STREAM BANK EROSION TRENDS AND SEDIMENT CONTRIBUTIONS IN A SOUTHWESTERN MISSOURI RIVER

A Masters Thesis

Presented to

The Graduate College of

Missouri State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science, Geospatial Sciences in Geography, Geology, and Planning

By

Ezekiel Kuehn

July 2015

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ABSTRACT

Bank erosion can be a significant source of in-stream sediment that negatively affects water quality and aquatic habitat. However, assessments of the role that eroding banks play in suspended and bed sediment supply are rarely available to managers. The purpose of this study was to quantify bank erosion rates for a **7** km conservation easement the James River in southwest Missouri to evaluate the annual contributions of bank sediment to the channel. The objectives were to: (1) monitor an eroding 260 m bank to better understand short-term, reach scale bank erosion rates; (2) determine historical rates of bank erosion for the entire riparian easement using aerial photographs from 1952, 1997, and 2008; and (3) determine the contribution of bank erosion to annual river sediment loads and in-channel gravel storage. The erosion rates of fine sediment from historical aerial photograph analysis averaged 210 Mg/yr/km. Bank erosion contributions to suspended sediment loads in the James River ranged from 16% to 50%. Bank erosion along the James River is often limited by bedrock outcrops which can protect banks, increase channel stability, and reduce sediment supply. However, flow disturbance zones at channel bends along bedrock bluffs can enhance bar formation locally which can force lateral channel shifting and increased bank erosion rates.

KEYWORDS: stream bank erosion, sediment transport, geographic information system, fluvial geomorphology

This abstract is approved as to form and content

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Robert T. Pavlowsky
Chairperson, Advisory Committee
Missouri State University

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ACKNOWLEDGEMENTS

First and foremost I would like to thank Dr. Pavlowsky for his patience and advice during my time as a graduate student at MSU. I would also like to thank Dr. Luo and Dr. Qiu for their time and advice as my committee members. A special thank you goes out to Marc Owen for his guidance and answering my never ending questions about GIS, field methods, and everything else. I would also like to acknowledge OEWRI for letting so many other students and myself obtain experience while helping us through Graduate College. I would like to thank my parents for bestowing upon me a love for the natural world, and supporting me through every step of my life. I would like to thank my beautiful wife Tiffany Kuehn for her unwavering support and patience during my years as a graduate student. I could not have done it without her.

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INTRODUCTION

Human activities can cause changes to watershed hydrology and sediment loads which result in relatively rapid geomorphic adjustments of stream channels, including increased rates of bank erosion and lateral channel migration in river systems (Knox, 2006; Owen et. al, 2011). For example, Fitzpatrick and Knox (2000) found that changes in runoff after forest clearance caused accelerated stream bank and channel erosion to be the main sources of sediment downstream. In addition, urbanization of watersheds can also result in increased rates of bank erosion and channel degradation. Trimble (1997) found that two thirds of the total sediment yield was supplied by bank erosion exacerbated by the addition of impervious surfaces in the watershed due to urbanization. As unstable channels shift laterally, sediment stored in flood plain deposits is released back into the stream. Therefore, the process of bank erosion is considered a source of reworked sediment to a river system, and relatively high rates of bank erosion can lead to channel instability and sedimentation problems downstream (Piégay et al., 2005). Further, Sediment –associated contaminants in floodplains are released to the stream to further threaten water quality as in the case of nutrients and metals (Simon et al., 2004).

Excess sediment in a river system can cause adverse conditions downstream as material is deposited due to sedimentation and degradation of water quality (Simon et al., 2004). In addition, frequent turbidity and siltation caused by suspended sediment fluxes in streams can negatively affect aquatic communities, hindering their abilities to feed and spawn (Berry et al., 2003). The Environmental Protection Agency (EPA) stated that rivers with excess sediment are 60% more likely to be in poor biological condition (U.S.

EPA, 2013). Therefore, efforts to understand how bank erosion affects watershed sediment loads are important to scientists and managers of wetlands (Piégay et al., 2005).

Causes of Bank Erosion

Bank erosion can cause a variety of problems. In the United States the annual bill for erosion protection and management is over 16 billion dollars (Pons, 2003). There are many negative effects of bank erosion, such as the loss of land and the resources it produces, infrastructure loss or damage, and poor water quality (Piégay et al., 2005). In some watersheds bank erosion can supply >50 percent of the total sediment input to the channel system (Trimble, 1997; Carter et al. 2003; Sekely et al., 2002). This along with the releases of large woody debris and loss of riparian forests can have negative effects that alter the channel morphology and flood capacity in downstream reaches (Piegay et al., 2005). Overall, urban and agricultural watershed are believed to have accelerated bank erosion rates that can be 3-6 times greater than pre-settlement periods (Neller, 1988; Zaimes, 2004).

Bank erosion is complex and hard to manage. In agricultural areas, managers typically address bank erosion by restricting livestock access to the stream and planting or maintaining riparian forested corridors (Schwarte et al., 2011). In urban areas, installation of rain gardens and other methods of storm water remediation are used to “slow, spread, and soak” storm water runoff (Walsh et al., 2009). There are many ways to manage erosion of stream banks. However, most erosion control measures are not cost effective and result in minimal financial return (Posthumus et al., 2013). Bank erosion is often linked to changes in watershed conditions caused by climate and land use changes that affect both discharge and sediment regime. Common anthropogenic watershed disturbances that can lead to geomorphic instability of stream channels are urbanization, agricultural practices, and timber harvest (Jacobson and Primm, 1997; Pavlowsky, 2004).

Urbanization of a watershed, increases overall runoff rates and erosive energy in the channel leading to a reduction in channel complexity and an increase in channel width and depth (Walsh et al., 2009). Grazing practices can also cause accelerated erosion of stream banks, such as allowing livestock to have unrestricted year around stream access (Zaimes, 2004). In-stream trampling by livestock causes bank instability, leading to incision. In channel grazing by livestock reduces sediment trapping by in-channel and stream bank vegetation. Trampling and Grazing can also cause soil compaction that can lead to higher peak flows that can cause erosion in downstream reaches (Belskey et al., 1999). Clearing of riparian areas and channelization of the stream to support row crops also results in excess transport capacity and bank instability (Zaimes, 2004; Belsky et al. 1999). Channelization of streams reduces sinuosity and in turn increases the velocity of the stream providing more power to erode bank and bed deposits (Zaimes, 2004).

Land clearing and timber harvest can also impact stream stability, and has been found to increase the bank erosion rate (Stott et al., 2001). Clear cutting of forests surrounding streams can reduce mean temperature of the watershed increasing frost and needle ice occurrence on bank substrate resulting in a loss of inter-ped cohesion (Stotts et al., 2001). Similarly, the reduction of evaporative losses from the lack of bank vegetation results in elevated soil moisture content and excess pore water pressure that can lead to bank failure (Stott, et al., 2001).

Bank erosion caused by channel widening and incision can occur as channels adjust to recover from past disturbance. According to the channel evolution model of Simon and Hupp (1986) stream channels will incise or degrade after an initial disturbance, leading to decreased channel gradients causing a decrease in stream velocity at certain flows. During the degradation process the channel banks often become steeper and taller due to degradation of the bed and undercutting of the bank toe. This causes de-stabilization of the banks leading to mass wasting and channel widening (Simon and Rinaldi, 2006). However, as channel widening occurs through slumping and mass wasting, the stream channel is also lowering its bank angles to promote form stability. This often creates a new floodplain leaving the old one behind as a terrace. The new low floodplain will become vegetated creating a new riparian buffer that can diminish near bank velocities during floods, anchor recently aggraded areas, and promote further deposition leading to channel recovery and stabilization (Simon and Rinaldi, 2006).

Bank erosion rates can be reduced by better management practices. Stream bank erosion rates have been found to decrease along a continuous 11 km stretch of Bear Creek in north central Iowa according to management practice in the order of: row-crop fields 0.25-0.52 m/yr; continuously grazed pasture, 0.18-0.41 m/yr; and meandering riparian buffer, 0.12 m/yr (Zaimes, 2004). Zaimes (2004) stated that if all segments of the Bear Creek had a forested buffer, total stream bank soil loss would probably reduced by 72%. Local channel disturbances like those mentioned above can contribute large masses of bank sediment to the channels annually (Zaimes, 2004).

Geomorphic Processes Controlling Bank Erosion

The erosion and entrainment of bank sediments from bank materials happens in two main ways: hydraulic action and mass failure. Hydraulic action is the dominant process of bank erosion for non-cohesive banks (Thorne, 1982). Erosion by hydraulic action is dependent on near bank shear stress (Julian and Torres, 2006). High rates of bank retreat are usually associated with bend apexes, due to the high velocity and sheer stress found against the outside of meander bends (Hudson and Kesel, 2000). In contrast, mass failures occur by rotational slip type or slab type failures. Rotational slip type failures occur when the bank's toe has been eroded by hydraulic action, leaving an overhanging mass of sediment that cantilevers over due to gravitational and weathering forces (Nardi et al., 2012). Slab type bank failures occur similarly to rotational slip type failures, but instead of cantilevering and rotating over into the stream channel the mass of sediment slides in slab form down into the channel (Davis and Harden, 2014). Bank failure is closely related to the shape of the channel. Higher bank angles initially can increase bank erosion rates (Nardi et al., 2012). Overhung and near vertical banks are more susceptible to mass failures due to gravitational forces and hydraulic action caused by turbulence of flow that is related to steeper bank slopes (Czarnomski et al., 2012).

Bank material types, sizes, and stratigraphy can affect a banks susceptibility to erosion (Julian and Torres, 2006). River banks composed of sand and gravel are more prone to erosion than banks with cohesive sediment with high silt and clay content (Bloom, 1998). Clay-size particles and other fine grained sediment have strong bonds between them referred to as cohesion. The degree of cohesion is determined by particle geometry and electrostatic charges on the grain surfaces (Bloom, 1998). Cohesive sediment is eroded as a chunk often called mass failure of many separate particles, while non-cohesive sediment is released by individual particle entrainment (Julian and Torres, 2006). However, numerous alluvial banks are composed of different layers of cohesive and non-cohesive sediments. How the horizontal layers of non-cohesive and cohesive sediments are arranged can affect the erosion rate. For example, if a bank has a low non-cohesive layer, which generally erode faster than the cohesive materials, it will often lead to an undercut bank that is more susceptible to erosion than a bank with a moderate slope (Thorne, 1991). Along with bank composition the banks soil moisture content also plays an important role in the erosion rate.

Antecedent conditions are meteorological-related conditions that precede a flood event that can greatly influence the amount bank erosion that can occur at a given locations. One example of this is the amount of moisture present in the soil due to precipitation events. The effectiveness of hydraulic action to erode cohesive river banks depends on the amount of moisture present in the soil which is linked to seasonal changes in wetting and drying (Grayson et al., 1997). Seasonal patterns in soil moisture tend to cause an increase in bank erosion rates during wet periods (Knighton, 1998). This is because dry banks are more cohesive and the most resistant to erosion and saturated banks are relatively easy to erode. Furthermore, the subsurface conditions of a bank can directly affect erosion potential since seepage forces and excess pore water pressure can lead to increased rates of bank erosion (Stott, 2001). Seepage forces and soil piping can also increase due to a flood of long duration that saturates banks, causing bank failure once the flood begins to decrease (Knighton, 1988). Another antecedent condition that increases erosion potential is frost action and needle ice, which widens tension cracks and loosens the bonds between cohesive bank sediments (Knighton, 1998). Vegetation can act to increase cohesion of bank sediments also.

Vegetation affects bank stability and flow erosion by decreasing turbulence and velocity near the bank by providing roughness. Bank vegetation can also increase soil cohesion reducing the potential of erosion. Banks with vegetation are less susceptible to the influence of soil moisture related erosion due to the better drainage that is present (Bull, 1997). However, not all vegetative cover can stabilize stream banks. Trimble (1997) found that forested stream banks can destabilize stream channels, and that grassed channel banks stored 2,100 to 8,800 m^3 more bank sediment than forested reaches. The disadvantageous effects of vegetation are due to excess weight from mature trees causes soil instability through an increase in soil creep down in to the channel (Pollen et al., 2004).

Contribution to Sediment Loads

To estimate the relationship between sediment load and bank erosion for a fluvial system, the quantity of eroded sediment and sediment loads must be known (Bull, 1997; Green et al., 1999; Ham and Church, 2000). Annual bank erosion rates can be calculated in several different ways. Common methods to measure bank erosion are erosion pins, aerial photograph analysis, successive digital elevation models, and repeat surveys, which all involve measuring the amount of bank sediment loss over a defined temporal scale. Sediments supplied to the channel add to both the bed-load and suspended sediment load of the stream (Bull, 1997; Green et al., 1999; Ham and Church, 2000). The bed load transfer rates are quantified by the net volumetric change between survey periods using successive aerial photographs or field surveys (Ham and Church, 2000). The suspended sediment loads are measured using discharge and suspended sediment data from event sampling or nearby gages due to the relationship between the two variables (Green et al., 1999). The concentration of suspended sediment and discharge typically have a positive relationship, because flow turbulence and mixing currents are needed to entrain the sediment and suspend it in flow (Hutchinson, 2010). The relationship between discharge and suspended sediment loads is often estimated and modeled using rating curves (Hutchinson, 2010).

Bank erosion has been found to contribute most of the suspended sediment in certain watersheds (Trimble, 1997). The percent of sediment loads supplied from channel banks varies highly from river to river (Table 1). Bank erosion rates are not uniform along the length of a river and they vary spatially according to characteristics of the watershed. An important variable influencing the spatial variation of bank erosion rates is stream power, which is a product of discharge and slope It has been theorized that bank erosion rates will increase where stream power is highest and erodible substrates are present (Lawler, 1992, 1999). Previous studies have also stated that lower gradient alluvial channels, which generally occur in the lower sections of rivers, have the highest bank erosion rates due to a greater occurrence of mass failure events (Fonstad and Marcus, 2003). Bank erosion rates are also influenced by local geology, which can limit erosion rates in areas in the form of bed rock outcrops and natural gravel armoring present in the channel. Bed rock and gravel where present armors banks and limits degradation (Pavlowsky, 2004).

Table 1. Bank contributions to the sediment loads in different watershed sizes and dominant land uses around the United States and Great Britain.

Region	Water Body	Drainage Area (km^2)	Land Use	% from Channel banks Sources	Reference
Southern CA	San Diego Creek	288	Urban	66%	Trimble, 1997
Southwest England	River Torridge	__	Agricultural	23%	Walling, 2005
Western England	River Severn	380	Commercial Forest	17%	Bull, 1997
Central MN	Blue Earth River	9,028	Agricultural	31-44%	Sekely et. Al, 2002
Eastern PA	Valley Creek	60.6	Urban	43%	Fraley et al.,2009
Northeast England	River Ouse	3,315	Agricultural/ Rural	37%	Walling et al., 1999
Northeast England	River Wharfe	818	Agricultural/ Rural	23%	Walling et al., 1999
Southern England	River Kinnet	214	Agricultural	31%	Collins et al., 2012
Southern England	River Frome	437	Agricultural	7-19%	Collins and Walling, 2007
Southern England	River Piddle	183	Agricultural	7-21%	Collins and Walling, 2007
Northern England	River Aire	1,004	Urban	43-84%	Carter et al., 2003
Northwest CA	Upper Truckee River	142	Urban	20%	Simon, 2008

Sediment loads and bank contributions in the Ozark Highlands

Previous studies point out that during the last 150 years land use changes in the Ozarks have supplied excessive amounts of sediment to stream channels released from tributaries by erosion of colluvium and alluvium from riparian areas, and soil erosion from uplands (Jacobson and Gran, 1999; Owen et al., 2011). Fine-grained sediment released to the channel can lead to water quality and sedimentation problems in rivers (U.S. EPA, 2013). Additionally, a major concern for managers of Ozarks streams is surplus gravel-sized sediment in the channel. Channel areas containing excess gravel bar deposits are often associated with channel instability and have been referred to as disturbance or active reaches that are characterized by high sinuosity, channel migration, and large unvegetated chert gravel bars (Jacobson and Gran, 1999; Martin and Pavlowsky, 2011). Disturbance reaches in the Ozarks have higher rates of channel migration and instability that can erode banks and remobilize sediments that were previously stored, degrading water quality and limiting biodiversity (U.S. EPA, 2013). They have also been found to be less biologically productive than other channel units, such as a bluff pool, due to the channel shape in disturbance reaches, which often have a high width to depth ratios unfavorable by popular game fishes in MO (Rabeni and Jacobson, 1993). The city of Springfield has also stabilized sections of tributaries to the James River to reduce bank erosion and enhance water quality (MDNR, 2004).

Ozark streams planforms characterized by alternating stable and disturbance reaches (Owen et al., 2011). Further, disturbance reaches are locations where bank erosion rates are high, and previously stored sediment is remobilized from flood plain and colluvial deposits. Owen et al. (2011) found lateral migration rates of the upper James

River at disturbance reaches to range from 0.7 to 1.6 m/yr and the stable reaches to be <0.1 m/yr. Martin and Pavlowsky (2011) defined four different types of disturbance reaches in the Finley River the largest tributary of the James River, which are: (1) extension, (2) translation, (3) cutoff, and (4) megabar. Extension and translation types indicate bank erosion rates directly so they will be explained here. Extension refers to lateral migration of a bend increasing sinuosity and decreasing sediment transport capacity. Bank erosion rates for extensions were found to be an average of 1.0 m/yr. Translation types are defined as the upstream or downstream shift of a bend overtime with path length, sinuosity and transport capacity remaining constant for the reach. Translation types had erosion rates on average of 2.7 m/yr. Jacobson and Gran (1999) found that large inputs of gravel bed load can decrease channel capacity and cause channel migration and bank erosion, contributing to the sediment load.

Purpose and Objectives

The influence of bank erosion on the suspended sediment loads in the Ozarks is poorly understood at the present. The purpose of this study is to provide an estimate of the contributions of bank erosion to the sediment loads of the James River in southwest MO (Figure 1). The present lack of knowledge of bank contributions to the suspended sediment load in the James River, and the increased urbanization in the watershed make the James River an ideal watershed to conduct this study. In addition, the needs of industries and people that rely on high quality water resources, and to further the knowledge on the relationships between channel morphology and sediment flux in the

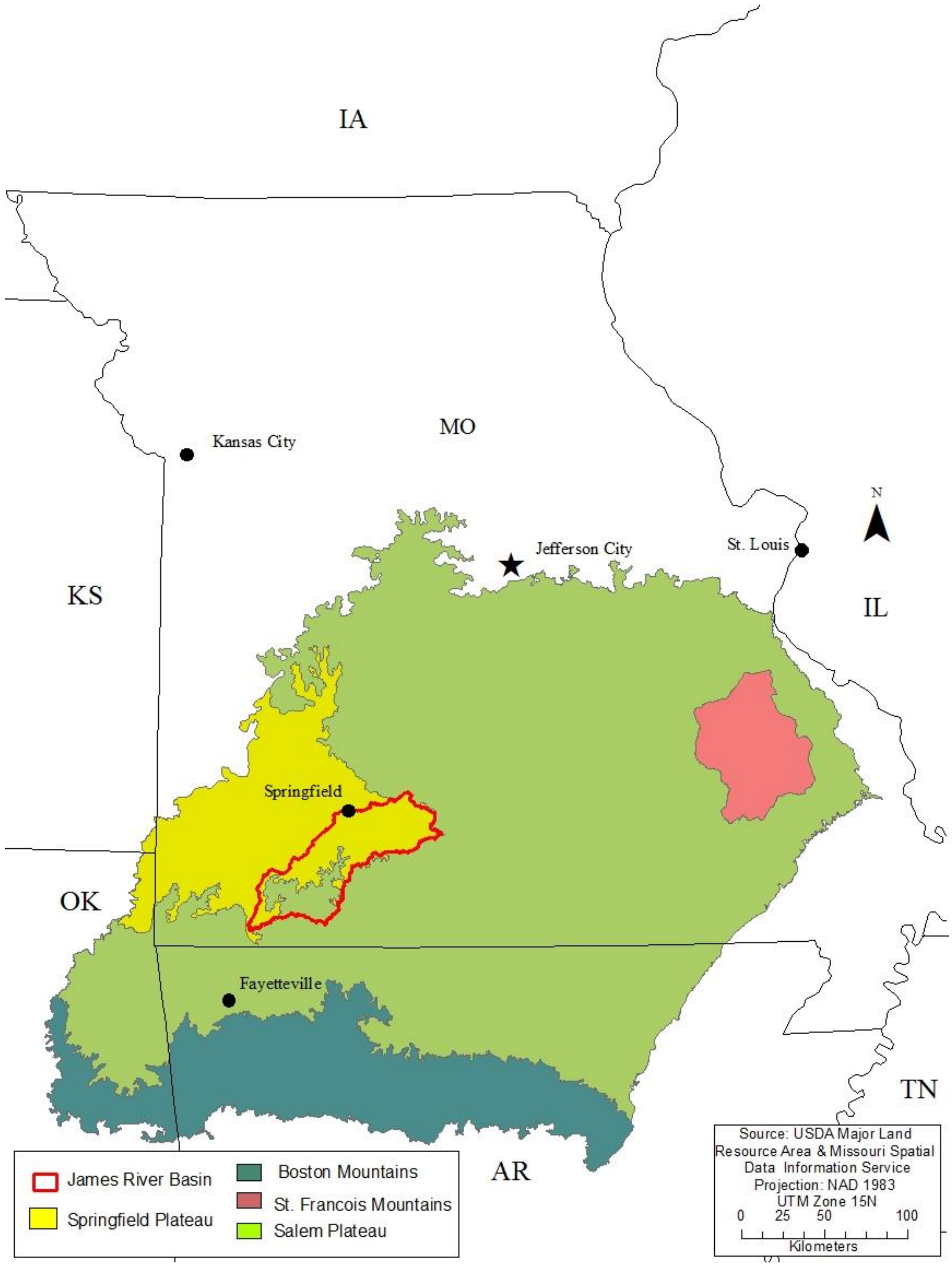


Figure 1. Physiographic map of the Ozarks and the location of the James River basin.

Ozarks warrant research on this topic. The James River empties into Table Rock Lake where excess nutrients and sediments have caused eutrophication in the past. The communities surrounding this lake rely heavily on tourism related to water recreation. Furthermore, in 2004 the EPA approved the James River Total Maximum Daily Load (TMDL), which lists excess nutrients and sediments as the main concern for water quality. This study is beneficial for environmental managers and local municipalities by identifying a source of sediment and nutrients that has been overlooked in the past.

In 2012, The James River Basin Partnership, Missouri Department of Natural Resources, and a landowner agreed to place a conservation easement on a 7.4 km stretch of the lower James River in Stone County. The objectives of conservation easements are aimed to create and enhance James River riparian corridors and protect their hydrological and ecological functions, specifically these are to: (1) develop and implement a riparian conservation easement program, (2) retain 20 miles of riparian corridor systems in the conservation easement program, (3) enhance or establish 10 miles of riparian corridor systems in high priority areas, (4) Create an educational program for riverfront property owners with regard to managing and protecting their riparian corridor systems, (5) Create a model riparian buffer ordinance and present the model ordinance to representatives of cities and counties within the James River Basin (James River Basin Partnership, 2014). This conservation program offers the chance to examine the role of bank erosion and sediment supply on sediment loads in the James River. The 7.4 km stretch will be evaluated using historical aerial photograph interpretation and field assessments to determine rates of bank erosion. Within the 7.4 km stretch of the James River, a 260 m cut bank actively eroding which had 100 m section of it treated with willow stakes by the

Missouri Department of Conservation. Erosion pin arrays have been placed on this cut bank to gain a better understanding of bank inputs to the suspended sediment loads.

The purpose of this study is to quantify the mass contributions of bank erosion sediment to the James River within the easement segment. The objectives of this study are to: (1) evaluate a 260 m long eroding bank that has been treated with willow staking to gain a better understanding of reach scale bank inputs to the sediment load, (2) determine historical rates of bank erosion using aerial photographs from 1952, 1997, and 2008 for the entire 7.4 km easement segment; (3) compare bank erosion inputs of fine and coarse sediment to the sediment load in the James River to determine bank erosions contribution of fine sediment in percent of annual load to Table Rock Lake and the contribution of bank erosion to the gravel bars in the study segment. The results of this study will be used to evaluate the significance of bank stability projects on the James River and their effect on meeting TMDL limits. In addition to suspended sediment, this study will also evaluate gravel inputs from banks, which has been found to be a source of instability and aquatic habitat degradation in Ozark river systems (Martin and Pavlowsky, 2011).

Benefits of the Study

This study is the first to evaluate bank erosion sediment inputs for fine and coarse sediment in the Ozarks. Through the aerial photograph analysis and erosion pin monitoring this study will identify and evaluate erosional processes in the lower James River. The results will help link bank erosion to water quality management goals, including total suspended sediment (TSS) and total phosphorus (TP) inputs to Table Rock

Lake. Further, this study will emphasize the role that riparian land and easement programs can play in non-point sediment load reduction.

STUDY AREA

This study focuses on both the reach and segment scale analysis of the James River channel. Segment-scale analysis evaluates historical bank erosion and deposition along a 7.4 km length of the James River in 400 m intervals (Figure 2). Reach-scale analysis evaluates bank erosion sediment contribution to the James River over a one year period using a 300 m long cut bank with erosion pin transect placed along the bank (Figure 3).

Regional Location

The physiographic region of the Ozark Highlands includes most of southern MO, and parts of AR, OK, and KA (Figure 1). It is composed five sub-regions, the Springfield Plateau, Salem Plateau, Osage Plains, St. Francois Mountains, and the Boston Mountains (Figure 1) (Jacobson, 1995). The Ozark Highlands is an area of relatively high relief compared to the adjacent landscapes of northern MO, KA, and OK (Owen et. al, 2011). The highest peaks in the Ozarks exceed 600 m in elevation in the Boston Mountains; some peaks even reach above 750 m (Rafferty, 2001). The James River watershed (3916 km^2) is a sub-basin of the White River Basin. It is seventh order stream that originates in Webster County at an elevation above 500 m and flows 160 km to Table Rock Lake, an impoundment of the White River. It has 5 major tributaries: Pearson Creek, Wilson Creek, Finley River, Crane Creek, and Flat Creek (Figure 4) (Kiner and Vitello, 1997). The study segment is in northern Stone County between the confluences of the Finley River above and Crane Creek below (Figure 4).

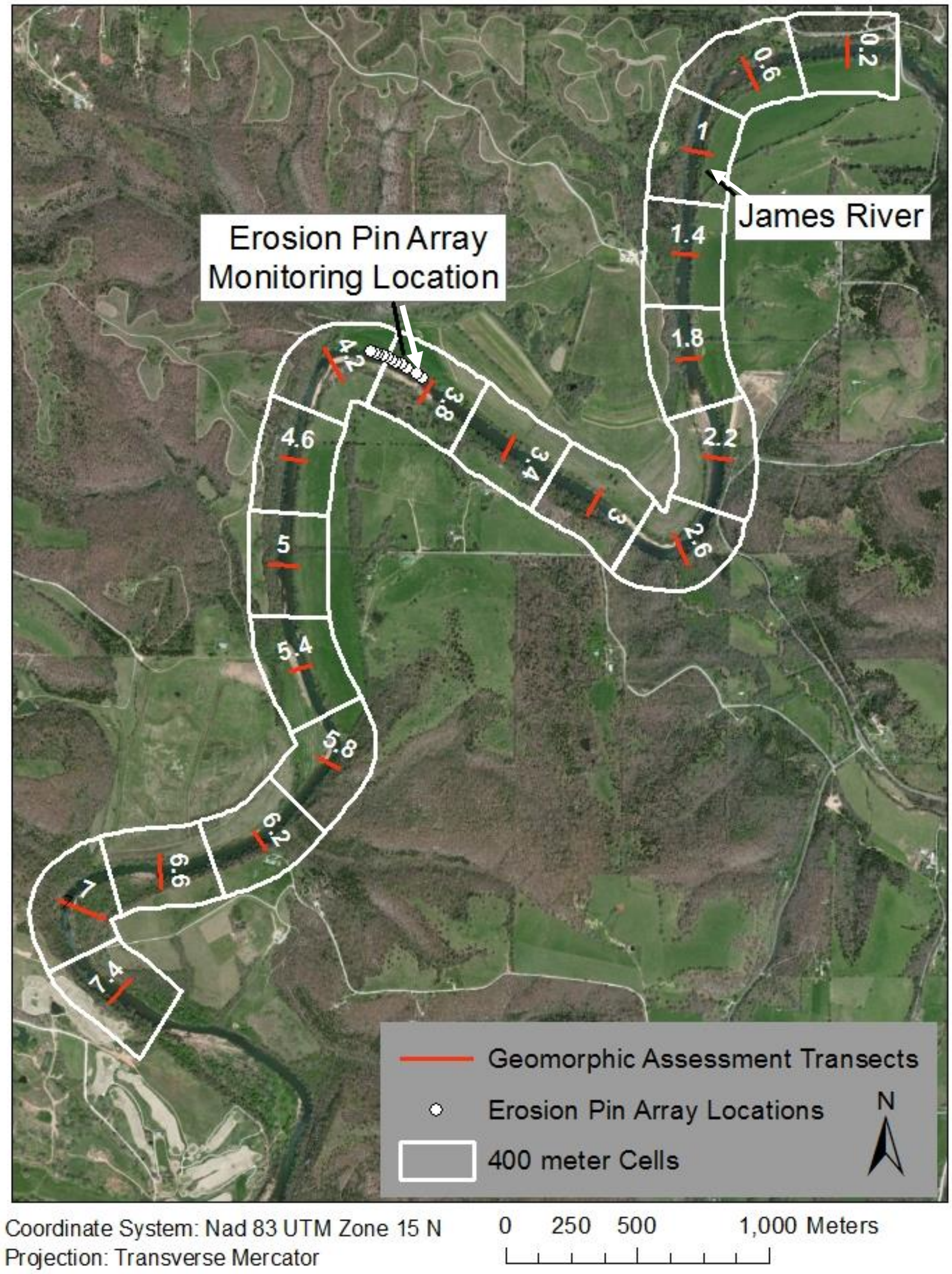


Figure 2. Segment scale study area.

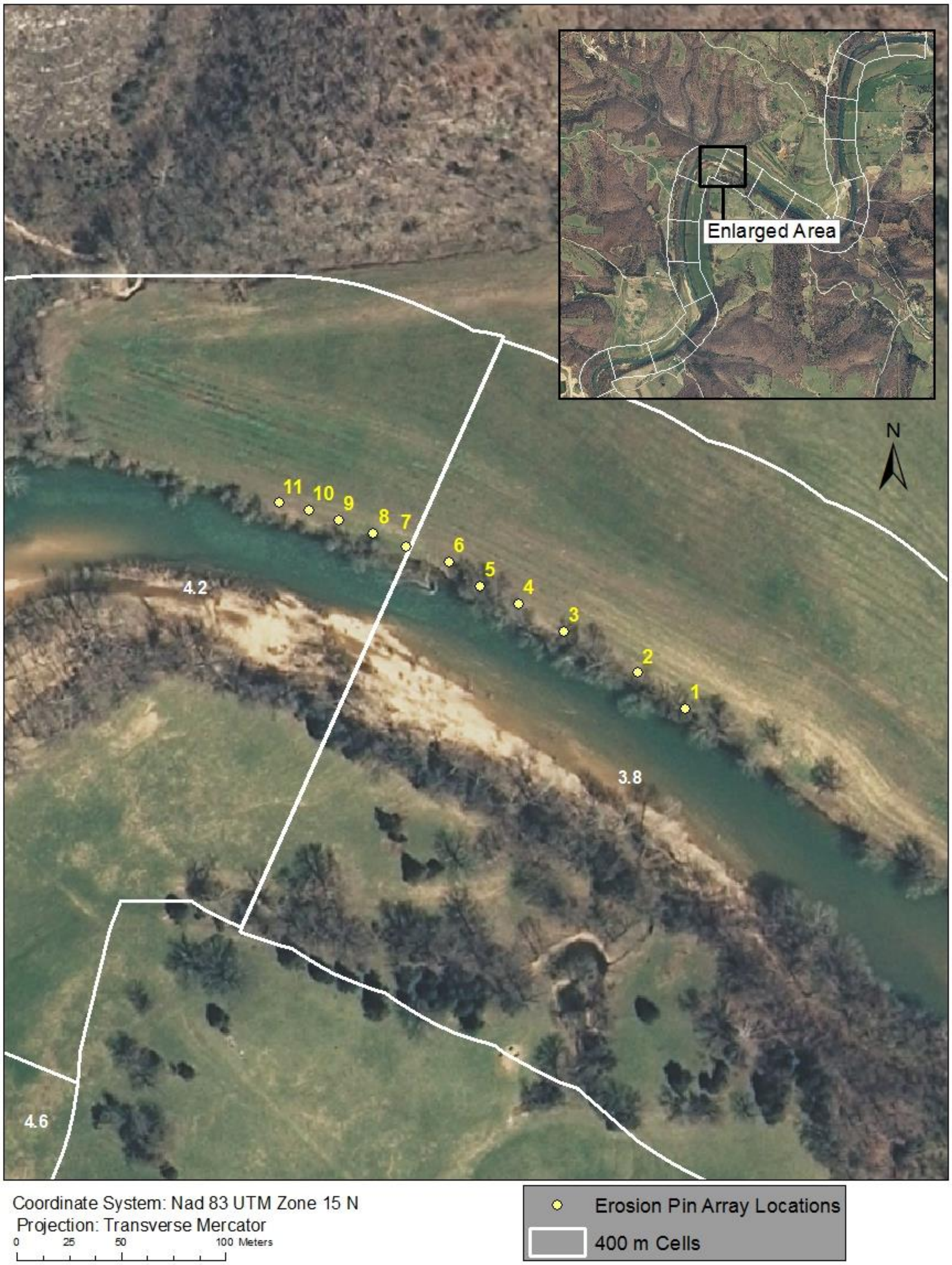


Figure 3. The erosion pin array study segment.

