HISTORICAL CHANNEL CHANGE AND MINING-CONTAMINATED SEDIMENT REMOBILIZATION IN THE LOWER BIG RIVER, EASTERN MISSOURI

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 and Geology

By

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May 2011

HISTORICAL CHANNEL CHANGE AND MINING-CONTAMINATED SEDIMENT REMOBILIZATION IN THE LOWER BIG RIVER, EASTERN MISSOURI

Geography, Geology, and Planning

Missouri State University, May 2011

Master of Science

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ABSTRACT

Historical mining operations were responsible for large scale contamination of floodplain deposits along the Big River in eastern Missouri. These contaminated deposits represent potential sources of future pollution due to remobilization by erosion and weathering. The purpose of this study is to evaluate the distribution and rates of contaminated sediment storage and remobilization in the lower 24 km of the Big River. Specifically, the objectives are to (i) assess and quantify historical channel planform change, (ii) identify spatiotemporal trends and determine bank erosion and bar deposition rates, and (iii) create a sediment- Pb budget to evaluate the role of stored alluvium and Pb as contemporary sources acting as threats to endangered mussel beds in the lower Big River. Results show that bank erosion occurs within localized disturbance reaches along 32% of the study reach. Bank erosion rates within disturbance reaches vary from 0.11 to 0.19 m/yr and lead (Pb) concentrations range from approximately 250 to 3,000 ppm. Total gravel bar surface area varies spatiotemporally in the study segment and ranges from approximately 70,000-120,000 m^2. Floodplain erosion within the lower Big River is the main source of contaminated fine-grained sediment to the study reach and represents an important source of future pollution. Approximately 31,000 Mg of sediment is being released from floodplains per year, and approximately 21 Mg of this is Pb.

KEYWORDS: river disturbance, sediment budget, bank erosion, Missouri, mining

This abstract is approved as to form and content

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ACKNOWLEDGEMENTS

I owe a great deal to those who have helped me complete this project and have supported me throughout. I would like to thank the members of my thesis committee, Dr. Melida Gutiérrez and Dr. Jun Luo for their input on this project and especially thank my thesis advisor, Dr. Robert T. Pavlowsky, for his endless academic knowledge and guidance over the past two years. I appreciate the help from Andrew 'Cookie' DeWitt, Dave Fritsche, Megan Harrington, Anna Larkin, Scarlet Casey, Derek Martin and Dr. Scott Lecce from East Carolina University for helping me complete field work. I especially want to extend a big thanks to Marc Owen for his help, patience, logistical support, ideas, and inputs throughout this project. Without all of these helping hands, this research may never have been possible.

Recognition is also in order for the great support and motivation I have received over the past few years. I owe it to my friends, colleagues and family, especially my parents and brother for always being there for me and encouraging me along the way. In addition, this project would not have been possible without grant funding from the U.S. Fish and Wildlife Service (USFWS) and partial funding from the Missouri State University Graduate College and the Ozarks Environmental and Water Resources Institute. To all those I have mentioned and those I may have missed, I appreciate everything you have done for me in order to complete this research. Thank you.

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INTRODUCTION

River systems are complex entities that adjust their channel geometry and shape to different hydrologic and sediment regimes in order to establish or maintain an equilibrium state (Graf, 1983). This equilibrium state is maintained by adjustments in multiple factors, but mainly channel slope, discharge, sediment transport and capacity at varying spatial and temporal scales. Rivers tend towards an equilibrium state, but many never reach this state or are in perfect equilibrium very long. Stream channels rarely achieve this state of equilibrium due in part to constantly having to adjust to variations in climate and human- induced land use changes.

As streams inherently migrate laterally across their floodplain, sediment is removed as channel banks are eroded by bank scour and undercutting typically occurring on the outside of meander beds (Wynn, 2006). Erosion is generally compensated on the opposite side of the channel by deposition of point bars. The rate at which erosion and deposition occur in normal channel conditions is a slow, natural process (Simon and Rinaldi, 2000). However, anthropogenic activities such as historical land use changes can accelerate this process of lateral channel migration and subsequently accelerate the rate of floodplain remobilization (Knox, 2006). Historical land use changes in a watershed can have significant impacts on the geomorphic processes of rivers, such as channel form, erosion, and floodplain sedimentation rates (Knox, 1977; Trimble and Lund, 1982; Magilligan, 1985; Jacobson and Primm, 1994).

As accelerated lateral channel migration occurs due to human-induced land use changes, alluvium and any anthropogenic pollutants are released back to the channel from floodplain storage by bank scour and undercutting (Knox, 2006; Wynn, 2006). Some contaminants that are typically found to be stored in floodplain deposits include phosphorus, pesticides, and heavy metals (Wynn, 2006). Thus, anthropogenic pollutants stored in floodplain deposits make floodplains an important non-point source of pollution due to the recycling of sediment (Novotny and Chesters, 1989; Marron, 1992; Macklin et al., 1997; Malmon et al., 2002). The long-term risk and fate of pollutants stored in floodplains is of geomorphic concern in areas of channel disturbance, where erosion and lateral channel migration occur at greater rates than normal channels.

Stream channel disturbances are typically characterized by changes in channel planform, aggradation of the channel bed with gravel, and/ or channel widening and incision due to bed and bank erosion (Jacobson, 1995). Channel disturbances are of particular concern to resource management officials, as disturbances can destroy riparian vegetation along a channel, adversely affect water quality, and degrade aquatic ecosystem functions. From a resource management standpoint, trends in channel disturbances in relation to geomorphic, geologic, climatic, and anthropogenic factors must be understood to properly manage a stream affected by disturbance (Jacobson, 1995).

Within the Big River watershed of the eastern Ozark Highlands physiographic region of Missouri, historical land use changes have caused both localized and regional stream disturbance and channel instability (Jacobson and Prim, 1994). Early European settlers cleared trees from large tracts of land to cultivate fields, plant row crops and for timber production (Rafferty, 1980; Jacobson and Primm, 1994). Relatively rapid land clearing caused increased soil erosion and runoff, leading to channel incision and increased coarse gravel delivery to rivers downstream (Jacobson and Primm, 1994).

Excess gravel loads were transported from headwater regions and deposited in the form of large gravel bars, forcing large Ozark streams, like the Big River, to adjust to new sediment loads and hydrologic regimes. The watershed-scale inputs of gravel and silty sediment were deposited on floodplains and in localized disturbance reaches (Jacobson, 1995). Moreover, the Big River is contaminated with mining sediment from historical lead and zinc mining operations. Thus, channel disturbances are of geomorphic concern in the Big River as accelerated floodplain erosion is remobilizing contaminated mining sediment from floodplain storage and further polluting the river system. This study will focus on the 24.2 kilometer segment of the lower Big River from the USGS gage at Byrnesville to the confluence with the Meramec River, a tributary to the Mississippi River. This segment of the Big River is known to be affected by channel disturbances, lead (Pb) contamination, and subsequent Pb remobilization in areas of channel instability.

Lead Contamination in the Big River

The mainstem of the Big River is contaminated with mining sediment due to historical mining operations in the Old Lead Belt Mining District (MDNR, 2007a; Pavlowsky et al., 2010) (Fig. 1). The Old Lead Belt Mining district operated from 1864 to 1972 and was a global leader in the production of lead (Pb) and zinc (Zn). Tailings are the waste materials left over from lead ore processing from which further Pb extraction is not economical. Six major tailing piles remain within the Big River watershed in St. Francois County more than 100 kilometers upstream of the study reach (Fig. 1). These tailings piles are: Leadwood, Desloge, National, Federal, Elvins, and Bonne Terre. Mining sediment was eroded and weathered from these piles into the Big River, but they have been stabilized by Superfund and sources have since been reduced. Contaminated mining wastes have been historically mixed with natural watershed derived un-contaminated minerals and are stored as channel, bar, and floodplain deposits along the mainstem of the Big River, which drains the majority of the once prominent mining district (Fig. 1). Mining sediment has different textural, mineralogical, and geochemical properties compared to natural, un-contaminated sediment. Approximately 3.7 million m^3 and 86.8 million m^3 of contaminated sediment is stored in the channel and floodplains of the Big River respectively (Pavlowsky et al., 2010). Channel instability and floodplain bank erosion is believed to be a major source of lead (Pb) to the channel as floodplain Pb concentrations are greater than 1000 parts per million (ppm) throughout the Big River (Pavlowsky et al., 2010). However, no study has yet evaluated the rate of Pb remobilization from floodplain storage to the present-day channel.

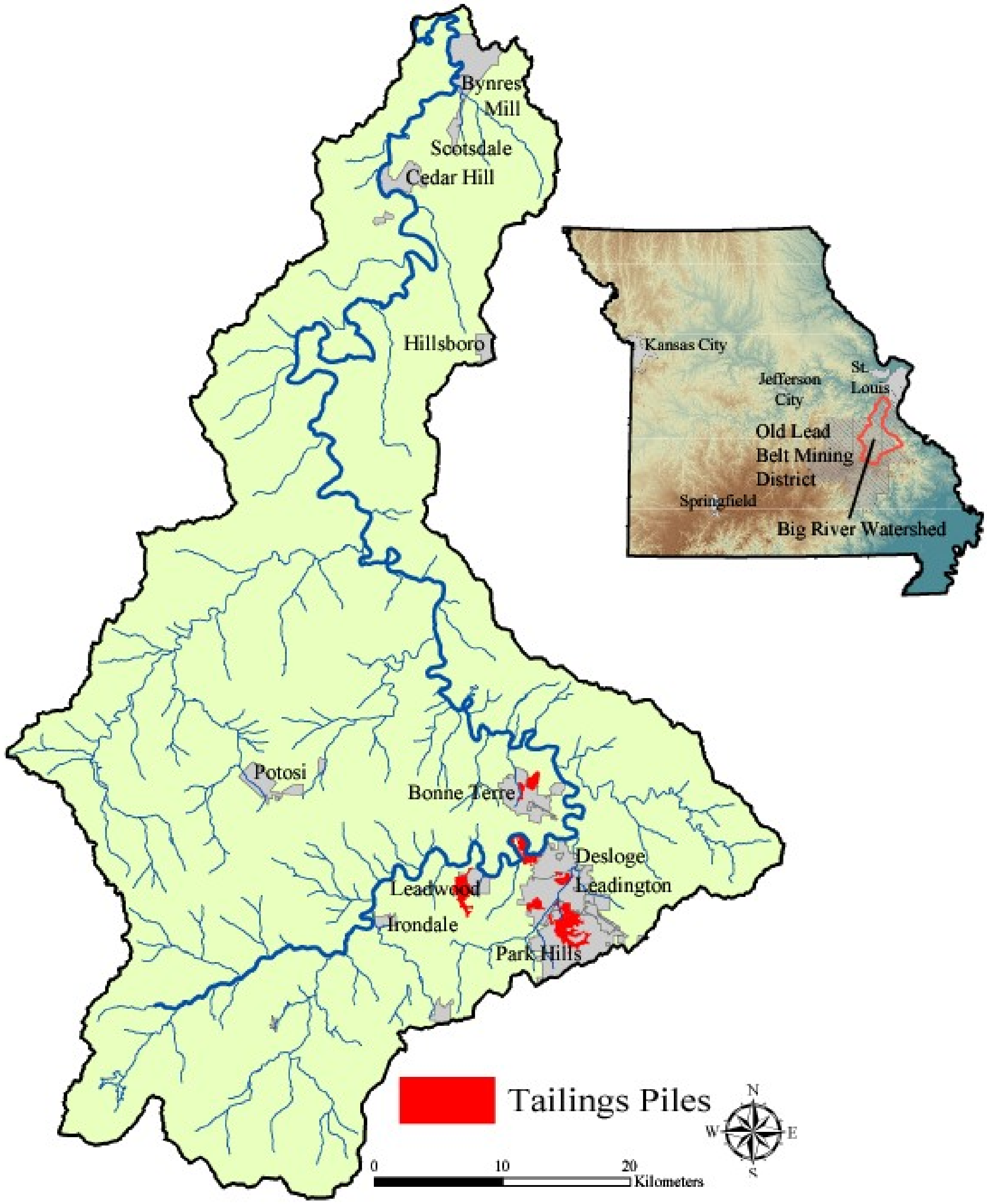


Figure 1. The Big River watershed draining the Old Lead Belt of eastern Missouri.

