rainfall. Freeze-thaw cycles, and frost heave may have exerted additional stress on the stream banks. This finding was consistent with the previous studies in similar settings (Zaimes et al., 2006). Peak discharge coupled to weakened stream bank after freeze-thaw cycles could cause a large volume of erosion. In this work, the forested land use was shown to help stabilize the stream bank due to the presence of woody roots and canopy cover, with the stream bank erosion 11 times less than the agricultural land.

Estimations of contributions of stream bank erosion and surface runoff to in-stream suspended sediment loading revealed that stream bank erosion contributed approximately 67 % of in-stream suspended sediment loading in WY 2011. Additional years of stream bank erosion and deposition data collection are necessary to better estimate and detect annual statistical trends of the stream bank erosion/deposition rates and response to variable climates and disturbance. The estimation of stream bank erosion contribution to total suspended sediment provided in this work is promising, partitioning in-stream suspended sediment loads from diffuse sources enables land managers to emphasize management activities with greater specificity, thus more directly improving aquatic water quality and ecosystem health.

Suspended sediment is just one of many principle issues affecting water quality in degraded aquatic ecosystems. In order to reduce suspended sediment and meet water quality standards, it is recommended to reestablish forested riparian buffers along water bodies. Winter season tends to have high erosion rate, especially in cold regions. It is therefore recommended that best management practices should be implemented to protect stream banks against erosion during the winter season by engineering (e.g. riprap) and bioengineering approaches, including planting perennial woody and herbaceous vegetation on or adjacent to the stream banks.

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APPENDIX A (PUBLICATION CHAPTER)

QUANTIFYING FLOODPLAIN STREAM BANK EROSION AND DEPOSITION RATES IN A CENTRAL U.S. URBAN WATERSHED

ABSTRACT: Stream bank erosion can contribute as much as 80% of suspended sediment to streams, particularly in urbanizing watersheds. Excessive suspended sediment in streams impairs water quality and degrades aquatic ecosystem. Ten stream bank erosion study sites were located on a lower reach of the Hinkson Creek Watershed located in Boone County, Missouri, USA during the 2011 water year (WY). Erosion and deposition rates were quantified using the erosion pin method comparing a remnant Bottomland Hardwood Forest (BHF) stream bank to an Agricultural (Ag) stream bank (922 m apart). Erosion pin plots (n = 342 pins) were installed to span the range of bank geometry and vegetation cover variability. Results indicated that during a drier (762 mm) than average (10yr avg=1077 mm) rainfall year (Water Year 2011) 15.7 and 177.8 tonnes of soil erosion occurred on the right stream bank alone of the BHF and Ag sites respectively. Average erosion depth of the BHF and Ag was 18 and 112 mm/yr respectively. The greatest average depth of erosion occurred during the winter season (44.7 mm), followed by summer (13.1 mm) and spring (6.3 mm), fall had the lowest average erosion rate (1.1 mm). There was an estimated 8049 tonnes stream bank erosion from both sides of the 1.15 km stream banks within the study reach during WY 2011, contributing approximately 67 % of the in-stream suspended sediment load. Thus,

approximately 33 % of in-stream suspended sediment originated from other sources (i.e. terrestrial surface runoff and channel bed erosion). Results hold important implications for land-use and land managers wishing to improve land-use practices, water quality and aquatic natural resource sustainability in dynamic urbanizing watersheds.

INTRODUCTION

Suspended sediment is one of the most pervasive non-point source pollutants impairing water quality globally (Nelson and Booth, 2002). Excessive suspended sediment reduces water clarity (Peng et al., 2002), endangers aquatic biota by blocking sunlight from submerged aquatic vegetation, and can detrimentally impact aquatic biota habitat (Davies-Colley and Smith, 2001; Russell et al., 2001). Sediment can fill water storage reservoirs, and impede navigation and water conveyance systems (Williams, 1989). Suspended sediment is a key transport vector of nutrients, heavy metals and pathogens (Bibby and Webster-Brown, 2005; Characklis and Wiesner, 1997; Gibbs, 1977; Neal et al., 1997; Tessier, 1992; Webster et al., 2000). Many efforts have been made to investigate sources, transport and deposition of suspended sediment (Collins and Walling, 2004; Zaimes et al., 2006). Nevertheless, much work remains to better understand suspended sediment processes to enable implementation of best management control strategies to meet water quality standards.

Two leading sources of in-stream suspended sediment include hillslope sources (particularly in the form of surface runoff) and river or stream channel sources (i.e. bank and bed erosion) (Collins and Walling, 2004; Juracek and Ziegler, 2009; Lawler et al., 1999; Prosser et al., 2000; Simon et al., 2000). The dominant sources of suspended sediment vary due to many reasons, including but not limited to geographical and climatic differences, research method differences, and varying timescales (Nelson and Booth, 2002). In addition, identifying the dominant sources of suspended sediment in rivers and streams remains confounded since sediment sources vary spatially and temporally in response to the complexity of sediment mobilization and delivery (Benda and Dunne, 1997).

Previous research showed that stream bank erosion accounted for as much as 80 % of in-stream suspended sediment loading (Lawler et al., 1999; Mukundan et al., 2011; Prosser et al., 2000; Simon et al., 2000). There are generally three processes that contribute to stream bank erosion: 1) fluvial processes, 2) subaerial processes, and 3) mass failures (Couper and Maddock, 2001; Hooke, 1979; Thorne, 1982). Fluvial erosion occurs when tractive forces (pushing and pulling forces) exerted by stream flow directly entrain stream bank materials and undercut the toe of stream banks (Hooke, 1979; Knighton, 1973; Wolman, 1959). Tractive forces increase with increases of flow velocity and depth, therefore, greater erosion often occurs with higher stream flow (Biedenharn et al., 1997). Based on the observation of Wolman (1959), medium to long duration precipitation events in the winter season resulted in greater stream bank erosion than the high, short precipitation events in the summer season. This was assumed to be due to longer duration precipitation creating persistent tractive force on saturated banks, and accompanying reduced soil shear strength due to soil saturation and possible freeze-thaw cycling during winter. Knighton (1973) indicated that multiple closely spaced peak precipitation events result in higher erosion rates than single peak events. Zaimes et al. (2006) concluded similarly that stream bank erosion often occurs after many medium (20-40 mm) or/and one or two large (>40 mm) closely spaced daily precipitation events. This was assumed to be due to previous flows that undercut and weaken stream banks so that stream bank erosion is imminent with the next high flow. Furthermore, short time intervals of precipitation events provide little time for stream banks to dry, thereby increasing the likelihood of stream bank erosion. Julian and Torres (2006) compared the impacts of four factors (peak discharge, magnitude, variation, and duration) to stream bank erosion and found that peak discharge (30-min maximum precipitation) was one of the most important factors affecting stream bank erosion. Subaerial erosion is climate-driven and can weather and weaken the stream bank (Thorne, 1982). It is understood to act as a "preparatory" process, weakening the bank face prior to fluvial erosion (Couper and Maddock, 2001; Wolman, 1959). Subaerial erosion is often driven by wetting-drying and freeze-thaw cycles of stream bank soils, and is affected by soil antecedent water moisture and temperature (Couper and Maddock, 2001; Wynn et al., 2008). Stream banks with high moisture content can have weak soil inter-particle forces (Craig, 1992), thus, reducing stream bank resistance against fluvial shear forces (Couper, 2004). Conversely, stream banks with low moisture content can form desiccation cracks (Osman and Thorne, 1988). Stream banks become even more vulnerable to failure when cracked stream banks immediately immerse in water and generate positive pore water pressures (Osman and Thorne, 1988). Mass failure occurs when gravitational forces of the stream bank override shear strength of the soils resulting in soil mass detachment from the bank. Increased positive soil pore water pressure is generated by precipitation infiltration, therefore, stream bank stability reduces when stream banks are saturated (Simon et al., 2000).