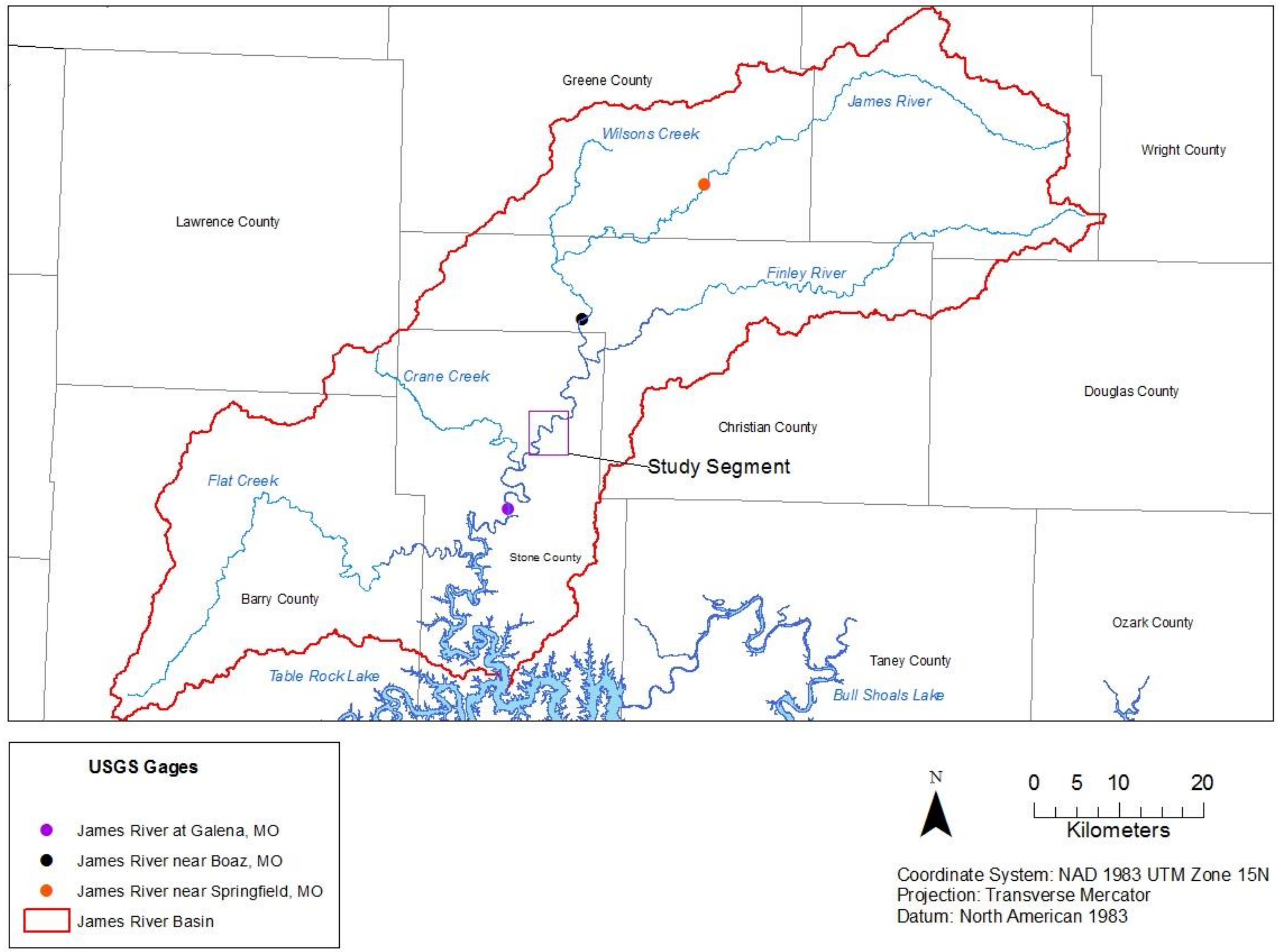


Figure 4. Study area location within the James River Basin, and the USGS Gage sites used for this Study.

Geology

The James River flows through the Springfield and Salem Plateaus as it winds through the Ozarks to join the White River as Table Rock Lake in Stone County. Both the Springfield and Salem Plateaus are underlain by limestone, dolomite, sandstone, and shale bedrock (Aldrich and Meinert, 1994) (Figure 5). The Springfield plateau is composed of limestone and cherty limestone of Mississippian age. The Salem Plateau is composed of Ordovician age cherty Dolomites (Peterson et al., 1995). The presence of soluble rocks has led to many karst features throughout the river basin. Carbonic acid is formed in the water and dissolves the carbonate rock, which leads to sinkholes, caves, springs, and losing and gaining streams (White, 1988). Springs, caves, and sinkholes are common features in the James River Basin. Due to weathering limestone and dolomite bedrock in the Ozark Plateaus, karst drainage systems have formed leaving some stream channels dry most of the year.

The valley floor of the study segment of the James River is underlain by Ordovician age Cotter Dolomite of the Ibexian series, which is described as fine crystalline, silty, cherty dolomite. Overlaying the Ordovician age dolomite is Mississippian age Kinderhookian and Osagean limestone. Osagean limestone is referred to as cherty with chert nodules and heads within the limestone. Kinderhokian series is composed of clastic shale and siltstone and carbonate limestone (Thompson, 1986). Limestone and dolomite weather to form clayey residuum and mantles of gravel sized sediment.

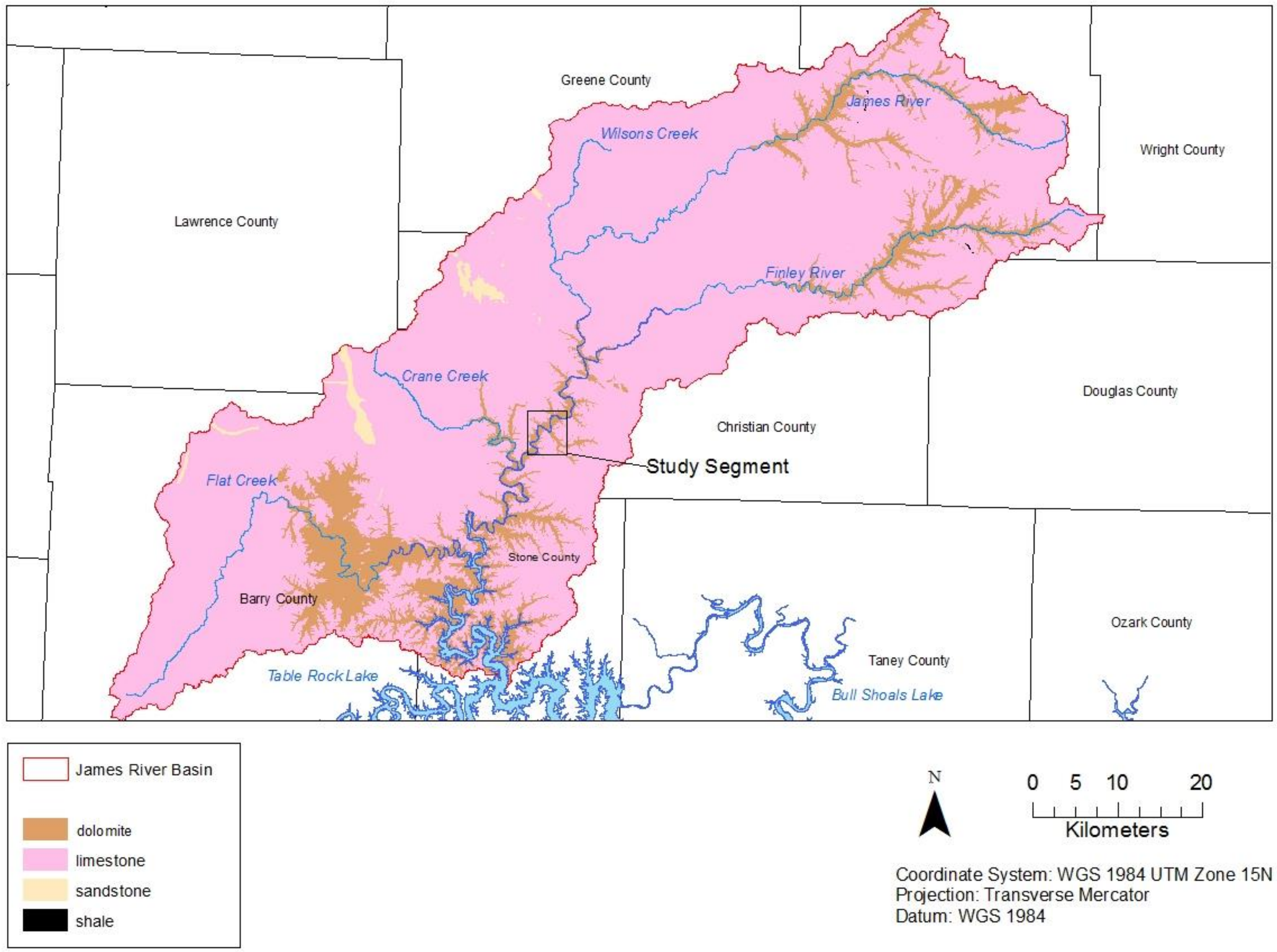


Figure 5. Bedrock of the James River basin. The areas of limestone are Springfield Plateau, and the areas of dolomite are Salem Plateau.

Climate

The climate in the Ozark region is temperate with mild winters and hot summers. The following climatic data is from Greene County in the James River Basin, although not at the exact study area the climatic conditions are similar. Average temperatures range from 0 to 18˚C in the winter and spring (Figure 6). In the summer season they range from 23 to 25 ˚C. Temperatures in the fall range from 20 to 7˚C (Figure 6). The temperature range is over 75 ˚C with the highest being 46˚C and the lowest was -32 ˚C. The average annual temperature (1981-2010) is 67 ˚C (NOAA, 2013) (Figure 6). The average annual precipitation (1981-2010) is 115 cm (NOAA, 2013). Monthly precipitation totals in the study region also vary season to season. In the winter months, the average monthly (1981-2010) precipitation ranges from 6.4 cm to 7.7 cm. During the spring and summer seasons the monthly average rainfall ranges from 9 cm to 13 cm. In the fall the precipitation monthly average varies from 9 cm to 12.3 cm.

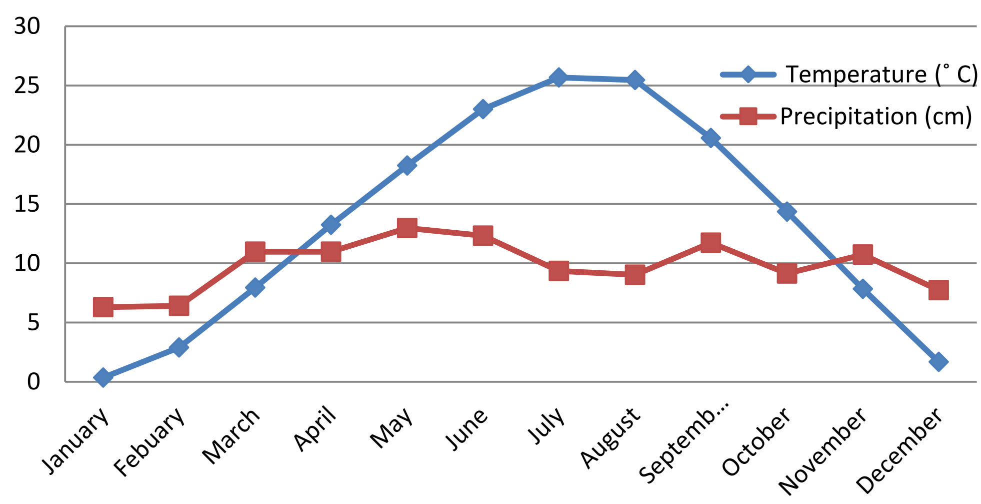


Figure 6. Climagraph for Greene County (1981-2010) (NOAA, 2013).

Land Use, Past and Present

Before European settlement, Native American tribes used areas around the James River as hunting and fishing grounds. The first recorded European settlement on the James River was at Delaware Town in 1822, which is located 8 miles southwest of Springfield, MO. After post European settlement, a great percentage of the pine and oak hickory forest were logged to build homes, open new fields for agriculture, and produce railroad ties. Some prairie lands were also cleared for towns and agriculture production (Rafferty, 2001). Modern land use for the James River Basin is approximately 63% agriculture, 30% forested, and 7% urban (MISDIS, 2005) (Figure 7). Currently, the state of MO was ranked seventh in cattle production in the United States from 2008 to 2012 (U.S. Census Bureau, 2012). The five counties that the James River Basin resides in are among the top beef producers in MO in 2010. Barry County had 82,000 head of cattle, Webster County had 69,000, Christian County had 49,500, and Stone County had 26,500 (NASS, 2010). Land use in the study segment consists of old field, likely used for hay production, livestock pasture, and deciduous forest.

Soils

Soils in the James River Basin are generally developed in clayey residuum that was formed by weathering of limestone and dolomite bedrock (Hughes, 1982). Some limestone and dolomite formations have chert nodules within in them which can lead to chert fragments being present in the residuum. Many areas in the basin have a thin cap (< 1 m) of Pleistocene loess that was deposited by eolian processes in the during past glacial periods (Hughes, 1982). Upland soil series in the study segment are the rock outcrop and

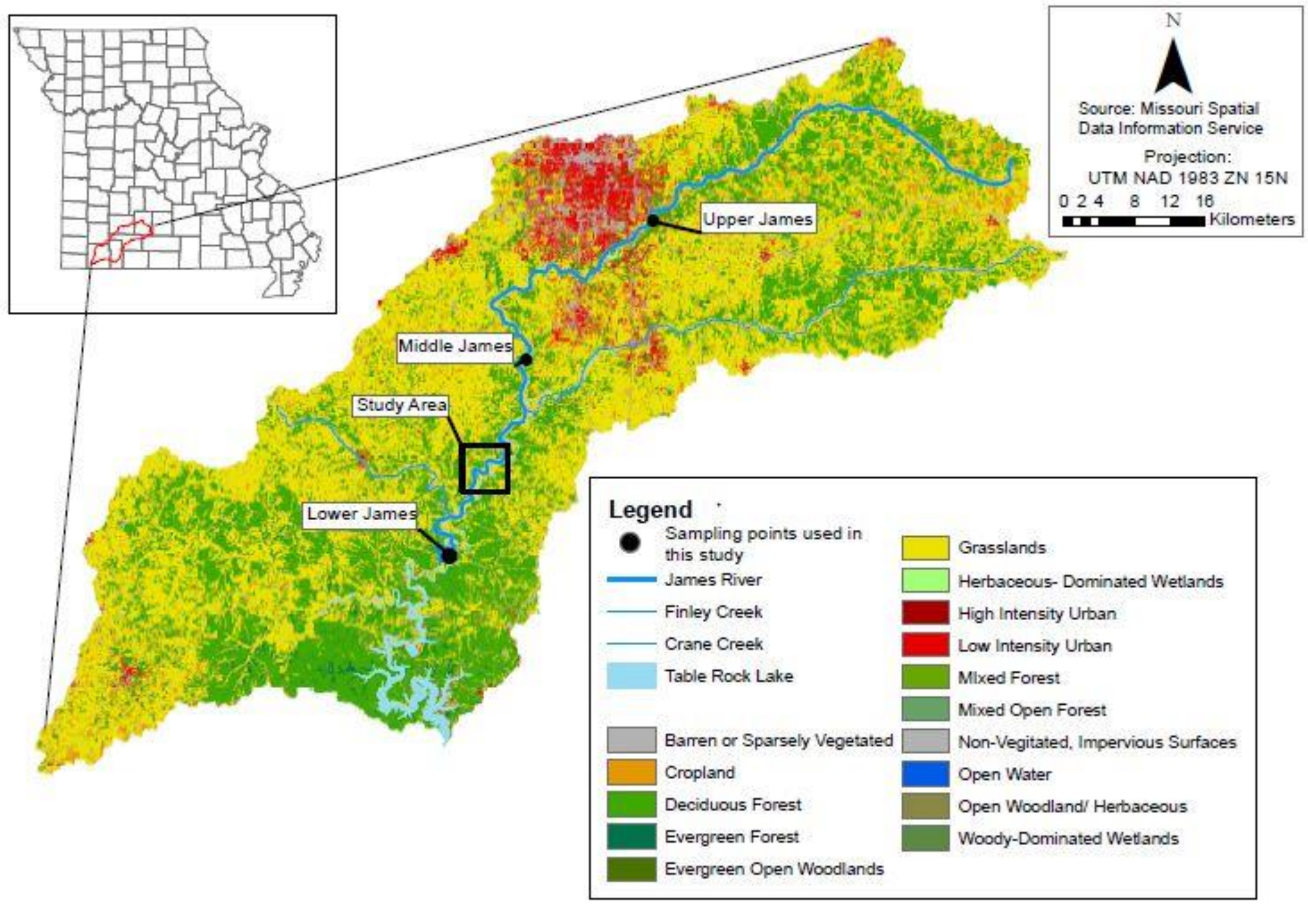


Figure 7. Land use in the James River Basin as of 2005 (Land Use and Land Cover, 2005).

hill slope soil series Gasconade, Gatewood, and Hailey (Figure 8). The Gasconade series was formed in weathered dolomite residuum found on hills under hardwood, and mixed conifers. The Gatewood series was formed in gravelly slope alluvium originating from chert and clayey residuum formed by weathering limestone found on upland slopes. The Hailey series was formed from limestone and colluvium on plateaus and slopes.

Alluvial soils in the study segment are the Hootentown series, Pinerun series, Horsecreek series, and Pomme series (Figure 8) (Table 3). The Hootentown series was formed in silty alluvium that is located on stream terraces in river valleys. The Pinerun series was formed in gravely alluvium formed from cherty limestone and is found to be from 52-55% chert fragments of 0.2 to 7.62 cm in size; it is located on flood plain steps in the river valleys, alluvial fans. The Horsecreek series is very fine silty alluvium that is also located on the floodplain. The Pomme series was formed in slope alluvium and is located on strath terraces in the James River Basin, (Gregg, 1995).

Hydrology

Discharge data from the United States Geological Survey (USGS) gage network is used to describe the hydrology of the James River (USGS, 2012; Table 4). Annual mean flow for the USGS gage James River near Boaz is 14.74 m^3/s. The downstream USGS gage, James River at Galena has an annual mean flow of 28.08 m^3/s. At the Boaz gage, the highest mean annual flow occurred in 2008 and was 31.14 m^3/s and the lowest mean annual flow was 2006 with 4.7 m^3/s. The highest mean annual flow at the Galena gage is 70.8 m^3/s and the lowest occurred in 1954 and was 3.4 m^3/s. The study segment is between gages 07052250 on the upstream side, and 07052500 downstream.

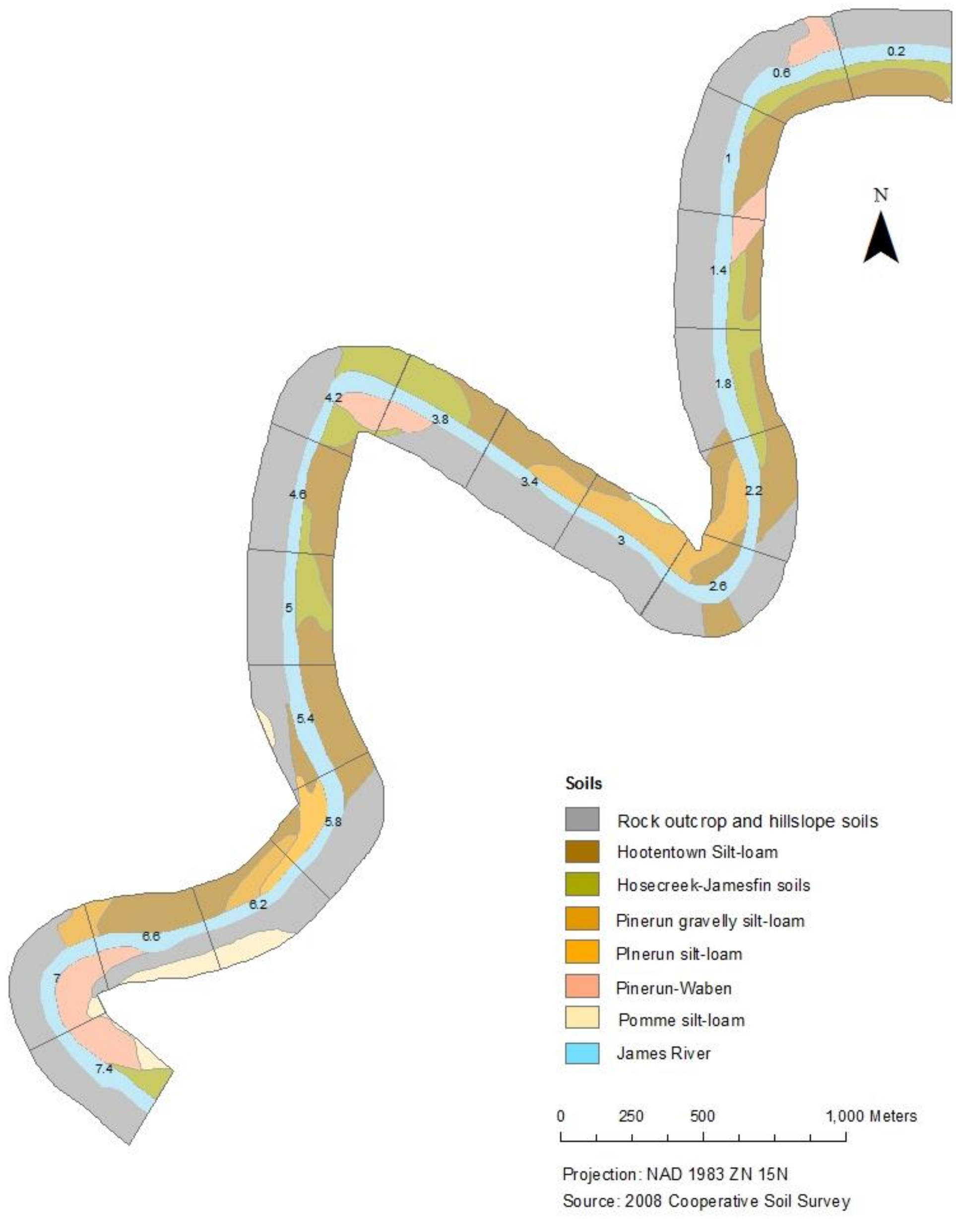


Figure 8. Soils of the James River Valley Study Segment (Gregg, 1995). Soils were mapped using a channel buffer of 200 m from the channel centerline of the James River.

Table 2. Alluvial soils and there characteristics of the study segment (Gregg, 1995).

Soil Series	Horizon	Depth	Clay	Silt	Sand	Chert Framents	Organic Matter	Landform Position	Flood Frequency
						0.2-7.62 (cm)			
		(cm)	%	%	%	%	%		
Pomme	Ap	0 -18	15	6	25	10	2	Strath Terrace	Rarley Flooded
	Bt1	18 - 48	28	6	12	10	1		
	2Bt2	48-145	32	51	17	65	0		
	3Bt3	145 - 203	61	25	14	75	0		
Hooten town	Ap	0-18	13	75	13	0	2	Terrace	Rarley Flooded
	BA	18-30	12	77	11	0	1		
	Bt1	30-81	17	74	10	0	1		
	Bt2	81-152	21	68	11	0	0		
Horse Creek	Ap	0-23	18	80	2	0	2	High Floodplain	Ocaisionally Flooded
	A	23-48	19	79	2	0	2		
	Bt	48-152	23	74	2	0	1		
Pine Run	Ap	0-13	17	60	24	52	3	Floodplain and Alluvial Fan Deposits	Ocasionally Flooded
	Bt	13-97	31	43	26	55	1		
	Bt2	91-152	36	40	24	53	0		

Table 3. USGS gage sites used in this study (Figure 4).

Name	Number	Drainage Area (km^2)	Record	Mean Q (m^3/s)	Max Q & Date (m3/s)
James River near Springfield	USGS 07050700	637	1955-2013	6.65	1160.71 9/25/1993
James River near Boaz	USGS 07052250	1,197	1972-1980 & 2001-2013	14.74	1186.19 3/19/2008
James River at Galena	USGS 07052500	2,556	1922-2013	28.08	2409.17 3/19/2008

METHODOLOGY

Site Selection and Study Design

The location for this study was selected by the Missouri Department of Natural Resources, The James River Basin Partnership, and a landowner to include the 7.4 km segment within a riparian conservation easement program (Table 1). To follow 319 requirements the present study evaluated the contribution of sediment supplied from the easement by bank erosion to the sediment loads in the lower James River. The segment was split into 400 m by 200 m cells to allow for the classification of different variables that influenced the erosion rate and active erosional and depositional processes in this segment of the James River (Figure 3). Using the cells also served to report average soil and bank characteristics along the James River for assessment of the sediment delivered to the stream. Similar studies have also used segments or cells to compare different channel reaches (Ferguson and Ashworth 1992; Geoff and Ashmore, 1994; Ashmore and Church, 1998; Ham and Church, 2000).

Data from geomorphic field assessments were combined with the segment-scale bank erosion rates from the aerial photograph analysis to estimate bank contributions to the suspended and coarse sediment loads (Figure 9). To gain a better understanding of reach scale bank sediment inputs to the sediment load erosion pin transects were place along a 260 m eroding bank. Erosion pin measurement's and the evaluation of bank sediment composition provided an erosion rate along with sediment mass eroded and deposited during the monitoring period. The reach-scale measurements helped to identify the processes affecting bank erosion rates (Figure 10).

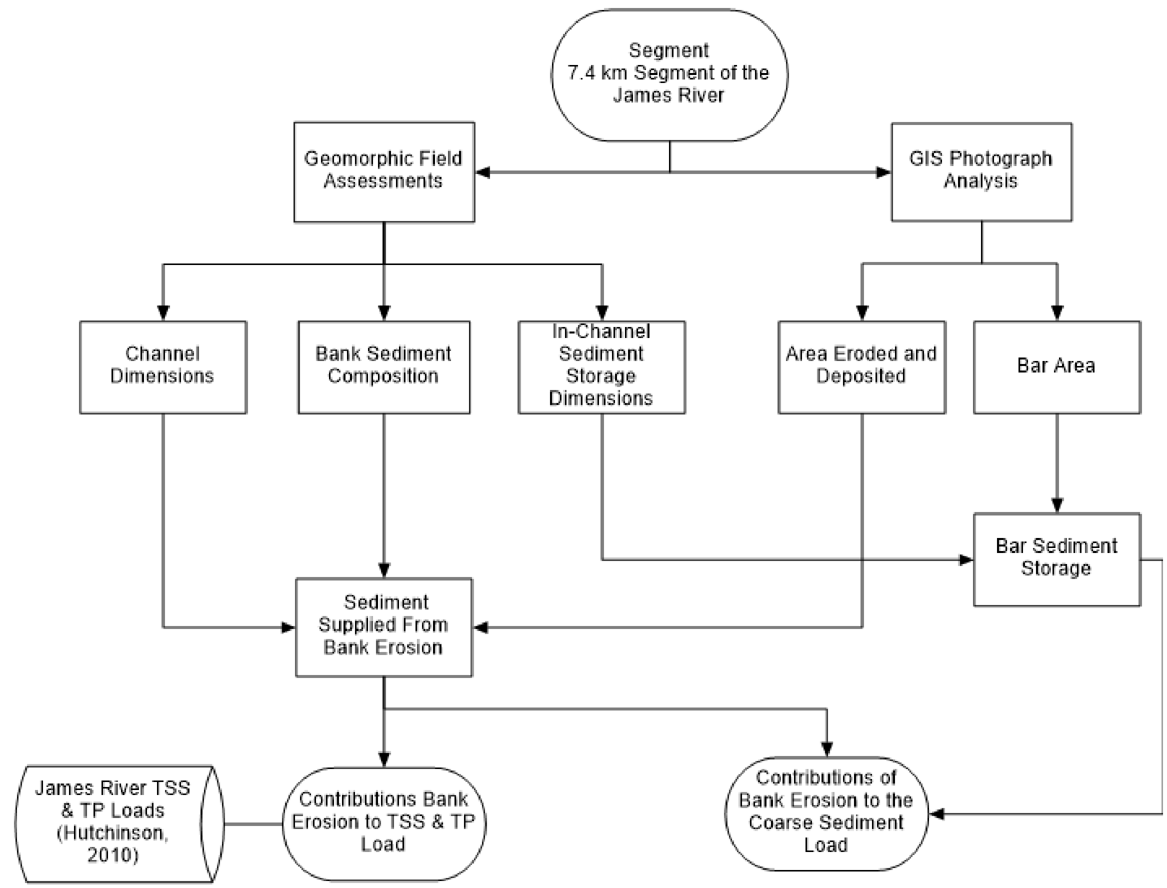


Figure 9. Data flow and experimental design to obtain final results for the segment scale study area.