Both state and federal officials are concerned about the ecological consequences involved with the large-scale contamination of in-channel and floodplain deposits of the Big River. The Missouri Department of Natural Resources (MDNR) reported in 2007 that the Big River has increased amounts of nonvolatile mining sediment in the water column (MDNR, 2007a). The Big River was added to the Missouri 303(d) List of waters not meeting water quality standards under the Clean Water Act in 2006 for being impaired with lead, zinc, and cadmium from abandoned tailings piles (MDNR, 2010). MDNR also has approved a Total Maximum Daily Load (TMDL) for the Big River. The TMDL addresses lead and zinc contaminants in the Big River and its major tributaries, and reports that 93 miles of mainstem of the Big River are 'impaired' due to the release of mining contaminated sediment from the channel bed and floodplains (MDNR, 2007a). The specific targets for Pb and total suspended sediment in the water column set forth by the approved TMDL for the Big River are 0.005 and 5 ppm respectively (MDNR, 2007a).

Fresh water mussels native to the Big River have decreased in density and diversity and have become federally endangered or are a federally endangered candidate as a result of channel instability and declining water quality from fine-grained sedimentation and sediment (Pb) toxicity (Buchanon et al., 1979; Roberts and Bruenderman, 2000). Mussels are sensitive to changes in channel morphology and have difficulty adjusting to changing channel conditions, especially unstable channel beds (Box and Mossa, 1999). Abundance and distribution of mussel populations is influenced by the composition of channel bed material and flow dynamics (Box and Mossa, 1999). One of the most common factors that adversely affect mussel populations is excessive fine-grained sedimentation, which can clog the gills and smother mussels, and reduce available sunlight needed to photosynthesize food sources (Box and Mossa, 1999). In the Big River, the main geomorphological threats are related to excess fine grained sediment deposition (MDNR, 2007a), exposure to Pb contaminated sediment (Pavlowsky et al., 2010), and bed instability related to channel migration, bank erosion, and excessive gravel bar deposits (Jacobson, 1995).

Purpose and Objectives

Several previous studies have made noteworthy contributions to the overall understanding of the location, amounts, dispersal and biological impacts of increased heavy metals stored in the Big River (Buchanan, 1979; Roberts and Church, 1986; Meneau, 1997; Roberts and Bruenderman, 2000; MDNR, 2007a; MDNR 2007c; MDNR, 2010; Pavlowsky et al., 2010). However, the Big River has not been extensively studied from the fluvial geomorphic perspective, which has resulted in a considerable gap in knowledge of the geomorphic processes associated in the transport, deposition, and storage of contaminated sediment. The exception to this is an unpublished U.S. Fish and Wildlife Service (USFWS) report conducted by Pavlowsky et al. (2010) which quantified the volume and downstream distribution of mining sediment storage in channel bed, bar and floodplain deposits, and determined the rate of mining sediment transport and residence times in the Big River watershed.

While the location and amounts of contaminated lead and zinc deposits have been documented (Pavlowsky et al., 2010, MDNR, 2007a; MDNR, 2007c), there is a considerable gap in knowledge that needs to be addressed as to how these stored contaminated sediments are being remobilized by bank erosion within disturbance reaches and the degree to which remobilized Pb is a cause of present and future contamination along the lower reaches of the Big River. The lower reaches of the Big River (river km 0-25) have relatively high banks containing high concentrations of floodplain Pb deposits and frequently show evidence of bank erosion and mass failure, which may act as a net source of future pollution.

The purpose of this study is to better understand the physical mobility and long-term fate of Pb contaminants, in order to assess the present sediment pollution problems in the lower Big River. This study will focus on the 24.2 kilometer segment of the lower Big River to the confluence with the Meramec River, a tributary to the Mississippi River. This study segment is characterized by channel disturbances, Pb contamination, and subsequent Pb remobilization in areas of channel instability that may further threaten three endangered mussel beds found in the lower Big River study reach. Specifically, the objectives are to:

(1) Assess and quantify historical channel planform change to locate disturbance reaches. Aerial photographs spanning 70 years and GIS will be used to map, identify, classify, characterize and explain areas of channel disturbance. This information will be used to understand historical trends in channel changes.

(2) Calculate and examine spatiotemporal trends of bank erosion rates and bar deposition. Features will be digitized in a GIS from aerial photographs to determine historical downstream trend of bank erosion and historical downstream trends in channel capacity and supply based off of gravel bar deposits.

(3) Create a sediment-Pb budget to evaluate the role of stored alluvium and Pb as contemporary sources acting as threats to endangered mussel beds in the lower Big River. GIS based erosion and deposition rates and areas will be coupled with field surveys, sediment samples, geomorphic assessments, and sediment geochemistry to quantify the net release of fine grained sediment and Pb to the channel and threaten already endangered mussel bed populations.

Benefits

This thesis will be the first known study to use a sediment budget approach to address river contamination problems in the Ozarks. There remains a gap in knowledge examining historical trends in channel changes, bank erosion and bar deposition at the reach scale and ultimately the role of bank erosion and floodplain reworking as contemporary sources of Pb contamination to the Big River. Moreover, this thesis will advance our understanding of how to combine GIS and field surveys for geographic and geomorphic assessments of river systems as a whole. Ultimately, the findings of this thesis will be used to address threats of contaminated sediment and better understand sources of water quality impairment to help prioritize the locations and best management practices needed to protect and properly manage the endangered mussel bed populations found in the lower Big River.

LITERATURE REVIEW

Fluvial geomorphology helps one understand formation and evolution processes of streams. In order to protect and properly manage river channels there is an increasing need for the combination of geospatial techniques in fluvial geomorphic studies. Implementing geospatial techniques into fluvial geomorphic studies allows river channels to be examined at a larger scale, longer time period, and better accuracy than historical manual methods used (Chandler et al., 2002). This chapter discusses basic fluvial processes and how geospatial sciences can be implemented with fluvial studies. Further, this chapter will discuss fluvial geomorphic trends related to river channels, floodplains, mining contamination within watersheds, and the use of sediment budget analysis as well as trends in geospatial analyses used for geomorphic assessments of fluvial systems.

Fluvial Geomorphology

Rivers are products of erosion, transportation and subsequent deposition of sediments in the watersheds they drain (Knighton, 1998). Sediment in a watershed is generally eroded, introduced to a river channel and transported downstream until the sediment exits its watershed. Schumm (1977) conceptualized sediment routing through a watershed into three separate zones in the downstream direction (Figure 2). The first zone is located in the upper reaches of the watershed and is a zone of sediment supply released from erosion (Schumm, 1977). Sediment released from zone 1 is eroded during rainfall events and/or mass wasting processes and is introduced to the river channel further downstream in zone 2, an area of net transport (Schumm, 1977). As long as inputs from zone 1 equal the outputs from zone 2, there will be no change in erosion or deposition in zone 2. Furthest downstream is zone 3, characterized by the surplus and deposition of sediment (Schumm, 1977). However, storage of sediments can occur anywhere in a watershed regardless of location in the upper or lower reaches. Sediment can be stored on hillslopes, in the channel, and in floodplains (Magilligan, 1985). Sediment stored in floodplain deposits can become remobilized by bank erosion (Wynn, 2006).

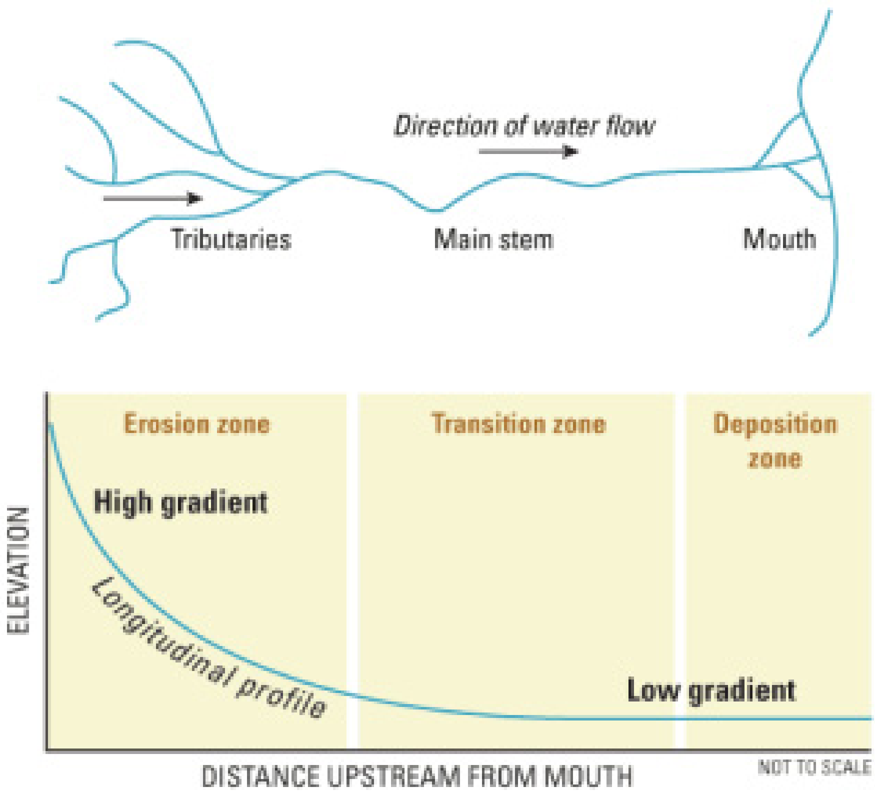


Figure 2. Longitudinal zones within a watershed (after Schumm, 1977).