Quantifying the magnitude and rates of stream bank erosion and deposition of various land use types (including urban) is important because it allows the examination of the impacts of land use change and climate (e.g. precipitation, temperature), which are critical for implementation of stream bank stabilization activities. In addition, estimation of stream bank erosion contribution to total channel suspended sediment flux will help to identify the greatest sources of in-stream suspended sediment loading. Consequently, land managers can focus their efforts on the most pressing issues and carry out the most effective mitigation practices to control in-stream suspended sediment load.

METHODS

Study Site

This research was located on a fourth order reach of an adjacent floodplain of the lower Hinkson Creek Watershed (HUC 103001020907) in Columbia, Missouri, USA. Hinkson Creek Watershed was equipped in the fall of 2008 with a nested-scale experimental watershed study design to investigate urban watershed scale physical hydrologic, land-use interactions (Figure 1). The Hinkson Creek Watershed (HCW) is part of the Lower Missouri-Moreau River Basin. The HCW encompasses approximately 230.8 km^2 (23,080 ha), originating northeast of Hallsville in Boone County and flows approximately 42 km in a southwestly direction to its mouth at Perche Creek. Land use in the HCW is comprised of 25% urban area, 38 % cropland and pasture, 34 % forest, and 3 % wetland, open, shrub and grassland area (Hubbart et al., 2010).

In the 19th and 20th centuries, most of the floodplain Bottomland Hardwood Forest (BHF) in Missouri was removed to develop agricultural land. Human engineered structures including ditches, levees and drainage tiles, combined with channel alterations and soil cover changes dramatically altered the hydrology of streams, floodplains and the remnant BHF (Carter and Biagas, 2007). Two stream bank sites one at a historical Bottomland Hardwood Forest (BHF) and the second at an Agricultural (Ag) site (722 m apart) within the lower HCW floodplain were selected for bank erosion monitoring

(Figure 3). The BHF site is characterized with a mature stand of Bottomland Hardwood Forest, including *Acer saccharinum* (silver maple), *Acer negundo* (boxelder), *Ulmus americana* (American elm), *Populus deltoids* (eastern cottonwood), and *Juglans nigra* (black walnut) surrounding an old stream meander (Hubbart et al., 2011). The site was BHF at least as far back as 1939 (the date of the earliest aerial photography), based on tree-ring aging of the oldest trees (Hubbart et al. 2011). The Ag site is an abandoned agricultural field, which was cultivated by private landowners until the mid-1960s when it and the BHF site came into ownership by the University of Missouri. The University of Missouri used the Ag site for experimental crop plots until approximately 2002. The agricultural experiment station has been mowing the field approximately once per year since 2002. Study sites were previously described in (Hubbart, 2011; Hubbart et al., 2011). The reader is referred to those publications for additional information.

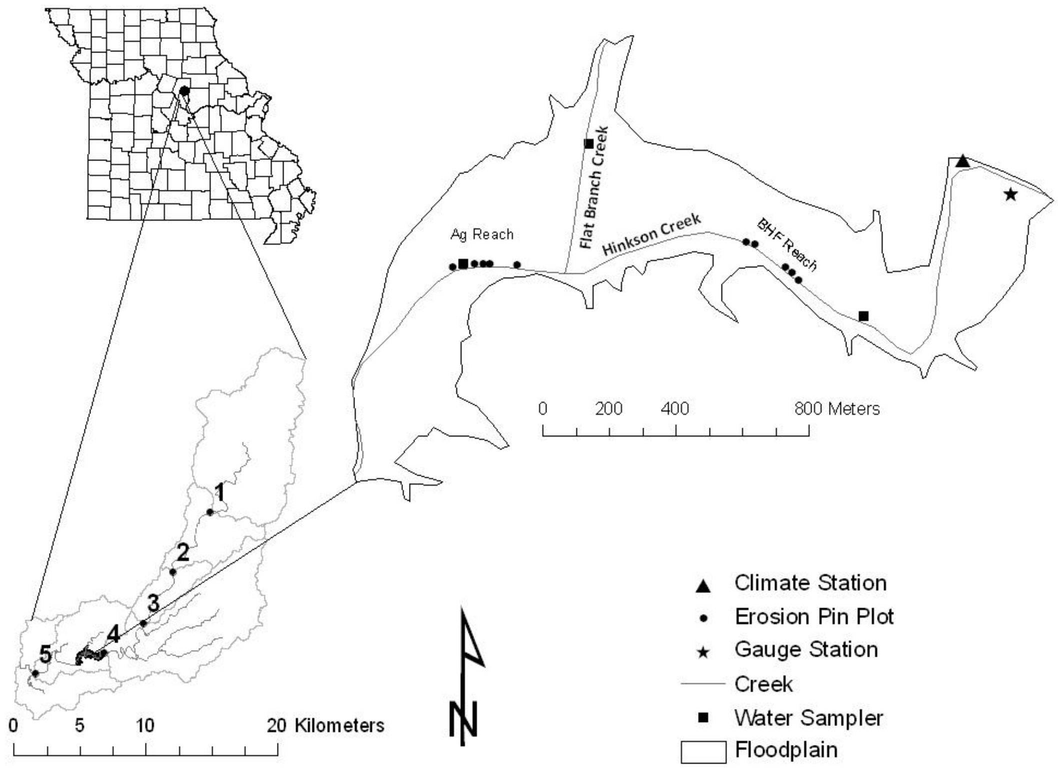

Figure 1: Map of floodplain study reach located on a fourth order reach of Hinkson Creek in the Hinkson Creek Watershed, located in Central Missouri, USA

Erosion Pin Method

The erosion pin technique was used to investigate stream bank erosion and deposition rates for this work. This method has been widely used since Wolman (1959), and is suitable for measuring cohesive stream bank erosion and deposition rates (Haigh, 1977). Ten erosion pin plots were installed in June 2010. Sites were selected representing the span of stream bank heterogeneity. Five plots were installed adjacent to the bottomland hardwood forest site and five adjacent to the abandoned agricultural site. All pin plots were placed on the right bank of the Creek if one is facing down-stream. A total of 342 steel pins (122 cm long; 10 mm diameter) were installed. Erosion pins were comprised of re-bar driven at a 90 ° angle, perpendicular to the creek-bank at 1m aerial distance from each other, as per the methods described in previous studies (Couper et al., 2002; Zaimes et al., 2004). Each erosion pin was inserted approximately 112 cm into the stream bank allowing 10 cm pin exposure (Zaimes et al., 2004; Zaimes et al., 2006). As bank erosion occurred, the length of pin exposed on the surface increased. Conversely, when deposition occurred, exposed pin length was reduced. Measurement (accurate to 1 mm) of exposed erosion pin length was conducted on a monthly basis, during the first few days of each month (weather contingent) (Gabet, 1998; Zaimes et al., 2004). Soil deposition was a positive value and erosion (i.e. soil loss) was a negative value. If buried or completely eroded pins were replaced, the readings were recorded as “zero” or “112 cm” respectively.