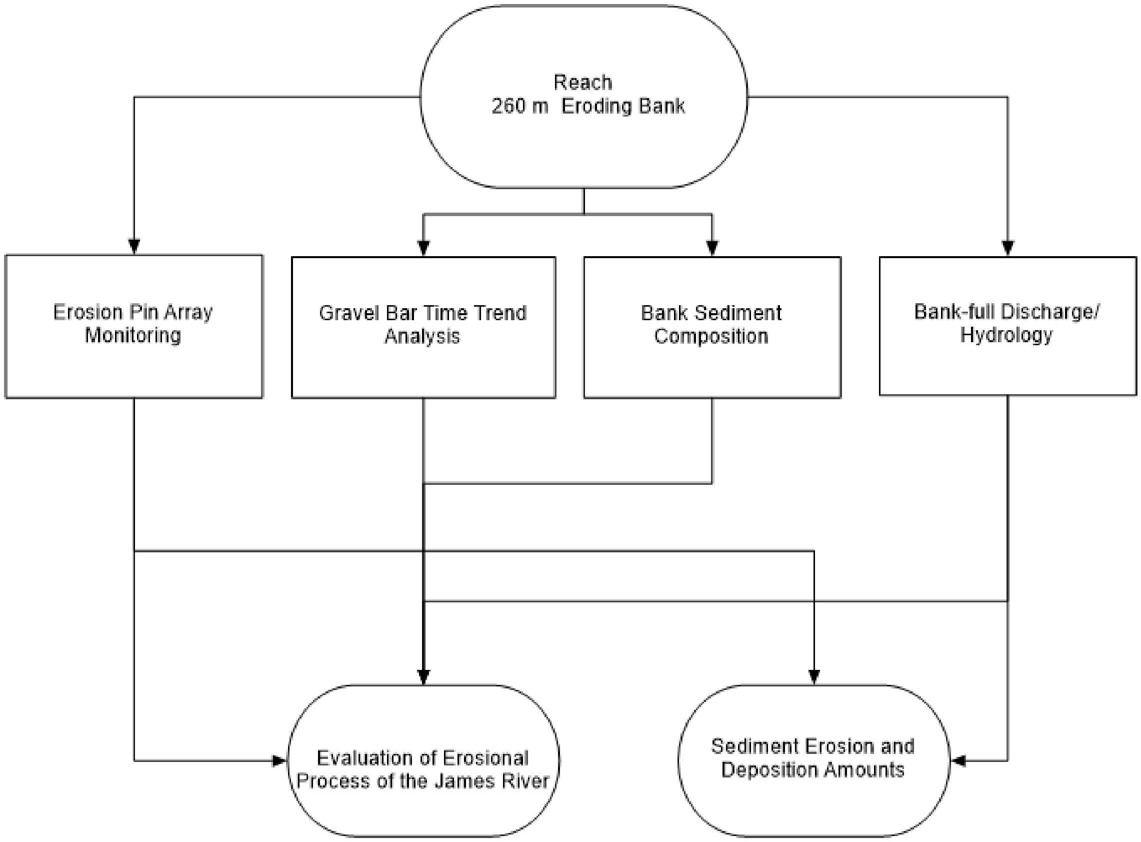


Figure 10. Data flow and experimental design for the reach scale study area.

Geomorphic Field Assessments

Geomorphic assessment methods are used to determine the direction, causes, and the rate of geomorphic change, and are used for the purpose of planning projects in the stream (Johnson et al., 1999; Shields et al., 2003). Geomorphic bank assessments were used to measure the channel dimensions, assess geomorphic characteristics, and evaluate dominant geomorphic processes within the study segment on the James River (Table 4). Field data were collected in May 2012. Channel dimensions were measured with a five meter stadia rod and 100 m tapes. The channel dimensions measured were wetted width, active channel, bar and bench widths and heights, bank heights, and the depth at the Thalweg.

The thalewg depth and the bank heights were measured at the center of 400 m river cells and are representative of the upstream and downstream 200 m (Figure 3). To understand the processes that are shaping the present and future channel, characteristics were quantified to supplement the aerial photograph time trend analysis (Table 5). The characteristics measured were channel unit type, gravel bar type, bank stratigraphy, and visual signs of erosion. The channel unit was classified as a riffle, run, pool, or glide after Montgomery and Buffington (1997). Gravel bars were classified as side, delta, point, or mid-channel (Figure 11) (Rosgen, 1996).

Bank conditions were measured for the left and right banks as follows: percent bank length eroded, percent rock toe armor, percent fine sediment present in the bank, and percent gravel content in the bank (Heeren et al., 2012). Bank condition variables were estimated visually while measuring the channel dimensions. Along with the bank heights and thalweg depth, the percent gravel content and fine sediment will be used to estimate the amount of fine and coarse sediment contributed from the banks of the reach to the stream through erosional processes.

Erosion Pin Array Monitoring

To gain a better understanding of bank erosion rates and releases of sediment to the James River, 11 vertical pin transects were installed along a cut-bank that was previously selected for riparian corridor restoration and protection (Figure 3). Each erosion pin records either erosion or deposition for a certain percent of bank over a year monitoring period (Figure 8). Erosion pins were made by cutting 12.7 mm (0.5 in) diameter steel rods into 70 cm (24 in) long pieces.

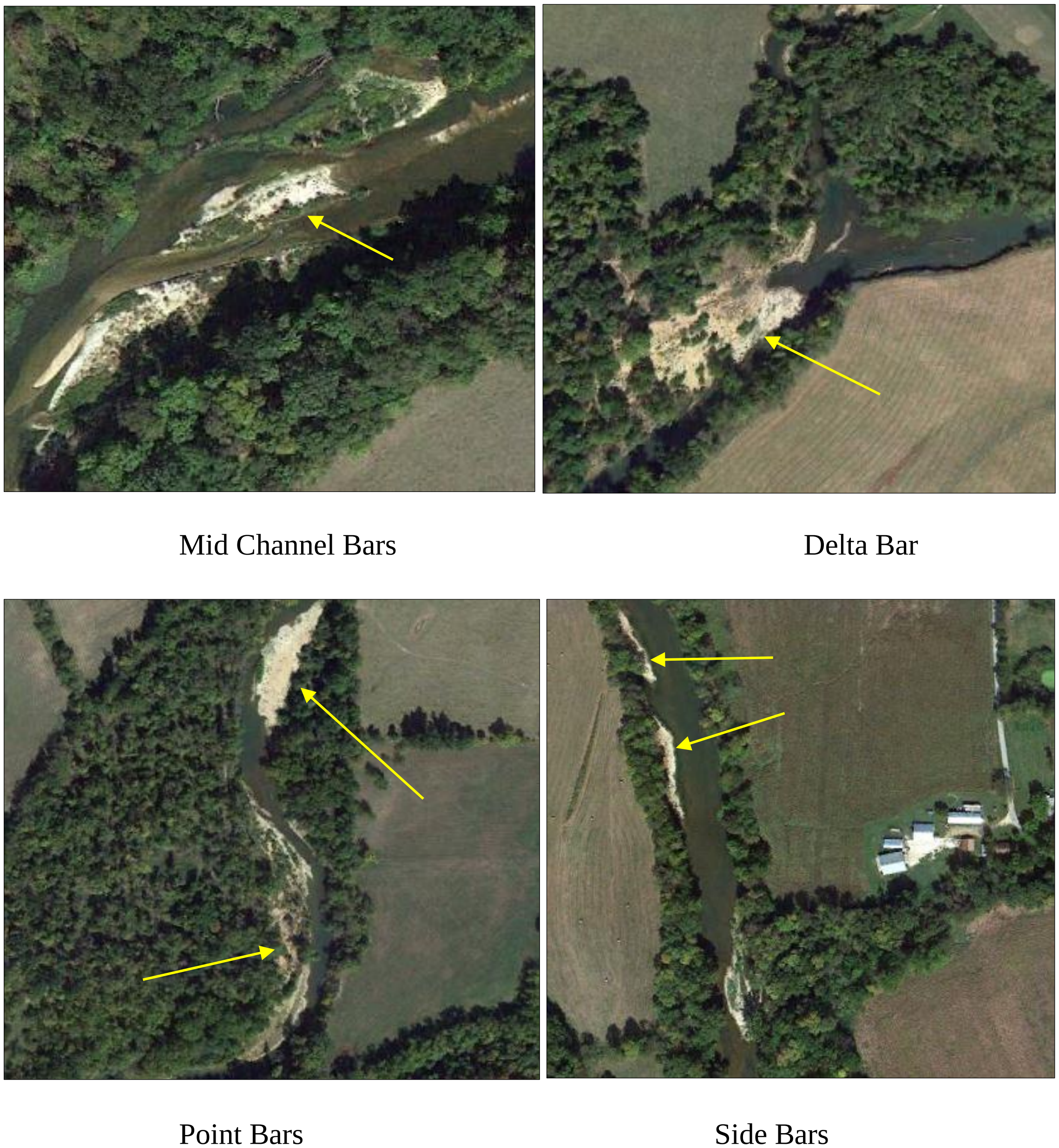


Figure 11. Gravel bar types (Rosgen, 1996). Note: Gravel bar features shown in photographs are not in the study segment and are used for reference only.

Table 4. Description of field measurements taken at each surveyed transect.

Variable Group	Measurement Taken
Channel Dimensions	Bank Height, Total and Active Channel Widths, Bed width, and Thalweg Depth
Reach Type at Transect	Channel Unit (Montgomery and Buffington, 1997)
In Channel Sediment Storage	Bar Height, Bar Width, Bar Type, Bench height, Bench Width
Bank Sediment Composition	% Fine Sediment in the Bank, % Gravel Content in the Bank
Bank Erosion	% Bank Length Eroded, % Rock Toe Armor

Erosion pins were installed with 15 cm (6 in) exposed. Erosion pin exposure was measured with a tape measure from the bank surface to the exposed end of the pin. If erosion had occurred since the previous monitoring date, then the pins were reset to 15 cm to continue the monitoring process and provide better accuracy in measurement.

Pin arrays were evaluated and installed as follows along the 260 m long cut bank (Figure 3). Pins were monitored monthly for a year providing a reference point on the river bank to document changes (Figure, 12) (Harden et al., 2009; Willet et al., 2012). Four pins were installed on each vertical pin transect excluding four sites, where circumstances did not allow placement of the lowest or highest pin. One pin was placed near the top of the bank just after the break in slope (pin 1), one was placed mid bank (pin 2), one just above the bank toe (pin 3), and one was placed at the ordinary waterline in the bank toe (pin 4) (Figure 12) (Harrelson et al., 1994; Harden et al., 2009; Harden et al. 2010). Erosion pin measurements are recorded as the sum of the length of pin that has been exposed at each monitoring date over the year period concluding in May, 2013. The amount of change is the rod exposure present at the time of observation minus the 15 cm of initial exposure. If deposition was evident, and a pin was buried it was not excavated and a value of -15 cm was given due to the original exposure of the pin (Harden et al., 2010). If erosion was evident and a pin was missing, then a value of 46 cm (18 in) was assigned, due to the fact that the overall pin length is 61 cm and the original exposure is 15 cm. For this study, it is assumed that a pin would fall out only having 5cm (2 in) of its length remaining in the bank (Harden et al., 2009).

Segment-Scale Bank Erosion Rates

To estimate sediment displacement rates from the banks within the segment scale a morphologic approach was employed. The morphologic approach was first used by Popov (1962), and then by Neill (1987). Neill found that estimates of sediment transport rates could be made by measuring erosion volumes over periods of time. The morphologic approach to sediment transport has been advanced since by Ferguson and Ashworth (1992), Geoff and Ashmore (1994), Ashmore and Church (1998), Ham and Church (2000), and Fuller et al. (2002). The mass of eroded bank soil material released to the channel can be calculated by measuring the distribution of channel bank line changes over time using historical aerial photographs (Ham and Church, 2001).

GIS Aerial Photograph Analysis. Geographic information systems (GIS) coupled with the use of recent and historical aerial photographs of Ozark Rivers has proven to be a powerful tool when measuring channel change over a period of time (Jacobson and Pugh, 1997; Hughes et al., 2006; Martin and Pavlowsky, 2011).

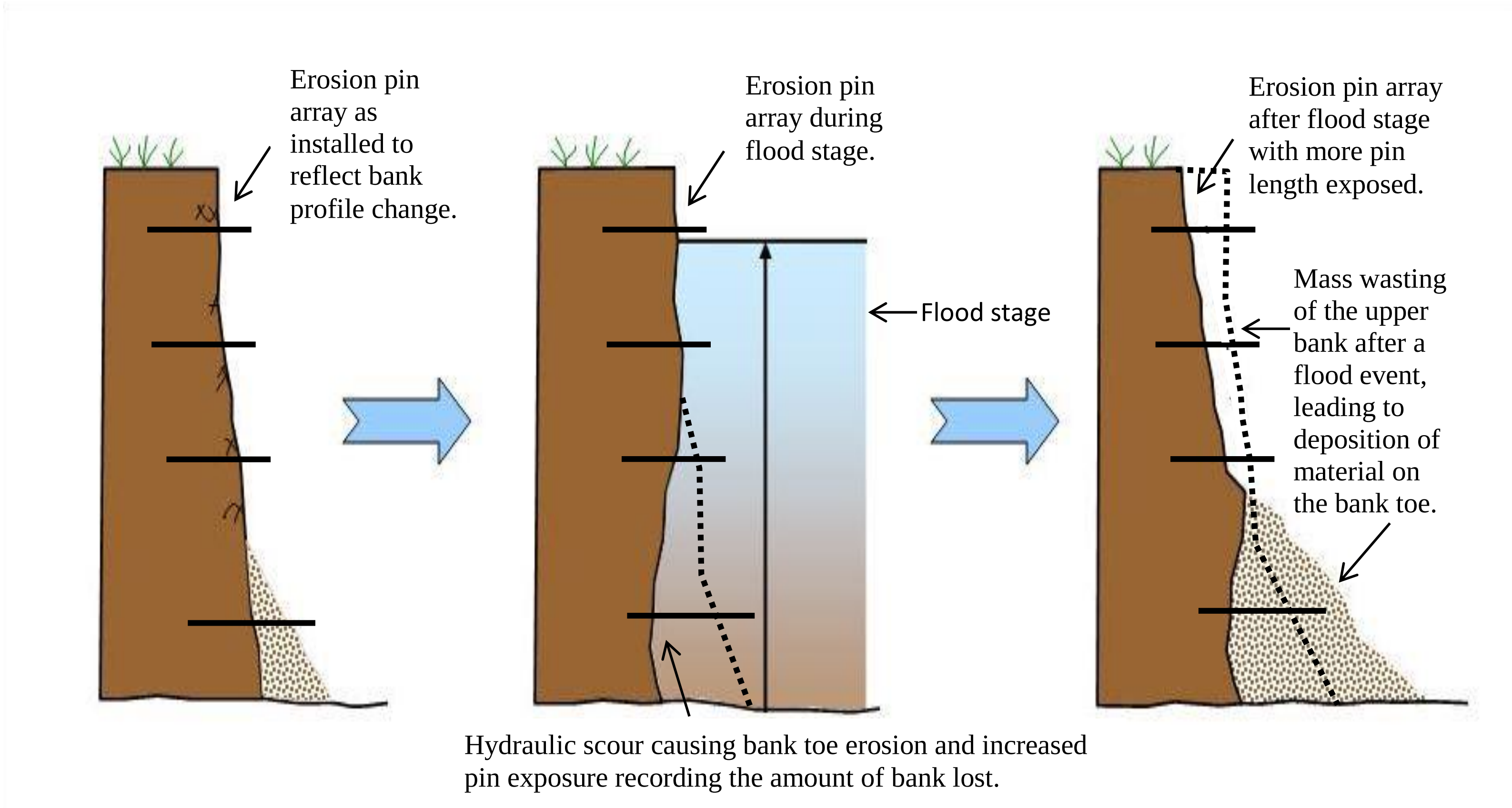


Figure 12. Erosion pin array reflecting bank erosion before and after a flood event, and the process of bank retreat (modified from Benham, 2006).

Overlaying of historical aerial photos in a GIS offers a relatively simple way to document changes and migration of channel banks (Lawler, 1993). Aerial photographs downloaded from USGS Earth Explorer were used from 1952, 1997, and 2008 to quantify bank erosion on the 7.4 km project segment of the James River. The photographs from 2008 have a spatial reolution of 0.61 m, and were used as a base for rectification for the 1952 image and 1997 images. This photograph record provides for the analysis of both the long-term (1952-2008) and short-term (1997-2008) erosion rates. All three photographs were acquired in the winter months when the leaves are off the trees to better identify bank features. Eight to ten ground control points per image were used to geo-reference the older image to the 2008 pre-rectified image (Hughes et al., 2006). Root mean square error was <2 m for the photographs and the average test point error was +/-2 m for the 1952 image +/- 3 m for the 1997.

To quantify bank erosion, the active channel banks were digitized using a polygon in Arc Map for overlay analysis. Left and right banks were digitized for the sets of photographs at a scale of 1:1,000. Channel bank line is usually easy to identify. However, the presence of dense riparian zones or bluff shadows covered the banks position in some places. In these cases, the bank line position had to be extrapolated between locations of visible banks. A previous study using this method found this caused errors that did not exceed 1 m (Winterbottom and Gilvear, 2000). The locations of rapid assessment transects were used to create the spacing for erosion cells used to evaluate bank erosion and deposition trends.

The next step involved using the “Erase analysis” in ArcMap to create erosion polygons by overlaying the older digitized active channel over the newer digitized active channel. If the newer active channel was outside the boundaries of the older digitized channel, then that portion was made into a new polygon and considered an area of past erosion. The area of the polygons is calculated and multiplied by average bank height, which was measured during rapid assessments procedures (Table 5).

Calculation of Bank Erosion Rates. The results of this study calculated the bank supply of both fine-grained (<2 mm) and coarse sediment to the channel. Gravel content of the banks was estimated using rapid assessment data (Table 5) and National Resource Conservation Service (NRCS) soil profile descriptions (Table 3). As described previously, the porosity of gravel for this study will be 33 percent assuming a mixture of cubic and rhombohedral modes of particle packing (Leeder, 1992). Limestone and dolomite bluffs are present in the study segment and are found to erode in temperate continental climates at a rate of 0-5 mm/yr (Saunders and Young, 1983). However, for the time period and level of accuracy used in this study the bluffs adjacent to the channel were not considered erodible and polygons that reported erosion or deposition on bedrock areas reflected photograph analysis errors. This error is likely due to the extrapolation between visible bank points through bluff shadows and has been found by previous studies to not exceed 1 m (Winterbottom and Gilvear, 2000).

A comparison of bank erosion rate provides not only insight into the rate of riparian landscape change, but also the comparison of how different land uses, plan-form, and geology affect the erosion rate in the study segment. The following steps were used to calculate the bank erosion and deposition rates for each 400 m cells bank side:

1. Sum all the erosional and depositional features in the long term and short term periods in each 400 m cell to determine a net bank change (m^2) for each cell.
2. Divide the net bank change by the length of the cell (400 m) to calculate the width of bank change per m for the cell length.
3. Divide the bank change per m by the period of years between the aerial photographs to determine the rate of bank change m/yr.

Sediment Volume and Mass Calculation

Calculating the mass of sediment lost to the stream for the study segment and reach-scale study area provided a means to estimate the contributions of bank erosion to the fine and coarse sediment loads. In each bank unit there was an aggregate of clay, silt, sand, and chert gravel (Figure 13). The amount of coarse and fine sediment for each pin array and cell was estimated using the soil survey for the reach-scale and segment-scale study areas, and by visual analysis of the gravel content of each (Figure 13). Further, in the study area there is fine sediment stored with in the chert gravel deposits, and the gravel porosity for a bank unit that is deposited gravel will be 33 percent assuming a mixture of cubic and rhombohedral modes of particle packing (Leeder, 1992). Alluvial soils in the reach scale erosion pin segment have chert fragments percentages >60 percent supporting the assumption of 33 percent gravel porosity (Gregg, 1995). Then the volumetric bank unit change is multiplied by the estimated bulk density of the bank unit soil to calculate the mass of sediment eroded or deposited. Bulk density values for fine alluvial soils in the study segment ranged from 1.36 g /cm^3 to 1.46 g /cm^3 (Gregg, 1995). A middle value of 1.41 g /cm^3 was used in this study to calculate the mass of eroded fine bank sediment. A bulk density value for chert gravel of 2.26 g /cm^3 and was used in this study for calculating the mass of eroded coarse sediment. Kris Breckenridge at Missouri State University determined an average chert gravel density of 2.26 g/cm^3

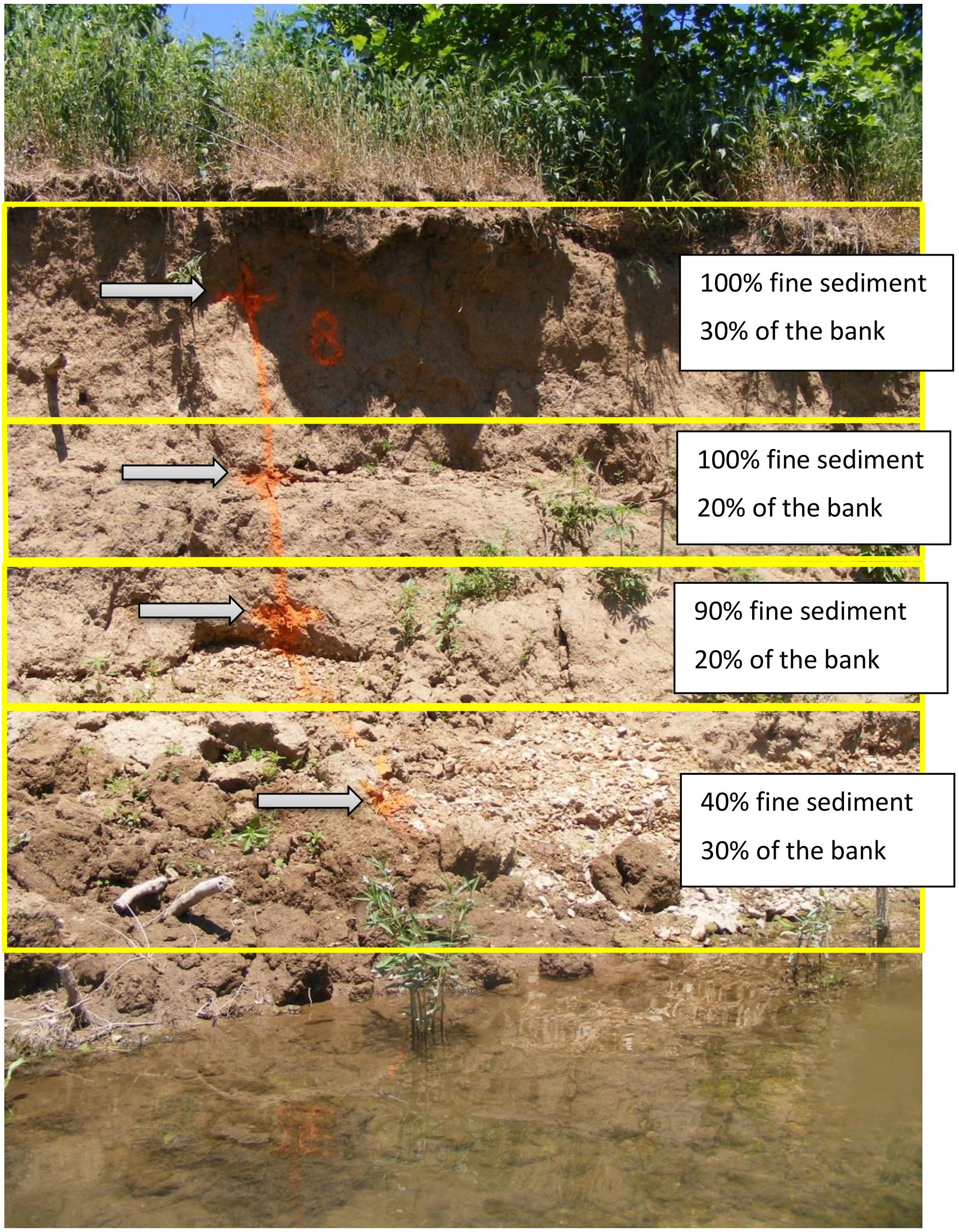


Figure 13. Erosion pin array 8. Arrows mark erosion pin locations. Rectangle units indicate the pin percentages for the vertical array. Each bank unit will be given a density value according to the amount of coarse and fine sediment present using visual assessment and also soil profile data from the NRCS (Gregg, 1995).

from a sample of 379 particles ranging in diameter from 16 mm to 45 mm collected from a tributary of the James River.

The following steps were taken to calculate the mass of fine and coarse sediment released to the channel by erosion:

1. Bank change volume was determined for each eroded or deposited area by multiplying the bank change (m^2) by the bank height at the corresponding bank side.
2. Bank change volume (m^3) is divided by the coarse gravel fraction that was determined by the geomorphic assessment.
3. To determine the amount of fine sediment within the gravel, the product of the previous step is divided by 33 percent, which is the assumed amount of fines sediment stored within coarse gravel fraction deposits in the study area (Leeder, 1992).
4. Fine sediment volume (m^3) was calculated by subtracting the coarse sediment fraction volume from the eroded or deposited area volume (m^3), and then adding the fine sediment stored within the coarse gravel bank deposits.
5. Coarse sediment volume (m^3) was determined by obtaining the amount of fines packed within the coarse gravel deposit and subtracting them from the total volume of coarse sediment.
6. Mass for the fine and coarse sediment volume (m^3) is calculated using the bulk densities of the different bank deposits for the study area.

Bar Sediment Storage

To estimate the contribution of coarse gravel deposits in the bank to the gravel load in the segment scale study area, the 2008 gravel bar volume within the study segment was quantified and compared to the amount of gravel that eroded from the banks during the period 1997-2008. Gravel bars were digitized at a 1:1000 scale, same as the erosional and depositional features along the banks. Gravel bar height or thickness from the thalweg was recorded in the geomorphic assessments (Table 5). Using the bar area determined from aerial photographs combined with the field measurements from geomorphic assessments, an estimate of bar volume and mass was made and then compared to the amount of gravel that was eroded into the study segment (Ham and Church, 2000). Additionally, the gravel bars were assumed to have 33% pore space filled with fine sediment that is not included in the gravel bars volume (Leeder, 1992). The estimate of bar volume and mass will provide an estimate of the percentage of the gravel bar volume in the channel of the study segment that is derived from channel sources.

James River Sediment Loads

This study compares annual bank sediment inputs to previously reported suspended sediment loads (Hutchinson, 2010). The Hutchinson study sampled suspended sediment at several USGS gage sites on the James and Finley Rivers during 2008 and 2009 (Table 6). Depth integrated sampling at the thalweg was used to collect a sample from the whole water column at equal volumes regardless of the velocity (Hutchinson, 2010). To determine the concentration of Total Suspended Sediment (TSS), 200 ml of the 500 ml water sample was filtered through a 1.5 µm Whatman nominal pore size glass microfiber filter. The 1.5 µm filter was heated to 104 ºC for one hour, and a mass differential of the filter provided the concentration of TSS in mg/L. It should be noted that a 0.45 µm filter was used to quantify fine suspended sediment in selected samples in the Hutchinson (2010) study, but watershed sediment loads, were based on 1.5 µm filtered samples. The annual loads used in the Hutchinson (2010) study were derived by the Flow Duration Curve Method. Hydrologists and geographers have employed sediment rating curves to estimate and predict suspended sediment loads to streams (Crawford, 1996).

To estimate the contribution of bank erosion to the suspended sediment and phosphorus (P) loads a combination of the Hutchinson (2010) data and the erosion rate per km derived from the study segment analysis was used (Table 7). To estimate the mass of sediment eroded from the entire James River Basin, the erosion rate per km from the long term study period will be applied to the entire length of the main stem of the James and Finley Rivers. That data is then compared to the Total Suspended (TSS) and Total Phosphorus (TP) yield from the Hutchinson (2010) study to calculate a percentage of the TSS and TP load that is supplied from in channel sources.

Table 5. Sites and calculated suspended sediment Loads from Hutchinson (2010).

Site ID	Location	UTM Northing	UTM Easting	Drainage Area (km2)	Annual Load (Mg/yr)	Annual Yield (Mg/yr/km^2)
F	Finley River at Seneca Bridge	4,092,114.74	470,810.64	676	6,103	9.03
UJ	James River at Kinser Bridge	4,111,529.73	481,982.02	637	25,252	39.64
MJ	James River at Shelvin Rock Bridge	4,095,680.40	467,576.89	1,197	104,520	87.32

Table 6. Hutchinson (2010) calculated TP Loads.

Site ID	Location	Channel Length to Site	Drainage Area	Annual TP Load Hutchinson (2010)
		(km)	(km^2)	($Mg/yr/km^2$)
UJ	James River at Kinser Bridge	52	637	12.74
MJ	James River at Shelvin Rock Bridge	99	1197	59.85

To obtain the levels of P in the bank sediments 20 soil samples were collected at one of the erosion pin vertical transect (#8). Sample collection followed obvious breaks in stratigraphy from the top of the cut bank to the bank toe. After transport to the lab, samples were dried at 60° C, and crushed with a mortar and pestle then sieved at 2 mm (0.08 in) then sieved again at 0.250 mm (0.01 in) and then tested for nutrient concentrations using aqua regia hot nitric and hydrochloric acid extraction (Houba et al., 1996). The P concentration for each soil sample will be used to obtain average parts per million (ppm) value for the James River floodplain deposits. The average ppm value will be extrapolated to the extent of net bank fine sediment erosion for the main stem of the James River, and then compared to the Hutchinson (2010) P yields for the James River watershed.

Determining Bank-Full Discharge

Bank-full stage relationships were used to compare the floods that occurred during the erosion pin monitoring period to evaluate which flows cause the largest amount of erosion or deposition. The bank-full flood stage is the point in elevation where the water would exit or over-flow the channel and inundate the floodplain (Harrelson et al., 1994). Furthermore, bank-full discharge is considered the most productive range of flows for transporting sediment, and removing and forming dynamic channel forms. To figure out the bank-full discharge for the erosion pin reach, the bank full discharge to watershed area relationship for the James River quantified in the Dewitt (2012) study was used (Figure 14). Dewitt (2012) used channel morphology equations to evaluate channel dimensions, and valley scale characteristics of the James River Basin of southwest Missouri. Cross sections and longitudinal profiles in the Dewitt (2012) study were taken using a Topcon AT-G7 Auto Level and stadia or the total station (Dewitt, 2012). Discharge for the James River was taken from USGS Gage 7052250 near Boaz and then adjusted for the drainage area at the reach scale study area where this data was applied (2081.2 km^2). Using the bank-full discharge to drainage area relationship found in the Dewitt (2012) study the calculated bank full discharge is 224 m^3/s.

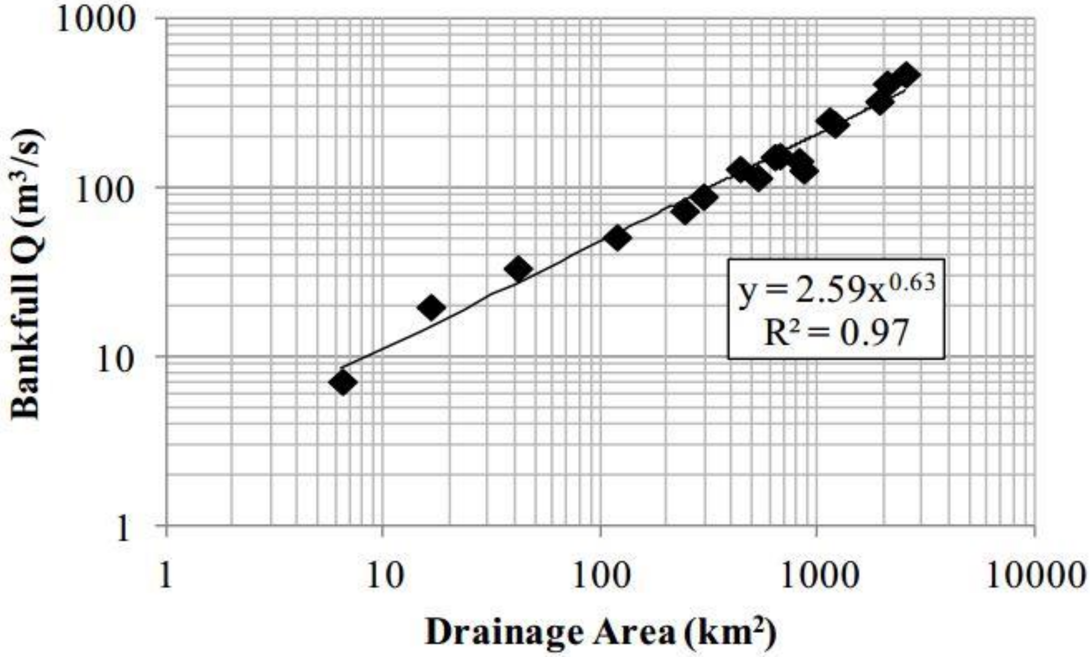


Figure 14. Bank full Q to drainage area relationship for the James River

(Dewitt, 2012)

RESULTS & DISCUSSION

Reach-Scale Bank Erosion Pin Trends

Erosion Pin Monitoring. Erosion pin arrays were installed in the bank May 2012 and monitored monthly for a one year period. Erosion pin monitoring indicated that both eroding and stable banks occur in the study reach (Figure 3). The highest rates of bank erosion were located on pin arrays #1, #2, and #9 through #11, while arrays #3 through #7 remained stable, with little erosion during the one year monitoring period (Table 8 : Figure 15). The average bank erosion rate for the study area was 0.2 m/yr for the entire reach, which was calculated by averaging the erosion rates for each pin array. The highest rate of bank erosion occurred during the spring season when soil moisture content was relativley high and more high flows and bankfull floods occurred. The sequence of bank erosion in the study reach is described below.