Human impacts on watersheds. Ever since European settlement, human induced changes in land use have accelerated erosion and sedimentation and affected sediment routing within watersheds (Knox, 1987; Faulkner, 1998; Lecce and Pavlowsky, 1997). In general, forests were historically cleared in order to plant crops and use timber for various purposes. Once vegetation is removed, infiltration capacity of soils is reduced because of decreased evapotranspiration by vegetation, causing more runoff. Bare soil is susceptible to gullying and rill formation on hillslopes and then becomes a product of weathering (Knighton, 1998). Increased erosion introduces more sediment to river channels, causing an increase in flood magnitude and frequency. In response to an increased sediment supply, river channels adjust their dimensions, patterns and slope so that all introduced sediment is routed through the watershed, resulting in areas of channel instability or referred to in the Ozarks as disturbances.

Channel Disturbances in the Ozarks

Channel instability and subsequent stream disturbance have been studied in the Ozark Highlands physiographic region of Missouri, referred to hereinafter as the Ozarks (Jacobson and Primm, 1994; Jacobson, 1995; McKenney et al., 1995; Jacobson and Gran, 1999; Pavlowsky et al., 2010). Channel patterns of Ozark streams have been characterized as an alternating pattern between stable and disturbance reaches with disconnected meander belts (Jacobson, 1995; Jacobson and Gran, 1999) (Fig. 3).

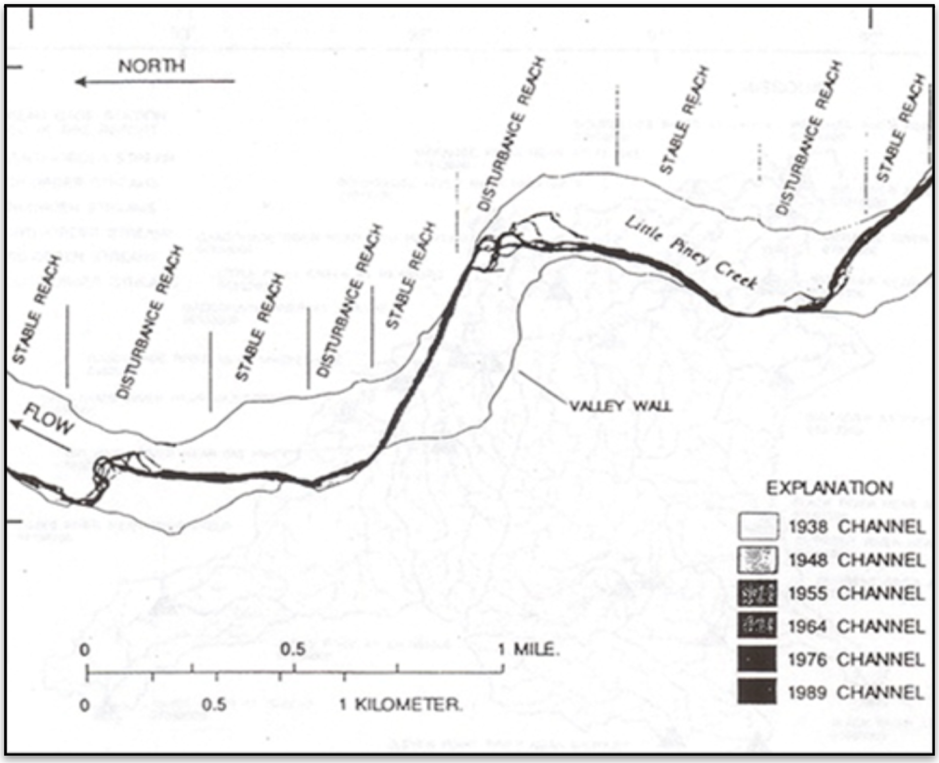


Figure 3. Typical Ozark channel morphology (after Jacobson, 1995).

Stable reaches are characterized by relatively long and straight channels which are interrupted by highly sinuous disturbance reaches. Disturbance reaches were originally classified as "sedimentation zones" where large, unstable gravel bars were deposited (Saucier, 1983). Disturbance reaches are characterized by rapid lateral channel migration, deposition of broad unvegetated gravel bars, and channel instability (Jacobson, 1995; McKenney et al., 1995; Jacobson and Gran, 1999). Disturbance reaches within the Ozarks are typically hundreds to thousands of meters in length and typically occur where the channel crosses the valley and then encounters the opposite valley wall (McKenney et al., 1995). Channel disturbances in the Ozarks occur because the channel is responding to changing sediment and hydrologic regimes from the onset of dramatic human-induced land use changes (Jacobson, 1995; McKenney et al., 1995; Jacobson and Gran, 1999).

Channel and floodplain processes. In-channel sediment is temporarily stored as sand and/or gravel bar deposits, which are re-worked and subsequently recycled back into flow during floods. Fine-grained sediment particles are generally transported as a rivers suspended load, but can be deposited on high bar surfaces, channel banks or on floodplains adjacent to the channel during increased flow (Knighton, 1998).

Floodplains are formed by two main processes: lateral point bar accretion and overbank vertical accretion. Lateral point bar accretion results from the progressive deposition of point bars in an actively migrating channel (Knighton, 1998). As the channel migrates laterally across its valley floor, deposition occurs on the inside of meander bends in the form of point bars and erosion occurs on the outside of bends in the form of cut banks. Erosion from one bank is usually compensated by point bar deposition on the opposite bank (Knighton, 1998). Coarse sediment such as sand and gravel associated with streams bedload are progressively deposited on the point bar during moderate flows. As the channel continues to migrate laterally, the point bar continues to grow in height. The same flows usually inundate the growing point bar less often and coarse material therefore is not able to be deposited on the bar surface due to the size exceeding transport capacity (Knighton, 1998). However, fine particles such as silt and clay from suspension are deposited on the point bar during increased flow. The point bar continues to aggrade with finer sediment, forming a fining upward sequence floodplain with the coarsest gravel near the bottom of the point bar closest to the channel and increasingly finer particles as one goes up in stratigraphy (Knighton, 1998). It is not uncommon for floodplains formed via the processes of lateral accretion to have unstratified basal coarse gravel overlain by progressively finer sediment.

While floodplains can be formed by in-channel processes of lateral point bar accretion, floodplains can also form due to overbank vertical accretion. During periods of flooding, increased flow can eventually top the channel banks, causing floodwaters to spread out and slow in over bank areas. As floodwaters slow away from the channel, energy is dissipated and coarser material is deposited near the channel banks in the form of natural levees and finer material such as silts and clays are deposited in vertical layers further from the channel. The overall rate of overbank deposition is a function of sediment load and flood frequency. This process of overbank deposition and vertical accretion with fine grained alluvium is repeated and over long periods of time, a distinct floodplain is constructed. The overall rate of overbank deposition is a function of sediment load and flood frequency. Once sediment is trapped in floodplains, it is stored for long periods of time compared to sediment stored in channel. Residence times of sediment stored within floodplains can range from decades to centuries (Marron, 1992). Alluvium stored in floodplains generally have much longer residence times compared to in-channel stored sediments because the floodplain is less susceptible to constant erosion as the channel (Malmon et al., 2002).

Floodplains are an important component of the fluvial system and play a critical role in the routing and storage of floodwaters and sediment loads. Hence, floodplain destruction may cause water quality and ecological habitat degradation within a river system. Floodplain destruction occurs as streams migrate laterally across their valley floors. A streams ability to shift laterally depends on the stability of its banks (Hickin and Nanson, 1984). The major factors that determine the stability of channel banks are composition and the amount and type of vegetation present on the banks (Hickin and

Nanson, 1984). Removal of riparian vegetation makes a bank become less stable because bare, exposed soil lacks the cohesion and strength provided by vegetation cover, thus making the banks more susceptible to bank erosion.

River bank erosion mechanisms generally fall into two main categories, bank scour and mass wasting (Wynn, 2006). Bank scour is the weakening of soil strength and subsequent removal of bank materials by undercutting water (Wynn, 2006). Mass wasting occurs when large portions of bank materials become saturated and lose stability, causing bank collapse and slumping (Wynn, 2006). The combination of bank scour and mass wasting erodes floodplain deposits and subsequently recycles once stored alluvium bank into flow and transported downstream. Floodplain sediment remobilization may be of concern if anthropogenic pollutants are stored within floodplain deposits.

Metal mining and floodplains. Present and historical mining operations have left many river systems polluted with heavy metals (Macklin, 1985; Bradley and Cox, 1986; James, 1989; Marron, 1992; Hudson-Edwards et al., 2001; Lecce and Pavlowsky, 2001; Malmon et al., 2002). One general way for sediment to become contaminated is through geochemical mixing of sediment. Clean, un-contaminated sediment is mixed with pollutants from industrial sources, stormwater runoff, and weathering inputs from tailings piles for example. The ‘clean’ sediment dilutes or overwhelms the mining contamination further downstream from mining sources; therefore metal concentrations generally decrease the further downstream from mining sources (Bradley and Cox, 1986; Graf, 1996; Lecce and Pavlowsky, 2001). Another general way for sediment to become contaminated is through physical dispersal. Contamination within the study reach in this thesis shows both geochemical and physical dispersal, but it is not clear the specific contribution of both to contamination.

Mineral contaminants such as tailings created by the milling process of Pb ore preferentially bind to fine-grained alluvium (Eisenbud, 1987; Malmon et al., 2002). Fine sediment also typically has higher concentrations of geochemically active components such as clay minerals, secondary Iron-Manganese coatings and organic matters. Heavy metals favor adherence to clay and silt-sized alluvium because of large surface area to volume ratios and higher sorption capacity of the fine-grained particles (Eisenbud, 1987; Malmon et al., 2002). However, more heavy metals are deposited within floodplains than in-channel deposits as floodplain contamination is mainly associated with pulses of metal rich fine grained materials that have the potential to be transported further downstream (Marron, 1992; Malmon et al., 2002). For example, floodplain-stored sediment contained 70% of the total contaminants within the entire fluvial system in the Los Alamos River in central New Mexico (Malmon et al., 2002). Marron (1992) suggests that of all contaminated mining sediment entering the Belle Fourche river system; approximately 30-45% is stored in floodplains. Also, contaminated floodplain deposits generally have higher concentrations of contaminants compared to channel bed and bar deposits (Lecce and Pavlowsky, 1997; Lecce and Pavlowsky, 2001). Lecce and Pavlowsky (1997) found zinc concentrations were five times higher in floodplain deposits than in-channel deposits.

Floodplain deposition and erosion processes can strongly influence the redistribution of contaminated sediment and anthropogenic pollutants in fluvial environments. Since heavy metals associated with historical mining operations do not chemically degrade with time (Csiki and Martin, 2008), heavy metals stored in floodplains act as long-term pollution threats. Heavy metals stored in floodplains can be re-worked and remobilized back into fluvial transport, making contaminated sediment in floodplains an important non-point source of pollution (Novotny and Chesters, 1989; Marron, 1992; Lecce and Pavlowsky, 1997; Macklin et al., 1997; Malmon et al., 2002). Increased bank erosion and subsequent remobilization of floodplain sediment make floodplains an important source of sediment and pollutants to a river system.