Soil cores were collected and analyzed to determine soil bulk density, soil moisture content, etc. A total of 232 soil cores (volume= 102.97 cm^3) were collected from the ten pin plots in September 2010. Soil core samples were delivered to the Interdisciplinary Hydrology Laboratory of the University of Missouri and dried in the oven at 105 ℃ for 24 to 48 hours, or until constant weight was obtained according to the methods described by Hillel (2004). Soil texture was determined using the hydrometer method according to methods described in previous studies (Bohn and Gebhardt, 1989; Grigal, 1973; Kettler et al., 2001). Ten soil samples were collected from the center of every four pins from each pin plot to capture soil heterogeneity of each plot (2 meter intervals, n=10 for each pin plot). Stream bank height and angle were determined using the clinometer method (Biedenharn et al., 1997), where vertical height is determined using right triangle theory (Gordon et al., 2004). The angle was determined by the clinometer, the horizontal side of the right triangle was determined by the horizontal erosion pin intervals (erosion pins were one aerial meter apart). The measurement (accurate to 1 dm) was collected at two meter linear intervals along each of the erosion pin plots (Zaimes et al., 2006). Vegetation species and density was identified in late June to early September 2011. A sampling frame of 1 x1 m inner dimension comprised of ½ inch polyvinylchloride (PVC) pipe was constructed for quadrat sampling (USDA, 1996). The PVC quadrat was set on selected pins (three meters interval from the first erosion pin, n=158) within each erosion pin plot, the percentage of vegetation (vascular) around each pin was averaged to obtain the percentage of the vegetation cover for the whole pin plot. Vegetation roots that were outside the quadrat but leaning into the quadrat were not recorded (USDA, 1996). Vegetation cover was quantified in terms of percent cover as per the methods of Laubel et al. (1999).

Soil Loss Calculation

The mass of eroded or deposited soil sediment was calculated using the following equation (Zaimes et al., 2004):

$$\mathrm{M} = \mathrm{L} \times \mathrm{A} \times \mathrm{B} \tag{1}$$

Where M is the mass of eroded or deposited soil sediment (kg) in the plot, L is the mean erosion rate in the plot (m),which is calculated by averaging the erosion rate of all the pins in the plot, A is the plot area (m^2), and B is the average site bulk density ($kg \cdot m^{-3}$) (Zaimes et al., 2004).

The mass of eroded or deposited soil sediment from each pin plot was divided by the length (m) of the plot to supply a linear erosion or deposition rate (kg/m) for each plot (Zaimes et al., 2004; Zaimes et al., 2006). To scale to the reach, the final linear erosion or deposition rate for each site was calculated by dividing the total eroded or deposited mass by the total length of the site.

Suspended Sediment Loading Estimation

Three automated water samplers (Sigma 900 MAX Portable Sampler, HACH Company) were deployed. One at the upstream end of the BHF site (306 m from the confluence of Hinkson Creek main stream and Flat Branch Creek), a second at the Flat Branch site (396 m from the confluence), and a third downstream of the Ag site reach (575 m from the confluence) (Figure 3). This design enabled estimation of suspended sediment within the study reach and suspended sediment contributed from Flat Branch Creek. Water samples were collected daily (12:00 hrs) during WY 2011. Water samples were delivered to the University of Missouri Interdisciplinary Hydrology Laboratory (IHL) for analysis of volume concentration of in-stream suspended sediment using Laser In-Situ Scattering and Transmissometry (LISST). More detailed information about the LISST can be found in Hubbart and Freeman (2010).

Suspended sediment flux was estimated by the product of daily mean discharge and suspended sediment concentration (SSC) at a single point of a cross section of the creek. Volumetric SSC (ul/l) generated by the LISST was converted to gravimetric SSC by multiplying by 1.9446 as per the findings of Freeman (2011) who collected grab samples four times per week from Hinkson Creek, and compared volumetric SSC using the LISST and gravimetric SSC by filtration. Sediment particle density was estimated by division of volumetric SSC and gravimetric SSC as per the methods of Freeman (2011).

Suspended sediment flux from the BHF, FB and Ag sites as well as stream bank erosion over WY 2011 was calculated as follows:

$$S_{Ag} = S_{BHF} + S_{FB} + BE \qquad (2)$$

Where S_{Ag} is the suspended sediment flux at the Agricultural site; S_{BHF} is the suspended sediment flux at the BHF site; S_{FB} is the suspended sediment from the Flat Branch; BE is the bank erosion from both sides of the stream banks. Streamflow data were obtained from the Columbia USGS gauge site (# 06910230), and were computed for Flat Branch creek, which drains a large portion of the City of Columbia (Figure 1). Depth of flow of Flat Branch Creek was monitored using a Solinst leveloader and barrowlogger pressure transducer system for stage data (mm). Flow was estimated using the Velocity-Area (V-A) method to create rating curves and compute flow as per Dingman (2008).

Data Analysis

Analysis of variance (ANOVA) was performed using Origin 8.5: Data Analysis and Graphing Software (Origin Corporation, Northampton, MA, USA). One-way Analysis of Variance (ANOVA) is often used when comparison of variance of test groups with only one treatment factor. As per the methods of Zaimes et al. (2004), one-way ANOVA was used to test whether there were significant differences of stream banks among the BHF and Ag sites pertaining to soil texture, soil characteristics (i.e. dry bulk density, porosity), stream bank height and angle, and vegetation cover respectively. Two-way ANOVA test was used to test spatial (BHF site and Ag site) and temporal (monthly and seasonal) soil loss/gain, erosion/deposition per unit length, and erosion/deposition rates over WY 2011 (Tusell, 1990; Willett, 2010). Linear Regression analysis was used to determine the strength of relationship between two variables (i.e. vegetation cover/stream bank erosion and deposition rates) (Wynn and Mostaghimi, 2006).

RESULTS AND DISCUSSION

Climate

Climate in Missouri is generally characterized by continental polar air masses in winter with maritime and continental tropical air masses in summer (Nigh and Schroeder, 2002). Historic precipitation and temperature data provide insights pertaining to stream bank antecedent (pre-existing) soil water trends, and is therefore best interpreted in terms of Water Year (WY). Use of water year as a standard time interval is often used in hydrological studies because hydrological systems in the northern hemisphere are typically at their lowest levels near October 1, and increased temperatures and generally drier weather patterns of summer give way to cooler temperatures, which decreases evaporation rates. Precipitation data collected at the University of Missouri Sanborn Field climate monitoring station from Water Year 2001 to 2011 (Water Year 2001: October 1st

2000 to September 31st 2001) indicated that the highest total annual precipitation in the last decade was in 2010 (1651 mm), the lowest annual precipitation was in 2006 (677 mm) (Table 1). Average temperature in Columbia, Missouri was 13.3 ℃. The coldest month is in January (average temperature -0.7 ℃), whereas the warmest month is usually between June and August (average temperature 24.3 ℃). From WY 2001 to 2011, the lowest temperature in Columbia (15th January in 2009) was -15.8 ℃; the hottest day in Columbia (2nd August in 2011) was 33.6 ℃.