June to mid-October 2012. Little bank change occurred due to a period of low rainfall during the summer months and early fall (Figure 16). During the summer and early fall nine rainfall events occurred in the watershed incurring a max stage of 120 m^3/s, but usually not exceeding 25 m^3/s (Figure 17). However, pin arrays #1 and #2 eroded 0.14 and 0.06 m, respectively (Figure 16). The erosional events at pin arrays #1 and #2 were due to hydraulic scour on the bank toe. Mass wasting was recorded on pin array #3 with evidence of upper bank collapse and accumulation at the toe. Furthermore, during the period from June to October, 0.03 m deposition on the bank toe was measured of arrays #3, #4, and #8. At pin array #7, 0.6 m of deposition was measured on the lowest pin. The deposition that occurred was caused by mass wasting of the upper bank verified by the presence of slump scars on the bank.

The lack of substantial bank erosion during the summer and early fall low rainfall period illustrates that bank stability dominates during periods of low precipitation. The lack of antecedent conditions such as high soil moisture content in the bank, excess pore water pressure, and frost action causes the banks to resist failure (Knighton, 1988; Julian and Torres, 2006). During the period of low rainfall the banks became resistant to erosion as the cohesive bank soil gained a hard consistency that was resistant to failure (Table 3).

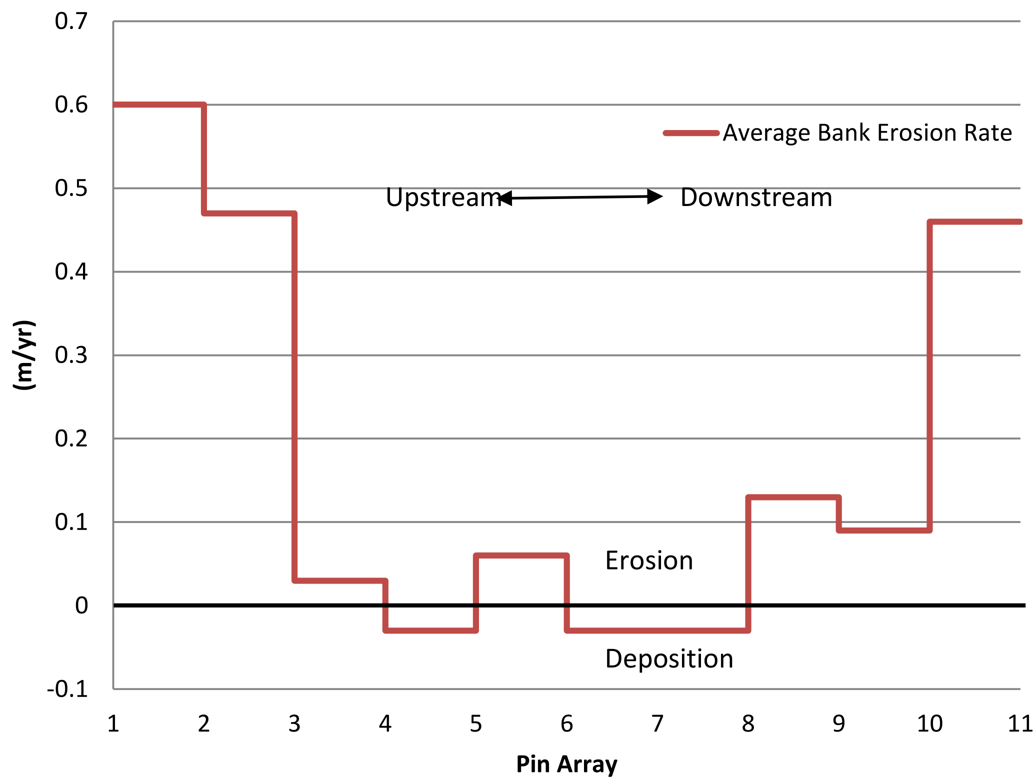


Figure 15. Average bank erosion rates for the erosion pin transects during the one year study period.

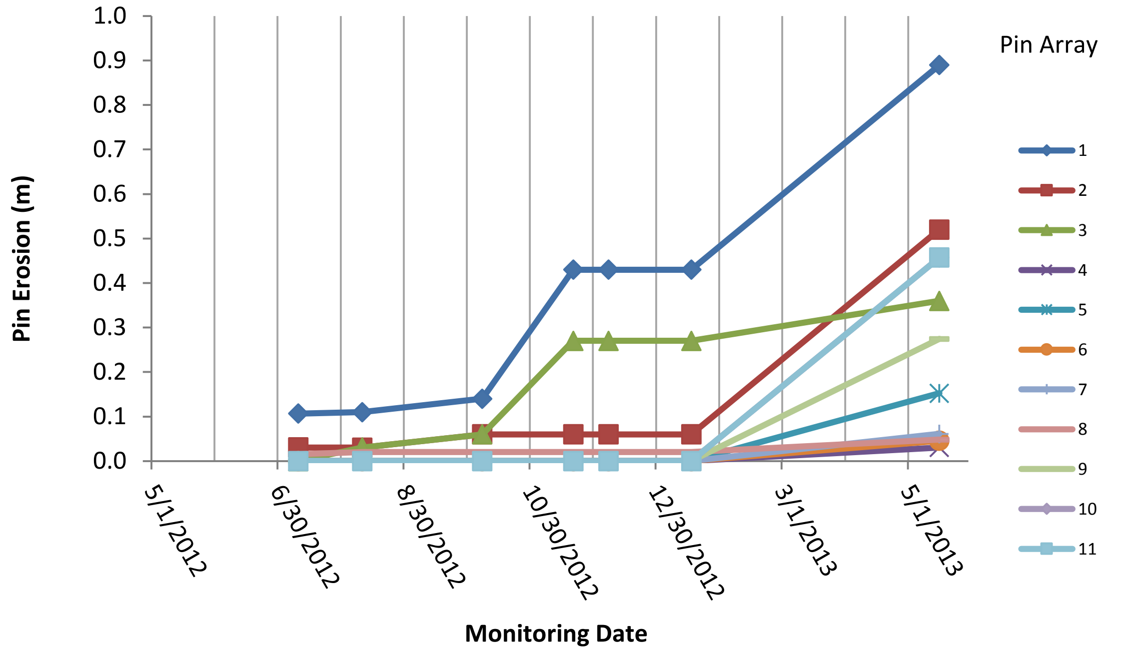


Figure 16. Cumulative erosion by monitoring date.

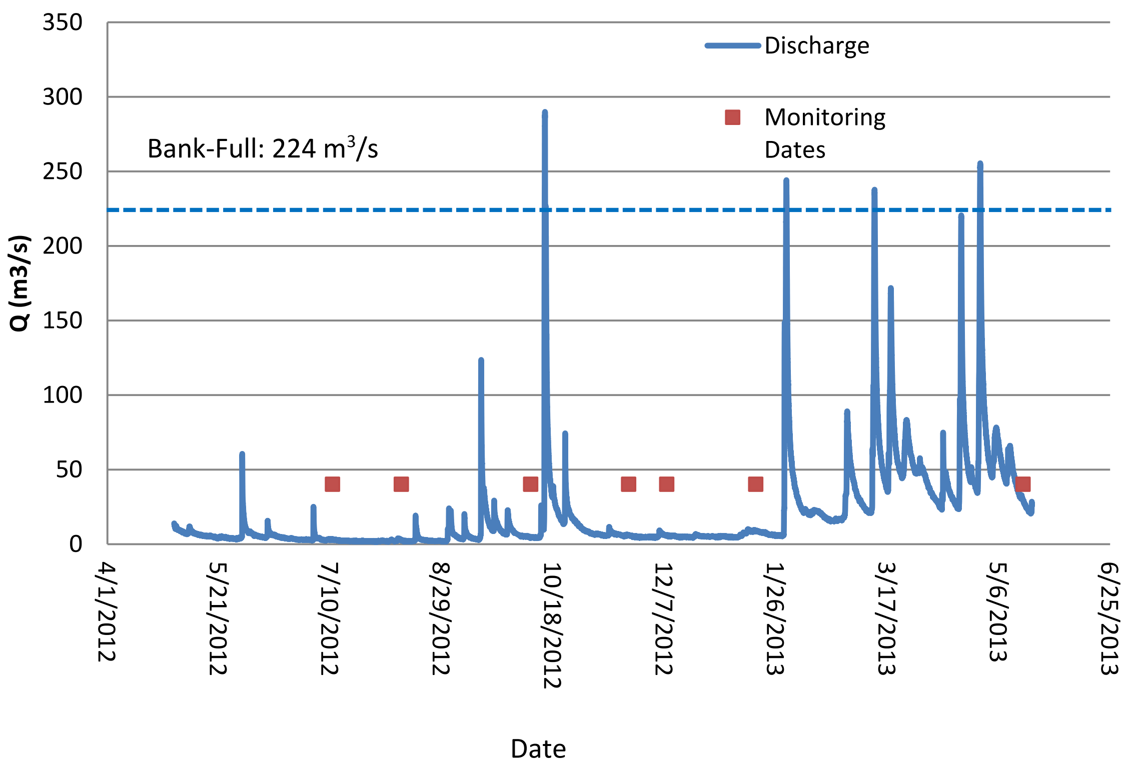


Figure 17. USGS gage site 07052345 hydrograph for the reach scale study period and

monitoring dates. Red squares are field monitoring dates. Bank-full values from Dewitt (2012).

October and November 2012. October 18The largest magnitude flood event occurred during the year monitoring period (Figure 17). The discharge at USGS gage 7052250 peaked at 168 m^3/s, after correction the value becomes 290 m^3/s (Figure 12) (USGS, 2012). The bank-full flood stage was previously determined for the study segment at 224 m^3/s for this reach (Dewitt, 2012). The October flood event lasted 6.25 hours at or above bank full stage (Figure 17).

During the monitoring period from October to November 2012 measurable erosion occurred at pin arrays #1, #2, and #3 (Table 7) (Figure16). At pin array #1, 0.32 m of the bank toe was eroded. The bank toe on pin array #1 is made up of a non-cohesive chert gravel deposit that was eroded by hydraulic scour. The erosion that was measured on pin array #2 was relatively minor and also occurred on the bank toe. Pin array #3, however, eroded 0.21 m at the mid bank second pin bank unit. The bank material in this area was fine silt & clay flood plain sediment that was assumed to be eroded by a mass failure at the peak or falling stage of the high magnitude flood event (Julian & Torres, 2006).

The flood event may have caused the bank unit at array #3 to become saturated, weakening the cohesive bonds between the silt and clay particles that result in tension cracks leading to mass failure (Thorne, 1982; Knighton, 1998; Julian and Torres, 2006). However, little erosion occurred across the entire reach, despite the largest magnitude flood during the monitoring period. The occurrence of little erosion is likely due to a lack of soil moisture in the bank preceding the flood event decreasing the effectiveness of hydraulic scour and gravitational pull to cause erosion.

November 2012 to January 2013. Lower rates of bank erosion occurred due to the lack of high discharges (Figure 17). The only bank adjustments that were recorded during this period were 0.03-0.05 m deposition on the bank toe at pin arrays #3, #4, and #8 (Table 8) (Figure 16).

January 2013 to May 2013. Frequent high discharges did not allow pin measurements to be collected for the months of February, March, and April. During this period four bank-full flood events lasted 15.25 hours, with a peak discharge of 254 m^3/s on April 27, 2013 (Figure 17). Pins at transects #1, #2, #10, and #11 were all eroded beyond their length and removed from the bank (Figure 15 &16). As mentioned in the methods, a value of 0.46 m was assigned due to the length of the pins. This assigned value should be considered a conservative estimate, the actual amount of erosion could be more than that value.

Pin array #1 recorded the most erosion with an average rate of 0.6 m/yr. However, pin array #2 eroded at a rate of 0.47 m/yr, and #10 #11 eroded at a rate of 0.46 m/yr. Bank erosion processes that took place during the period from January to May 2013 are hydraulic scour of the bank toe, and mass wasting increased by antecedent conditions. The multiple flood events that occurred probably caused bank saturation and excess pore-water pressure that caused large mass failure events after the removal of the less cohesive bank toe by hydraulic scour in pin arrays #1, #2, #3, and #11.

Bank Sediment Loss. The total volume of coarse and fine sediment released to the stream by bank erosion along the 260 m reach over the one year period was 223 m^3 (Table 9) . Calculation methods can be found on page 40. Fine sediment in the form of

Table 7. Erosion pin records during the year monitoring period, erosion and deposition values in bold. Continued on next page.

Pin Array	Pin	7/11/12 (m)	8/11/12 (m)	10/8/12 (m)	11/21/12 (m)	12/8/12 (m)	1/17/13 (m)	5/17/13 (m)	Total (m)
		Monitoring Date							
1	1	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	2	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	3	**-0.11**	0.00	**-0.03**	**-0.29**	0.00	0.00	**-0.46**	-0.88
2	1	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	2	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	3	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	4	**-0.03**	0.00	**-0.03**	0.00	0.00	0.00	**-0.46**	-0.52
3	1	0.00	**-0.03**	**-0.03**	0.00	0.00	0.00	0.00	-0.06
	2	0.00	0.00	0.00	**-0.21**	0.00	0.00	**-0.09**	-0.30
	3	0.00	**0.03**	0.00	**0.05**	**0.05**	**0.05**	0.00	0.17
	4	0.03	0.03	0.03	0.00	0.00	0.00	0.00	0.09
4	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.00	0.00	0.00	**-0.03**	-0.03
	3	0.00	**0.03**	0.00	**0.05**	**0.03**	**0.03**	**-0.03**	0.11
	4	0.00	-0.03	0.03	0.00	0.00	0.00	**-0.03**	-0.03
5	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.00	0.00	0.00	**0.05**	0.05
	3	0.00	0.00	0.00	0.00	0.00	0.00	**-0.03**	-0.03
	4	0.00	0.00	0.00	0.00	0.00	0.00	**-0.15**	-0.15
6	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.00	0.00	0.00	**0.05**	0.05
	3	0.00	0.00	0.00	0.00	0.00	0.00	**0.12**	0.12
7	1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	2	0.00	0.00	0.00	0.00	0.00	0.00	**-0.03**	-0.03
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	4	**0.06**	**0.06**	**0.06**	**0.05**	0.00	0.00	**-0.06**	0.17
8	1	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	2	0.00	0.00	0.00	0.00	0.00	0.00	**-0.21**	-0.21
	3	0.05	0.00	0.00	0.00	0.00	0.00	**0.05**	0.10
	4	**0.03**	**0.03**	0.00	0.00	0.00	0.15	0.00	0.21

Table 7. Erosion pin Records (Continued from previous page).

Pin Array	Pin	Monitoring Date 7/11/12 (m)	8/11/12 (m)	10/8/12 (m)	11/21/12 (m)	12/8/12 (m)	1/17/13 (m)	5/17/13 (m)	Total (m)
9	1	0.00	0.00	0.00	0.00	0.00	0.00	**-0.27**	-0.27
	2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10	1	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	2	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	3	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	4	0.00	0.00	0.00	0.00	0.00	**0.05**	**-0.46**	-0.41
11	1	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	2	0.00	0.00	0.00	0.00	0.00	0.00	**-0.46**	-0.46
	3	0.00	0.00	0.00	0.00	0.00	**0.15**	**-0.46**	-0.3

silt and clay was 82 percent of the total volume, and the remaining 18 percent is gravel. Sediment mass inputs to the channel were calculated using the bank change volume and multiplying it by the dry bulk density of the two types of sediment which are 1.41 cm^3/g for fine sediment and 2.26 cm^3/g for chert gravel (Table 9). Total annual mass of all eroded sediment was 1388.46 Mg/km/yr with 988 Mg/km/yr fine sediment and 350 Mg/km/yr of coarse sediment (Table 9). Pin arrays one and two released almost 250 Mg of flood plain sediment into the James River over the year monitoring period. Pin arrays 10 and 11 released close to 100 Mg and the middle pin arrays, 3 through nine, released the smallest amount of flood plain sediment at 14 Mg (Figure 18).

Table 8. Summary of erosion pin analysis results. Negative values are erosion.

Pin Array	Mean Bank Erosion Rate	Fine Sediment Volume	Fine Sediment Mass	Coarse Sediment Volume	Coarse Sediment Mass	Total Volume	Total Mass
	(m/yr)	(m^3)	(Mg)	(m^3)	(Mg)	(m^3)	(Mg)
1	-0.60	-59.09	-83.32	-21.33	-48.20	-80.42	-131.53
2	-0.47	-44.39	-62.59	-22.95	-51.87	-67.34	-114.46
3	-0.03	-17.71	-24.97	6.04	13.65	-11.67	-11.32
4	0.03	0.46	0.65	1.78	4.02	2.24	4.67
5	-0.06	-2.08	-2.93	-1.17	-2.64	-3.25	-5.57
6	0.03	1.32	1.85	2.34	5.29	3.66	7.15
7	0.03	0.51	0.72	2.41	5.45	2.92	6.17
8	-0.13	-12.00	-16.92	3.44	7.78	-8.56	-9.14
9	-0.09	-3.73	-5.26	0.00	0.00	-3.73	-5.26
10	-0.46	-20.72	-29.22	-3.75	-8.47	-24.47	-37.69
11	-0.46	-25.07	-35.35	-7.02	-15.86	-32.09	-51.21
Total	-0.20	-182.51	-257.33	-40.20	-90.85	-222.70	-348.18

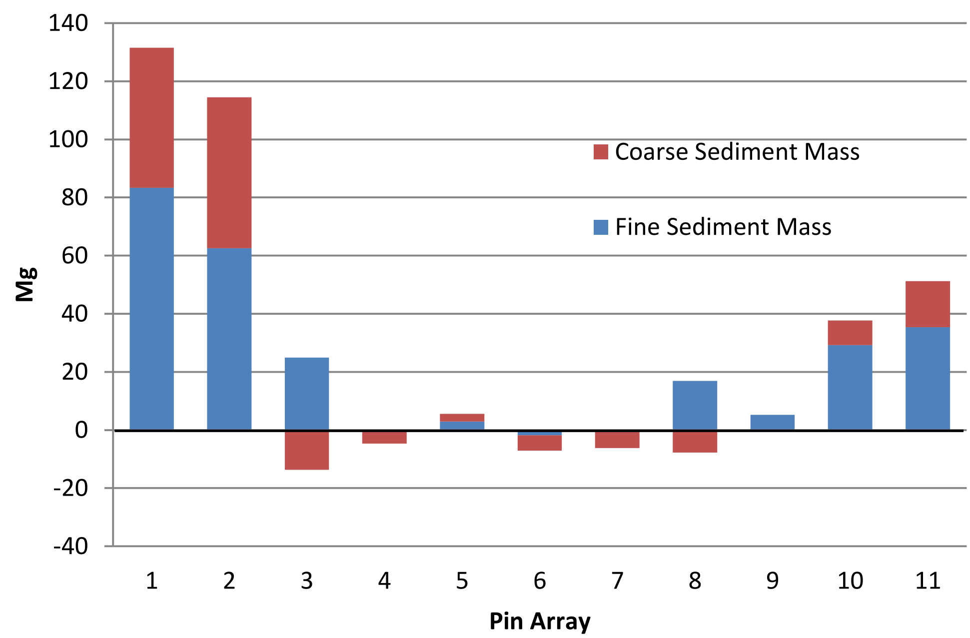


Figure 18. Sediment mass input to the channel in the reach scale erosion pin study area.

Segment Scale Bank Erosion Trends

Bank Erosion Rates. Bank erosion rates were calculated for the entire 7.4 km segment using time trend analysis for long term (1952-2008) and short term (1997-2008) periods. The average erosion rates for the 56 year period was found to be 0.04 m/yr on the left bank and 0.01on the right. The more recent 11 year period average erosion rates were 0 m/yr on the left bank, and 0.07 m/yr on the right bank (Table 10).

Table 9. Bank Erosion Rates for the long term and short term time periods. Negative values indicate erosion.

	1952-2008		1997-2008	
RKM	Left Bank Change	Right Bank Change	Left Bank Change	Right Bank Change
	(m/yr)	(m/yr)	(m/yr)	(m/yr)
0.2	-0.04	0	0	0.02
0.6	-0.04	0.28	0.06	-0.03
1	-0.26	0	-0.02	0
1.4	-0.31	0	-0.06	0
1.8	-0.2	-0.07	0.01	-0.32
2.2	0	0.08	-0.09	0.01
2.6	0.01	0.13	0	-0.11
3	0	-0.12	0	0.02
3.4	0	-0.07	0	-0.01
3.8	-0.01	-0.1	0.03	-0.16
4.2	0.06	-0.18	0.08	-0.27
4.6	0.03	0	0.07	0
5	-0.01	0	-0.19	0
5.4	-0.04	-0.04	0.14	-0.07
5.8	0	-0.04	0	-0.34
6.2	0	0	0	-0.04
6.6	0	0	0	0.02
7	0.03	0.03	0.02	0
7.4	0.05	0	0	0
Average	-0.04	-0.01	0.00	-0.07

After completion of the long-term channel overlay analysis, it was found that there was no major plan-form changes within the study segment since 1952 such as channel cutoffs and a switch from a single thread channel to a braided stream. The lack of plan-form change is likely due to the overall effect of bedrock control on channel behavior along the James River (Dewitt, 2012). Stable reaches, or reaches with little to no erosion were sometimes found downstream of meander bends where bedrock bluff was adjacent to the channel and the outside bank was protected by boulders and bedrock on the bank toe armoring erodible material (Figures 19A & 19B). Eroding bank sections were also present in the study segment. The erosional processes found in the study segment were meander bend extension, channel widening, and gravel bar forcing of the thalweg into previously stored bank sediments. The channel widening in the study segment occurs along the alluvial banks opposite more resistant bedrock controlled banks that confine the channel and increase velocity in nearby bedrock pools that has (Montgomery and Buffington, 1997). Evidence of gravel bar accretion leading to thalweg forcing into the opposite bank has been found in the Ozarks previously and bank erosion as lateral channel migration (Martin, 2005).

The results from the long-term period show that bank erosion rates are variable throughout the study segment. Erosion rates peak in the upstream half of the study segment and then decrease and become very low downstream (Table 10) (Figure 21). The highest erosion rate occurred in cell 1.4 on the left bank, which was 0.31 m/yr. On the left bank of cell 1.4, channel widening is the dominant process and bank erosion is active on both sides. Field notes documented that 100 % of the left bank of cell 1.4 was

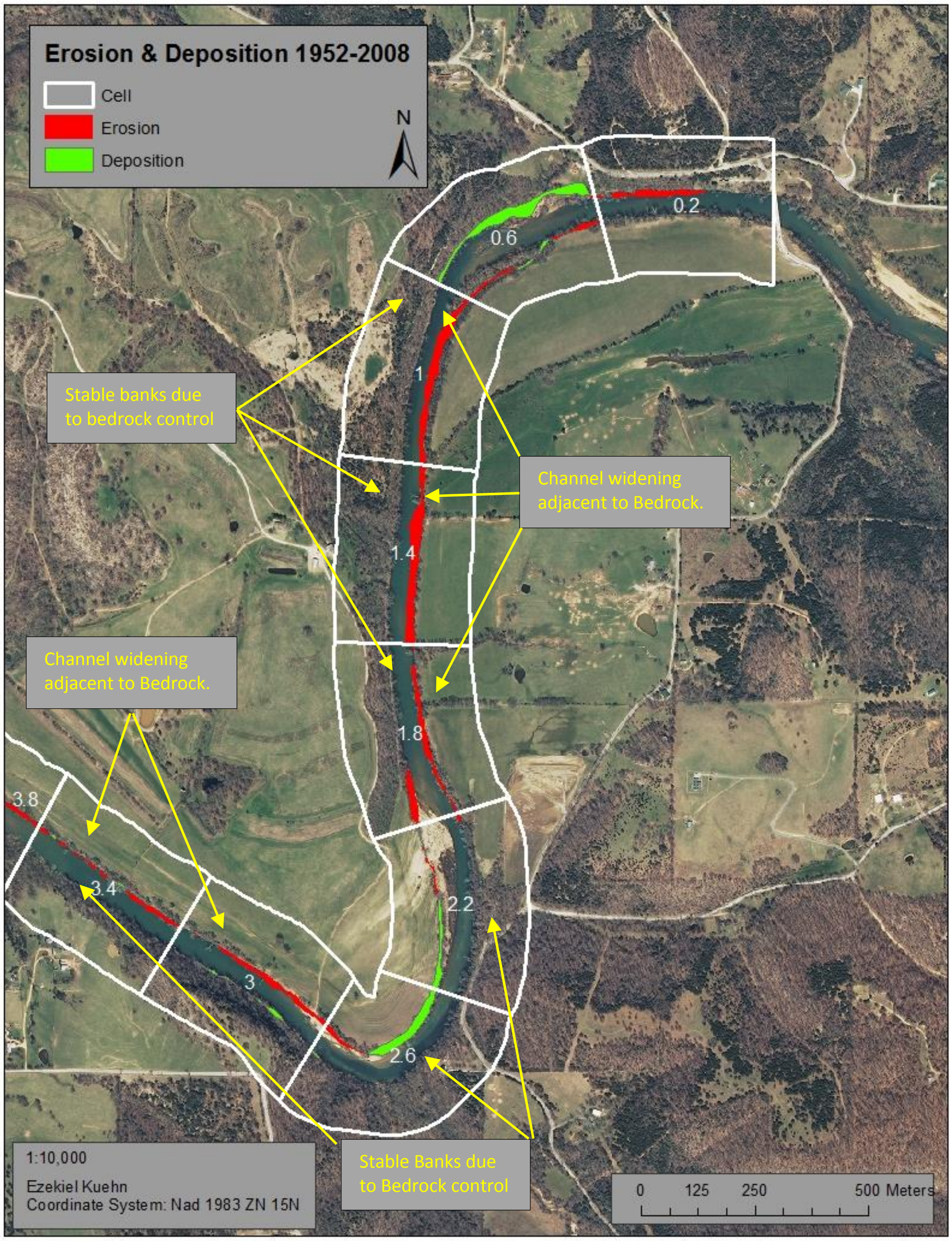


Figure 19 . Study segment erosion and deposition locations 1952-2008. The upper half.

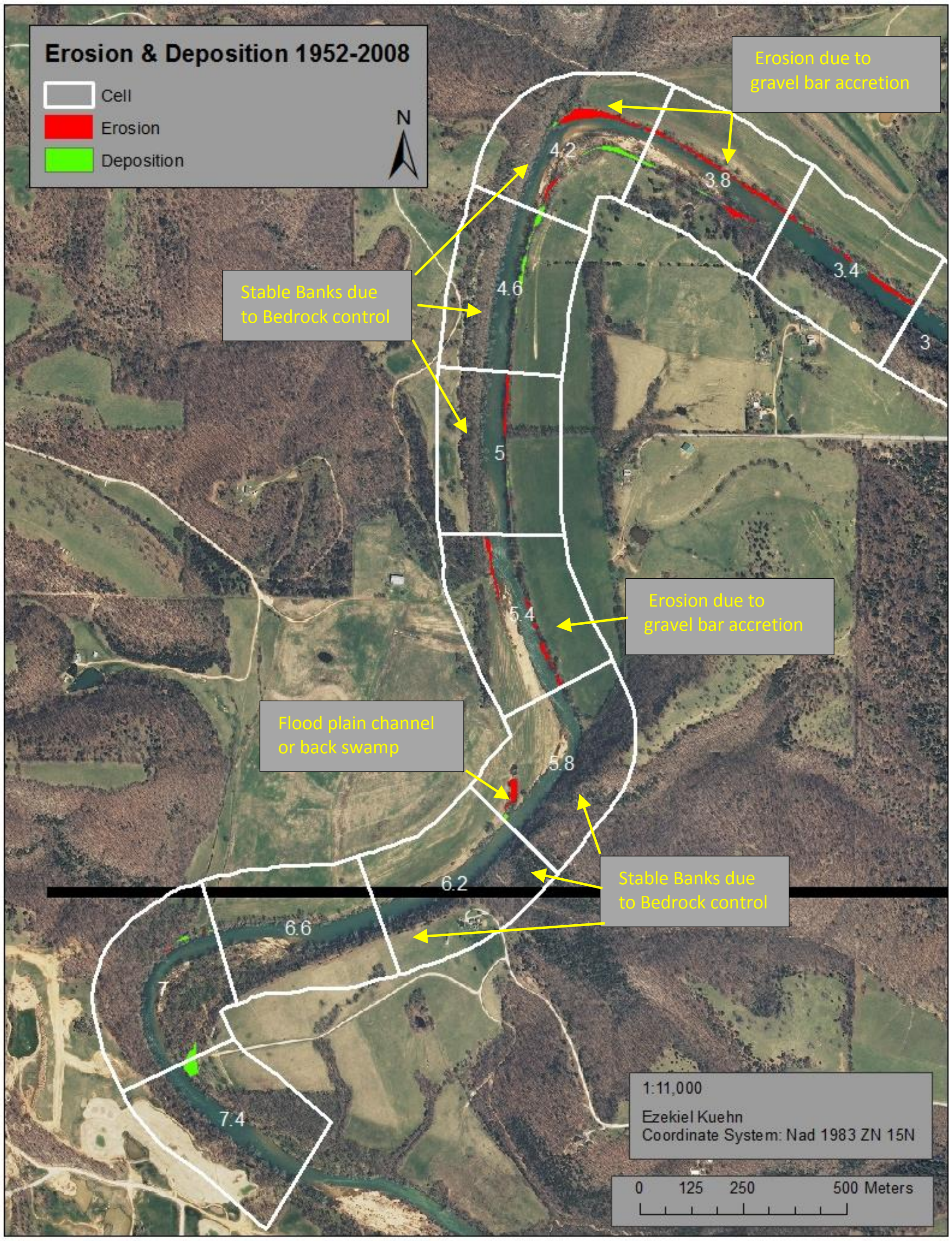


Figure 20. Study segment erosion and deposition locations 1952-2008. The lower half.

eroding. The highest net erosion rate for the right bank is 0.18 m/yr at cell 4.2, and is adjacent to a large gravel bar deflecting flow towards the right bank. The highest net deposition rate was 0.28 m/yr at cell 0.6, which could be due to a tributary within the cell that supplies gravel and fine sediment (Figure 21).

The results of both short term and long term segment bank erosion trends were similar (Figure 19 A-B & 20 A-B). However, the highest erosion rates occur in the lower reaches of the segment. Cells with the highest erosion rate of 0.3 m/yr were 1.8, 4.2, and 5.8 (Table 10) (Figure 22). Factors influencing erosion on the left bank in cell 1.8 were possibly higher flow velocities against the banks associated with bedrock pools (Montegomery & Buffington, 1997). Erosion in cell 4.2 on the right bank is directly across from the large gravel bar mentioned in the paragraph above. Cell 5.8 is the location of channel back swamp or flood plain channel that developed between photograph years increasing the erosion rate at this cell.

One area where a large erosion event occurred was in cell 0.6. The erosion recorded in cell 0.6 was different than the others in that during the 1952-2008 period it showed deposition, but then in the short term period the previously deposited material around the tributary was eroded away (Figures 19A & 20A). Temporary storage of sediment can occur around confluences. The variable sedimentation in the location is likely due to the influence of an unnamed spring fed tributary confluence at this spot which can affect flow velocities and create separation zone location that induce sedimentation (Best, 1988; Ridley & Rhoads, 2012).