Sediment Budget Concepts

In order to protect and manage natural resources, resource management officials are concerned with channel erosion and deposition due to land use changes within a watershed or at an individual reach scale. Understanding how river channels will react to changes in land use is useful in the prediction of erosion rates and locations as well as predicting areas of deposition, residence times, and how these deposits may be potentially remobilized. One important and useful tool used to assess the balance between erosion and sediment yield is the sediment budget. A sediment budget quantifies sediment sources (erosion), sinks (deposition) and sediment delivery routes to calculate changes in sediment storage and transport rates through watersheds or individual reaches of a stream (Trimble, 1983). A sediment budget accounts for rates and processes of erosion, sediment transport, and for temporary storage of sediment within in-channel bars and floodplains.

One of the earliest and most recognizable applications of the sediment budget was by Trimble (1983) in the Coon Creek Basin of the Driftless Area of southwest Wisconsin. Trimble (1983) prepared two separate sediment budgets based off different land uses.

One sediment budget was created from 1853-1938, a time period characterized by severe degradation in the form of increased upland soil erosion from poor agricultural practices. The other sediment budget was created from 1938-1975, a time period in which soil conservation methods were used and reduced upland soil erosion by 26% (Trimble, 1983). Sediment budget analysis between the two time periods show that a large portion of the sediment eroded during the first time period was stored in the valley floors or as colluvium and was subsequently remobilized during the second time period, causing little change in total sediment yield between the two time periods (Trimble, 1983).

Since Trimble's (1983) important studies in southwestern Wisconsin, sediment budgets have been applied for a wide range of assessments including clear cut logging (Roberts and Church, 1986), historical gravel mining (Rovira et al., 2005) and estuary sediment (Renwick and Ashley, 1984). However, little research exists on sediment budgets being applied to river channels affected by mining for heavy metals (Marcus et al., 1993). This thesis will be the first known study to use a sediment budget approach to address river contamination problems in the Ozarks.

Geospatial Analysis

Fluvial geomorphologists have long been interested in understanding and quantifying river morphology. One of the simplest ways to monitor and assess historical changes in streams is by channel planform mapping. Channel planform mapping is used to assess the historical stability of a river channel and help determine how channels have been affected by human induced land use changes (Downward et al., 1994). Traditional methods used to monitor river channel change are often time consuming and expensive.

Leopold (1972) was one of the first documented studies using traditional manual methods to examine channel change of a small tributary stream to the Potomac River in Maryland. Fourteen channel cross sections were placed at a variety of random meander curves and straight reaches along the stream, and steel rods were buried into the ground at the ends of each cross section. Distance between pins and given landmarks was measured using tape measures and data collection was problematic as erosion destroyed buried rods. Each cross section was surveyed using this method every other year for twenty years. Although Leopold's study was one of the first documented attempts to quantify river channel change, data collection using traditional manual methods to quantify river channel change was time consuming and not able to quantify areas of channel change between cross sections.

Trends in measuring river morphology have recently moved away from the traditional methods used by Leopold (1972) to more sophisticated methods implementing geographic information systems (GIS) and historical aerial photography to quantify changes in channel planform (Downward et al., 1994, Chandler et al., 2002, Mount et al., 2003, Hughes et al., 2006). Technological advances in GIS and remote sensing allow for quicker, more efficient, and cheaper assessments of channel planform change. Chandler et al. (2002) monitored channel change using aerial photography and automated digital photogrammetry on the Sunwapta River in the Canadian Rockies of Alberta. Compared to Leopold's manual methods described above, Chandler et al. (2002) reduced surveying time significantly, increased the size of the study area, and created accurate (0.2 meter resolution) Digital Elevation Models (DEM) at both high spatial and temporal densities.

Use of aerial photography on Ozark streams. Historical aerial photographs have been used in the Ozarks to effectively monitor and assess channel morphology (Jacobson and Pugh, 1995; Legleiter, 1999; Martin, 2005). Jacobson and Pugh (1995) used multiple sets of low-altitude aerial photographs to quantify location and rates of channel migration and show how historical channel migration affected riparian land use over a 50 year period on the Little Piney Creek, Missouri. Legleiter (1999) several sets of aerial photographs over a 60 year record to compare rates of channel erosion and deposition among two reaches of the James River that are separated by a dam. Legleiter (1999) also used aerial photography to quantify lateral channel migration and examine spatiotemporal trends in gravel bar deposition in both reaches. Martin (2005) also used multiple sets of aerial photographs to assess the historical movement of gravel bar deposition and determine channel migration rates and the influence of riparian land use on channel migration and subsequent gravel bar deposition. Martin (2005) suggested that gravel bar deposition occurs in waves and may control migration rates of the Current River channel. All of these previous studies implemented historical aerial photography into fluvial geomorphic analyses. It is evident throughout these studies that historical aerial photography proves to be an effective tool used for monitoring and analyzing historical Ozark stream behavior.

Sources of error. Despite the advantages of using GIS and remote sensing to quantify channel planform change described above, spatial error is an inevitable problem with this technology. Quantifying river channel change using aerial photogrammetry is only credible if errors in processing and digitizing the channel can be minimized. Mount et al. (2003) believe that the error inherent in planform mapping should always be reported along with the results of a study of historical planform channel change. Downward et al. (1994) describe three elements of error resulting from planform mapping: the registration of images, digitizing, and transformation of the aerial photograph from vector to raster. Vector data in a GIS uses points and their x and y coordinates to represent spatial features. In raster data, on the other hand, the world is made up of properties varying continuously across space. Hughes et al. (2006) examined the spatial accuracy of georectification process of aerial photographs used to quantify lateral channel change. To minimize error in the georectification process of aerial photographs, Hughes et al. (2006) suggest multiple random independent ground control points (GCPs) should be combined with the Root Mean Square Error (RMSE), which can routinely minimize georectification error to approximately five meters. Mount et al. (2003) estimated the errors associated with measuring 185 bankfull width changes using sequences and image to image comparison. They find that spatial error from image to image comparison is significantly smaller than using just the root mean square error (RMSE), but utilizing both image to image comparison and the RMSE can greatly reduce spatial error.

Summary

Historical mining operations have polluted river channels throughout the world, especially the Big River in eastern Missouri. Anthropogenic pollutants introduced into a stream can be dispersed by the geomorphic processes that shape and maintain a channel. These contaminants have the ability to be stored for long periods of time as floodplain deposits, but floodplain bank erosion can cause these stored pollutants to be recycled back into flow, making the floodplain an important non-point source of pollution.

Technological advances have allowed easier, cheaper, and more accurate geomorphic assessments of river channels. GIS and remote sensing have become valuable tools used for the geomorphic assessments of fluvial systems. Geomorphologists are now capable of studying larger areas over longer time frames much easier, faster, and cheaper than before. This study will implement GIS and historical aerial photography to map river disturbances and create a sediment-lead budget for the lower 24.2 km reach of the Big River. Little research exists that documents the creation of a lead (Pb) budget by the use of modern geospatial technologies at the reach and segment-scales as will be done here.

STUDY AREA

The Big River watershed (2,473 km^2) is located in eastern Missouri south of St. Louis in the greater Ozark Highlands physiographic region (Fig. 4). Headwaters of the Big River originate approximately 530 meters above mean sea level (masl) at Buford Mountain in the St. Francois Mountains physiographic region (Meneau, 1997). From there, the Big River flows north approximately 225 kilometers before emptying into the Meramec River (a tributary to the Mississippi River) near Eureka, Missouri at an elevation of 124 masl (Meneau, 1997). The Meramec River flows into the Mississippi River approximately 30 river kilometers below Eureka. The Big River drains portions of Jefferson, Washington, Franklin, St. Francois, Ste. Genevieve, and Iron counties in eastern Missouri within the Upper Mississippi River basin. The channel reach of particular interest for this study is the lower 24.2 km of the Big River from the USGS gage at Byrnesville (USGS #07018500) to the confluence with the Meramec River.

Figure 4. Big River watershed within the greater Ozark Highlands physiographic region of Missouri.

Geology

The Ozark Highlands, or referred to simply as the Ozarks, is an area of broad geologic uplift underlain by Paleozoic sedimentary rocks, mainly cherty dolomite, limestone and local sandstone outcrops (Jacobson and Primm, 1994; Meneau, 1997). The Ozark Highlands physiographic region is divided into four major subdivisions: the Boston Mountains, Springfield Plateau, Salem Plateau, and the St. Francois Mountains (Fig. 4). Headwaters of the Big River rise approximately 530 meters above mean sea level at Buford Mountain in the St. Francois Mountains, a geologically older area characterized by erosion resistant igneous peaks and relatively high relief (Figs. 4 and 5).

However, the majority of the Big River drains the northern portions of the Salem Plateau, an area characterized by gently rolling topography and carbonate sedimentary rocks, mainly dolomite with some limestone and shale units and local sandstone outcrops (Meneau, 1997) (Figs. 4 and 5). Geologic formations within the Big River watershed range in age from Pennsylvanian to Precambrian (Table 1) (Fig. 5). The vast majority, approximately two-thirds of the Big River flows through areas characterized by Bonne Terre (Ceb), Eminence, and Potosi (Cep) dolomite of Cambrian age (Table 1) (Fig. 5). As the Big River flows north, it flows through progressively younger geologic formations associated with the Ordovician, Devonian, Mississippian, and Pennsylvanian systems. The Big River flows exclusively through Ordovician aged Jefferson City and Cotter dolomite (Ojc), until the upper extent of the lower Big River study reach at the USGS gage at Byrnesville (Table 1) (Fig. 5).

Table 1. Descriptions of bedrock geology in the Big River watershed

Subsystem	Symbol	Comments
Pennsylvanian	Pu	Pennsyvlanian undifferentiated
Mississippian	Mo	Osagean Series limestone
Devonian	D	Devonian System
Ordivican	Omk	Maquoketa Shale
	Odp	Decorah Group shale and Plattin Group limestone
	Ojd	Joachim Dolomite with interbedded limestone and shale
	Ospe	St. Peter Sandstone
	Ojc	Jefferson City and Cotter Dolomite
	Or	Roubidoux Formation-sandstone, chert, and interbedded dolomite
	Og	Gasconade Dolomite
Cambrian	Cep	Eminence and Potosi Dolomite
	Ceb	Derby-Doerun and Bonne Terre Dolomite
	Clm	Lamotte Sandstone
Pre-Cambrian	d	Diabase dikes and sills
	i	St. Francois Mountains Intrusive suite
	v	St. Francois Mountains Volcanic Subgroup

Upland areas located within the lower Big River study reach are dominated by Ordovician-aged shale and shaley limestone of the Decorah and Plattin formations (MDNR, 2007b) (Fig. 6). Bedrock of the lower Big River valley consists of Ordovician aged massive cross bedded dolomite of the Joachim and Dutchtown formations, dolomite with interbedded limestone and sandstone of the Everton formation and sandstone of the St. Peter formation (MDNR, 2007b) (Fig. 6). Local outcrops are mainly Mississippian aged Osagean series limestone with chert nodules, which are surrounded by geologically younger shale and limestone of the Maquoketa and Kimmswick formations (MDNR, 2007b).