Table 1: Historic yearly total precipitation (mm) and average daily temperature (℃) in Columbia, Missouri, USA from Water Year 2001 to 2011(Water Year 2001: October 1st 2000 to September 31st 2001) (data source: Sanborn Field, University of Missouri).

Year	**Total Precipitation (mm)**	**Average Temperature (℃)**
2001	1133	12.39
2002	1094	14.14
2003	989	12.48
2004	1018	12.99
2005	1134	14.01
2006	677	14.06
2007	786	13.88
2008	1517	12.51
2009	1088	12.56
2010	1651	13.01
2011	762	13.09

WY 2011 was generally drier than the average previous 10 years. Total precipitation in WY 2011 was 762 mm, which is 46 % lower than the 10-yr average. Daily air temperature reached its peak on August 2nd (33.61 ℃) and dropped to the lowest value of -13 ℃ on February 3rd. Average daily temperature during the period of this work was 13.2 ℃, which is nearly identical to the average past 10 years value (0.0 % difference). In agreement with historical seasonal precipitation distributions, the spring season was the wettest season of the year. During WY 2011, 414 mm precipitation fell in Columbia during March 2011 and June 2011 totaling 54.4 % of the total precipitation of WY 2011 (762 mm).

Figure 2 shows average daily precipitation, average daily discharge, and average daily temperature in Hinkson Creek Watershed. There were four relatively large precipitation events during the 2011 water year. Those events were on 12/31/2010 (37.1 mm), 5/12/2011 (30.7 mm), 5/25/2011 (43.2 mm), and 6/27/2011 (51.8 mm). Stream discharge had three peaks on 12/31/2010 (26.1 m^3/s), 2/28/2011 (25 m^3/s), and 5/25/2011 (35 m^3/s) respectively. The high stream discharge on 12/31/2010 and 5/25/2011 was likely due to high precipitation events; however, the stream discharge peak on 2/28/2011 may be due to snowmelt of approximately 46 cm of snowfall two days before 2/28/2011. The rise of temperature from below 0 ℃ in early February 2011 to a peak in mid-February (18 ℃) and stayed above 0 ℃ through the rest of the February resulted in rapid snowmelt, thus contributing to peak flows in February 2011.

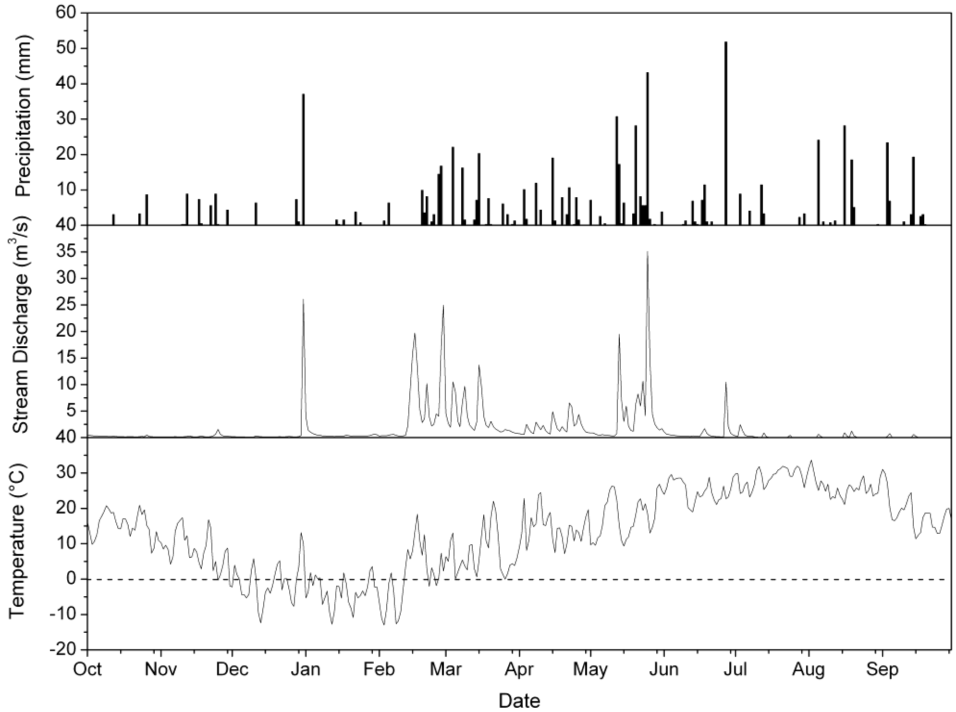

Figure 2: Mean daily precipitation, stream discharge, and air temperature for WY 2011. Discharge data collected from USGS gauging station (#06910230). Precipitation and temperature data collected from Sanborn Field on the University of Missouri Campus in Columbia, Missouri, USA.

Precipitation vs. Stream Bank Erosion and Deposition

Figure 3 shows that the significant erosion events were not coincident with high precipitation events or associated stream flow events in this study, but were more likely affected by a combination of several factors. The magnitude of bank erosion in December (3195 kg) was approximately seven times greater than in November (444 kg). There were nine small-sized (< 20 mm) precipitation events in November 2010, however, the temperature stayed above 0 ℃. There were three small sized (< 20 mm) and one medium sized (20-40 mm) precipitation event in December, and the temperature dropped to -12 ℃ in mid-December, freeze-thaw processes in December were likely to weaken the stream banks, reducing the stream bank shear strength prior to the medium size precipitation event (37 mm) occurring on December 31st 2010, causing much larger soil erosion comparing to the magnitude of soil erosion in November 2010. January had the highest magnitude of erosion (4980 kg), there were five small size precipitation events in January after the medium size precipitation on December 31st 2010. Stream banks may have been more susceptible to low stream flow erosion after freeze-thaw cycles (Zaimes et al., 2006). Stream discharge reached its peak on February 28th 2011, which contributed by snowmelt, may have prompted another high stream bank erosion event on the already weakened stream banks.

There were 40 medium (20-40 mm) to small (<20 mm) precipitation events during the spring months. High frequency of smaller precipitation events conceivably puts little hydraulic stress on stream banks (relative to larger events), and could lead to accumulation of sediment on stream banks. This may also be attributable to root systems of woody and herbaceous vegetation that increase stream bank surface roughness. Sediment may thus settle out of suspension and deposit on the stream banks. Relatively low precipitation was therefore adequate for vegetation growth, but not sufficient for soil erosion (Zaimes et al., 2006). The peak precipitation events did impact stream bank erosion in this study. For example, a great deal of erosion in May 2011 was likely due to high peak discharge associated with high precipitation. Rapid drawdown of the water table in the banks during the recessional limb of hydrographs may also cause substantial bank erosion (Lawler et al., 1999; Simon et al., 2000). Similar studies conducted by

Hooke (1979), Knighton (1973), Zaimes et al. (2006), and Julian and Torres (2006) showed that peak flow intensity is one of the most significant factors causing stream bank erosion. Several small precipitation events (<30 mm) in August and September 2011, were not high enough to maintain higher flows. This coupled with high surface evaporation and plant transpiration (ET) and soil infiltration (Zaimes et al., 2006) can effectively reduce surface runoff leading to reduced streamflow.