Deposition was also measured in the short term analysis 1997-2008. Gravel deposition rates ranging from 0.02 m/yr to 0.08 m/yr in the study segment

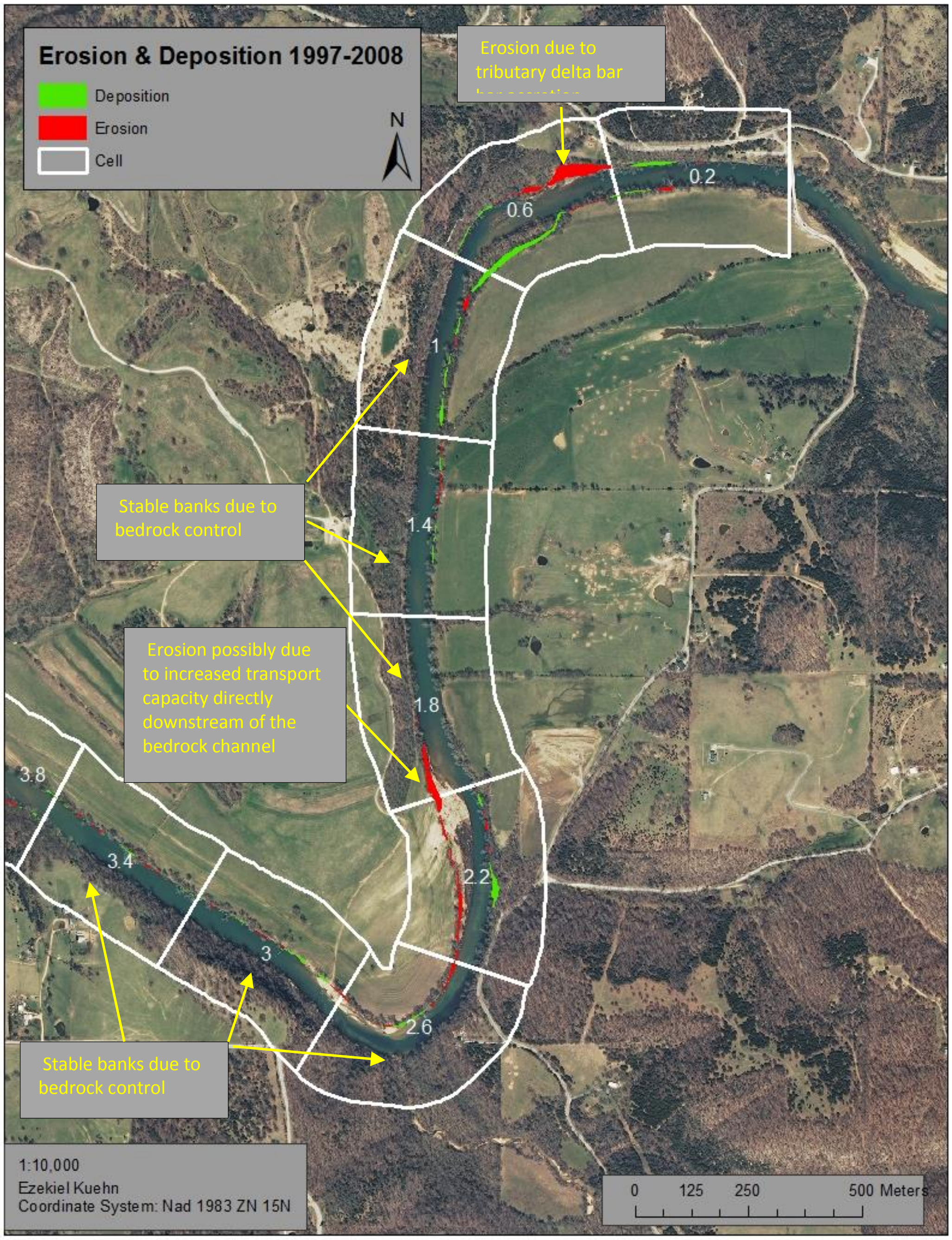


Figure 21. Study segment erosion and deposition locations 1997-2008. The upper half.

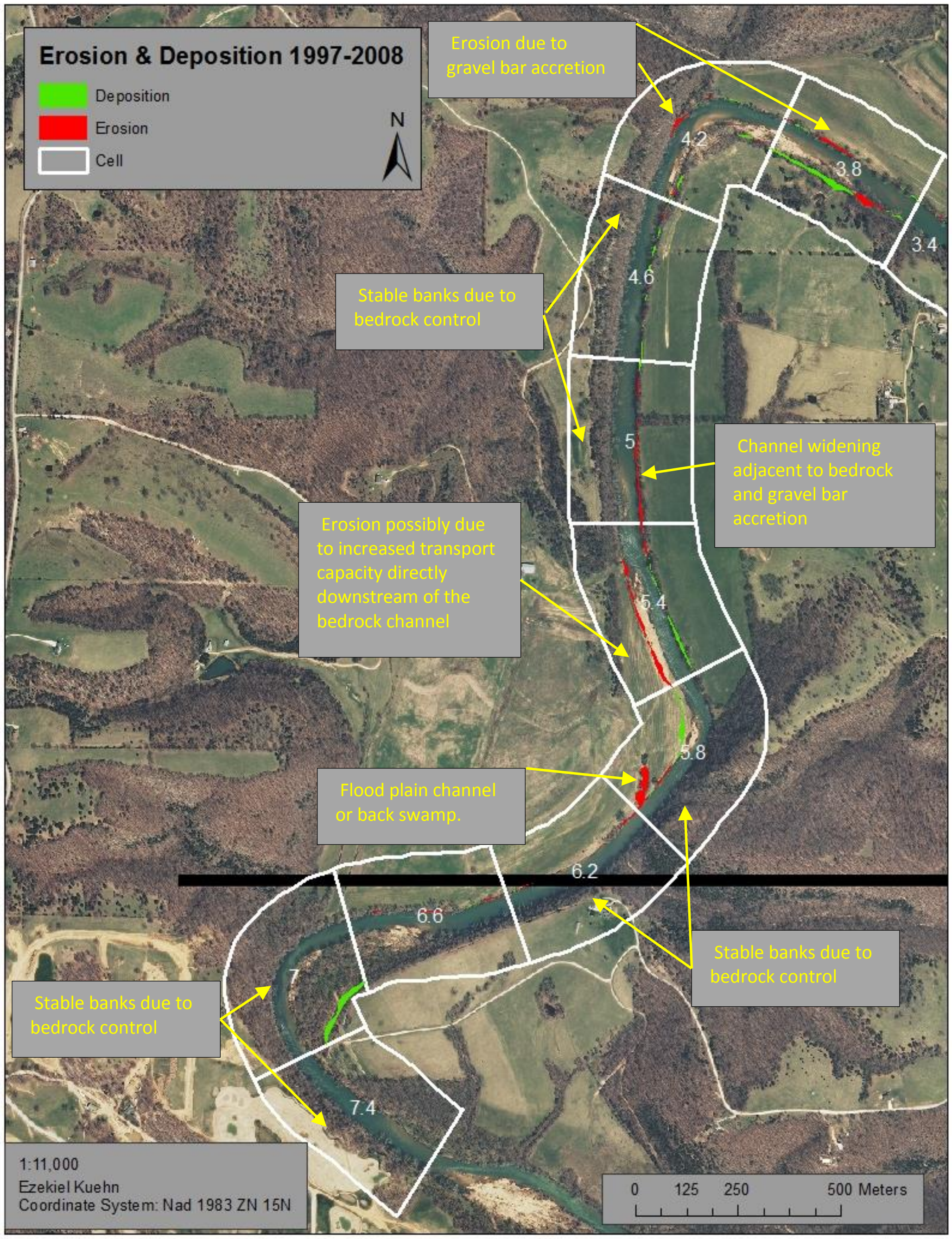


Figure 22. Study segment erosion and deposition locations 1997-2008. The lower half.

occurred on point bars with riparian vegetation at cells 3.8, 4.2, and 7. Deposition also occurred in cell 5.4 with a rate 0.14 m/yr . Deposition in cell 5.4 is assumed to be linked to the slumping of alluvial sediments into the channel, rebuilding the bank toe and recovering bank angle.

River Bank Conditions. Generally the banks of the study segment are alluvial depositional land forms opposite limestone and dolomite bedrock bluffs or gravelly slope colluvium originating from clayey residuum and cherty colluvium originating weathering limestone found on upland slopes that can reach heights of 60 m above the bank-full channel elevation. The average bank height on the left bank is 4.7 m, not including the bluffs, and the average on the right side is lower at 4.0 m. Bank types follow this landform sequence starting from the lowest in height: floodplain, terrace, and bedrock bluff (Figure 23 A & 23 B). Floodplains in the study segment range from 2.5 to 3.5 meters above the thalweg. Terrace heights were found to be from 3.5 to 7.7 meters from the thalweg. Fine sediment within the reach varies abruptly from landform to landform. Landforms in order of increasing fine sediment are bedrock bluff, gravel bars, flood plains, and terraces (Figure 24 A & 24 B). However, terraces in the James River valley can at times have 60 % gravel in certain horizons (Gregg, 1995). Gravel bars in the study segment were estimated to be 10% to 30% fine sediment based on packing of fines within the gravel (Leeder, 1992). Flood plains were estimated to contain 30% to 95% fine sediment. Terraces in the study segment were visually estimated to contain 30% to 100% fine sediment. Different patterns of fine sediment deposition (Figures 24 A and 24 B) in the study segment show the influence of bedrock on the sedimentation of the James River valley. Bedrock is assumed to contain no soil or sediment and therefore it is 0% fines.

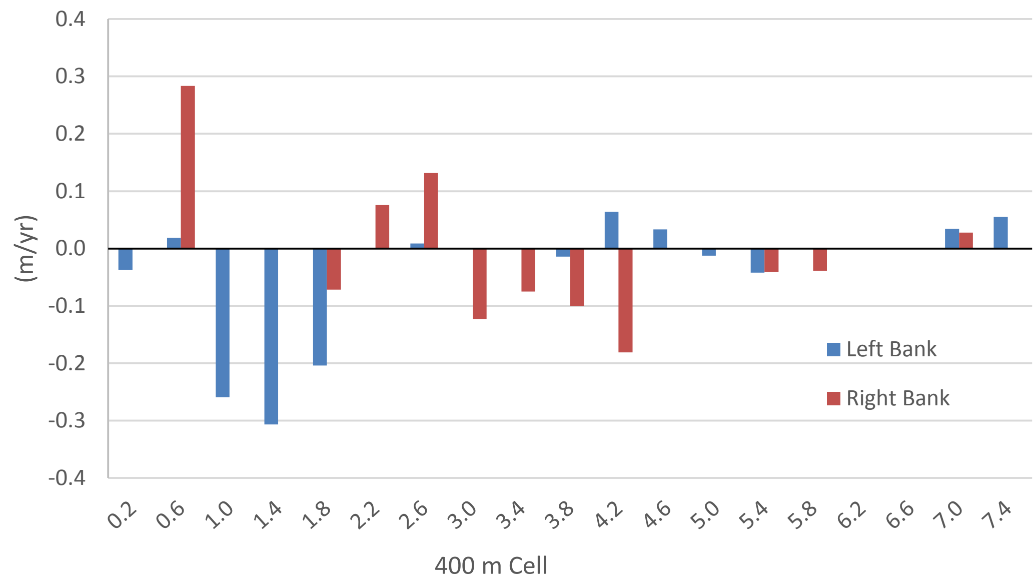


Figure 23. Erosion and deposition rates for the 1952-2008 period.

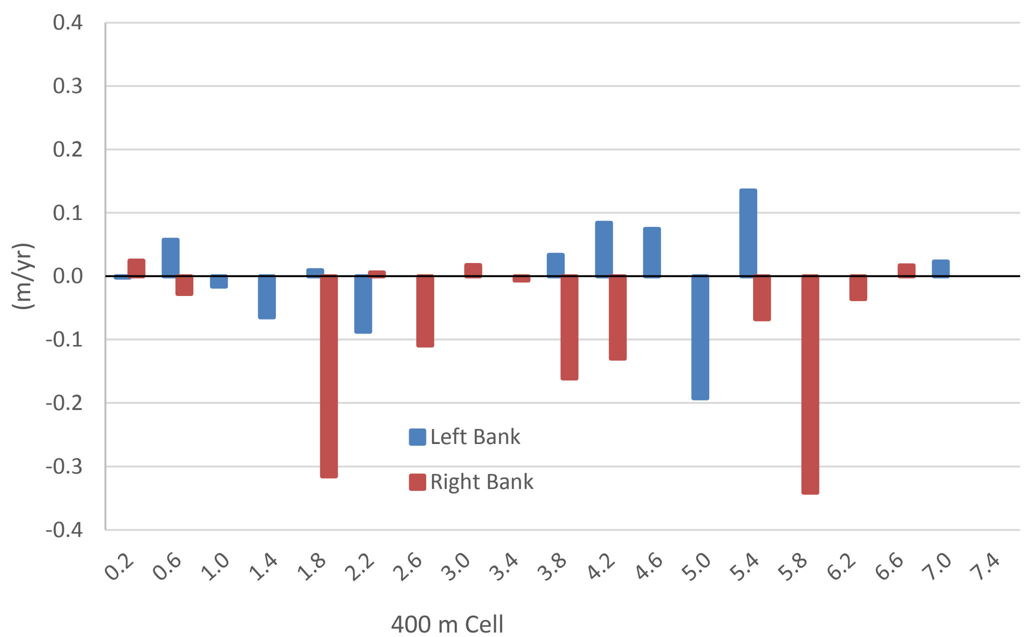
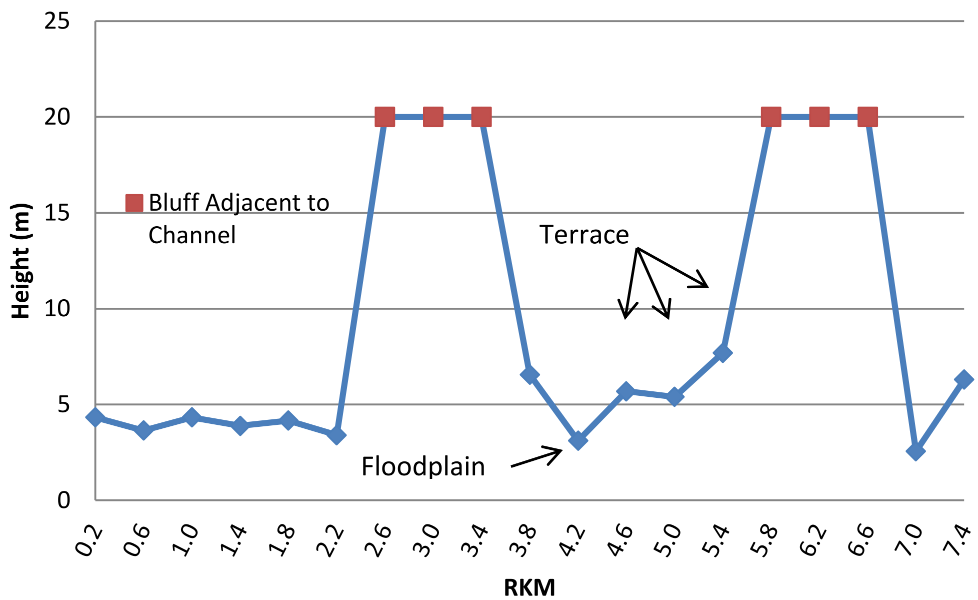


Figure 24. Erosion and deposition rates for the 1997-2008 period.



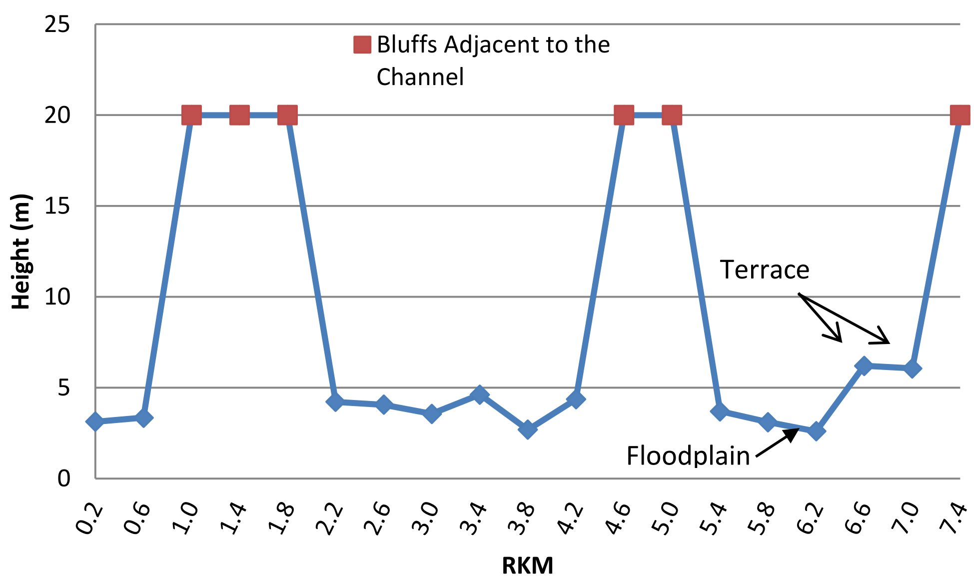


Figure 25. Left bank (top) and right bank (bottom) heights for the study segment.

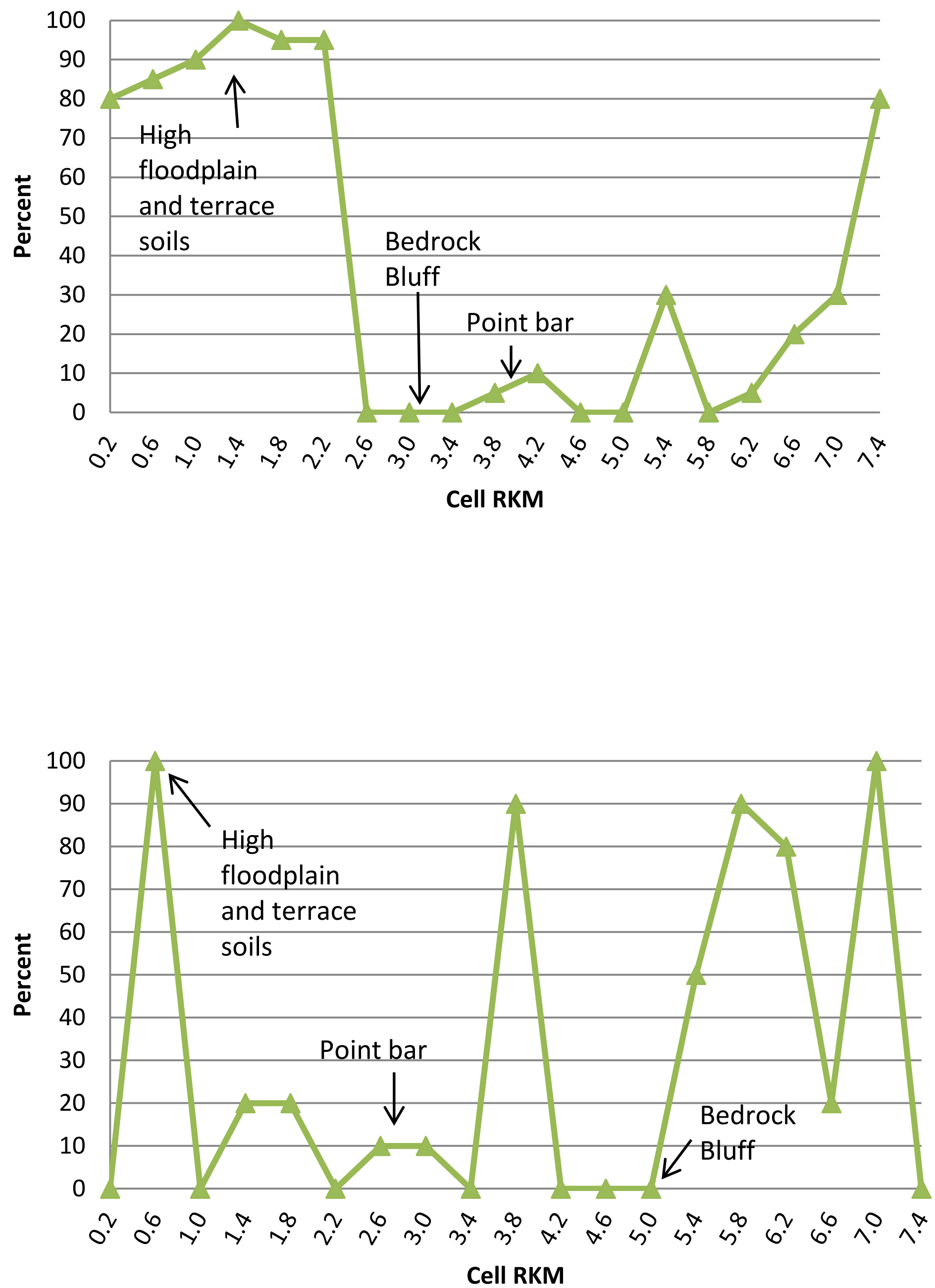


Figure 26. Fine sediment percentage for the left bank (top) and right bank (bottom) in the study segment.

Bank Sediment Inputs to the James River. Using the erosion and deposition polygons from the aerial photograph overlay analysis combined with the bank dimensions and substrate data derived from the geomorphic assessments a volume and mass of net bank erosion and deposition of fine and coarse sediment was calculated for the 1952-2008 long term and 1997-2008 short term study periods.

In total, the banks supplied 130,000 Mg of fine sediment and 16,000 Mg of coarse sediment over the long term period of 56 years. The short term period of 11 years totaled 20,000 Mg of fine sediment and 8,300 of coarse sediment eroded from the banks. The rate of the long term and the short term fine sediment erosion was 2,320 Mg/yr and 1,830 Mg/yr, respectively. The rate of coarse sediment erosion from the banks is 280 Mg/yr for the 56 year period and 760 Mg/yr for the 11 year period. The higher erosion rate of fine sediment of the 56 year period than the 11 year period indicates that the segment may be becoming more stable in recent years. However, the drastically larger rate of coarse gravel erosion during the 11 year period from the banks points out that during the period from 1997 to 2008 different areas were being eroded than in the 1952-2008 period, and that these areas that were eroded more recently had larger deposits of gravel in the banks. These gravelly deposits likely formed during previous historical floodplain or bench deposits formed in association with disturbance areas or periods with more gravel in the channel (Jacobson and Gran, 1999).

During the long term 56 year period the banks of the James River release large quantities of fine sediment to the channel. During the long term period the range of fine sediment erosion and deposition rates vary greatly from cell to cell (Figure 29). The bulk of the fine sediment is supplied from the upper half of the segment ending at cell 3.8, which supplied 110,000 Mg of the total 130,000 Mg for the whole segment. For example the cell that released the largest quantity of fine sediment was Cell 1.4 which supplied 38,000 Mg of fine sediment to the channel from bank erosion. Furthermore, large quantities of deposited fine sediment were measured in in the segment. Cell 0.6 deposited 25,000 Mg of fine sediment over the 56 year period related to the confluence of a tributary in the cell.

Coarse sediment inputs to the channel total 15,000 Mg, with erosion being the dominant process measured in the study segment. However, the margin between erosion and deposition was not very large. The total eroded coarse sediment was 70,000 Mg and the total deposited amount was 54,000 Mg. Out of the 19 cells, nine of them released coarse sediment, seven of were recorded depositing quantities of coarse gravel, and three neither released nor gained coarse sediment (Table 11). The largest amounts of net coarse sediment erosion occurred in cells 1.0 which released 19,000 Mg, and 3.0 that released 13,000 Mg. Both of these where followed by the highest net coarse sediment deposition in cells 2.6 and 4.6 which were 16,000 Mg and 7,600 respectively (Figure 25 A). During the 11 year period the banks continued to provide some fine sediment to the channel. The highest amounts of net fine sediment erosion were measured from the middle of the reach in cells 3.8, 4.2, and 5 totaling 14,000 Mg (Table 9 and Figure 25 B). There were also large amounts deposition measured within the study segment in cells 2.6, 4.6, and 5.4 totaling 4,000 Mg.

Table 10. 1952-2008 erosion and deposition volume and mass by cell.

Cell RKM	Fine Sediment		Coarse Sediment	
	(m^3)	(Mg)	(m^3)	(Mg)
0.2	-2858	-4030	-719	-1625
0.6	17670	24914	0	0
1	-16721	-23576	-8423	-19037
1.4	-26719	-37673	0	0
1.8	-15022	-21181	-3999	-9037
2.2	-25325	-35709	3836	8670
2.6	4755	6704	7222	16321
3	-3984	-5618	-6052	-13678
3.4	-5151	-7263	-2778	-6278
3.8	-5390	-7601	-2716	-6137
4.2	-15598	-21994	2400	5425
4.6	6683	9423	3367	7609
5	-982	-1385	-495	-1118
5.4	-5668	-7992	-5578	-12607
5.8	-2518	-3551	-181	-409
6.2	14	20	4	8
6.6	-1659	-2339	0	0
7	2301	3244	3469	7839
7.4	4116	5804	3636	8216
Average	-4845	-6832	5145	-834
Total	-92059	-129804	-7008	-15838

Table 11. 1997-2008 erosion and deposition volume and mass by cell.

Cell RKM	Fine Sediment		Coarse Sediment	
	(m^3)	(Mg)	(m^3)	(Mg)
0.2	-424	-598	-9	-20
0.6	189	267	323	730
1	-102	-144	-208	-469
1.4	-1,104	-1,556	0	0
1.8	-1,152	-1,625	-581	-1,312
2.2	-1,048	-1,478	-476	-1,075
2.6	809	1,141	47	-105
3	110	155	1,141	2,579
3.4	-93	-131	-47	-105
3.8	-2,456	-3,463	-1,237	-2,796
4.2	-4,734	-6,675	616	1,393
4.6	1,241	1,750	625	1,413
5	-3,044	-4,292	-1,533	-3,465
5.4	921	1,298	-1,009	-2,280
5.8	-657	-927	-998	-2,256
6.2	-1,837	-2,590	-284	-642
6.6	-927	-1,307	-233	-527
7	204	288	414	936
7.4	-179	-253	-158	-358
Average	-752	-1,060	-190	-440
Total	-14,283	-20,140	-3,607	-8,359

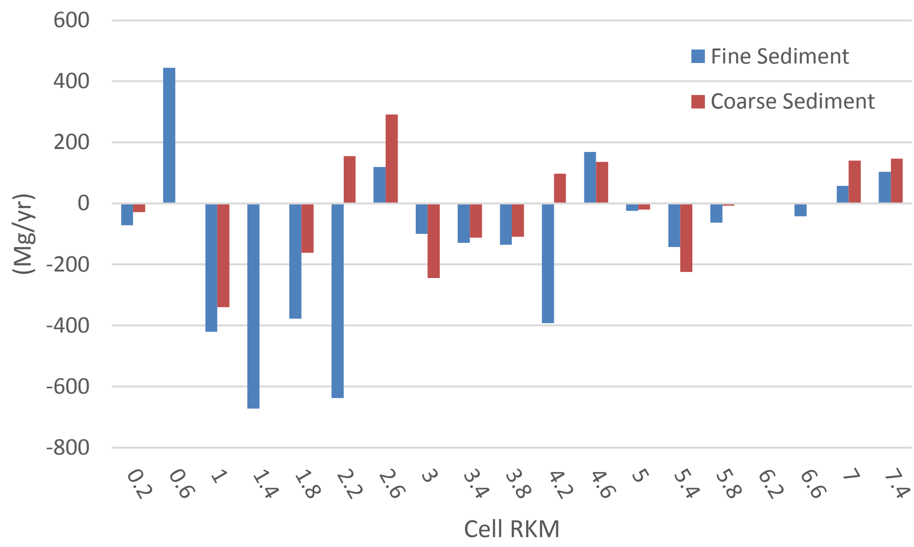


Figure 27. Bank fine and coarse sediment eroded and deposited in the study segment (1952-2008).

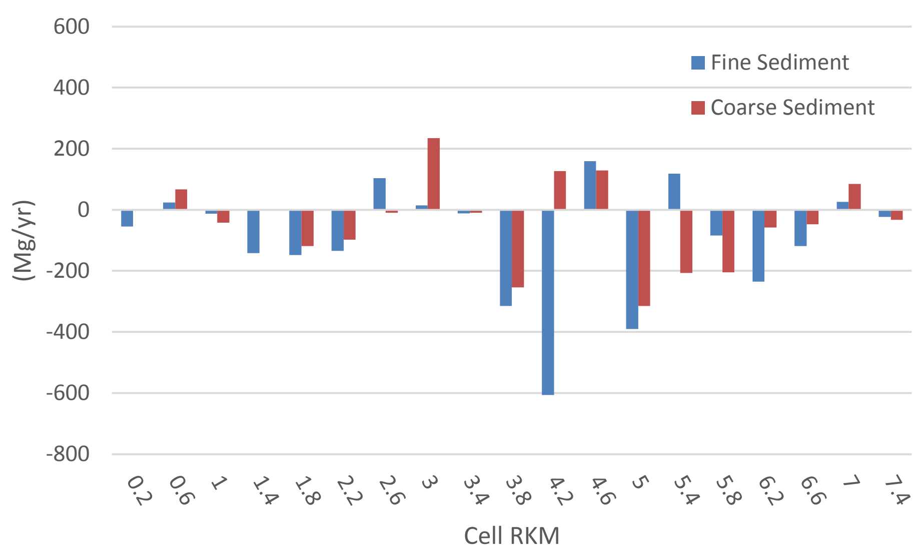


Figure 28. Bank fine and coarse sediment eroded and deposited in the study segment (1997-2008).

The total coarse sediment input during the short term period is much higher than that of the long term period (Figure 30). The higher amounts of coarse sediment is due to the presence of stratified banks with large deposits of chert gravel within the alluvial bank soils. Nevertheless, some cells did receive deposits of coarse gravels during the period. These cells are 0.6, 3, 4.2, 5.4, 5.8 and 7 totaling 4,700 Mg.

Bar Distribution and Storage. Gravel bars are found in every cell of the segment except cell 1.4. The 7.4 km segment has 60,000 m^2 of gravel bars. The gravel bar heights from the thalweg range from 0.5 m to 2.7 m with an average of 1.8 m. Gravel bars that were found were delta, mid-channel, point, and side. To calculate a volume of gravel bars in the segment bar heights from the thalweg were recorded during geomorphic field assessments and then multiplied by the area which was measured using 2012 aerial photographs in a GIS. The bar distribution throughout the reach is not uniform there are peaks in bar volume and transport reaches that lack bar deposition (Figure 26). The highest volume of gravel bars occurs in cells 2.2, 3.8, 4.2, and 5.4 are all the cells that are directly before meander bend apexes (2.2, 3.8, and 5.4) or at the meander bend apexes on the inside of the bends (4.2). This illustrates that gravel clogs the channel when it meets the meander bends in this segment of the James River possibly inducing erosion in certain areas. Furthermore, comparing the gravel bar volume to the gravel released from the banks volume for the short term assessment period 1997-2008 it was found that 18% of the gravel bar volume could be supplied from eroding deposits of gravel in the banks.

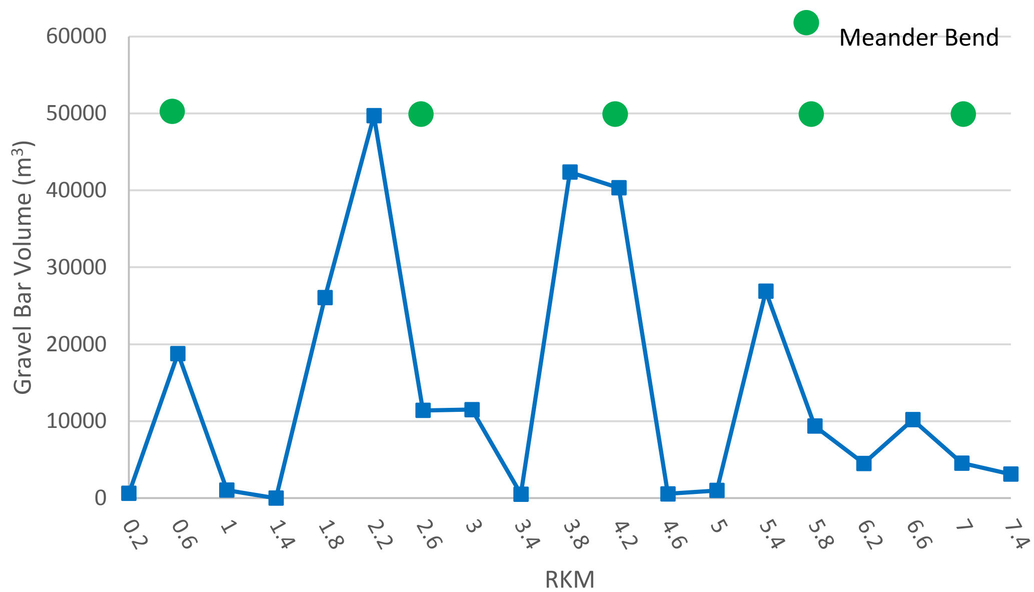


Figure 29. Gravel bar storage volume in the study segment.