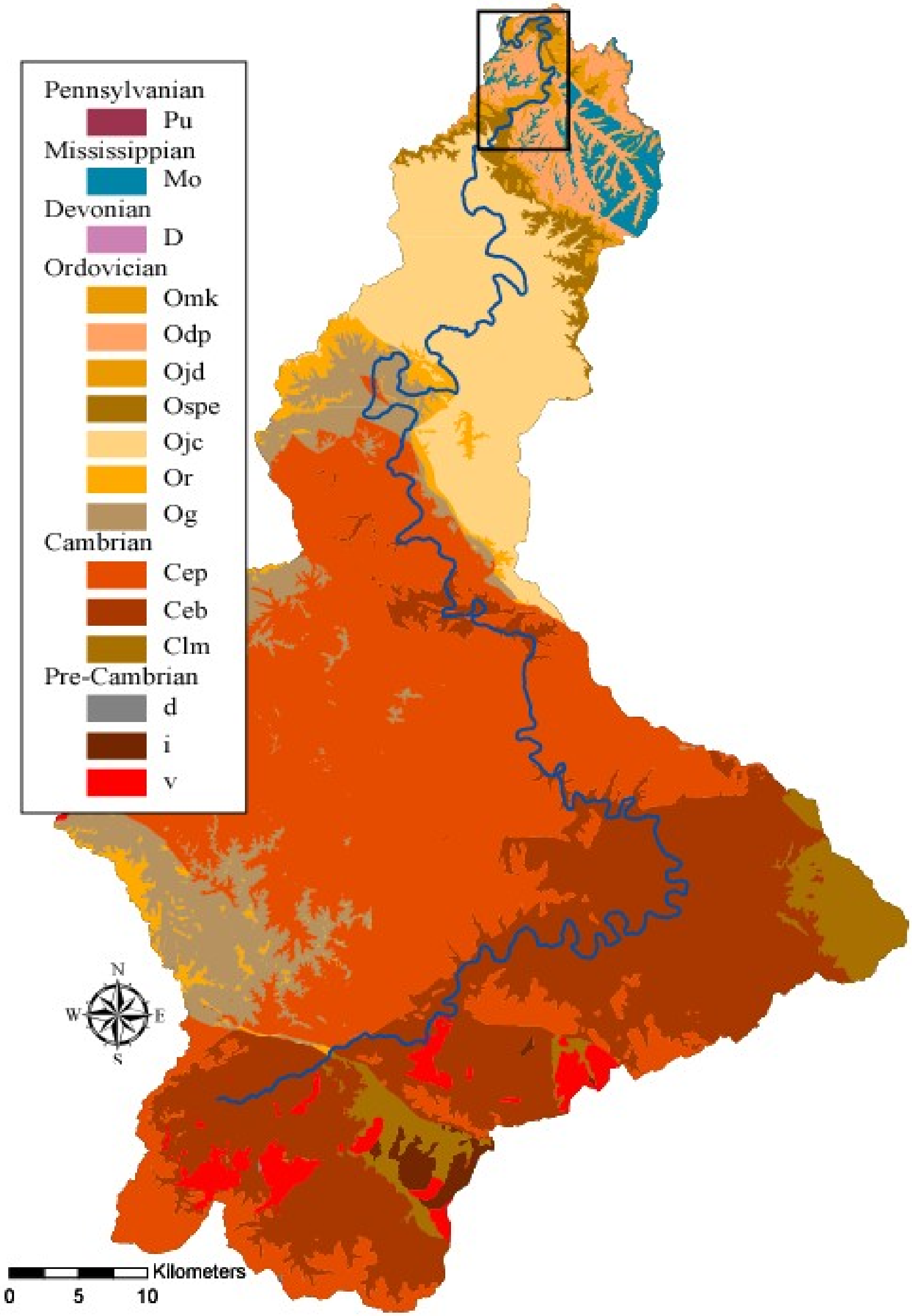


Figure 5. General bedrock geology of the Big River watershed. Black box indicates 24.2 km study reach.

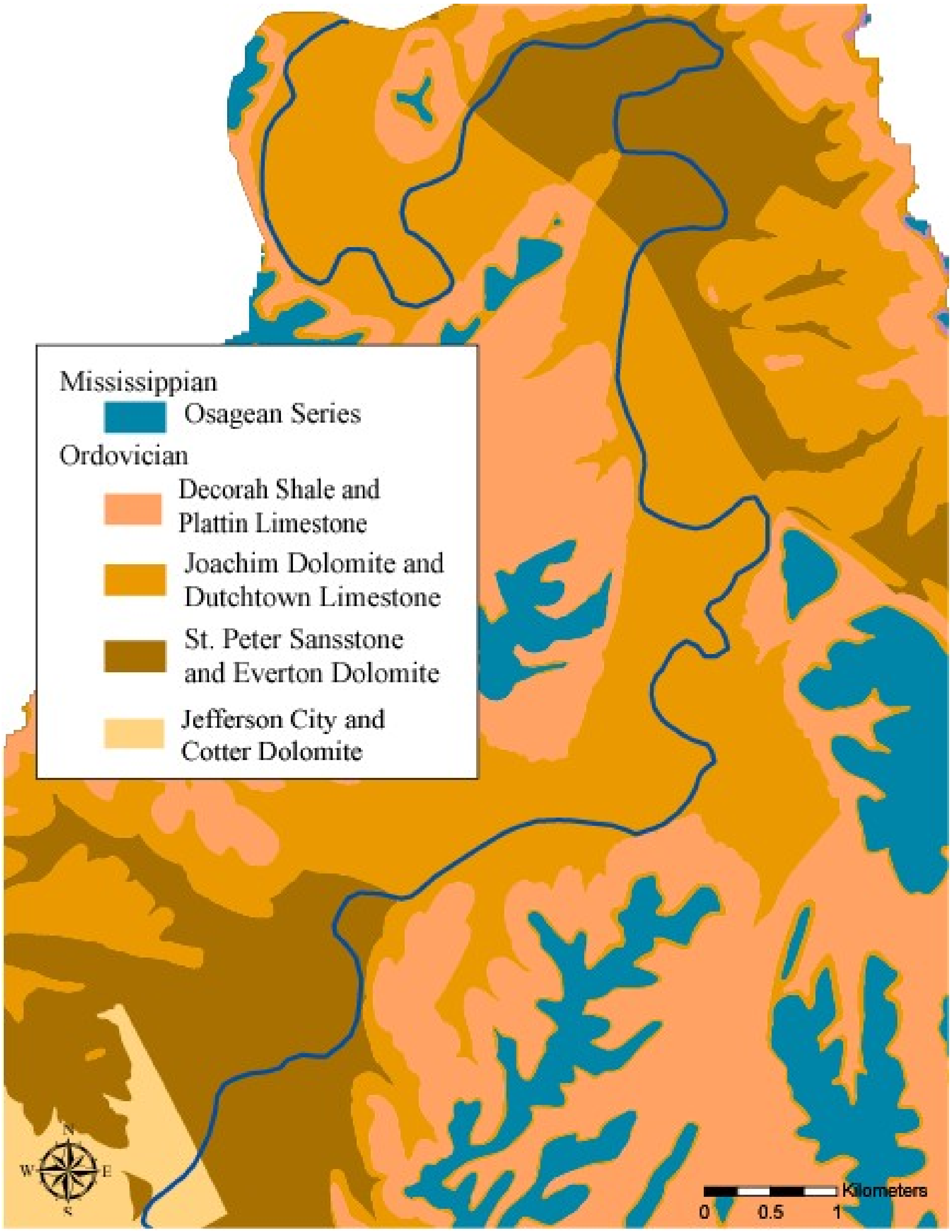


Figure 6. Bedrock geology of Mississippian and Ordovician age within the lower Big River study segment.

Soils

Most of the soils within the Big River watershed are classified as Sonsac (gravelly silt loam) and Useful (silt loam) series, both consisting of moderately deep to deep, moderately well to well drained and moderately permeable soils (NRCS, 2006). Sonsac series soils are formed coarse colluvium superimposed on weathered residuum from dolostone and limestone. Useful series soils are similar to the Sonsac series soils but a thin layer of glacial loess is found at the surface (NRCS, 2006). Both soil series are found on slopes ranging from 3 to approximately 55 percent (NRCS, 2006).

Upland soils consist of moderately deep, well drained gravelly silt loam colluvium and are formed over clayey residuum that has been weathered from cherty dolomite and limestone (NRCS, 2006). Holocene terrace soils of the Gabriel, Horsecreek, Moniteau, and Freeburg series are rarely or never inundated during floods (Skaer, 2000).

Alluvial soils occupying the lower Big River valley consist of deep to very deep, poor to well drained silt loam of the Kaintuck, Haymond, Wilbur and Sturkie series and are formed on floodplains and/or low terraces (Skaer, 2000; NRCS, 2006). These alluvial soils occupying the Big River valley floor are inundated by floods with return frequency of 1 to 20 years and occur within the historical meander belt and floodplain of the river (Skaer, 2000, NRCS, 2006). Kaintuck series soils consist of very deep, well drained, moderately permeable loamy alluvium that represent the active floodplain of the lower Big River (Skaer, 2000; NRCS, 2006) (Table 2) (Fig. 7). Approximately 0.45 km^2 in the lower Big River study reach is mapped as Kaintuck series. Low terraces are mapped as the Haymond series, which consists of very deep, well drained, moderately permeable alluvium (Skaer, 2000; NRCS, 2006) (Table 2) (Fig. 7). The Wilbur series is found on similar landform positions as the Haymond series soils, but occurs in backswamp areas that are poorly drained and slightly lower in elevation (Skaer, 2000; NRCS, 2006) (Table 2). Sturkie series soils, consisting of very deep, well drained, moderately permeable soils are found on low terraces of the lower Big River at elevations slightly higher than the Haymond series (Skaer, 2000; NRCS, 2006) (Table 2). Approximately 0.45, 4.98, 0.93, and 0.54 km^2 in the lower Big River study reach is mapped as Kaintuck, Haymond, Wilbur and Sturkie series, respectively (Skaer, 2000; NRCS, 2006). All of the four aforementioned alluvial soils series are potentially contaminated with mining-related heavy metals, mainly lead and zinc (Pavlowsky et al., 2010).

Table 2. General descriptions of soils found along the lower Big River (NRCS, 2006).