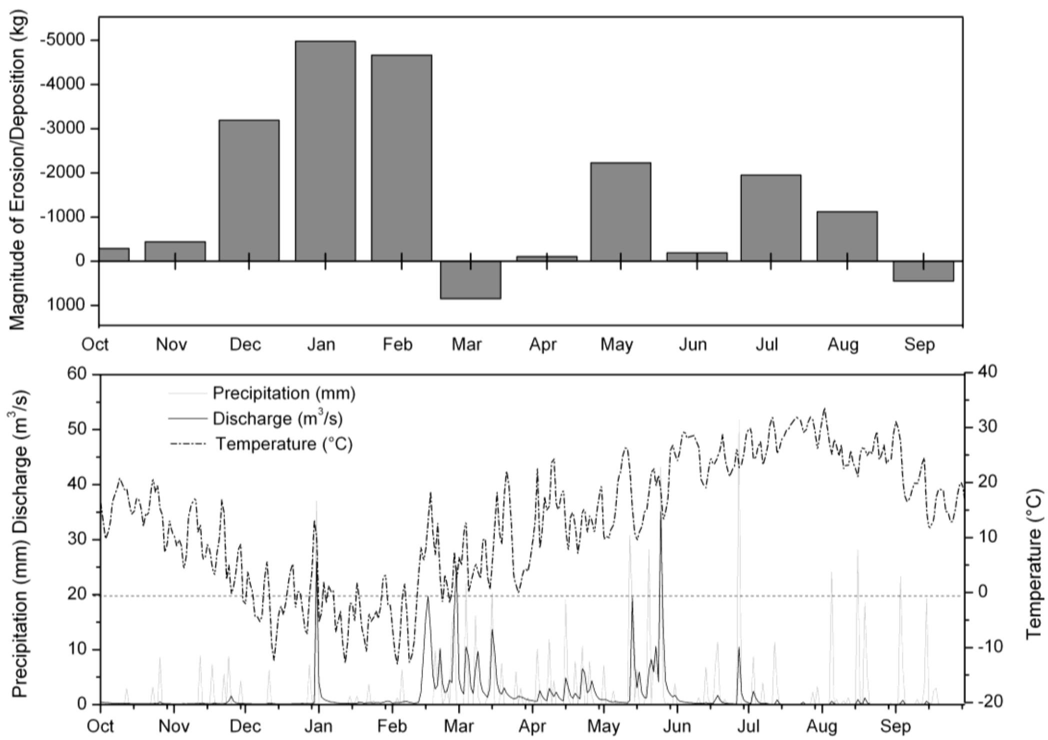

Figure 3: Cumulative monthly magnitude of erosion/deposition of stream banks and daily mean precipitation, daily mean stream discharge, and daily mean temperature in the floodplain of Hinkson Creek Watershed, Missouri, USA (WY 2011).

Erosion/Deposition among Erosion Pin Plots

The maximum soil deposition occurred at pin plot J (1655 kg), while the maximum soil loss (erosion) occurred at pin plot I (8307 kg) over WY 2011 (Table 2). Total soil loss from the ten erosion pin plots was estimated to be 17.88 tonnes. The maximum erosion rate was 280 mm at plot I, the maximum deposition rate was 50 mm at plot J, the mean erosion rate for the ten erosion pin plots was 65 mm. Clearly, stream bank erosion (i.e. soil loss) dominated over all study plots.

Table 2: Total soil loss/gain, erosion/deposition per unit length, and erosion/deposition rate of ten erosion pin plots in Columbia, Missouri, USA. Data collected from October 2010 to September 2011. Where (-) indicates soil loss.

Pin Plot	**Mean Erosion/Deposition Rates* (mm)**	**Total Soil Loss/Gain** (kg)**
A	-8	-347
B	-14	-571
C	7	114
D	-1	-43
E	-74	-1165
F	-10	-347
G	-234	-6292
H	-87	-2577
I	-280	-8308
J	50	1655
Max	50	1655
Min	-280	-8308
Mean	-65	-1788
Median	-12	-459
SD	109	3126
Total	-	-17881

Note: * Mean erosion/deposition rates were calculated by averaging all the pin measurements (depth) in the plot. Mean erosion/deposition rate for a year was calculated by averaging monthly erosion/deposition rate for each pin plot.
** Total soil loss is cumulative soil loss over one year period of WY 2011.

Comparison of the soil bulk density of the stream banks at plot I and Plot J indicated that the bulk density at Plot I was 3.7 % higher than plot J. Previous research showed that higher soil bulk density results in greater soil critical shear strength (Asare et al., 1997; Wynn and Mostaghimi, 2006). The water moisture content and vegetation cover at Plot I was 10 % and 12 % less than plot J respectively. Wynn and Mostaghimi (2006) stated that maintaining at least 10 % pore water in the soil profile can improve soil strength by improving cohesion among soil particles. Silt-clay content of the stream bank soil at pin plot I was 65 % higher than pin plot J, stream banks with high silt-clay content may have been susceptible to sub-aerial erosion but had high resistance against fluvial entrainment (Couper, 2004). Therefore, pin plot I was probably more susceptible to sub-aerial erosion. Furthermore, the average bank height and angle of plot I was 49 % and 84 % higher than that of plot J. Due to a relatively high and steep stream bank at pin plot I, the stream bank was thus physically more prone to failure. In May 2011, the stream bank collapsed due to high rainfall thus contributing greatly to total erosion.

Table 3. Comparison of stream bank soil parameters, stream bank characteristics, soil loss/gain, and erosion/deposition rate between pin plot I and J in the Floodplain study reach of Hinkson Creek Watershed, central Missouri, USA.

Pin Plot	**BD (g/cm^3)**	**SWC**	**PS<53 µm (%)**	**VC (%)**	**ABH (m)**	**ABA (°)**	**TSLG (kg)**	**EDR (mm/WY)**
I	1.39	37	53	68	4.9	74.7	-8308	-280
J	1.34	28	32	61	3.3	40.7	1655	50
%diff	3.7	-10	65	-12	49	84	-	-

Note: BD: Bulk Density; SWC: Soil Water Content; PS: Particle Size; VC: Vegetation Cover; ABH: Average Bank Height; ABA: Average Bank Angle; TSLG: Total Soil Loss/Gain; EDR: Erosion/Deposition Rate.