Bank Erosion Relationships

Using the data collected during this study, several factors were found to influence the rate of bank erosion: bank composition, valley morphology, and channel pattern. This section will report and discuss the relationships between the factors mentioned above and bank erosion trends in the segment.

Fine Sediment Composition. In the study segment the erosion rate is greater with banks that contain more than 50 percent fine sediment. However, not conclusive enough to show a trend (Figure 27). However, the results also show that cells that were estimated to be 100 percent fine sediment did not always erode the most. This is likley due to layers of non-cohesive sediment in form of chert fragments. The presence of of layers of chert gravel can increase the eroison rate of a bank leading to higher inputs of both fine and coarse sediment (Samadi et al., 2011). The layers of the non-coheasive gravel erode faster then the coheasive fine silt and clay leaving overhanging deposits of sediment that is more susceptable to failure (Samadi et al., 2011; Czarnomski et al., 2012).

Valley Morphology and Channel Pattern. Evaluating the relationship between the percent fine sediment and the erosion rate further, banks were classified according to their geomorphic location. The geomorphic locations found in the study segment are inside bends (IB), outside bends (OB), straight valleys (SV), or straight bluffs (SB). IB in the study segment are area's with point bars and low floodplains. OB occur along bluffs, terraces and high floodplains in the study segment.

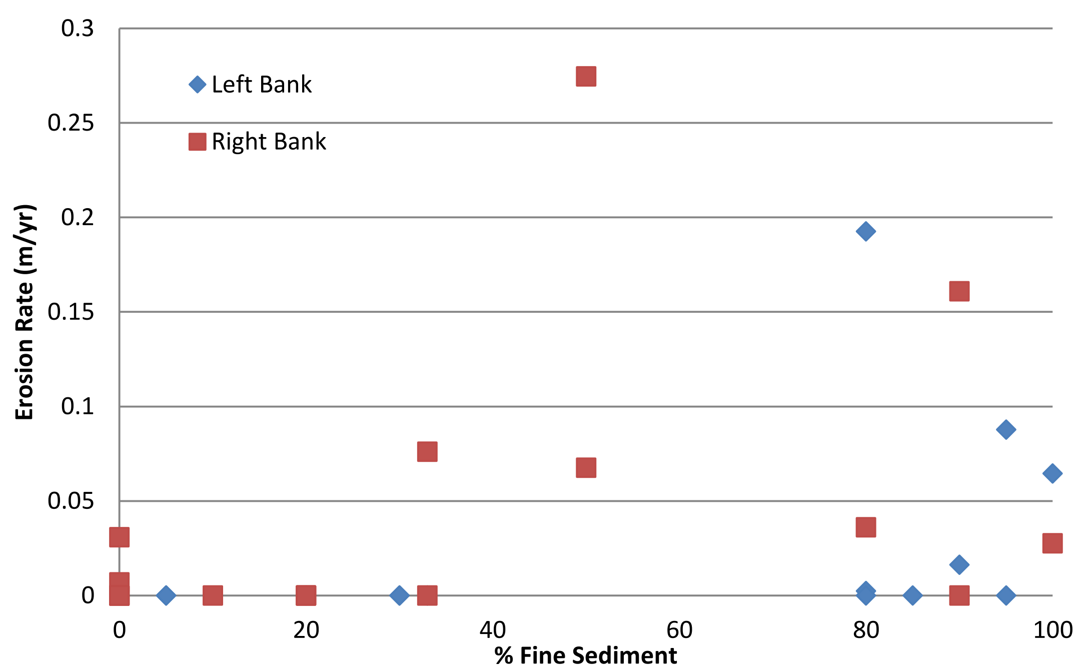


Figure 30. Erosion rate compared to percent fine sediment (1952-2008). Cells with with mixed coarse and fine sediment often have increased erosion rates.

Straight Valley sections in the study segment are straight reaches where low to high floodplains and terraces are adjacent to the James River in the study segment. SB are straight reaches with very little fine sediment and bedrock is adjaecent to the James River.

Comparing the the erosion rate to the fine sediment percentage of the different geomorphic locations it was found that the geomorphic location and the fine sediment percentage both influence the erosion rates. Inside bends had similar erosion rate despite the percentage of fine sediment (Figure 28). Inside Bends had erosion rates that ranged from 0 m/yr to 0.08 m/yr and fine sediment percentages that ranged from 5 to 90. Conversely, SV and OB had increasingly larger erosion rates as the fine sediment percentage beacme higher (Figure28). Outside Bends had erosion rates ranging from 0 m/yr in reaches with little fine sediment to 0.28 m/yr at reaches with 100% fine sediment. Straight Valleys had a similar relationship of fine sediment to erosion rate with places that were less than or equal to 50% fine sediment had low bank erosion rates then SV with higher fine sediment perentages. Straight bluffs have very little fine sediment and the lowest erosion rates (Figure 28). Outside Bends and SV will have an increased erosion rate relative to the locations if alluvial sediment is available. This is important because the relationship of fine sediment to bank erosion rates in the lower James River could be used along with other relationships to evaluate a reaches stability and erosion potential to help select area's for erosion mitigation projects. Evaluating the geomrphic locations alone the average bank erosion rates were found to decrease in order: OB, SV, IB, and SB. Outside Bends were found to have the highest average bank erosion rates at 0.19 m/yr, next was SV at 0.11 m/yr then SB and IB at 0.04 m/yr (Figure 29).

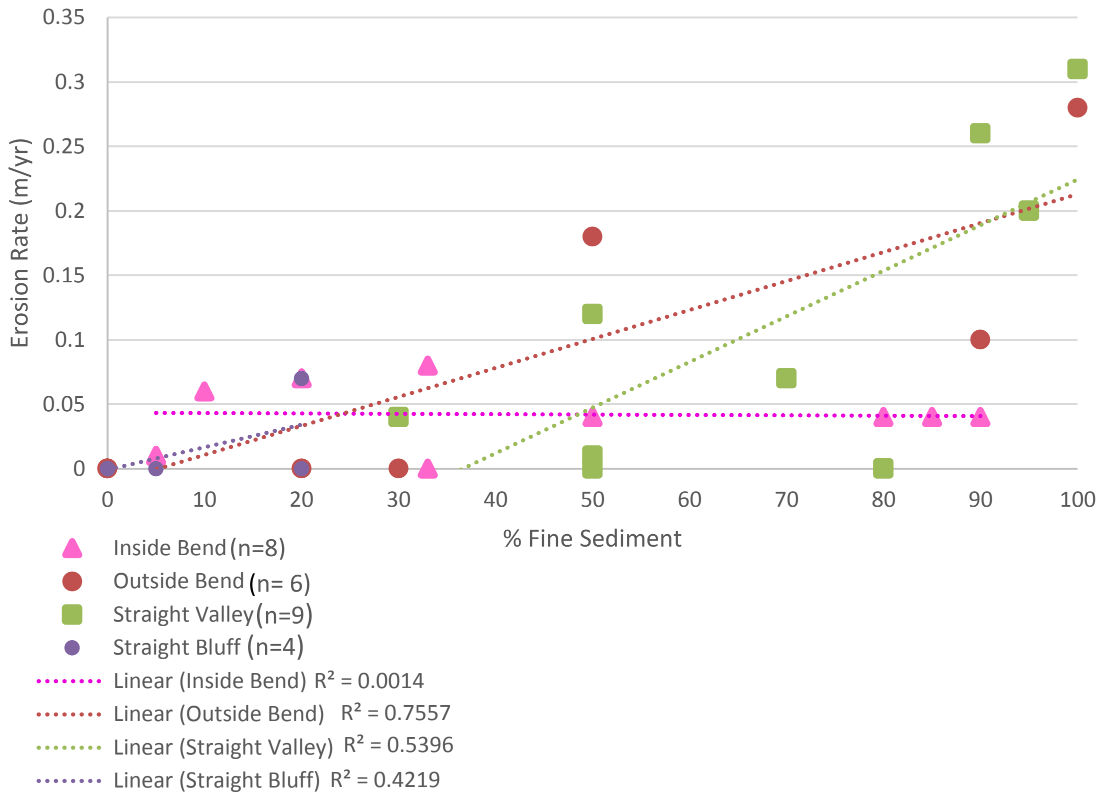


Figure 31. Geomorphic classifications and % fine sediment relationship.

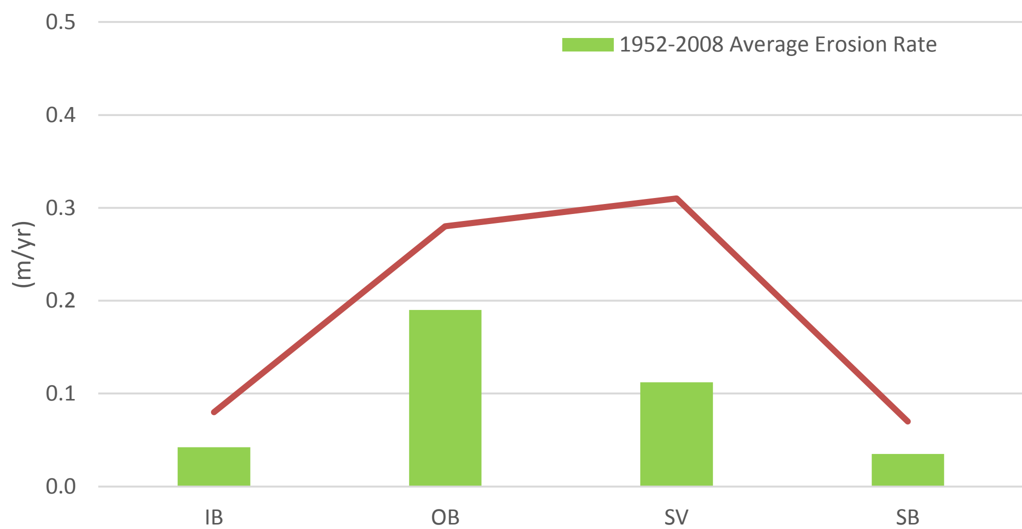


Figure 32. Lateral bank erosion rates for geomorphic locations.

OB of rivers have excess boudary shear stress and gravel bar forcing in the study segment that can entrain sediments causing the erosion rate to be higher than other geomorphic locations (Rosgen, 1996). In contrast, the SV usally lack gravel bars and the excess shear stress present at outside meander bends but are found to be eroding at a faster rate than the IB and SB locations. The higher erosion rates found at the SV could be due to an increased discharge that is causing channel widening. Montegomery and Buffington (1997) conceptualized that pool riffle streams are likely to become wider with an increase in discharge. Which in the case of the James River an increase in discharge could be linked to climate change or increased urbanization of the watershed.

Gravel bars located in the channel may also influence or indicate a higher erosion rate. In the study segment, cells containing unvegetated gravel bars eroded at a rate of 0.04 m/yr and cells without unvegetated gravel bars eroded at a rate of 0.01 m/yr (Table 13). The higher erosion rate near unvegetated gravel bars indicates that either the gravel bars are occupying space in the channel and deflecting flow towards banks, or the banks that are eroding are sources of gravel to the channel in the study segment, or both. Flow deflection or obstruction by gravel bars as a cause of bank erosion has been noted in other studies of Ozark streams (Martin, 2005)

Bank Contribution to Sediment Loads in the James River

Fine Sediment Contributions. To estimate the contribution of bank erosion to the total suspended sediment (TSS) load of the James River, the net bank erosion rate of 234 Mg/yr/km of the long term period was assumed for the length from the James River's headwaters to suspended sediment sample sites used in the Hutchinson (2010) study, to the Galena gage site above Table Rock Lake. The estimated annual TSS load contribution from the bank erosion for the sites used are in order from upstream to downstream are as follows: 12,160 Mg/yr for the Upper James (UJ), 23,150 Mg/yr for the Middle James (MJ) site, and 35,246 Mg/yr at Galena for the full length of the James and Finley Rivers (JF) (Table 12). Comparing the estimated TSS contributions from the banks to the calculated TSS loads from the Hutchinson (2010) study, the percentages supplied form the banks for each site, from upstream to downstream are 48% for the UJ, 22% for the MJ, and 16% for the JF (Table 14). A survey of previous studies quantifying the TSS load supplied from the banks of rivers in the United States and Great Britain shows that 15-50% is an acceptable range for a watershed with the primary and secondary land uses of agriculture and deciduous forest like the James River (Table 1). Looking at seven previous studies with watersheds that have dominantly agricultural land use, it was found that the range of bank contributions to the TSS loads spanned from 7-44%, with an average of 25% (Table 1).

Banks in the study segment have elevated levels of P and are a significant source of P to the James River. The James River flood plain core data shows that P ppm crests at a depth of 65 cm with a concentration of 480 ppm, this could possibly be a buried A horizon however more research is needed to determine the reason for the high P concentration at this depth. The average ppm concentration was 357.5 for the <2 mm and 366.5 for the <250 um (Figure 30). The <250 um average concentration of 366.5 ppm was used with the long term net erosion rate of 234 Mg/yr/km to calculate the mass of TP contributed from the length of the banks to each sampling site (UJ, MJ) used the Hutchinson (2010) study and the calculated load at the LJ site. Comparing the TP contributed from the banks to the calculated TP loads from the Hutchinson (2010) study shows that the banks are estimated to be supplying 10-40% the TP load in the James River (Table 14).

Bank Erosion Contribution to the Gravel Bars in the James River. Gravel bars were found throughout the study segment. However, definite transport reaches were located where gravel deposition was minimal or absent (Figure 31) (Montgomery & Buffington, 1997) The 7.4 km segment of the James River has 60,000 m^2 of gravel bars. The average gravel bar height from the thalweg was 1.8 m, the minimum gravel bar height was 0.5 m the maximum was 2.7 m.

Gravel bar volume in the study segment was calculated using aerial photographs to measure the bar area, and heights were measured in the field from the thalweg using a stadia and auto-level (Figure 26). banks in the study segment. Then the bar volumes were compared to the volume of gravel eroded form the banks in the study segment. The coarse sediment input rates from the 1997-2008 period were calculated to be 2,080 m^3/yr. The total gravel bar storage volume in the segment was 124,000 m^3. Comparing the rate of coarse sediment input and the total bar storage it was found that the gravel inputs from the banks approximately 60 years to supply the total bar storage volume in the segment.

Table 12. Bank change rates, land use, plan-form, and gravel bar presence.

	1952-2008		Erosion Controlling Factors				
RKM	Left Bank Change (m/yr)	Right Bank Change (m/yr)	Percent Fines Left Bank %	Percent Fines Right Bank %	Geomorphic Location Left Bank	Geomorphic Location Right Bank	Unvegetated Gravel Bar within cell (Y/N)
0.2	-0.04	0	80	0	IB	OB	N
0.6	-0.04	0.28	85	100	IB	OB	N
1	-0.26	0	90	0	SV	SB	N
1.4	-0.31	0	100	20	SV	SB	N
1.8	-0.2	-0.07	95	20	SV/OB	IB	Y
2.2	0	0.08	0	30	OB	IB	Y
2.6	0.01	0.13	0	0	OB	IB	Y
3	0	-0.12	0	50	SB	SV	Y
3.4	0	-0.07	0	70	SB	SV	N
3.8	-0.01	-0.1	5	90	IB	OB	Y
4.2	0.06	-0.18	10	50	IB	OB	Y
4.6	0.03	0	50	0	SV	SB	N
5	-0.01	0	50	0	SV	SB	N
5.4	-0.04	-0.04	30	50	SV/OB	SB/IB	Y
5.8	0	-0.04	0	90	OB	IB	Y
6.2	0	0	5	80	SB	SV	N
6.6	0	0	20	20	IB	OB	Y
7	0.03	0.03	30	30	OB	IB	N
7.4	0.05	0	80	0	SV	SB	N

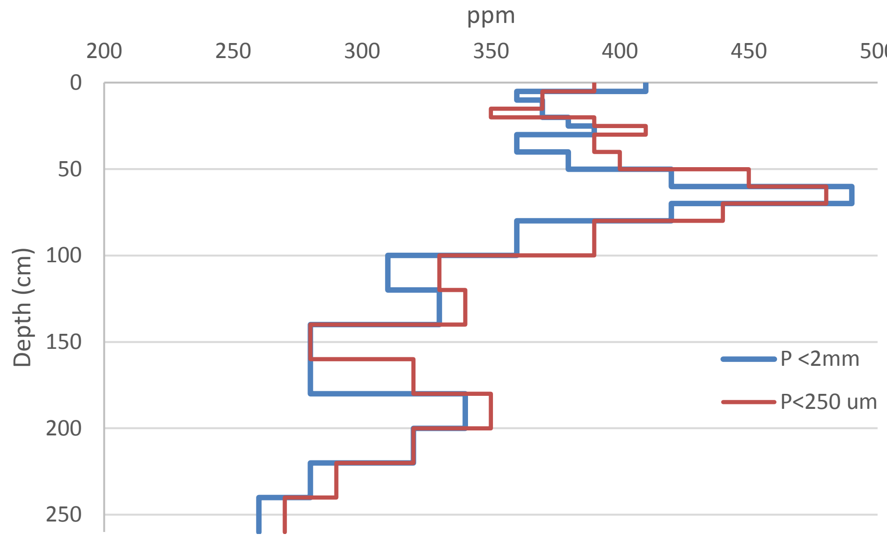


Figure 33. Phosphorus ppm from a floodplain core in the study segment.

Subtle or minor changes in bed/bar storage like scour and glide extension can release significant amounts of gravel to the active channel. Presently, bank gravel deposits in the bank are likely an important source of gravel to the study segment. Nevertheless, There are three tributaries in the study segment, two unnamed second order streams and Goff Creek a third order stream. Only one of these tributaries has a delta chert gravel bar at the confluence with the James River (Figure 31) indicating it as a probable source of gravel to the study segment that could move downstream. Conversely, the absence of delta gravel bars at the other two tributaries does not mean that the other two tributaries are not sources of gravel to the channel since both of the confluences are at outside meander bend locations, which areas with higher velocity relative to the rest of the stream (Motta et al., 2012). It is possible that the gravel from these tributaries is transported from the confluence during flood events and deposited downstream.

Table 13. Fine sediment and TP bank erosion inputs compared to the river loads.

Site	Watershed Characteristics			Bank Erosion Inputs 1952-2008 (Mg/yr)		River Load (Mg/yr)*		Bank Erosion Contribution (%)	
	Location	Drainage Area (km2)	Contributing Channel Length (km)	Fine Sediment	TP	Fine Sediment	TP	Fine Sediment	TP
UJ	at Kinser Bridge	637	52	12,160	4.5	25,252	12.7	48%	35%
MJ	at Shelvin Rock Bridge	1197	99	23,150	8.5	104,520	59.8	22%	14%
LJ	Main-Stem James and Finley Rivers	2556	157	35,246	13.5	223,186	127.8	16%	10%

* Hutchinson (2010) with samples collected from 09/2008 to 09/2009

Coarse sediment deposition peaks in the cells with the two tributary confluences (Figure 31). However, gravel deposition may not be associated with these two tributaries because the locations where they meet the James River are opposite from point bars. Tributaries are an important source of gravel in the study segment. However, with only one tributary clearly supplying coarse sediment presently there is no clear link to the rest of the gravel bars and tributaries in the study segment.

When comparing the locations of peak long term bank erosion of coarse sediment to the bar volume in the study segment it is found that peaks in coarse sediment inputs from the bank are followed by downstream peaks in bar area (Figure 31). For example, the high inputs of coarse sediment at cells 1.0 and 1.8 are followed by an increase in bar area downstream. Another location where this is found is at cells 3.0, 3.4, 3.8 where coarse sediment input lead to the peak gravel bar areas at cells 3.8 and 4.2. The increased bar area after the coarse sediment inputs in the segment is evidence that the banks play a vital role in coarse sediment supply in the study segment.

Lack of strong evidence of tributaries as a major source of gravel in the Ozark Highlands was also found in a previous study done by Jacobson and Gran (1999). Jacobson and Gran (1999) found that gravel bar area did peak after certain tributary confluences; however, they reported gravel bar area peaks were weakly related to tributary influences. Furthermore, Juracek and Perry (2004) found that the bank deposits of gravel in the alluvial bank sediments to be the main source of gravel presently in the Neosho River Basin in the Flint Hills region of KA. Although this region is outside the Ozarks, in the study segment the results are very similar. Basal gravel deposits were measured in each cell in the study segment and gravel bars were found in almost every cell. The tributary that is clearly delivering gravel to the study segment is likely to only do so at the largest of flows, which are infrequent.

Additionally, the past land use periods of ubiquitous row cropping and timber harvest that initiated gully erosion releasing tons of colluvium and alluvium throughout the watershed, is all but gone (Owen et al., 2011). Due to the relative stabilization of the watershed compared to the past, it is likely that the tributaries and uplands are not the main source of gravel anymore. Previously released gravel from the tributaries has been deposited into the main stem of the James River and has been and will continue to be reworked as the James River in the study segment plan-form changes.

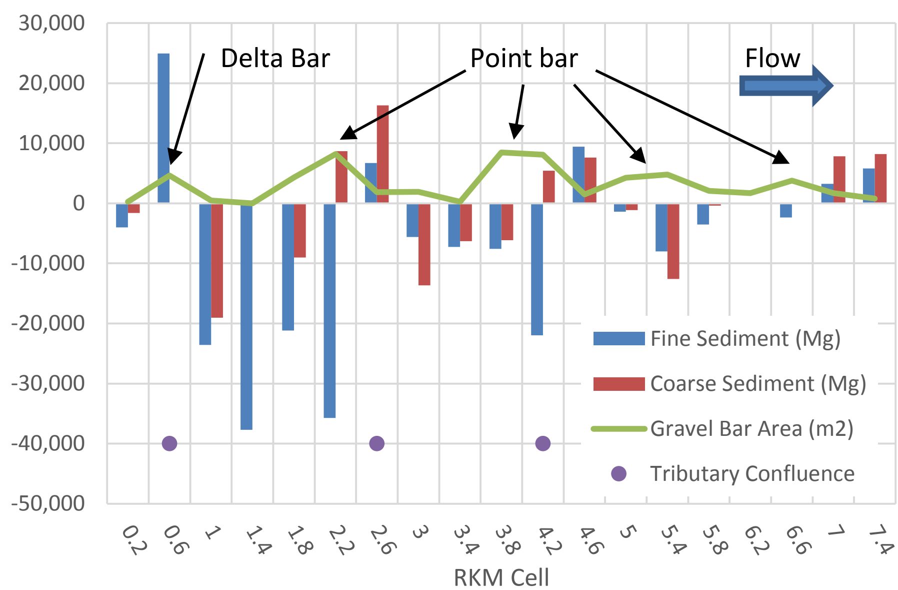


Figure 34. Gravel bar volume m^3 and bank sediment inputs Mg along with confluences of tributaries within the segment. Tributaries at cells 0.6 and 4.2 are unnamed second order streams. The tributary at 2.6 is Goff Creek a third order stream.

Causes of Bank Erosion in the James River

Hydrologic Factors. Factors include seasonal variations in soil moisture, and precipitation events leading to multiple high floods scouring the bank toe contributing to mass wasting. During the spring season the reach scale study area monitored bank became saturated due to multiple floods and precipitation events that led to greater amount of erosion than the largest magnitude flood in the fall, which caused little erosion because of the lack of antecedent soil conditions contributing to erosion. The multiple bank-full floods that occurred from January to May 2013 likely caused removal of the bank toe leaving little support for the saturated bank soils that have reduced cohesion through excess pore-water pressure and saturation (Simon, 2004).

Geomorphic Influences. Geomorphic causes of bank erosion include bank angle, bank material and stratigraphy, planform location, and bar forcing. In the reach-scale study area pin arrays with steep bank angle had an erosion rate far greater than those with lower bank angles. The bank angle of the eroded pin arrays, #1, #2, #10, and #11 were the steepest bank sections being overhung and near vertical, which are more susceptible to mass failures (Knighton, 1998) (Figure 32). The stable pin arrays #3 through #7 exhibited low bank angles with a gradual slope from the top of the bank to the toe (Figure 32). Previous studies have found vertical banks are more susceptible to mass failures due to gravitational forces and hydraulic action caused by turbulence of flow that is related to steeper bank slopes (Nardi et al., 2012; Czarnomski et al., 2012).

The pin arrays with stratified layers of cohesive and non-cohesive sediment had the highest bank erosion rates. The bank material in pin arrays #1 and #2 were the least cohesive, and contained the largest quantity of coarse gravels. Pin arrays #1 and #2 had the highest average bank erosion rates of 0.6 and 0.47 m/yr, respectively (Figure 33). Bar deposits of chert gravel in the lower sections of the bank and the bank toe erode by individual particle entrainment generally quicker than the cohesive layers of silt and clay above leaving overhung banks that more susceptible to failure. (Thorne, 1991; Julian & Torres, 2006).

Channel Planform. The reach scale erosion pin study area lies upstream of a bedrock bluff meander bend apex. The study area is part of the outside meander bend (Figure 2). The outside banks of meander bends are effected by excess shear stress exerted by the water's flow on the banks increasing the erosion and transport of bank materials (Motta et al., 2012). Pin arrays four through seven remained stable through the five near bank full flood events (Figure 32). The stability of pin arrays four through seven suggest that there are limits to channel widening in the study reach and could be linked to reaching a stable channel form at these pin arrays. A stable channel is where the dimension, pattern, and profile of the channel have adjusted to the conditions that are present, and neither aggrades or degrades (Rosgen, 1996). Nevertheless, this study period was only a year in length and further research is needed to conclude that these pin arrays have reached a stable form.

Bar Deposition and Forcing. In the reach-scale study area, gravel deposition in the form of a point bar head on the oppisite bank has been growing in area over the past two decades. Aerial photographs from 1997, 2008, and 2012 were available for the site and the gravel bar demensions were measured and compared for the photographs (Figure 34). In 1997, the point bar is relatively small when compared to the size of the same gravel bar in recent 2008 (11 year span) and 2012 (15 year span) photographs. In the

Pin arrays one and two. The bank profile is very steep and over hung in areas. (July, 2012)

Looking upstream from pin array six, the bank has gentle transitions from bed to toe and toe to the upper section of the bank. This type of bank profile can dissipate energy better than the upper and lower parts of the reach remaining stable through the study period (Knighton, 1998; Czarnomski et al., 2012). (July, 2012)

Looking downstream from pin array nine, the bank profile is very steep increasing the potential for erosion (Rosgen, 2001). (October, 2012)

Figure 35. Reach scale study areas with different channel geometry.

Figure 36. Pin arrays one and two. This area of the bank was composed of previously deposited gravel that can lead to higher erosion rates (August, 2012).

2008 and 2012 photographs the head of the point bar grows substantially becoming large enough to deflect the channel flow toward the eroding bank. The tail of the point bar also grows downstream of the study area. However, downstream of the reach-scale study the outside bank is bedrock and colluvial soils that are not eroded as easily as the alluvial soils in the study reach. The total area of the point bar increased from 4000 m^2 in 1997, 8000 m^2 in 2008, and 19,810 m^2 in 2012. Increasing five times in total area in 15 years (Figure 34). The degree to which bar deposition directed flow toward the study bank was also evaluated. Gravel bar widths and wetted channel widths at three transects located at pin arrays three, six, and eleven were measured and compared over time (Figure 35). At each transect the gravel bar widths increased from 1997 to 2008 and the wetted widths erosion pin reach.

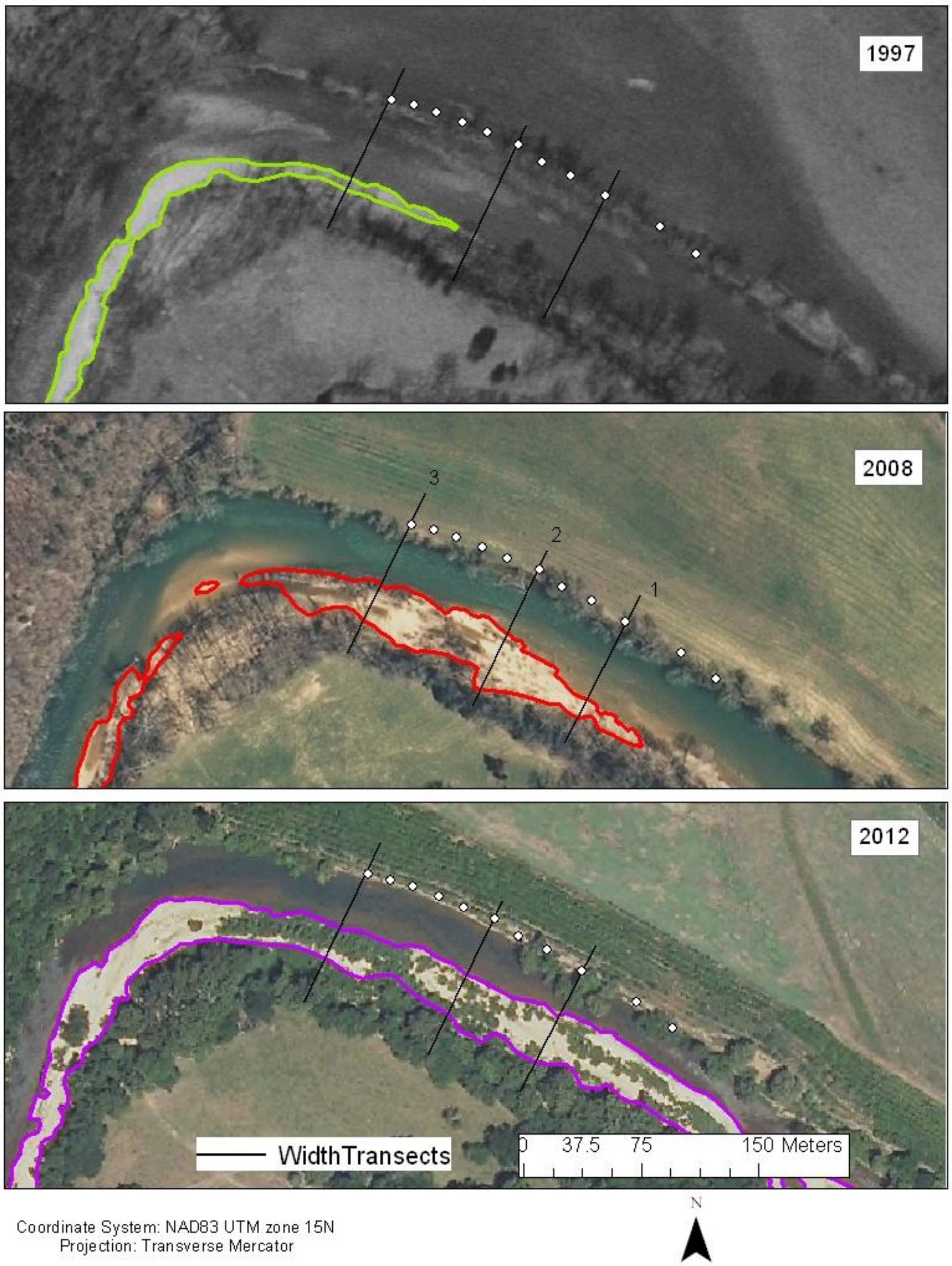


Figure 37. Historic aerial photographs sequence of the gravel bar growth adjacent to the erosion pin reach.