Soil Series	Parent Material	Landform Position	Flood Frequency	Slope (%)	Taxonomic Class
Kaintuck	coarse-loamy alluvium on floodplains	Active Floodplain	Frequently	0 to 3	coarse-loamy, siliceous, superactive, nonacid, mesic Typic Udiflevents
Haymond	coarse-silty alluvium on floodplains	Low Terrace	Frequently	0 to 3	coarse-silty, mixed, superactive, mesic Dystric Fluventic Eutrudepts
Wilbur	silty-alluvium on floodplains	Low Terrace	Frequently	0 to 2	coarse-silty, mixed, superactive, mesic Fluvaquentic Eutrudepts
Sturkie	silty-alluvium on terraces	Low Terrace	Occasionally	0 to 2	fine-silty, mixed, superactive, mesic Cumulic Hapludolls
Freeburg	silty alluvium on terraces and footslopes	High Terrace	Rarely	0 to 9	fine-silty, mixed, superactive, mesic Aquic Hapludalfs
Moniteau	silty alluvium on terraces	High Terrace	Rarely	0 to 2	fine-silty, mixed, superactive, mesic Typic Endoaqualfs
Horsecreek	silty alluvium on terraces	High Terrace	Rarely	0 to 5	fine-silty, mixed, active, mesic Mollic Hapludalfs
Gabriel	silty alluvium on terraces	High Terrace	Rarely	0 to 2	fine-silty, mixed, superactive, mesic Typic Argiaquolls

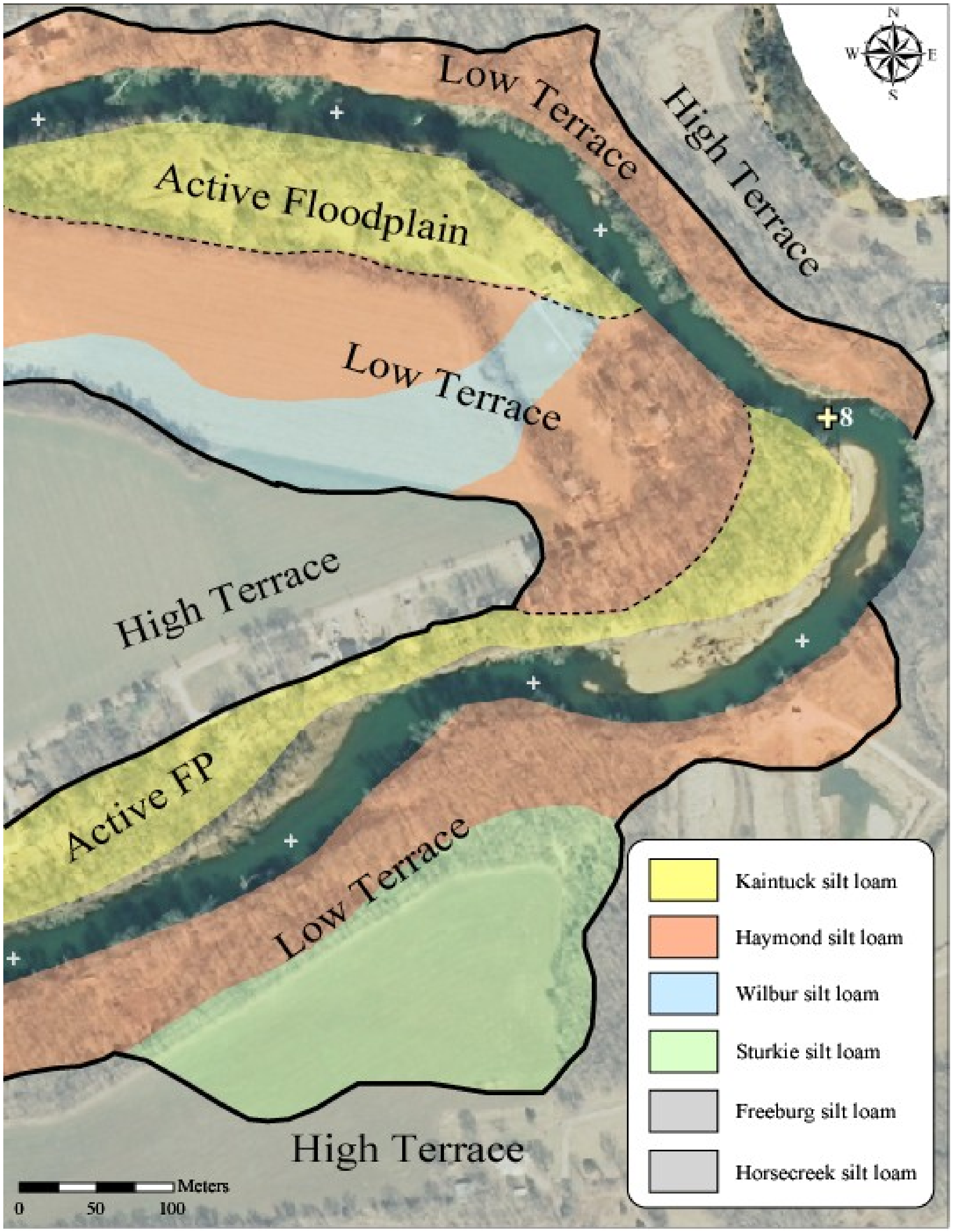


Figure 7. Potentially contaminated alluvial soils and associated landforms of the lower Big River.

Climate

The Ozarks have a humid continental climate, although the climate is rather variable both spatially and temporally due to the Ozark's latitudinal position (Jacobson and Primm, 1994; Rafferty, 1980). Prevailing east-moving storm systems and moisture from the Gulf Coast cause diurnal and seasonal fluctuations in temperature, precipitation, and humidity within the Ozarks. Average annual temperature ranges from approximately 15-18˚C, but extreme temperatures can reach 38˚C or more and -26˚C in the summer and winter respectively (Rafferty, 1980). Average annual precipitation in the eastern Ozarks ranges from approximately 100-120 cm per year with rainfall accounting for approximately 75% of annual total (Meneau, 1997). Typically, the wettest month of the year is May in which the average precipitation is 33 cm and driest month is February with an average precipitation of 15 cm (Meneau, 1997).

Hydrology

The Big River has a typical Ozark riffle-pool sequence morphology and a relatively flashy hydrologic regime as short, intense storm events are coupled with thin, impermeable soils (Meneau, 1997; Panfil and Jacobson, 2001). Average gradient of the Big River is approximately 0.32%, but ranges from 0.064% near the confluence with the Meramec River to 9.8% in the headwaters in the St. Francois Mountains (Meneau, 1997). There are three active U.S. Geological Survey (USGS) gaging stations located within the Big River watershed that measure discharge and flood stage instantaneously: Big River at Irondale, Big River at Richwoods, and Big River at Byrnesville (Table 3).

Table 3. Hydrologic characteristics of gaging stations within the Big River basin (USGS, 2010).

USGS Station Number	USGS Station Name	Record Length (yrs)	Drainage Area (km^2)	Datum (masl)	Main-channel slope (%)	Mean Annual Q (m^3/s)	10% exceedance Q (m^3/s)	Maximum Peak Flow (m^3/s)
07018500	Big River at Byrnesville, MO	87	2,375	132.3	0.06	24.5	48.4	1,801 (Sep 25, 1993)
07018100	Big River near Richwoods, MO	26	1,903.6	159.4	N/A	19.9	37.1	1,693 (Sep 23, 1993)
07017200	Big River at Irondale, MO	43	453.3	229.6	0.37	5.2	10.3	1,390 (Nov 14, 1993)

The USGS gage at Byrnesville has an 87 year period of record dating back to 1923 and drains an area of approximately 2,375 km^2 (Table 3). Maximum annual peak discharge for the USGS gage at Byrnesville ranges from 78 to 1801 m^3/s in 1976 and 1993 respectively (Fig. 8a). The mean flood of all annual peak floods on record is 538 m^3/s, and river stage associated with this stage is 2.65 meters. Average river stage associated with the maximum annual peak discharge is approximately 6 meters, but ranges from 2.61 to 8.95 meters (Fig. 8b). Flood frequency analysis of the USGS gage at Byrnesville indicates that the largest floods on record have been occurring in the recent past. Four of the top five largest maximum annual peak discharges on record have occurred in the past 25 years in 1993, 1994, 2008, and 1986 respectively.

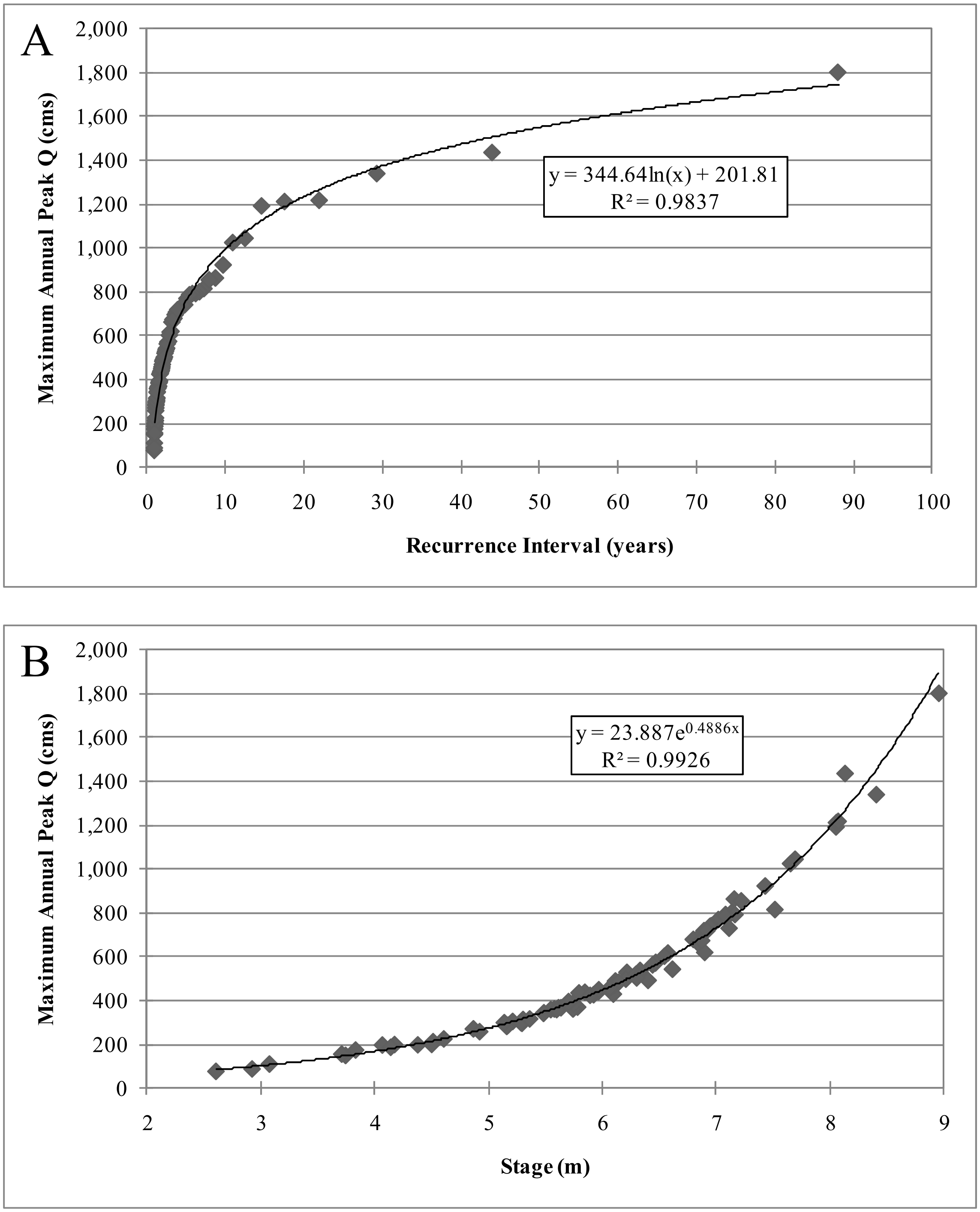


Figure 8a-b. Flood frequency analysis of the Big River gage at Byrnesville (USGS # 07018500).