As previously discussed, woody vegetation can help improve microclimate around stream banks by providing shading in summer time thus reducing dryness of stream banks (Wynn and Mostaghimi, 2006). In addition, strong root systems can maintain higher amounts of soil water in the near surface soil, thus preventing soil dryness and supporting soil aggregation that prevents soil sub-aerial erosion (Wynn and Mostaghimi, 2006). There was a lack of woody vegetation at or adjacent to pin plot I at the Ag site. At the Ag site, the upper stream bank was covered by herbaceous vegetation, including the dominant plant *Humulus japonicus* (japanese hop), *Glechoma hederacea* (ground ivy), and *Sorghum halepense* (johnson grass). Even though herbaceous species can provide some stream bank protection against erosion, the contribution was less obvious since the stream bank was observed to dry much more quickly under herbaceous vegetation cover due to high surface evapotranspiration and corresponding shallow root systems. The exposed lower portions of the stream bank were frequently immersed in water and impacted by hydraulic erosion, causing the stream bank toe undercutting that reduced stream bank stability. Zaimes et al. (2006) corroborated this finding concluding that upper parts of the stream bank protected by perennial vegetation had less erosion than lower exposed parts of the stream bank that were susceptible to fluvial entrainment. Pin plot J was covered by herbaceous vegetation as well as woody vegetation, with short and gradual slope stream bank relative to pin plot I. It was more likely that the sediment settled out of the flow and deposited on the stream bank at pin plot J, soil erosion reduced due to the surrounding trees and herbaceous vegetation cover.

Forested vs. Non-Forested Stream Bank Soil Loss

The average erosion rate (in depth) was 18 mm/WY at the BHF site, it was 112 mm/WY at the Ag site (WY 2011). The magnitude of soil erosion from the stream banks (both sides of the stream banks within the study reach) at the Ag site was nearly 11 times greater than the BHF site (355.5 tonnes vs. 31.3 tonnes) over WY 2011. Considering all available data, the total magnitude of soil erosion from the stream bank within the study site was approximately 8049.1 tonnes for WY 2011. The stream bank soil erosion per unit length (i.e. per linear meter) at the BHF site was 65 kg/m, whereas it was 635 kg/m at the Ag site.

There were no statistically significant ($P<0.05$) differences between bulk density, herbaceous vegetation cover and stream bank slope between the BHF site and Ag sites, however, volumetric water content, silt-clay component (particle size <53 μm), and stream bank height were significant different between the BHF and Ag site ($P<0.05$) (Table 4). It was observed that woody vegetation at the BHF site adjacent to the stream bank had strong root systems to support the stream bank and retain soil particles in place, thus helping prevent stream bank erosion. Other authors have likewise made these connections (Burckhardt and Todd, 1998; Zaimes et al., 2004). Smith (1976) reported that erosion rates were inversely proportional to root volume in bank soils. The stream bank soils composed of silt without roots had erosion rate of 264.5 kg/hr, while the stream banks consisting of silt and 16 to 18 % root reinforcement had erosion rates of only 0.55 kg/hr. Erosion rates reduced to 0.01 kg/hr when the stream bank consisted with silt and 16 to 18 % root reinforcement and 5 cm of root riprap. Burckhardt and Todd (1998) indicated that non-forested stream banks suffered from five times greater erosion than their forested counterparts during high flow events. As mentioned earlier, woody vegetation also provides shading in the summer time, thus reducing soil temperature and maintaining higher soil moisture relative to non-forested banks. Wynn and Mostaghimi (2006) reported that soil water stress was 13 to 57 % lower in a woody vegetation dominated environment than herbaceous vegetation dominated environments, because large volume of roots of woody vegetation has wider and deeper extension in soil profiles than herbaceous vegetation to satisfy evapotranspiration demands and still maintain relatively high level of water in near surface soils. Conversely, stream banks covered with herbaceous vegetation may have lower capacity of maintaining soil water content during the summer time due to high rates of water consumption by relatively shallow rooted and low-lying herbaceous plant species.

Table 4. Comparison of stream bank soil parameters and stream bank characteristics of the BHF and Ag site at the Floodplain of Hinkson Creek Watershed, central Missouri, USA.

Study Site	**Bulk Density (g/cm^3)**	**Vegetation Cover (%)**	**Volumetric Water Content**	**Particle size <53 μm (%)**	**Particle size >53 μm (%)**	**Average Bank Height (m)**	**Averaged Bank Angle (%)**
BHF	1.32	58.54	0.29	31.59	68.41	3.27	54.36
Ag	1.32	65.78	0.35	36.39	63.61	3.79	51.8
P-value	0.77	0.74	5.6E-8	0.091	0.0012	0.00888	0.67

Erosion rates in this study varied with land use. The Bottomland Hardwood Forest had less stream bank erosion than the Agricultural land (18 mm/year vs. 112 mm/year).

Other studies with comparable drainage area sizes show similar results ranging from 4 mm/year to 580 mm/year in different land uses and soil types (Table 5).

Table 5: Erosion rate comparisons of streams of comparable drainage area size (0-200 km^2) using the erosion pin method.

Reference	**Location**	**Drainage Area (km^2)**	**Erosion Rate (mm/WY)**
Current study (HCW)	Central Missouri, USA	179.5	
Bottomland Hardwood Forest			18
Agricultural land			112
Willett (2010)	Northeastern Missouri, USA	284	4-387
Zaimes et al. (2006)	Iowa, USA	52	4-387
Gardiner (1983)	Lagan, North Ireland, UK	85	80-140
Twidale (1964)	R. Torrens, Australia	77.8	580

Seasonal Effects on Stream Bank Erosion

Considering the entire study reach (n = 10 erosion pin plots), the winter season (December, January, and February) had largest cumulative erosion of 12.841 tonnes, with erosion per unit length of 83 kg/m, and erosion rate of 45 mm, followed by summer (June, July, and August) (3.266 tonnes, 21 kg/m, 13 mm) and spring (March, April, and May) (1.491 tonnes, 10 kg/m, 6 mm), fall (September, October, and November) season had lowest cumulative erosion (0.283 tonnes, 2 kg/m, 1 mm) over the WY 2011. For the BHF site (analysis of the erosion pin plots A, B, C, D, E.), winter had largest cumulative erosion of 1.854 tonnes, with erosion per unit length of 20 kg/m, and erosion rate of 12 mm. The Ag site had largest cumulative erosion in winter of WY 2011 with cumulative erosion of 10.987 tonnes, erosion per unit length of 146 kg/m, and erosion rate of 78 mm,

(Table 6). Two-way ANOVA test indicated that there were significant differences between seasonal erosion/deposition among overall, BHF and Ag site ($p<0.01$).

Table 6: Seasonal comparison of magnitude of erosion/deposition, and average erosion/deposition per unit length, and average erosion/deposition rate of the stream banks in the floodplain of Hinkson Creek Watershed, central Missouri, USA.

	Total Mass of Erosion/Deposition* (kg)			**Average Erosion/Deposition Per Unit Length** (kg/m)**			**Seasonally Erosion/Deposition Rate*** (mm/season)**		
	Overall	BHF	**Ag**	Overall	BHF	**Ag**	Overall	BHF	**Ag**
Spring	-1491	494	-1985	-10	6	-26	-6	2	-15
Summer	-3266	-326	-2940	-21	-4	-39	-13	-6	-20
Fall	-283	-326	43	-2	-4	1	-1	-2	0
Winter	-12841	-1854	-10987	-83	-20	-146	-45	-12	-78

Note: * Total mass of erosion was estimated by summing the monthly erosion from the ten erosion pin plots.
**Average erosion/deposition per unit length was calculated by averaging the monthly erosion/deposition per unit length for the ten erosion pin plot.
*** Seasonal erosion/deposition rate was calculated by summing the mean monthly erosion rate from the ten erosion pin plots.