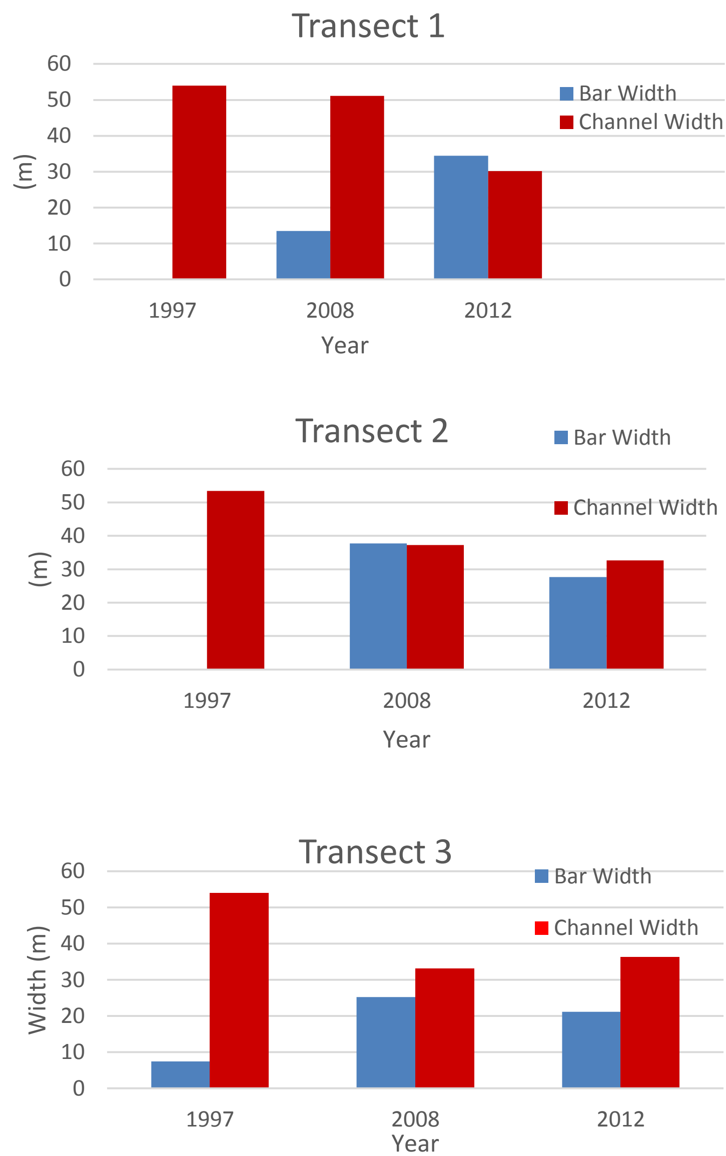


Figure 38. Gavel bar and wetted width trends for the erosion pin reach since 1997.

decreased. At transect one, the gravel bar continues to widen from 2008-2012, which is the largest change in bar width/channel width since 2008.The large influx of gravel during the period from 1997 to 2008 filled the channel and the gravel has pushed the flow towards the opposite bank causing erosion. To be clear, bar deposition occurs first then increased rates of bank erosion followed. Martin and Pavlowsky (2011) stated that an increased supply of channel sediment released from an actively eroding reach can cause instability downstream where the material is being deposited; this is possibly occurring at the erosion pin reach study area, and further inquiry is needed to locate the upstream source of the gravel material. As extension continues and overall bend length increases, the bank erosion rates can increase, releasing large masses of fine and coarse sediment (Martin and Pavlowsky, 2011). The bar and channel widths and areas are subject to change with discharge. Variation in channel discharges at the time of aerial photograph capture can affect bar area measurements. The mean daily discharges at Galena USGS gage site on imagery acquisition dates are 55 m^3/s in 1997 89 m^3/s in 2008, and 2.3 m^3/s in 2012.

It should be noted that erosion of the bank opposite the point bar does not occur at the same time of the bar formation. The bank erosion lags behind as the bar grows in width. For example, a large flood event erodes a flood plain deposit with layers of chert gravel and entrains the gravel in the flow upstream of a meander bend. On the inside of this meander bend the transport capacity is lower than the rest of the channel and the chert gravel begins to deposit in the form of point bar. The large flood event subsides and then next year another large flood event occurs at the meander bend where the newly deposited gravel bar is. The channel in this location has lost some of its capacity due to the point bar deposit and in turn deflects the waters flow towards the outside bank more so then the year before. Last year's deposit contributed in part with the other factors mentioned above to this year's erosion.

Geologic Factors. Bedrock outcrops in the channel and on the banks influence erosion, and channel morphology (Jacobson and Gran, 1999). In the reach scale study area there is no bed rock present in the channel or the banks, but 100 m downstream there is a large bedrock outcrop in the form of a bluff in cell 4.2 that may be influencing channel morphology and erosion upstream (Figure 8). Previous studies done on Ozark gravel bed streams similar to the James River found that disturbance reaches formed where the channel meets the bluff, which is similar to the area downstream of the erosion pin reach (Jacobson and Gran, 1999). Jacobson and Gran (1999) also suggest that during flood events the waters flow and sediment transport are reduced where the channel meets bluff leading to aggradation of the channel bed. This aggradation often creates extensive chert gravel bars that decrease the channels capacity, and increase the meander extension rate in that area (Martin and Pavlowsky, 2011). It is possible that a reduced channel capacity linked to the bedrock bluff outcrops is causing increased rates of bank erosion in this segment.

Vegetation. Forested riparian buffers are often found to resist erosion, however if the rooting depth to bank height ratio is low than much of the root protection benefit is lost (Rosgen, 2001). This is the case at pin array one, the rooting depth of the trees only extends to one half of the total bank height leaving the bank toe without root protection (Figure 33). Further, it is possible that the weight of the large mature trees could not be supported by the saturated bank soil leading to a mass failure at these transects. Mature trees on the top and middle of the banks of pin arrays #1 and #2 likely contributed to the increased erosion rates at these locations in concert with increased flow velocities and scour (Trimble, 1997; Pollen et al., 2004). Furthermore, a mature trees rooting depth is dependent on the species and the type of soil is growing in. However, two large datasets found that generally 95% of tree roots do not exceed >2m in depth (Gasson and Cutler, 1990; Gilman, 1990). In the study segment the flood plains bank heights range from 2.5 m to 3.5 m and terraces are 3.5 m to 7.7 m in height. These high banks with established healthy riparian corridors generally lack root protection and anchoring at the bank toe.

Evaluation of Bank Sediment Sources in the Ozarks

Fine Sediment. The contribution of bank erosion to the annual fine sediment load for the James River is estimated to be between 15-50%, given average hydrological and watershed conditions. Previous studies indicate bank contributions between 15-50% annually is similar to most of the agricultural land use dominated watersheds in previous studies (Table 1). However, the bulk of the agriculture in the James River watershed is livestock related, which results in lower erosion rates than those with row crops as the dominant form of agriculture (Zaimes, 2004). At the upper James River site of Hutchinson (2010), bank erosion input of fine sediment is likely over-estimated with the bank contributions at 48% of the total TSS load. The over estimation is due to the possibility of there being lower bank heights in the upper watershed than in the study segment. It should be noted that this study does not take into account the bank contributions of all other large or small tributary streams in the watershed or the main stem of the James River below Galena. These bank may also have a net erosion rate and supply sediment and P to the main channel.

Another consideration is the sediment delivery ratio of the James River to Table Rock Lake. It is not likely that that all the sediment eroded from the banks in the James River makes it to Table Rock Lake. It has been found that some watersheds have low sediment delivery ratios storing previously eroded sediment before it reaches the watershed outlet (Walling, 1999). However, floodplain deposition rates in the study segment were not measured and considered outside the scope of this study. Further, TSS sediment load contribution reflect the output of load left over after both bank erosion and floodplain deposition so it is difficult to evaluate the rate of deposition.

Coarse Sediment. The coarse sediment supply from the banks from 1997-2008 was estimated at 18% of the total gravel bar volume in the study segment. However, this does not reflect the gravel volume in the channel. There are tons of chert gravel stored in the bed of the James River in the study segment and this study just estimated the bank contribution to the study segments gravel bar volume. Therefore, the gravel contribution from the banks to the entire channel bed is lower than 18% annually. However, if the eroded gravel is not transported out of the segment then over time the banks could be a substantial source of gravel.

If the segments gravel transport rate is low then it is likely that the banks are a major source of gravel in the channel. Conversely, if the gravel transport rate is high then the banks are probably not a major contributor of coarse sediments to the channel. Without knowing the transport rate of coarse gravel in the segment it is only possible to hypothesize the banks role in coarse gravel supply. However, the gravel bar in the reach scale study area has steadily grown over the 1997 to 2012 period illustrating that more is being deposited than is being transported out of the reach (Figure 34). So it is likely that chert gravel in the James River may be transported only during infrequent high flows. Once gravel is eroded form the bank it may not move far from its source during the time-scale considered in this study. As mention earlier it would take 60 years for the gravel erosion volume from the banks to equal the total bar volume in the study segment. Simply put, the study segments banks may not contribute a large amount of the gravel volume in the channel annually, but over time the banks are likely a significant source of gravel in the study segment, and possibly for the James River.

Previous studies done in upland watersheds report that the relative contribution of bed load sediment supply from the hill slopes and from the channel itself to be on average 22% from the hill slopes and 78% from in-channel sources (Raven et al., 2010). These results highlight the importance of re-worked sediment to the sediment supply in certain reaches. Actively eroding reaches such as the reach scale study area can have accelerated erosion rates due to what is probably a lack in sediment transfer causing gravel-sized sediment to accumulate. Kondolf et al. (2002), found that changes in bed load supply due to land use can result in significant channel changes such as cut-offs, meander extension, and translation. Parker (1979), postulated that a 30% increase in gravel load would require a 40% increase in channel width. These results illustrate that excess gravel supply in upland river systems has been found to lead to channel instability and plan-form change similar to the results found in this study. However, hill slopes as sediment sources should not be forgotten or discounted, because the in-channel sources of sediment are limited and not the original source of materials.

Study Limitations

Limitations for this study stem from only using a 7.4 km study segment of James River, annual historical aerial photographs of the study area, and watershed scale data needs to have precise calculations rather than estimates. In this study the rates of bank erosion applied to the entire length of the James River were not weighted by the lowering bank heights upstream, possibly causing an overestimate of the bank contributions. A full set of annual aerial photographs of the study segment would benefit this study by increasing the accuracy of the annual erosion rate estimations. Furthermore, suspended sediment data for the entire range of flows of the James and Finley Rivers would eradicate error derived from load estimate techniques. Furthermore, the erosion rates used in this study were derived from the aerial photograph analysis and applied for many unmeasured lengths of channel banks. The results of this study should be considered as a possible example of erosion rates and an example of the potential source of fine sediment and P that bank erosion could be for the James River.

The effect of bank erosion on water quality in the watershed has the potential to be very significant and erosion control measures would be a valuable ‘best management practice’ (BMP) in the James River watershed. Bank erosion could be supplying large amounts of sediment and P to the James River relative to other sources in the watershed. The results from the erosion pin reach scale analysis illustrate that large amounts of sediment can come from a single cut bank in a year with lower than normal flows. The erosion pin reach by itself lost 257 Mg of fine sediment and attached to the sediment particles were 94 kg of P. Non-point source nutrient pollution could be decreased significantly if BMPs to reduce bank erosion were instituted in the eroding areas like the ones measured in this study.

CONCLUSION

The goals of this study were to quantify the contribution of bank erosion to the fine and coarse sediment loads to a 7.4 km study segment of the James River, and using that information to evaluate the contributions of bank erosion to the TSS load to Table Rock Lake. Little knowledge existed about the influence of bank erosion on suspended sediment loads in James River before this study. It also provides results on when and how much fine and coarse sediment can erode from a single cut-bank in a year period. The findings of this study can be used as an example of bank erosion rates and their caused processes for future studies done on the James River and other Ozark rivers. However, more research is needed to fully understand erosion controlling factors and processes in the James River.

The primary factors controlling bank erosion in the study segment were: bed rock, gravel deposition, bank composition, and vegetation. The overwhelming influence on the spatial distribution of bank erosion in the study segment and reach scale study area was bedrock along the channel boundary. Bedrock acts as a barrier to limit the degradation and migration of the channel bed that influences flow direction and velocity within channel bends by the deflection of the thalweg towards the opposite bank encouraging instability and increased fine and coarse sediment erosion in these areas (Jacobson, 1995; Pavlowsky, 2004; Martin, 2005). Bar deposition and lateral accretion also appears to enhance bank erosion. Bank erosion rates in the study segment were found to increase by 25% in cells with recently deposited unvegetated gravel bars than the cells without (Table 13). Furthermore, in comparing the fine sediment percentage it was found that banks with ≥50% fine sediment had 90% higher erosion rates than banks with <50% fine sediment. Vegetation controls on bank erosion in the segment were related to the presence of bank toe vegetation and root protection anchoring the banks and increasing sediment trapping and velocity reduction (Rosgen, 2001; Pollen et al.,2004).

The banks of the study segment released large amounts of sediment at each scale and time period analyzed. Erosion pin monitoring revealed that cut banks on the James River can supply relatively large amounts of sediment to the channel. The 260 m monitored cut bank released 183 m^3 of fine sediment, and 40 m^3 of chert gravel and cobble to the river channel in one year. The erosion that occurred at the monitored cutbank coincided with seasonal variations in precipitation and antecedent conditions increasing the effectiveness of hydraulic scour and bank failure. Historical aerial photographs and field assessments of a 7.6 km segment of the lower James River were used to acquire long-term and short-term bank erosion rates. The long-term fine sediment loss rate was 222 Mg/yr/km and the short-term rate was 200 Mg/yr/km. Using this data and the annual TSS loads estimated from Hutchinson (2010) the contribution of bank erosion to the suspended sediment load from Kinser Bridge to Galena was estimated to range from 16% to 50%. Even at 16% of the annual TSS load, bank erosion contribution is significant and should be considered a major contributor to the TSS load. Nevertheless, bank contributions clearly need more research to better understand how to apply these findings to meet management goals.

The banks of the James River in the study segment may be significant source of gravel in the channel. Banks with deposits of chert gravel were found in almost every cell and during the period from 1997 to 2008 it was found that 18% of the gravel bar storage in the channel could be supplied from bank erosion or 1.7% per year. The total gravel bar storage in the segment channel is 186,638 Mg. The contribution rate from bank erosion is 3136 Mg/yr. This is significant because gravel bars in the segment are source of bank instability in the channel where deposited, which can release more fine sediment and gravel perpetuating the process creating a positive feedback loop.

The establishment of conservation easements with the goal of enhancing the riparian areas along the James River should benefit water quality. A healthy riparian area can reduce the waters temperature through shading, anchor nutrients through sediment trapping, and reduce the effectiveness hydraulic and mass failure (Rosgen, 2001; Anbumozhi et al., 2006). A lack of vegetation and root protection on the bank toe that can reduce velocity and increase the soils cohesion was found in certain areas on the reach-scale cut bank supporting practice that riparian tree planting could reduce erosion of fine and coarse sediment. However, in the study segment a major source of instability was gravel bar deposition, which in some cases caused the erosion of forested riparian areas over the course of the 56 year time trend analysis. Bar deposition and flow deflection historically and presently was able to drive bank erosion into forested riparian corridors. With regards to the reduction of sediment and nutrients supplied from the banks, the effects of the conservation easements may be variable because they do not address an important source of instability in the study segment, gravel. That being said the preservation and establishment of healthy riparian corridors and conservation easements should be a priority because of the water quality benefits and long term bank protection easements afford.

In the southwestern Missouri Ozarks an abundance of high quality water resources is an important economic and physical feature in the region. Increased urbanization, a growing population, and large tourism industry in the James and White River basins rely on clean water resources. Without good quality surface water supplies the region would surely suffer. Water quality in the James River and Table Rock Lake is of the upmost importance to the surrounding communities. In the James River, bank erosion and alluvial deposits are a major sink for sediments and nutrients in the watershed that are easily accessed by the stream and should be considered a significant source of both fine and coarse sediment that can reduce water quality and bank stability downstream.

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APPENDICIES

Appendix A. Aerial Photograph Analysis 1952-2008

Type	RK M	Bank Side	Area (m^2)	Gravel Fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	0.2	L	10.04	0.3	1.299	4.33	43.49	13.05	4.31	34.75
E	0.2	L	845.07	0.3	1.299	4.33	3659.14	1097.74	362.25	2923.65
E	0.2	R	2343.92		0	3.13	7336.47	0.00	0.00	7336.47
D	0.6	L	426.23		0	3.65	-1555.72	0.00	0.00	-1555.72
D	0.6	R	6377.74		0	3.35	-21365.40	0.00	0.00	-21365.40
E	0.6	L	642.65		0	3.65	2345.66	0.00	0.00	2345.66
E	0.6	R	31.63		0	3.35	105.95	0.00	0.00	105.95
E	0.6	L	767.04		0	3.65	2799.71	0.00	0.00	2799.71
D	1	R	5133.00	0.1	0	0	0.00	0.00	0.00	0.00
E	1	L	5806.94	1	4.33	4.33	25144.00	25144.00	8297.52	8297.52
D	1.4	R	4562.46	0.8	0	0	0.00	0.00	0.00	0.00
E	1.4	L	6868.51		0	3.89	26718.50	0.00	0.00	26718.50
D	1.8	L	0.03	0.05	0.208	4.16	-0.13	-0.01	0.00	-0.13
D	1.8	L	12.14	0.05	0.208	4.16	-50.52	-2.53	-0.83	-48.83
D	1.8	R	1901.64	0.8	0	0	0.00	0.00	0.00	0.00
E	1.8	R	1608.12	0.8	0	0	0.00	0.00	0.00	0.00
E	1.8	L	3.33	0.05	0.208	4.16	13.86	0.69	0.23	13.40
E	1.8	L	81.72	0.05	0.208	4.16	339.94	17.00	5.61	328.55
E	1.8	L	2891.37	0.05	0.208	4.16	12028.10	601.41	198.46	11625.16
D	2.2	R	1903.57	1	4.22	4.22	-8033.06	-8033.06	-2650.91	-2650.91
D	2.2	R	0.45	1	4.22	4.22	-1.91	-1.91	-0.63	-0.63
D	2.2	R	58.01	1	4.22	4.22	-244.81	-244.81	-80.79	-80.79

Appendix A. Aerial Photograph Analysis 1952-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	2.2	R	2.20	1	4.22	4.22	9.27	9.27	3.06	3.06
E	2.2	L	8425.63	0.05	0.17	3.4	28647.10	1432.36	472.68	27687.42
E	2.2	R	21.35	1	4.22	4.22	90.09	90.09	29.73	29.73
D	2.6	L	112.31	0.7	0	0	0.00	0.00	0.00	0.00
D	2.6	R	3706.71	0.9	3.654	4.06	-15049.20	-13544.28	-4469.61	-5974.53
E	2.6	L	7231.00	0.7	0	0	0.00	0.00	0.00	0.00
E	2.6	R	756.94	0.9	3.654	4.06	3073.17	2765.85	912.73	1220.05
D	3	L	288.79	0.1	0	0	0.00	0.00	0.00	0.00
D	3	L	521.36	0.1	0	0	0.00	0.00	0.00	0.00
D	3	L	65.90	0.1	0	0	0.00	0.00	0.00	0.00
D	3	L	187.33	0.1	0	0	0.00	0.00	0.00	0.00
D	3	L	0.04	0.1	0	0	0.00	0.00	0.00	0.00
D	3	L	1.01	0.1	0	0	0.00	0.00	0.00	0.00
D	3	R	28.44	0.9	3.204	3.56	-101.23	-91.11	-30.07	-40.19
D	3	R	2.43	0.9	3.204	3.56	-8.66	-7.79	-2.57	-3.44
E	3	L	1.89	0.1	0	0	0.00	0.00	0.00	0.00
E	3	L	62.25	0.1	0	0	0.00	0.00	0.00	0.00
E	3	L	0.01	0.1	0	0	0.00	0.00	0.00	0.00
E	3	L	28.13	0.1	0	0	0.00	0.00	0.00	0.00
E	3	L	1.70	0.1	0	0	0.00	0.00	0.00	0.00
E	3	R	2756.05	0.9	3.204	3.56	9811.54	8830.39	2914.03	3895.18
E	3	R	29.90	0.9	3.204	3.56	106.43	95.79	31.61	42.25

Appendix A. Aerial Photograph Analysis 1952-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel Fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	3	L	25.24	0.1	0	0	0.00	0.00	0.00	0.00
D	3.4	L	9.25	0.5	0	0	0.00	0.00	0.00	0.00
D	3.4	R	118.11	0.5	2.31	4.62	-545.65	-272.83	-90.03	-362.86
D	3.4	R	1.44	0.5	2.31	4.62	-6.65	-3.32	-1.10	-4.42
D	3.4	R	63.00	0.5	2.31	4.62	-291.06	-145.53	-48.02	-193.55
E	3.4	L	110.57	0.5	0	0	0.00	0.00	0.00	0.00
E	3.4	R	1129.70	0.5	2.31	4.62	5219.21	2609.61	861.17	3470.77
E	3.4	R	137.14	0.5	2.31	4.62	633.57	316.78	104.54	421.32
E	3.4	R	382.08	0.5	2.31	4.62	1765.21	882.61	291.26	1173.86
E	3.4	L	2152.66	0.5	0	0	0.00	0.00	0.00	0.00
E	3.4	R	210.34	0.5	2.31	4.62	971.78	485.89	160.34	646.24
D	3.8	L	4.17	0.5	3.28	6.56	-27.34	-13.67	-4.51	-18.18
D	3.8	L	230.95	0.5	3.28	6.56	-1515.02	-757.51	-249.98	-1007.49
D	3.8	L	31.38	0.5	3.28	6.56	-205.84	-102.92	-33.96	-136.89
D	3.8	L	315.44	0.5	3.28	6.56	-2069.30	-1034.65	-341.43	-1376.08
E	3.8	L	656.97	0.5	3.28	6.56	4309.74	2154.87	711.11	2865.98
E	3.8	L	11.78	0.5	3.28	6.56	77.29	38.64	12.75	51.40
E	3.8	L	2.00	0.5	3.28	6.56	13.09	6.55	2.16	8.71
E	3.8	R	2254.43	0.5	1.345	2.69	6064.42	3032.21	1000.63	4032.84
E	3.8	L	222.40	0.5	3.28	6.56	1458.96	729.48	240.73	970.21
D	4.2	L	268.95	0.8	2.488	3.11	-836.44	-669.15	-220.82	-388.11
D	4.2	L	1512.67	0.8	2.488	3.11	-4704.40	-3763.52	-1241.96	-2182.84

Appendix A. Aerial Photograph Analysis 1952-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	4.2	L	341.72	0.8	2.488	3.11	1062.75	850.20	280.57	493.12
E	4.2	R	2967.26		0	4.36	12937.30	0.00	0.00	12937.30
E	4.2	R	1198.62		0	4.36	5225.98	0.00	0.00	5225.98
D	4.6	L	0.86	0.5	2.845	5.69	-4.90	-2.45	-0.81	-3.26
D	4.6	L	29.84	0.5	2.845	5.69	-169.76	-84.88	-28.01	-112.89
D	4.6	L	3.12	0.5	2.845	5.69	-17.73	-8.87	-2.93	-11.79
D	4.6	L	6.58	0.5	2.845	5.69	-37.45	-18.72	-6.18	-24.90
D	4.6	L	1780.76	0.5	2.845	5.69	-10132.50	-5066.25	-1671.86	-6738.11
E	4.6	L	22.64	0.5	2.845	5.69	128.84	64.42	21.26	85.68
E	4.6	L	2.67	0.5	2.845	5.69	15.17	7.59	2.50	10.09
E	4.6	L	10.45	0.5	2.845	5.69	59.47	29.74	9.81	39.55
E	4.6	L	17.88	0.5	2.845	5.69	101.76	50.88	16.79	67.67
E	4.6	L	1.29	0.5	2.845	5.69	7.35	3.67	1.21	4.89
E	4.6	R	5153.20		0	0	0.00	0.00	0.00	0.00
D	5	L	210.31	0.5	2.7	5.4	-1135.66	-567.83	-187.38	-755.21
D	5	L	304.44	0.5	2.7	5.4	-1643.98	-821.99	-271.26	-1093.25
D	5	L	52.87	0.5	2.7	5.4	-285.47	-142.74	-47.10	-189.84
E	5	L	13.84	0.5	2.7	5.4	74.73	37.36	12.33	49.69
E	5	L	40.29	0.5	2.7	5.4	217.55	108.77	35.90	144.67
E	5	L	786.98	0.5	2.7	5.4	4249.71	2124.86	701.20	2826.06
E	5	R	3711.14	0.5	0	0	0.00	0.00	0.00	0.00
D	5.4	L	0.00	0.7	5.39	7.7	-0.01	0.00	0.00	0.00

Appendix A. Aerial Photograph Analysis 1952-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
D	5.4	L	0.01	0.7	5.39	7.7	-0.07	-0.05	-0.02	-0.04
D	5.4	L	729.84	0.7	5.39	7.7	-5619.7	-3933.83	-1298.16	-2984.09
D	5.4	R	2426.84	0.5	1.85	3.7	-8979.3	-4489.65	-1481.59	-5971.24
E	5.4	L	446.34	0.7	5.39	7.7	3436.8	2405.78	793.91	1824.96
E	5.4	R	107.25	0.5	1.85	3.7	396.84	198.42	65.48	263.90
E	5.4	L	205.99	0.7	5.39	7.7	1586.1	1110.31	366.40	842.25
E	5.4	R	1293.72	0.5	1.85	3.7	4786.7	2393.38	789.82	3183.20
E	5.4	L	188.19	0.7	5.39	7.7	1449.0	1014.34	334.73	769.45
D	5.8	R	221.13	0.1	0	0	0.00	0.00	0.00	0.00
D	5.8	R	4555.89	0.1	0	0	0.00	0.00	0.00	0.00
E	5.8	R	870.69	0.1	0.31	3.1	2699.1	269.91	89.07	2518.30
E	5.8	L	5618.20	0.9	0	0	0.00	0.00	0.00	0.00
D	6.2	L	5.47	0.3	0.78	2.6	-14.22	-4.27	-1.41	-11.36
D	6.2	R	6214.09	0.2	0	0	0.00	0.00	0.00	0.00
E	6.2	L	5694.60	0.3	0	0	0.00	0.00	0.00	0.00
E	6.2	L	202.16	0.3	0	0	0.00	0.00	0.00	0.00
D	6.6	R	7153.60	0.8	4.96	6.2	-1153.81	-923.05	-304.60	-535.37
E	6.6	L	6040.79	0.8	0	0	0.00	0.00	0.00	0.00
D	7	L	771.02	0.7	1.792	2.56	-1973.81	-1381.67	-455.95	-1048.09
D	7	R	4.87	1	6.06	6.06	-29.49	-29.49	-9.73	-9.73
D	7	R	144.89	1	6.06	6.06	-878.02	-878.02	-289.75	-289.75
D	7	R	7.59	1	6.06	6.06	-46.01	-46.01	-15.18	-15.18

Appendix A. Aerial Photograph Analysis 1952-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
D	7	R	89.94	1	6.06	6.06	-545.01	-545.01	-179.85	-179.85
E	7	R	0.14	1	0	0	0	0.00	0.00	0.00
E	7	R	0.03	1	0	0	0.00	0.00	0.00	0.00
E	7	R	35.25	1	0	0	0.00	0.00	0.00	0.00
E	7	R	24.20	1	0	0	0.00	0.00	0.00	0.00
E	7	L	1101.82	0.7	1.792	2.56	2820.66	1974.46	651.57	1497.77
E	7	R	3025.26	1	0	0	0.00	0.00	0.00	0.00
D	7.4	L	1230.43	0.7	4.41	6.3	-7751.71	-5426.20	-1790.65	-4116.16
E	7.4	R	22116.60	1	0	0	0.00	0.00	0.00	0.00

Appendix B. Aerial Photograph Analysis 1997-2008

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
D	0.2	R	2.05		0.00	3.13	-6.42	0.00	0.00	-6.42
D	0.2	R	7.23		0.00	3.13	-22.63	0.00	0.00	-22.63
D	0.6	L	2018.39	0.5	1.83	3.65	-7367.12	-3683.56	-1215.58	-4899.14
D	0.6	L	263.98	0.5	1.83	3.65	-963.54	-481.77	-158.98	-640.76
D	0.6	R	311.72		0.00	0	0.00	0.00	0.00	0.00
D	0.6	R	39.95		0.00	3.35	-133.83	0.00	0.00	-133.83
D	1	L	663.22	1	4.33	4.33	-2871.76	-2871.76	-947.68	-947.68
D	1	L	910.20	1	4.33	4.33	-3941.17	-3941.17	-1300.59	-1300.59
D	1	R	86.90	0.1	0.00	0	0.00	0.00	0.00	0.00
D	1	R	304.60	0.1	0.00	0	0.00	0.00	0.00	0.00
D	1	R	63.17	0.1	0.00	0	0.00	0.00	0.00	0.00
D	1	R	21.63	0.1	0.00	0	0.00	0.00	0.00	0.00
D	1	R	435.41	0.1	0.00	0	0.00	0.00	0.00	0.00
D	1.4	L	194.81		0.00	3.89	-757.81	0.00	0.00	-757.81
D	1.4	L	30.01		0.00	3.89	-116.74	0.00	0.00	-116.74
D	1.4	R	1866.91	0.8	0.00	0	0.00	0.00	0.00	0.00
D	1.8	L	3.11	0.5	2.08	4.16	-12.93	-6.46	-2.13	-8.60
D	1.8	L	193.22	0.5	2.08	4.16	-803.79	-401.90	-132.63	-534.52
D	1.8	L	24.20	0.5	2.08	4.16	-100.68	-50.34	-16.61	-66.95
D	1.8	L	0.18	0.5	2.08	4.16	-0.75	-0.37	-0.12	-0.50
D	1.8	L	0.45	0.5	2.08	4.16	-1.88	-0.94	-0.31	-1.25
D	1.8	L	13.28	0.5	2.08	4.16	-55.23	-27.61	-9.11	-36.73

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
D	1.8	R	816.48	0.8	0.00	0	0.00	0.00	0.00	0.00
D	2.2	L	8.62	0.5	2.11	4.22	-36.39	-18.20	-6.00	-24.20
D	2.2	L	870.56	0.5	2.11	4.22	-3673.76	-1836.88	-606.17	-2443.05
D	2.2	L	5.81	0.5	2.11	4.22	-24.51	-12.25	-4.04	-16.30
D	2.2	L	102.36	0.5	2.11	4.22	-431.95	-215.98	-71.27	-287.25
D	2.2	R	26.08	1	3.40	3.4	-88.68	-88.68	-29.26	-29.26
D	2.2	R	4.38	1	3.40	3.4	-14.88	-14.88	-4.91	-4.91
D	2.6	L	10.59	0.7	0.00	0	0.00	0.00	0.00	0.00
D	2.6	L	283.34	0.7	0.00	0	0.00	0.00	0.00	0.00
D	2.6	R	261.96	0.9	3.65	4.06	-1063.56	-957.20	-315.88	-422.23
D	2.6	R	145.04	0.9	3.65	4.06	-588.87	-529.98	-174.89	-233.78
D	2.6	R	1.45	0.9	3.65	4.06	-5.87	-5.28	-1.74	-2.33
D	3	L	10.95	0.1	0.00	0	0.00	0.00	0.00	0.00
D	3	L	3.63	0.1	0.00	0	0.00	0.00	0.00	0.00
D	3	R	85.11	0.9	3.20	3.56	-303.00	-272.70	-89.99	-120.29
D	3	R	173.08	0.9	3.20	3.56	-616.16	-554.55	-183.00	-244.62
D	3	R	35.63	0.9	3.20	3.56	-126.85	-114.17	-37.68	-50.36
D	3	R	5.44	0.9	3.20	3.56	-19.36	-17.42	-5.75	-7.69
D	3	R	15.56	0.9	3.20	3.56	-55.38	-49.84	-16.45	-21.99
D	3.4	L	35.59	0.5	0.00	0	0.00	0.00	0.00	0.00
D	3.4	L	3.74	0.5	0.00	0	0.00	0.00	0.00	0.00
D	3.4	L	13.39	0.5	0.00	0	0.00	0.00	0.00	0.00