The Big River is mostly navigable but there are seven low water bridges or mill dams throughout the river. Over 170 kilometers of the Big River below Leadwood, there are two low water bridges at Leadwood and the Bone Hole and five mill dams at Morse Mill, Cedar Hill, Byrnesville, Rockford Beach, and Byrnes Mill. Specifically, the Byrnesville Dam (river km 24.2), Rockford Beach Dam (river kilometer 17.4) and the Byrnes Mill Dam (river kilometer 14.5) are located within the study reach. Both the Byrnesville and Rockford Beach dams are generally intact and still impound water, but the Byrnes Mill dam is breached in the mid section due to improper construction and poor maintenance which allows watercraft to pass.

Land Use History

Pre-settlement conditions. Prior to European settlement, numerous Native American tribes lived along the well drained, fertile, alluvial soils found in the river valley bottomlands in Jefferson County (Rafferty, 1980; Jacobson and Primm, 1994; NRCS, 2006). Although not directly examining the Big River watershed, Schoolcraft (1821) embarked on a journey west starting in present day Potosi (Fig. 1) and described pre-settlement vegetation from Potosi to the Meramec River. These accounts are the best available for pre-settlement vegetation conditions within the Big River watershed. Schoolcraft (1821) described valley bottomlands and valley slopes as being dominated by thick forests, except for one unknown stream that had extensive prairies along its banks. Hilltop ridges in this area were characterized by thin clumps of oak savannah with tall grass undergrowth (Schoolcraft, 1821).

Ozark settlement. As pioneers started settling in the Ozarks during the 1800's, valley bottoms of relatively thick deciduous and evergreen forests were quickly cleared for row crops and grazing (Rafferty, 1980; Jacobson and Primm, 1994). The valley bottomlands were the first to be cleared and settled, followed by uplands because of poorer soils. Virtually all of the upland prairie grass was removed or converted for agriculture uses, subsequently increasing soil erosion (Rafferty, 1980). Agricultural practices gave way to increased logging around 1880, as lumber demand increased due to the vast expansion of the railroad system throughout the United States. Large-scale logging operations throughout the Ozarks cleared valley bottoms and slopes of second growth forests from around 1880-1920. Intense exploitation of Ozark forests slowed around 1920 and residents returned to agricultural practices of grazing and crop production (Rafferty, 1980; Jacobson and Primm, 1994). Grazing and field cultivation has decreased since the 1960's, but cattle populations are still increasing in the Ozarks (Jacobson and Primm, 1994) (Figure 9b).

Present day land-use. Seasonal burning of Ozark uplands has led to the rejuvenation, development and maintenance of grasslands and forests. Current land use within the Big River watershed is dominated (> 75%) by mixed deciduous-conifer second growth forest and grassland (MoRAP, 2005). Only approximately 10% of the Big River watershed is classified as urban or impervious area (MoRAP, 2005). Population and subsequent population density has increased recently in Jefferson County, due to expansion of the greater St. Louis metropolitan area (Fig. 9a). St. Francois and Washington Counties are also increasing in population, but not as rapid as Jefferson County.

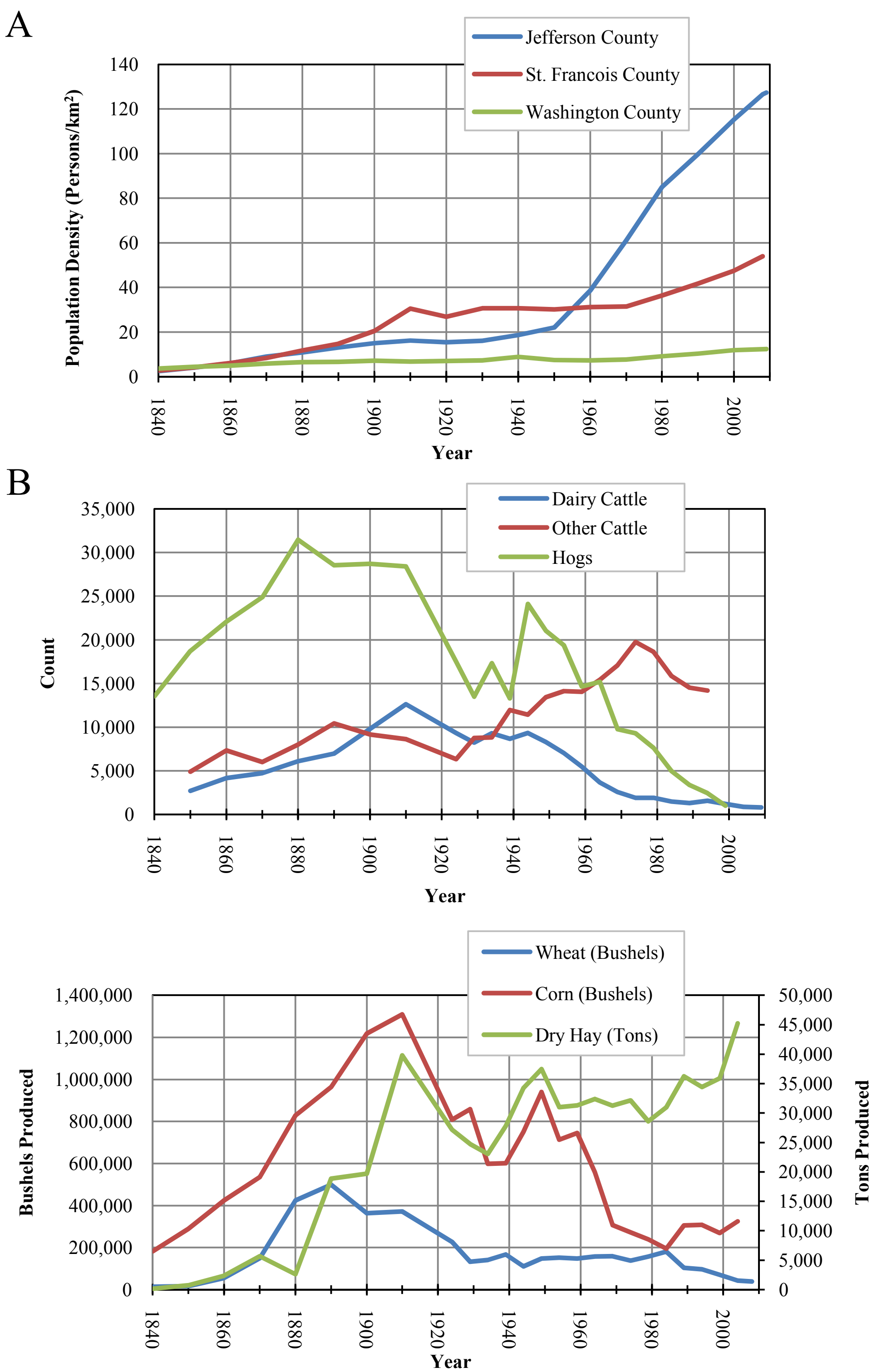


Figure 9a-c. Historical population density (A), livestock production (B), and crop production (C) in Jefferson County, Missouri.

Mining History

Early mining. Around the onset of the 18th century, French settlers were the first documented to find lead (Pb) deposits near the Big River watershed (Rafferty, 1980). At this time, prospecting for lead and other heavy metals occurred in shallow pits near the surface, as lead deposits weren't very deep and often times outcropped at the surface (Rafferty, 1980). The first organized ore mining operation opened in 1720 and consisted of approximately 200 people near the confluence of the Big and Meramec Rivers (Rafferty, 1980). Digging and smelting of lead ore at this time was completed in the fall and winter, after crops were harvested and pits were driest (Rafferty, 1980). In 1789, the first large scale mining settlement was established near present day Potosi (Rafferty, 1980) (Fig. 1). Relatively shallow deposits of Galena ore were uncovered by hard-rock miners and initially broken into smaller pieces using a hammer, hoisted by buckets, transported to the crude mill by horses and/ or donkeys (Rafferty, 1980). Once at the mill, Galena (lead sulfide) was further crushed into smaller pieces, ran through rolls to pulverize the ore, and added with water to hand-operated jigs to separate the economical value of Pb. Eventually, galena ore was introduced into a crude-rock furnace and exposed to high temperatures. High temperatures and continuous stirring of the material eventually produced metallic lead, but this process was rather slow and required large amounts of manual labor (Rafferty, 1980).

Modern mining in St. Francois County. Around the end of the Civil War, commercialized mining operations within eastern Missouri expanded quickly due to the onset of technological advances such as dynamite blasting, the diamond drill, and reflecting furnace (Rafferty, 1980). The diamond drill allowed miners to explore several hundred feet deeper than previous for geological deposits of Galena ore and the reflecting furnace made Pb mining operations quicker, more efficient, and essentially more economical. In 1869, the St. Joseph Lead Company used the diamond drill to make an exploratory mine shaft several hundred feet below the surface in the Bonne Terre dolomite formation (Rafferty, 1980). The exploratory shaft drilled by the St. Joseph Lead Company found large amounts of galena ore deposits associated with the Lamotte sandstone and throughout the entire 400 foot thick Bonne Terre formation. From this point on, these formations were targeted for galena extraction, which caused rapid mining expansion.

Mining expansion occurred in eastern Missouri until the mid 1800s and the area grew into one of the most prominent lead mining districts in the world, known as the Old Lead Belt Mining District. Just five years after the initial exploratory shaft sunk into the Bonne Terre dolomite, the St. Joseph Lead Company drilled an additional five mining shafts and modernized machinery, the refining mill, and hoist houses (Rafferty, 1980). Between 1890 and 1910, mining operations began using push carts and eventually steam powered hoists and engines to haul ore underground in the vast system of mining tunnels and dynamite was used to break up larger amounts of galena. During this time, numerous, modern mine shafts opened in St. Francois County near Bonne Terre, Missouri.

Environmental impact. As mining companies expanded their operations until peak production around 1942, the environmental impact these large scale mining operations became more significant. Large volumes of mineral mining wastes were stored in large piles near the refining mill (Fig. 2). These waste piles are generally referred to as tailings piles and are composed of sand and fine gravel (chat) sized particles that still contain high concentrations of heavy metals. Few environmental regulations existed or were enforced between 1850 and 1940, so mining wastes stored in tailings piles or slurry ponds were often times discharged directly into surrounding streams. Soon after World War II, environmental restrictions were put in place to stop the direct release of mining wastes into streams.

Around 1972, several nonpaying mining shafts were abandoned and large scale mining operations in the Old Lead Belt subsequently closed because of reduced production (Rafferty, 1980). Since then, six major tailings piles located within the Big River watershed have been or are currently being stabilized by federal Superfund. However, tailings and mine wastes with relatively high concentrations of heavy metals have been and still are being introduced to the Big River by erosion and weathering of contaminated in-transit channel sediment, bar deposits, and floodplains (Pavlowsky et al., 2010).