These findings are consistent with previous research. Wolman (1959) and Lawler et al. (1999) indicated that the greatest magnitude of stream bank erosion occurred in the winter season (December- March) due to high precipitation events and freeze-thaw mechanisms. During the winter season of WY 2011, there was a total of 18 precipitation events (one medium size (20-40 mm) and 17 smaller events (<20 mm). This was the fewest precipitation events occurring among the four seasons (Table 7). However, freeze and thaw cycling occurred in the stream bank may have weaken the stream bank. Thus, soil cohesion was reduced and the stream bank was more vulnerable to fluvial entrainment (Hooke, 1979), thus resulted in greater magnitude of bank erosion. In addition, in winter time, stream banks are generally wet and near saturated. With relatively high water content in stream bank soils, the stream banks are not able to absorb large volumes of rainfall or overland flow, thus resulting in higher peak discharge and higher potential bank erosion. These findings are corroborated in the results of multiple previous studies (Willett, 2010; Wolman, 1959; Zaimes et al., 2006).

There were more medium to high precipitation events in the spring and summer seasons (Table 7) than the winter and fall seasons. The high erosions likely occurred after each high precipitation events with high peak discharges in the study reach (the urban area of Hinkson Creek Watershed) as discussed earlier. The fall season had lowest erosion (283 tonnes), it was primarily due to less frequency and intensity of precipitation events, and high water absorption and strong soil erosion prevention effects of the vegetation can help retain the stream bank soil particles, and thus stabilize the stream banks as mentioned earlier.

Table 7: Low, medium and high precipitation events in Spring, Summer, Fall, and Winter of WY 2011 in Columbia, Missouri, USA.

Season	**Low (< 20 mm)Daily Precipitation Events**	**Medium (20-40 mm) Daily Precipitation Events**	**High (>40 mm) Daily Precipitation Events**
Spring	36	4	1
Summer	21	2	1
Fall	19	1	0
Winter	17	1	0

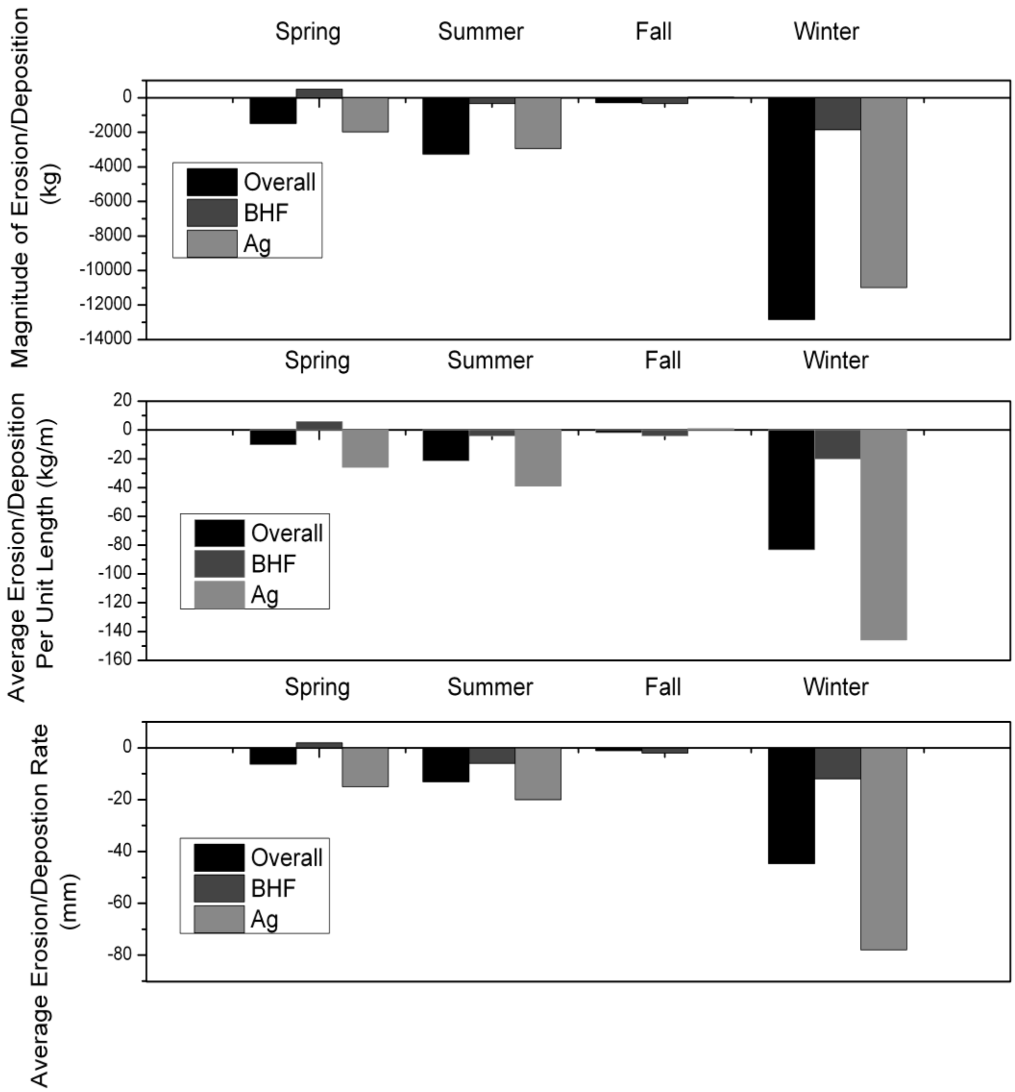

Figure 4: Seasonal erosion rates of stream banks at the floodplain of Hinkson Creek Watershed, Missouri, USA (WY 2011). Spring: March, April, and May: Summer: June, July, and August; Fall: September, October, and November; Winter: December, January, and February. Where erosion denotes (-).

Bank Erosion Contribution to Suspended Sediment

Suspended sediment concentration derived from daily samples obtained (306 m upstream from the confluence of Hinkson Creek and Flat Branch Creek) at the BHF site was 45817 tonnes for the WY 2011. Suspended sediment totaled 65461 tonnes (575 m downstream from the confluence of Hinkson Creek and Flat Branch Creek) at the Ag site. Total suspended sediment contribution from Flat Branch (FB) creek during WY2011 was 7606 tonnes. Total bank soil erosion (i.e. both stream banks) was estimated to be 8049 tonnes in WY 2011. Based on this computation, there was a difference of 12037 tonnes of suspended sediment between the BHF site (upstream) (45817 tonnes) and contributions of Flat Branch creek (7606 tonnes) and the Ag site (65461 tonnes). There was therefore 3988 tonnes of in-stream suspended sediment that must have come from other sources, such as channel bed incision and terrestrial surface runoff or measurement error.