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
D	3.4	L	6.22	0.5	0	0	0.00	0.00	0.00	0.00
D	3.4	R	19.92	0.5	2.31	4.62	-92.03	-46.02	-15.19	-61.20
D	3.4	R	15.04	0.5	2.31	4.62	-69.51	-34.75	-11.47	-46.22
D	3.4	R	2.71	0.5	2.31	4.62	-12.54	-6.27	-2.07	-8.34
D	3.4	R	117.51	0.5	2.31	4.62	-542.91	-271.46	-89.58	-361.04
D	3.4	R	0.30	0.5	2.31	4.62	-1.38	-0.69	-0.23	-0.92
D	3.4	R	14.98	0.5	2.31	4.62	-69.22	-34.61	-11.42	-46.03
D	3.4	R	28.14	0.5	2.31	4.62	-130.01	-65.01	-21.45	-86.46
D	3.8	L	51.95	0.5	3.28	6.56	-340.77	-170.39	-56.23	-226.61
D	3.8	L	16.89	0.5	3.28	6.56	-110.80	-55.40	-18.28	-73.68
D	3.8	L	1845.13	0.5	3.28	6.56	-12104.05	-6052.03	-1997.17	-8049.20
D	3.8	L	80.93	0.5	3.28	6.56	-530.90	-265.45	-87.60	-353.05
D	3.8	R	80.70	0.5	1.345	2.69	-217.08	-108.54	-35.82	-144.36
D	3.8	R	15.58	0.5	1.345	2.69	-41.92	-20.96	-6.92	-27.88
D	3.8	R	1075.21	0.5	1.345	2.69	-2892.31	-1446.16	-477.23	-1923.39
D	4.2	L	38.23	0.8	2.488	3.11	-118.90	-95.12	-31.39	-55.17
D	4.2	L	142.39	0.8	2.488	3.11	-442.82	-354.26	-116.90	-205.47
D	4.2	L	3.83	0.8	2.488	3.11	-11.90	-9.52	-3.14	-5.52
D	4.2	L	0.56	0.8	2.488	3.11	-1.76	-1.40	-0.46	-0.81
D	4.2	L	178.62	0.8	2.488	3.11	-555.51	-444.41	-146.66	-257.76
D	4.2	L	6.08	0.8	2.488	3.11	-18.91	-15.13	-4.99	-8.78
D	4.2	R	2.14		0	4.36	-9.34	0.00	0.00	-9.34

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
D	4.2	R	112.50		0	4.36	-490.50	0.00	0.00	-490.50
D	4.2	R	4.89		0	4.36	-21.30	0.00	0.00	-21.30
D	4.2	R	2.34		0	4.36	-10.21	0.00	0.00	-10.21
D	4.2	R	5.11		0	4.36	-22.29	0.00	0.00	-22.29
D	4.6	L	145.12	0.5	2.845	5.69	-825.73	-412.86	-136.24	-549.11
D	4.6	L	30.53	0.5	2.845	5.69	-173.70	-86.85	-28.66	-115.51
D	4.6	L	0.16	0.5	2.845	5.69	-0.93	-0.47	-0.15	-0.62
D	4.6	L	78.94	0.5	2.845	5.69	-449.17	-224.58	-74.11	-298.70
D	4.6	L	91.81	0.5	2.845	5.69	-522.41	-261.21	-86.20	-347.40
D	4.6	L	114.01	0.5	2.845	5.69	-648.73	-324.36	-107.04	-431.40
D	4.6	L	13.58	0.5	2.845	5.69	-77.27	-38.64	-12.75	-51.39
D	5	L	81.54	0.5	2.7	5.4	-440.30	-220.15	-72.65	-292.80
D	5	L	57.80	0.5	2.7	5.4	-312.12	-156.06	-51.50	-207.56
D	5.4	L	707.72	0.7	2.59	3.7	-2618.56	-1832.99	-604.89	-1390.46
D	5.4	L	155.76	0.7	2.59	3.7	-576.31	-403.42	-133.13	-306.02
D	5.4	R	20.65	0.5	3.85	7.7	-159.03	-79.51	-26.24	-105.75
D	5.4	R	2.67	0.5	3.85	7.7	-20.55	-10.28	-3.39	-13.67
D	5.4	R	914.46	0.5	3.85	7.7	-7041.37	-3520.69	-1161.83	-4682.51
D	5.8	L	43.89	0.1	0.31	3.1	-136.06	-13.61	-4.49	-126.95
D	5.8	L	346.03	0.1	0.31	3.1	-1072.71	-107.27	-35.40	-1000.83
D	5.8	L	64.69	0.1	0.31	3.1	-200.55	-20.05	-6.62	-187.11
D	5.8	L	81.25	0.1	0.31	3.1	-251.87	-25.19	-8.31	-234.99

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
D	5.8	R	3.58	0.9	0	0	0.00	0.00	0.00	0.00
D	5.8	R	2804.44	0.9	0	0	0.00	0.00	0.00	0.00
D	6.2	L	3.76	0.3	0.78	2.6	-9.79	-2.94	-0.97	-7.82
D	6.2	L	1120.16	0.3	0.78	2.6	-2912.42	-873.72	-288.33	-2327.02
D	6.2	L	633.80	0.3	0.78	2.6	-1647.89	-494.37	-163.14	-1316.66
D	6.2	R	9.74	0.2	0	0	0.00	0.00	0.00	0.00
D	6.2	R	756.41	0.2	0	0	0.00	0.00	0.00	0.00
D	6.2	R	2.16	0.2	0	0	0.00	0.00	0.00	0.00
D	6.2	R	0.00	0.2	0	0	0.00	0.00	0.00	0.00
D	6.2	R	0.01	0.2	0	0	0.00	0.00	0.00	0.00
D	6.6	L	4.35	0.8	0	0	0.00	0.00	0.00	0.00
D	6.6	L	41.95	0.8	0	0	0.00	0.00	0.00	0.00
D	6.6	L	28.55	0.8	0	0	0.00	0.00	0.00	0.00
D	6.6	L	892.65	0.8	0	0	0.00	0.00	0.00	0.00
D	6.6	L	69.27	0.8	0	0	0.00	0.00	0.00	0.00
D	6.6	R	0.59	0.3	1.86	6.2	-3.66	-1.10	-0.36	-2.92
D	6.6	R	43.50	0.3	1.86	6.2	-269.71	-80.91	-26.70	-215.50
D	6.6	R	56.97	0.3	1.86	6.2	-353.19	-105.96	-34.97	-282.20
D	6.6	R	31.03	0.3	1.86	6.2	-192.36	-57.71	-19.04	-153.69
D	6.6	R	55.76	0.3	1.86	6.2	-345.73	-103.72	-34.23	-276.24
D	7	L	2405.61	0.7	1.79	2.56	-6158.36	-4310.85	-1422.58	-3270.09
D	7	R	0.66	1	0	0	0.00	0.00	0.00	0.00

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
D	7	R	10.54	1	0	0	0.00	0.00	0.00	0.00
D	7	R	4.64	1	0	0	0.00	0.00	0.00	0.00
D	7	R	15.72	1	6.06	6.06	-95.28	-95.28	-31.44	-31.44
D	7	R	86.31	1	6.06	6.06	-523.06	-523.06	-172.61	-172.61
D	7.4	L	1124.53	0.7	4.41	6.3	-7084.54	-4959.18	-1636.53	-3761.89
D	7.4	L	1760.15	0.7	4.41	6.3	-11088.95	-7762.26	-2561.55	-5888.23
E	0.2	L	10.24	0.3	1.299	4.33	44.36	13.31	4.39	35.44
E	0.2	R	340.21		0	3.13	1064.85	0.00	0.00	1064.85
E	0.2	R	6.00		0	3.13	18.77	0.00	0.00	18.77
E	0.2	R	24.36		0	3.13	76.24	0.00	0.00	76.24
E	0.2	R	122.19		0	3.13	382.44	0.00	0.00	382.44
E	0.6	L	12.13		0	3.65	44.27	0.00	0.00	44.27
E	0.6	R	51.17		0	3.35	171.41	0.00	0.00	171.41
E	0.6	R	5.12		0	3.35	17.15	0.00	0.00	17.15
E	0.6	R	90.17		0	3.35	302.06	0.00	0.00	302.06
E	0.6	R	15.08		0	3.35	50.53	0.00	0.00	50.53
E	1	L	0.01	1	4.33	4.33	0.03	0.03	0.01	0.01
E	1	L	71.52	1	4.33	4.33	309.68	309.68	102.20	102.20
E	1	R	49.05	0.1	0	0	0.00	0.00	0.00	0.00
E	1	R	1.10	0.1	0	0	0.00	0.00	0.00	0.00
E	1	R	0.09	0.1	0	0	0.00	0.00	0.00	0.00
E	1	R	0.18	0.1	0	0	0.00	0.00	0.00	0.00

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	1.4	L	173.94		0	3.89	676.64	0.00	0.00	676.64
E	1.4	L	64.49		0	3.89	250.86	0.00	0.00	250.86
E	1.8	L	0.00	0.5	2.08	4.16	0.00	0.00	0.00	0.00
E	1.8	L	13.32	0.5	2.08	4.16	55.42	27.71	9.14	36.85
E	1.8	L	5.11	0.5	2.08	4.16	21.24	10.62	3.51	14.13
E	1.8	L	0.43	0.5	2.08	4.16	1.81	0.90	0.30	1.20
E	1.8	L	43.36	0.5	2.08	4.16	180.38	90.19	29.76	119.95
E	1.8	L	209.18	0.5	2.08	4.16	870.21	435.10	143.58	578.69
E	1.8	L	186.39	0.5	2.08	4.16	775.37	387.69	127.94	515.62
E	1.8	R	1387.66	0.8	0	0	0.00	0.00	0.00	0.00
E	1.8	R	33.55	0.8	0	0	0.00	0.00	0.00	0.00
E	2.2	L	313.52	0.5	2.11	4.22	1323.08	661.54	218.31	879.85
E	2.2	L	95.46	0.5	2.11	4.22	402.83	201.41	66.47	267.88
E	2.2	L	3.51	0.5	2.11	4.22	14.83	7.41	2.45	9.86
E	2.2	L	20.63	0.5	2.11	4.22	87.04	43.52	14.36	57.88
E	2.2	L	45.41	0.5	2.11	4.22	191.64	95.82	31.62	127.44
E	2.2	L	23.85	0.5	2.11	4.22	100.63	50.31	16.60	66.92
E	2.2	R	1070.48	1	4.22	4.22	4517.43	4517.43	1490.75	1490.75
E	2.2	R	682.04	1	3.4	3.4	2318.93	2318.93	765.25	765.25
E	2.6	L	1878.44	0.7	0	0	0.00	0.00	0.00	0.00
E	2.6	R	68.31	0.9	3.07	3.41	232.95	209.66	69.19	92.48
E	2.6	L	0.23	0.7	0	0	0.00	0.00	0.00	0.00

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	2.6	R	35.89	0.9	3.654	4.06	145.72	131.14	43.28	57.85
E	2.6	R	21.45	0.9	3.654	4.06	87.07	78.36	25.86	34.57
E	2.6	R	355.60	0.9	3.654	4.06	1443.72	1299.34	428.78	573.16
E	3	L	54.45	0.1	0	0	0.00	0.00	0.00	0.00
E	3	R	107.14	0.9	3.204	3.56	381.41	343.27	113.28	151.42
E	3	R	28.90	0.9	3.204	3.56	102.88	92.59	30.56	40.84
E	3	L	1852.23	0.1	0	0	0.00	0.00	0.00	0.00
E	3	L	418.22	0.1	0	0	0.00	0.00	0.00	0.00
E	3	R	82.99	0.9	3.204	3.56	295.43	265.89	87.74	117.29
E	3	R	0.06	0.9	3.204	3.56	0.22	0.20	0.07	0.09
E	3	R	17.88	0.9	3.204	3.56	63.65	57.29	18.90	25.27
E	3.4	R	38.07	0.5	2.31	4.62	175.88	87.94	29.02	116.96
E	3.4	R	54.76	0.5	2.31	4.62	253.01	126.51	41.75	168.25
E	3.4	R	6.85	0.5	2.31	4.62	31.64	15.82	5.22	21.04
E	3.4	R	1.41	0.5	2.31	4.62	6.49	3.25	1.07	4.32
E	3.4	L	686.26	0.5	0	0	0.00	0.00	0.00	0.00
E	3.4	L	11.64	0.5	0	0	0.00	0.00	0.00	0.00
E	3.4	L	45.84	0.5	0	0	0.00	0.00	0.00	0.00
E	3.4	L	59.98	0.5	0	0	0.00	0.00	0.00	0.00
E	3.4	R	1.26	0.5	2.31	4.62	5.81	2.90	0.96	3.86
E	3.4	R	94.50	0.5	2.31	4.62	436.60	218.30	72.04	290.34
E	3.4	R	0.96	0.5	2.31	4.62	4.41	2.21	0.73	2.93

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	3.8	L	1.64	0.5	3.28	6.56	10.77	5.39	1.78	7.16
E	3.8	L	0.06	0.5	3.28	6.56	0.37	0.19	0.06	0.25
E	3.8	L	713.20	0.5	3.28	6.56	4678.62	2339.31	771.97	3111.28
E	3.8	R	5.70	0.5	1.345	2.69	15.34	7.67	2.53	10.20
E	3.8	R	5.68	0.5	1.345	2.69	15.27	7.64	2.52	10.16
E	3.8	R	61.07	0.5	1.345	2.69	164.29	82.14	27.11	109.25
E	3.8	R	18.64	0.5	1.345	2.69	50.15	25.07	8.27	33.35
E	4.2	L	31.21	0.8	2.488	3.11	97.07	77.66	25.63	45.04
E	4.2	L	412.58	0.8	2.488	3.11	1283.12	1026.50	338.74	595.37
E	4.2	L	36.92	0.8	2.488	3.11	114.84	91.87	30.32	53.28
E	4.2	L	147.88	0.8	2.488	3.11	459.92	367.94	121.42	213.40
E	4.2	R	635.84		0	4.36	2772.27	0.00	0.00	2772.27
E	4.2	R	380.12		0	4.36	1657.34	0.00	0.00	1657.34
E	4.2	R	26.68		0	4.36	116.32	0.00	0.00	116.32
E	4.2	R	164.15		0	4.36	715.67	0.00	0.00	715.67
E	4.2	L	4.03	0.8	2.488	3.11	12.53	10.02	3.31	5.81
E	4.2	R	1.10		0	4.36	4.79	0.00	0.00	4.79
E	4.2	R	0.32		0	4.36	1.39	0.00	0.00	1.39
E	4.6	L	45.65	0.5	2.845	5.69	259.75	129.88	42.86	172.74
E	4.6	L	25.68	0.5	2.845	5.69	146.13	73.06	24.11	97.17
E	4.6	L	2.05	0.5	2.845	5.69	11.69	5.85	1.93	7.77
E	4.6	L	63.61	0.5	2.845	5.69	361.92	180.96	59.72	240.68

Aerial Photograph Analysis 1997-2008 continued

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	4.6	L	6.87	0.5	2.845	5.69	39.11	19.56	6.45	26.01
E	4.6	R	3234.58		0	0	0.00	0.00	0.00	0.00
E	5	L	895.81	0.5	2.7	5.4	4837.38	2418.69	798.17	3216.86
E	5	L	91.10	0.5	2.7	5.4	491.93	245.96	81.17	327.13
E	5	R	4449.83	0.5	0	0	0.00	0.00	0.00	0.00
E	5.4	R	925.95	0.7	5.39	7.7	7129.84	4990.89	1646.99	3785.94
E	5.4	R	0.11	0.7	5.39	7.7	0.87	0.61	0.20	0.46
E	5.4	R	308.87	0.7	5.39	7.7	2378.32	1664.83	549.39	1262.89
E	5.4	L	4.80	0.7	2.59	3.7	17.78	12.44	4.11	9.44
E	5.4	L	264.14	0.7	2.59	3.7	977.34	684.14	225.76	518.97
E	5.8	L	68.03	0.1	0.31	3.1	210.89	21.09	6.96	196.76
E	5.8	L	32.34	0.1	0.31	3.1	100.25	10.03	3.31	93.54
E	5.8	L	32.03	0.1	0.31	3.1	99.29	9.93	3.28	92.64
E	5.8	L	123.33	0.1	0.31	3.1	382.32	38.23	12.62	356.70
E	5.8	R	1503.00	0.9	0	0	0.00	0.00	0.00	0.00
E	5.8	R	151.99	0.9	0	0	0.00	0.00	0.00	0.00
E	6.2	L	94.43	0.3	0.78	2.6	245.51	73.65	24.31	196.16
E	6.2	R	21.33	0.2	0.32	1.6	34.13	6.83	2.25	29.55
E	6.2	R	136.76	0.2	0.32	1.6	218.82	43.76	14.44	189.50
E	6.2	R	0.25	0.2	0.32	1.6	0.40	0.08	0.03	0.34
E	6.2	L	0.20	0.3	0.78	2.6	0.52	0.16	0.05	0.41
E	6.2	R	49.87	0.2	0	0	0.00	0.00	0.00	0.00

Appendix B. Aerial Photograph Analysis 1997-2008 (continued)

Type	RKM	Bank Side	Area (m^2)	Gravel fraction	Gravel Height in Bank (m)	Bank Heights (m)	Volume (m^3)	Gravel in Bank (m^3)	Fines within Gravel (m^3)	Total Fine Sediment (m^3)
E	6.2	R	45.76	0.2	0	0	0.00	0.00	0.00	0.00
E	6.6	L	0.78	0.8	0	0	0.00	0.00	0.00	0.00
E	6.6	L	2.54	0.8	0	0	0.00	0.00	0.00	0.00
E	6.6	R	158.67	0.3	1.86	6.2	983.74	295.12	97.39	786.01
E	6.6	R	11.77	0.3	1.86	6.2	72.97	21.89	7.22	58.30
E	6.6	L	10.13	0.8	0	0	0.00	0.00	0.00	0.00
E	6.6	L	10.00	0.8	0	0	0.00	0.00	0.00	0.00
E	6.6	R	21.38	0.3	1.86	6.2	132.59	39.78	13.13	105.94
E	6.6	R	68.99	0.3	1.86	6.2	427.74	128.32	42.35	341.77
E	6.6	R	1.55	0.3	1.65	5.5	8.51	2.55	0.84	6.80
E	7	R	1030.60	1	5.50	5.5	5668.30	5668.30	1870.54	1870.54
E	7	R	7.63	1	5.50	5.5	41.97	41.97	13.85	13.85
E	7	R	1.75	1	5.50	5.5	9.64	9.64	3.18	3.18
E	7	R	58.47	1	5.50	5.5	321.58	321.58	106.12	106.12
E	7	R	94.37	1	5.50	5.5	519.02	519.02	171.28	171.28
E	7	R	3.08	1	5.50	5.5	16.93	16.93	5.59	5.59
E	7.4	L	53.61	0.7	4.41	6.3	337.75	236.43	78.02	179.35
E	7.4	R	3543.25	1	0	0	0.00	0.00	0.00	0.00

Appendix C. Field Assessments

Site		Bar Type		Left Bank Condition			R Bank Condition			Water Depth	
RKM	Chan. Unit	Left side	Right Side	Eroding	Rock toe	Fine sed.	Eroding	Rock toe	Fine sed.	Mean	Max
				%	%	%	%	%	%	(m)	(m)
0.2	Glide	side/mid	side/mid	80	60	80	0	0	0	0.83	0.83
0.6	C, Riff, G	side/mid	center/head	0		85	60	0	100	0.45	0.45
1	Glide	none	none	80		90	0	100	0	0.53	0.53
1.4	Pool	none	none	100	0	100	50	80	20	0.89	0.89
1.8	Pool	none	none	100	5	95	30	80	20	0.96	0.96
2.2		none	side	80	5	95	40	100	0	1.4	1.4
2.6	Run	none	side	10	70	0	0	0	10	0.65	0.65
3	Pool	none	none	10	10	0	10	0	10	1.14	1.14
3.4		none	none	25	0	0	55	0	0	0.8	0.82
3.8	Riff/Run	center	side	10	0	5	100	50	50	0.56	0.56
4.2	Pool	side	none	0	0	10	90	0	0	1.26	1.26
4.6	Glide	none	none	80	0	0	30	10	0	0.65	0.69
5	Glide	none	none	70	0	0	45	0	0	0.7	1.1
5.4	Run	none	side/mid	40	0	30	40	0	50	0.7	0.7
5.8	Pool	none	point/tail	0	90	0	0	0	90	1.3	1.6
6.2	Run	none	side/tail	0	30	5	30	0	80	0.9	1
6.6	Riff	side (small)	none	30	0	20	5	0	20	0.7	0.7
7	Glide	point/mid	none	0	0	30	60	100	100	0.56	0.56
7.4	Pool	none	none	20	0	80	0	90	0	1.3	1.3

Appendix C. Field Assessments (continued)

	Channel Width			Bar Width-Left				Bar width -Right			
RKM	Bed (m)	Act. Chan. (m)	Tot. Chan. (m)	Act. Bar (m)	Veg. Bar (m)	Low B (m)	High B (m)	Act. Bar (m)	Veg. Bar (m)	Low Bar (m)	High Bar (m)
0.2	53.7	29.2	53.7	4					16.2		
0.6	42.2	79.2	79.2			62					
1	48.7	48.7	48.7								
1.4	54	54	54								
1.8	55.5	55.5	55.5								
2.2	37.7	37.7	37.7								
2.6	34.5	34.5	63.4					17.8			
3	52.2	60									
3.4	56.3	60.4	70.4								
3.8	56	56	86	3.3		30			6.63		
4.2	35.3	35.3	68	32.7							
4.6	54.2	54.2	54.2								
5	57	57	57								
5.4	28.5	36	75					4.2	34.5		
5.8	20	50	50					11	9		
6.2	35	50						15			
6.6	63.2	65	90	1		20				0.5	
7	37	52	73	5						5	
7.4	70	72	80								

Appendix C. Field Assessments (continued)

	Landform Height (from water line) Left					R Landform Height (from water line) Right				
RKM	Bar (m)	Bar (veg) (m)	Low Bench (m)	High Bench (m)	Bank (m)	Bar (m)	Bar (veg) (m)	Low Bench (m)	High Bench (m)	Bank (m)
0.2	0.3				3.5		0.15			2.3
0.6				0.4	3.2	2	0.5			2.3
1					3.8					0
1.4					3					0
1.8					3.2					0
2.2					2					3.4
2.6					Bluff	1.64				3.41
3					Bluff					2.42
3.4					10					3.8
3.8	mid 0.2		2.65		6		0.35			2.13
4.2	0.95				1.85					3.1
4.6					5					Bluff
5					4.3					Bluff
5.4			1.1		7	0.5	1.1			3
5.8			1.5		Bluff	0.7	1.5			1.5
6.2					Bluff	0.3				1.6
6.6	0.5		10		50			0.5		5.5
7	0.5		5	1	2			5	0.1	5.5
7.4			0.5		5					Bluff

Appendix D. Erosion Pin Survey

Pin Array Number	Pin Number	Total Change (m)	Bank Height (m)	Percent of Bank %	Length of PA (m)	Total Change (m^3)	Total Change (Mg)
1	1	0.46	4.36	63.1%	34.7	43.65	61.54
	2	0.46	4.36	10.5%	34.7	7.26	10.24
	3	0.88	4.36	26.3%	34.7	35.17	49.59
2	1	0.46	4.36	63.1%	33.7	42.39	59.77
	2	0.46	4.36	10.5%	33.7	7.05	9.95
	3	0.46	4.36	10.5%	33.7	7.05	9.95
	4	0.52	4.36	15.8%	33.7	12.03	16.96
3	1	0.06	4.36	63.1%	43.5	7.30	10.29
	2	0.30	4.36	10.5%	43.5	6.07	8.56
	3	-0.17	4.36	10.5%	43.5	-3.34	-4.71
	4	-0.09	4.36	15.8%	43.5	-2.74	-3.86
4	1	0.00	4.055	29.6%	25.7	0.00	0.00
	2	0.03	4.055	20.5%	25.7	0.65	0.92
	3	-0.11	4.055	23.0%	25.7	-2.56	-3.61
	4	-0.03	4.055	26.9%	25.7	-0.85	-1.20
5	1	0.00	4.125	22.2%	12.87	0.00	0.00
	2	0.05	4.125	23.4%	12.87	0.57	0.80
	3	0.03	4.125	26.7%	12.87	0.43	0.61
	4	0.15	4.125	27.7%	12.87	2.24	3.16

Appendix D. Erosion Pin Survey (continued)

Pin Array Number	Pin Number	Total Change (m)	Bank Height (m)	Percent of Bank %	Length of PA (m)	Total Change (m^3)	Total Change (Mg)
6	1	0.00	4.15	27.0%	21.88	0.00	0.00
	2	0.05	4.15	24.6%	21.88	1.02	1.44
	3	-0.12	4.15	48.4%	21.88	-5.36	-7.56
7	1	0.00	3.605	30.5%	18.5	0.00	0.00
	2	0.03	3.605	24.0%	18.5	0.49	0.69
	3	0.00	3.605	15.6%	18.5	0.00	0.00
	4	-0.17	3.605	29.9%	18.5	-3.34	-4.71
8	1	0.46	3.8	31.6%	18.08	9.93	14.00
	2	0.21	3.8	19.7%	18.08	2.89	4.07
	3	0.06	3.8	11.8%	18.08	0.49	0.70
	4	-0.21	3.8	36.9%	18.08	-5.41	-7.63
9	1	0.27	3.65	31.5%	17	5.36	7.56
	2	0.00	3.65	24.6%	17	0.00	0.00
	3	0.00	3.65	43.9%	17	0.00	0.00
10	1	0.46	3.65	31.5%	14.5	7.62	10.75
	2	0.46	3.65	24.6%	14.5	5.95	8.39
	3	0.46	3.65	22.0%	14.5	5.32	7.51
	4	0.46	3.65	22.0%	14.5	5.36	7.55
11	1	0.46	3.65	31.5%	19	9.99	14.08
	2	0.46	3.65	24.6%	19	7.80	11.00
	3	0.46	3.65	43.9%	19	14.00	19.75

Appendix E. Fine and Coarse Sediment released from the study segment (1997-2008)

RKM	Net Fine Sediment Change (m^3)	Net Fine Sediment Change (Mg)	Net Coarse Sediment Change (m^3)	Net Coarse Sediment Change (Mg)
0.2	-1489.07	-2099.59	-8.92	-20.15
0.6	189.16	266.72	322.79	729.50
1	-102.21	-144.11	-207.51	-468.97
1.4	-1103.60	-1556.08	0.00	0.00
1.8	-1152.42	-1624.91	-580.54	-1312.03
2.2	-1047.90	-1477.54	-475.72	-1075.13
2.6	-521.94	-735.94	-735.94	-1663.22
3	110.03	155.14	-735.94	-1663.22
3.4	-92.65	-130.63	-46.67	-105.48
3.8	-2456.08	-3463.07	-1237.27	-2796.23
4.2	896.57	1264.16	-438.27	-990.50
4.6	-1188.96	-1676.43	625.32	1413.23
5	-3043.63	-4291.52	-1533.26	-3465.17
5.4	920.71	1298.21	-1009.03	-2280.40
5.8	810.24	1142.44	58.18	131.50
6.2	-1836.78	-2589.86	-284.21	-642.32
6.6	-926.70	-1306.65	-233.13	-526.86
7	204.05	287.71	414.29	936.29
7.4	-179.35	-252.88	-158.41	-358.00

Appendix F. Fine and coarse sediment released from the study segment (1952-2008).

RKM	Net Fine Sediment Change	Net Fine Sediment Change	Net Coarse Sediment Change	Net Coarse Sediment Change
	(m^3)	(Mg)	(m^3)	(Mg)
0.2	-10194.81	-14374.68	-719.06	-1625.07
0.6	17669.83	24914.47	0.00	0.00
1.0	-16720.79	-23576.32	-8423.26	-19036.56
1.4	-26718.50	-37673.09	0.00	0.00
1.8	-11918.16	-16804.60	-413.10	-933.60
2.2	-25325.27	-35708.63	3836.29	8670.02
2.6	4754.50	6703.85	7221.57	16320.75
3.0	-3984.48	-5618.12	-6051.99	-13677.51
3.4	-5151.37	-7263.43	-2777.84	-6277.93
3.8	-5390.48	-7600.58	-2715.51	-6137.05
4.2	-15598.40	-21993.75	2400.25	5424.57
4.6	6683.11	9423.18	3366.68	7608.69
5.0	-982.12	-1384.79	-494.75	-1118.14
5.4	2084.15	2938.66	-540.71	-1222.00
5.8	-2518.29	-3550.79	-180.84	-408.70
6.2	11.36	16.02	2.86	6.46
6.6	-368.27	-519.25	-92.64	-209.37
7.0	2300.58	3243.82	3468.65	7839.14
7.4	4116.16	5803.78	3635.55	8216.35

Appendix G .Flood Plain Core Data

Sample ID		Size	Sample Depth	Properties		P
No.	Code	Fraction	(cm)	Color	Texture	ppm
1	OJR 1A	<2 mm	2.5	10yr		410
2	OJR 2A	<2 mm	7.5	10yr		360
3	OJR 3A	<2 mm	12.5	10yr		370
4	OJR 4A	<2 mm	17.5	10yr		370
5	OJR 5A	<2 mm	22.5	10yr		380
6	OJR 6A	<2 mm	27.5	7.5yr	clay	390
7	OJR 7A	<2 mm	35	7.5yr	clay	360
8	OJR 8A	<2 mm	45	7.5yr	clay	380
9	OJR 9A	<2 mm	55	7.5yr	clay	420
10	OJR 10A	<2 mm	65	7.5yr	clay	490
11	OJR 11A	<2 mm	75	7.5yr	clay	420
12	OJR 12A	<2 mm	90	7.5yr	sand	360
13	OJR 13A	<2 mm	110	7.5yr	sand	310
14	OJR 14A	<2 mm	130	7.5yr	sand	330
15	OJR 15A	<2 mm	150	7.5yr	sand+clay	280
16	OJR 16A	<2 mm	170	7.5yr	sand+clay	320
17	OJR 17A	<2 mm	190	7.5yr	sand+clay	340
18	OJR 18A	<2 mm	210	7.5yr	sand+clay	320
19	OJR 19A	<2 mm	230	7.5yr	sand+clay	280
20	OJR 20A	<2 mm	250	7.5yr	sand+clay	260

Appendix G. Flood Plain Core Data (continued)

Sample ID		Size	Sample Depth	Properties		P
No.	Code	Fraction	(cm)	Color	Texture	ppm
1	OJR 1B	<250 um	2.5	10yr		390
2	OJR 2B	<250 um	7.5	10yr		370
3	OJR 3B	<250 um	12.5	10yr		370
4	OJR 4B	<250 um	17.5	10yr		350
5	OJR 5B	<250 um	22.5	10yr		390
6	OJR 6B	<250 um	27.5	7.5yr	clay	410
7	OJR 7B	<250 um	35	7.5yr	clay	390
8	OJR 8B	<250 um	45	7.5yr	clay	400
9	OJR 9B	<250 um	55	7.5yr	clay	450
10	OJR 10B	<250 um	65	7.5yr	clay	480
11	OJR 11B	<250 um	75	7.5yr	clay	440
12	OJR 12B	<250 um	90	7.5yr	sand	390
13	OJR 13B	<250 um	110	7.5yr	sand	330
14	OJR 14B	<250 um	130	7.5yr	sand	340
15	OJR 15B	<250 um	150	7.5yr	sand+clay	280
16	OJR 16B	<250 um	170	7.5yr	sand+clay	320
17	OJR 17B	<250 um	190	7.5yr	sand+clay	350
18	OJR 18B	<250 um	210	7.5yr	sand+clay	320
19	OJR 19B	<250 um	230	7.5yr	sand+clay	290
20	OJR 20B	<250 um	250	7.5yr	sand+clay	270