If it is assumed that the major sources of in-stream suspended sediment originated from stream bank erosion, channel bed incision and surface runoff, stream bank erosion comprised as much as 67 % of in-stream suspended sediment loading, other sources (e.g. surface runoff, stream bed incision) consist 33 % of in-stream suspended sediment loading during WY 2011. These results are generally consistent with previous findings reported from watersheds with similar characteristics. Trimble (1997) investigated 196 permanent marked cross sections at intervals along San Diego Creek, Southern California from 1983 to 1993 and found that channel incision was responsible for approximately two thirds of the sediment yield. Willett (2010) indicated that 58 % of suspended sediment originated from bank erosion, 42 % of suspended sediment was from overland areas in Crooked and Otter Creek Watersheds located in northeastern Missouri within the Salt River Basin. Mukundan et al. (2011) reported that stream bank erosion contributed as much as 90 % of the total sediment load in the North Fork Broad River watershed in the Piedmont region of Georgia that drains an area of 182 km^2. Laubel et al. (1999) conducted a stream bank erosion survey in a basin located in central Jutland, Denmark and found that 60 to 90 % of the suspended sediment load was derived from stream bank erosion.

The in-stream suspended sediment flux estimated in this work was based on the following assumptions: (1) particle density was 1.95 g/cm^3. This value was derived from Freeman (2011) (see the method); and (2) there is an equal magnitude of erosion from the opposite side (left side when facing downstream) of the stream bank. Since the stream channel is meandering, stream flow scours the right bank side and deposits sediment on the left bank side, as stream flow goes further downstream, it scours the left bank side and deposits sediment on the right bank side, therefore, estimation of total soil erosion from both stream banks within the study site by doubling erosion from one single side is a reasonable approach; (3) suspended sediment is distributed in the stream homogenously. This is understood to be the case particularly during high flow events which are common in flashy hydrocliamte on the Mid-West, USA (Edwards and Glysson, 1970; Porterfield, 1972). Previous authors used employing point-based, or grab-sample based sampling methods to investigate suspended sediment loading (Horowitz, 2003; Lee et al., 2009), and found it an appropriate method to estimate suspended sediment load.

Effects of Urbanization on Bank Erosion Processes

Human activities can have significant impacts on stream bank stabilization, especially in urbanizing watersheds. Increased impervious surface area, including buildings, parking lots, and pavement enhances surface runoff. Increased stream discharge scours stream banks and causes increased suspended sediment load. These impacts have been observed by other researchers. For example, Bledsoe and Watson (2001) claimed that 10 to 20 % impervious surface can destabilize stream banks and abruptly degrade indices of aquatic ecosystem integrity. The city of Columbia has developed and expanded quickly. In 1993, there was only 7.9 % of urban area; by 2005, it was 20.7 % of urban area; it was 25 % urban area in 2010 (Hubbart et al., 2010).

Additional years of stream bank erosion and deposition data collection are necessary to detect annual statistical annual trends of stream bank erosion/deposition rates and response to variable climate and disturbances (Laubel et al., 1999). Zaimes et al. (2006) conducted a stream bank erosion survey from June 1998 to July 2002, four years of stream bank erosion data provides an improved evaluation of the temporal variation of stream bank dynamics. In the current study, the winter in WY 2011 was cold, while the winter in WY 2012 was warmer. Climate differences such as these will provide useful comparisons of stream bank erosion under different climate scenarios.

Ultimately results indicate that stream banks in a forested land use setting with woody and herbaceous vegetation adjacent or cover potentially have less bank erosion than Agricultural land use or bare lands. Stream bank soil erosion is affected by stream flow associated with precipitation, and freeze-thaw cycling and drying-wetting processes governed by soil moisture content and temperature. Winter season tend to have larger bank erosion comparing to the other three seasons, especially in cold regions. It is recommended to construct riparian forested buffer to improve microclimate around the stream banks, and thus stabilize the stream banks. In addition, engineering or bioengineering approaches are suggested to be implemented to protect the stream banks during winter, such as riprap roots or cold tolerant vegetation.

CONCLUSIONS

This work quantified annual and seasonal stream bank erosion and deposition rates, and bank erosion contributions to total suspended sediment loading in a 4th order stream of an urbanizing watershed in central Missouri. In WY2011, the magnitude of erosion Bottomland Harwood Forest (BHF) site was 31.3 tonnes as opposed to 355.5 tonnes in an agricultural (Ag) site. Soil erosion per unit length was 65 kg/m at the BHF site and 635 kg/m at the Ag site. The erosion rate was 18 mm/year at the BHF site and 112 mm/year at the Ag site. Stream bank erosion was affected by factors including precipitation, peak discharge, and land use types, and it also varied seasonally and yearly. The erosion rate in the winter (45 mm) was 3.4 times greater than the summer season (13 mm). The fall season had smallest erosion rate (1 mm). During the winter season, when evaporation and temperatures were low, stream bank soil was nearly saturated; the stream banks were therefore vulnerable to fluvial entrainment and rainfall. Freeze-thaw cycles, and frost heave may have exerted additional stress on the stream banks. This finding was consistent with the previous studies in similar settings (Zaimes et al., 2006). Peak discharge coupled to weakened stream bank after freeze-thaw cycles could cause a large volume of erosion. In this work, the forested land use was shown to help stabilize the stream bank due to the presence of woody roots and canopy cover, with the stream bank erosion 11 times less than the agricultural land.

Estimations of contributions of stream bank erosion and surface runoff to in-stream suspended sediment loading revealed that stream bank erosion contributed approximately 67 % of in-stream suspended sediment loading in WY 2011. Additional years of stream bank erosion and deposition data collection are necessary to better estimate and detect annual statistical trends of the stream bank erosion/deposition rates and response to variable climates and disturbance. The estimation of stream bank erosion contribution to total suspended sediment provided in this work is promising, partitioning in-stream suspended sediment loads from diffuse sources enables land managers to emphasize management activities with greater specificity, thus more directly improving aquatic water quality and ecosystem health.

Suspended sediment is just one of many principle issues affecting water quality and degrading aquatic ecosystems. In order to reduce suspended sediment and meet water quality standards, it is recommended to reestablish forested riparian buffers along water bodies. Winter season tends to have high erosion rate, especially in cold regions. It is therefore recommended that best management practices should be implemented to protect stream banks against erosion during the winter season by engineering (e.g. riprap) and bioengineering approaches, including planting perennial woody and herbaceous vegetation on or adjacent to the stream banks. Information generated in this work will lead to improved stream ecosystem health and water quality management in complex urban ecosystems and provide information to managers wishing to implement the most cost effective measures to reduce suspended sediment load in urban streams.

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APPENDIX B PHOTOS OF TEN EROSION PIN PLOTS

The ten erosion pin plots studied in this research are shown as follows: (photos taken on April 3rd 2011).

Erosion Pin Plot A

Erosion Pin Plot B

Erosion Pin Plot C

Erosion Pin Plot D

Erosion Pin Plot E

Erosion Pin Plot F

Erosion Pin Plot G

Erosion Pin Plot H

Erosion Pin Plot I

Erosion Pin Plot J