Little to no mining occurred adjacent to the lower Big River study segment. Most of the large-scale historical mining operations occurred approximately 100+ kilometers upstream in St. Francois County. Most if not all Pb produced in the Old Lead Belt Mining District was extracted in St. Francois County. However, mining sediment traveled long distances to the study segment. Relatively large volumes of fine gravel, sand and fines from tailings piles were introduced to the Big River in St. Francois County. Little fine gravel-sized 'chat' has reached Jefferson County and there is little evidence in the study area of bar and bed contamination in the fine gravel fraction. However, the less than 2 mm fraction is contaminated with 200 to 500 ppm Pb in channel sediments. Silty floodplains represented by the Haymond, Wilbur, and Kaintuck soil series are heavily contaminated in places with >1,000 ppm Pb (Pavlowsky et al., 2010).

METHODS

Changes in channel patterns are most effectively analyzed using historical aerial photography in a Geographic Information System (GIS) to quantify spatiotemporal patterns in erosion and deposition. Historical aerial photography allows for the opportunity to study river systems at a large spatial and temporal scale compared to traditional methods. GIS-based aerial photography is increasingly being integrated within fluvial studies, especially of historical channel planform change (Downward et al., 1994; Gurnell and Downward, 1994; Chandler et al., 2002). This study uses six sets of historical aerial photography to examine historical channel planform changes, characterize and classify disturbance reaches, and examine patterns in historical bank erosion and bar deposition. GIS analyses are coupled with channel surveys, field sediment sampling, geomorphic assessments, and sediment geochemistry to create a sediment-Pb budget for the lower 24.2 km of the Big River from the Byrnesville gage to the confluence with the Meramec River.

Geospatial Methods

Aerial photograph acquisition. Six sets of aerial photographs from the years of 1937, 1954, 1968, 1979, 1992, and 2007 were acquired in digital format from the United States Geological Survey's (USGS) Earth Explorer program (http://edcsns17.cr.usgs.gov/NewEarthExplorer/) and the Missouri Spatial Data Information Service (MsDIS at http://msdis.missouri.edu/) (Table 4). All photographs acquired prior to 1992 are black and white images and required rectification in order to create and maintain a uniform spatial reference throughout each data set.

Photograph rectification and error assessment. Since the photographs prior to 1992 were not geo-referenced, a spatial reference was created by the process of rectification. High resolution digital orthophotograph quarter quadrangles (DOQQ) aerial photographs from 2007 were downloaded from MSDIS and were used as basemaps to rectify historical images. Rectification is the process of matching known locations of ground control points (GCPs) on a real-world, projected basemap to those same points on an un-projected aerial photograph, essentially making the aerial photograph with no spatial reference 'stretch' and distort so it overlaps the known basemap image to give the image a uniform projection. Errors inherent in the rectification process can lead to large variations in river connectivity among aerial photographs, causing widespread error throughout (Martin, 2005). Therefore, a minimum of eight ground control points (GCPs) were used to rectify each set of historical aerial photographs using a second degree polynomial transformation function (Hughes et al., 2006). Only 'hard' GCPs, or those that do not move throughout time such as road crossings and corners of buildings, were used in this study (Hughes et al., 2006).

Rectification may seem elementary, but is quite possibly one of the most important steps in analyzing historical planform changes and patterns of erosion and deposition in fluvial systems. Since this study is examining channel planform development using a variety of different aerial photograph years, it is imperative that rectification is as accurate as possible. Errors introduced during the rectification process could potentially falsely identify channel banks and/or patterns of erosion and deposition, so errors must be controlled and minimized. Spatial error is inevitable in the rectification process of aerial photography (Hughes et al., 2006). However, error can be assessed and subsequently minimized by the root mean square (RMS) error (Mount et al., 2003; Mount and Louis, 2005; Hughes et al., 2006). The RMS is a measure of the differences between predicted (un-rectified images) and actual (basemap) values. Large RMS errors can lead to channel locations being misidentified by 10+ meters. In order to maintain consistency and accuracy throughout the rectification process, RMS error was kept below 1.0 meter. However, due to poor image resolution, or amount of detail an image has, some images from 1937 and 1954 have an RMS error above these guidelines (Table 4). Additionally, rectification error was assessed by measuring the distances between known random test points from the rectified image to the corresponding point on the basemap for each set of aerial photographs (Hughes et al., 2006). This will be referred to hereinafter as the point to point measurement (p2p).

Table 4. Characteristics of aerial photographs used in study.

Date	Acquired From	Remarks	Resolution (m)	RMS error range (m)	Max p2p error (m)	Daily Mean Q (m^3/s)	Stage (m)
Aug. 15, 1937	USGS Earth Explorer	Black and White Geotiff	0.91	0.6-2.0	5.5	3.1	0.3
Nov. 13, 1954	USGS Earth Explorer	Black and White Geotiff	1.02	0.6-2.34	9.2	3.0	0.3
Feb. 23, 1968	USGS Earth Explorer	Black and White Geotiff	0.61	0.50	3.7	10.6	1.3
Dec. 1, 1979	USGS Earth Explorer	Black and White Geotiff	2.13	0.65-0.86	4.3	7.4	1.0
Apr. 3, 1992	MsDIS	Black and White DOQ Geotiff	1.00	already georeferenced	3.3	24.9	1.6
Mar. 10, 2007	MsDIS	True Color MrSID DOQQ leaf off	0.61	already georeferenced	basemap	14.6	1.2

Feature extraction. In order to quantify historical channel changes and identify areas of channel disturbance within the lower Big River, several GIS data layers from each set of historic aerial photographs were digitized using a heads up digitizing technique, instead of a computer automated classification algorithm. Channel boundaries were digitized individually as the edge of both the wetted and active channel for each respective set of aerial photograph. The wetted channel is where the water level meets the bank boundary, which excludes bar deposits while the active channel includes the entire area of wetted channel and bar features (Fig. 10). Digitized channel banks were collapsed in a GIS using the Collapse Dual Lines function in ArcMap9.3 to create a channel centerline for each set of aerial photographs. An error buffer was created around each channel centerline as the distance equivalent to the maximum point to point rectification error associated with the corresponding set of images (Fig. 11). Point to point errors were measured for each aerial photograph to the basemap, but the maximum point to point error buffer within each set of aerial photographs was used to account for all rectification error. As opposed to mean or median point to point error values, the maximum point to point error measurement was used as a conservative representation accounting for the maximum amount of inherent rectification error. If mean or median point to point error measurements were applied as buffers instead of maximum errors used hereinafter, all rectification error would not be accounted for.

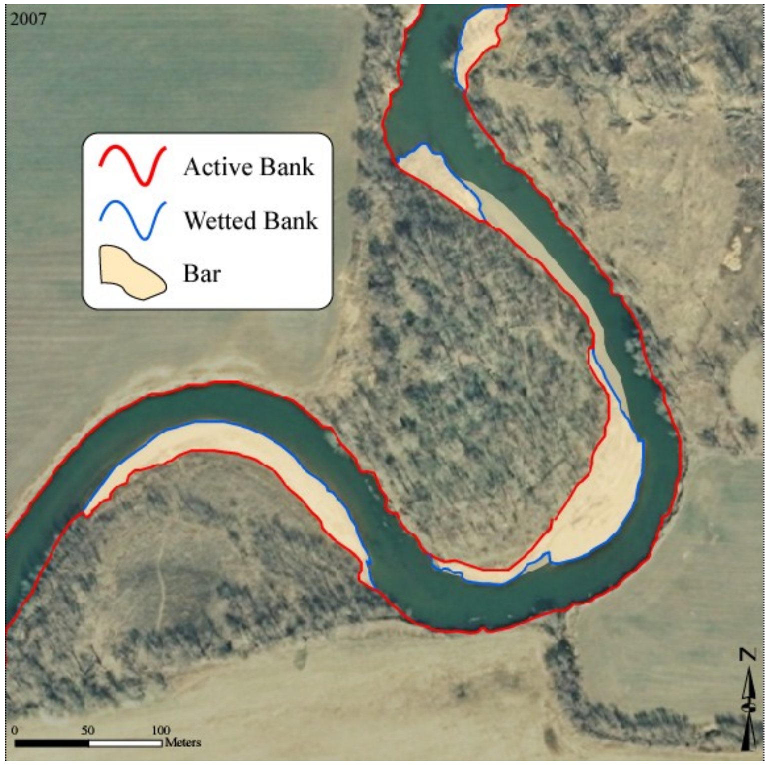


Figure 10. Digitized example of active and wetted banks and bar outline.

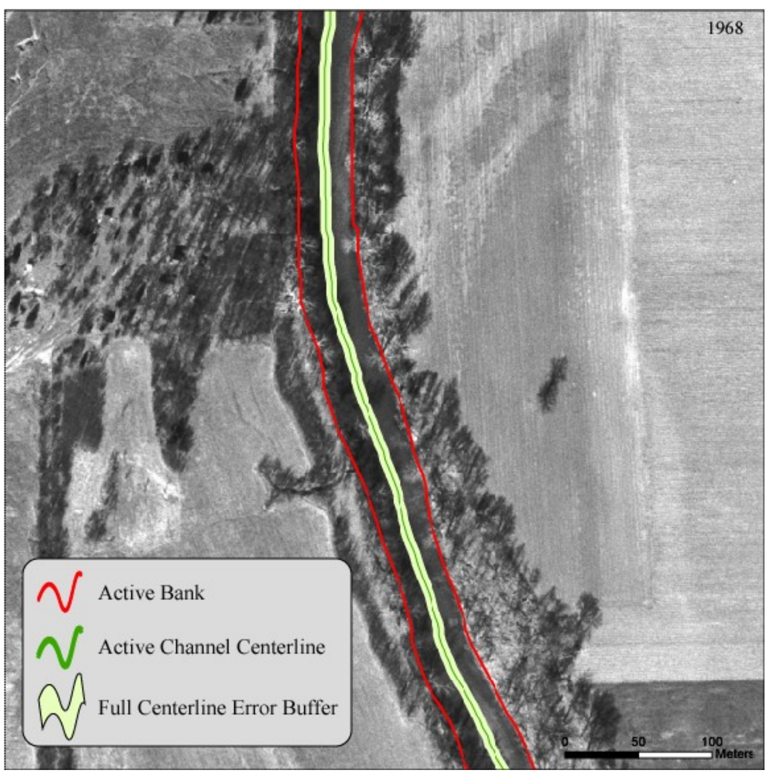


Figure 11. Channel banks collapsed to form centerline with full error buffer.

Disturbance reach identification. Individual channel centerlines and their subsequent error buffers were superimposed over one another and analyzed to identify stable and disturbance reaches along the lower Big River (Fig. 12). Reaches were classified as stable if there was no visual change in the overlapping error buffers from 1937-2007 (Fig 12). Although there may historically be slight movement of channel, the movement is below the threshold of total error, and therefore the reach is classified as stable. Disturbance reaches were identified as areas where all six channel buffers do not overlap and channel movement is beyond the range of inherent error (Fig. 12).

Initially, disturbance reaches were identified based solely off of non-overlapping historical error buffers, where channel movement is outside the inherent error between each set of aerial photograph year. Furthermore, disturbance reaches along the lower Big River were classified based off of length and maximum deflection within the disturbance reach between 1937 and 2007. Disturbances with maximum deflection less than 60 meters from 1937 to 2007 were classified as local or minor disturbance reaches. Disturbances with maximum deflection greater than 60 meters were therefore classified as major disturbance reaches.

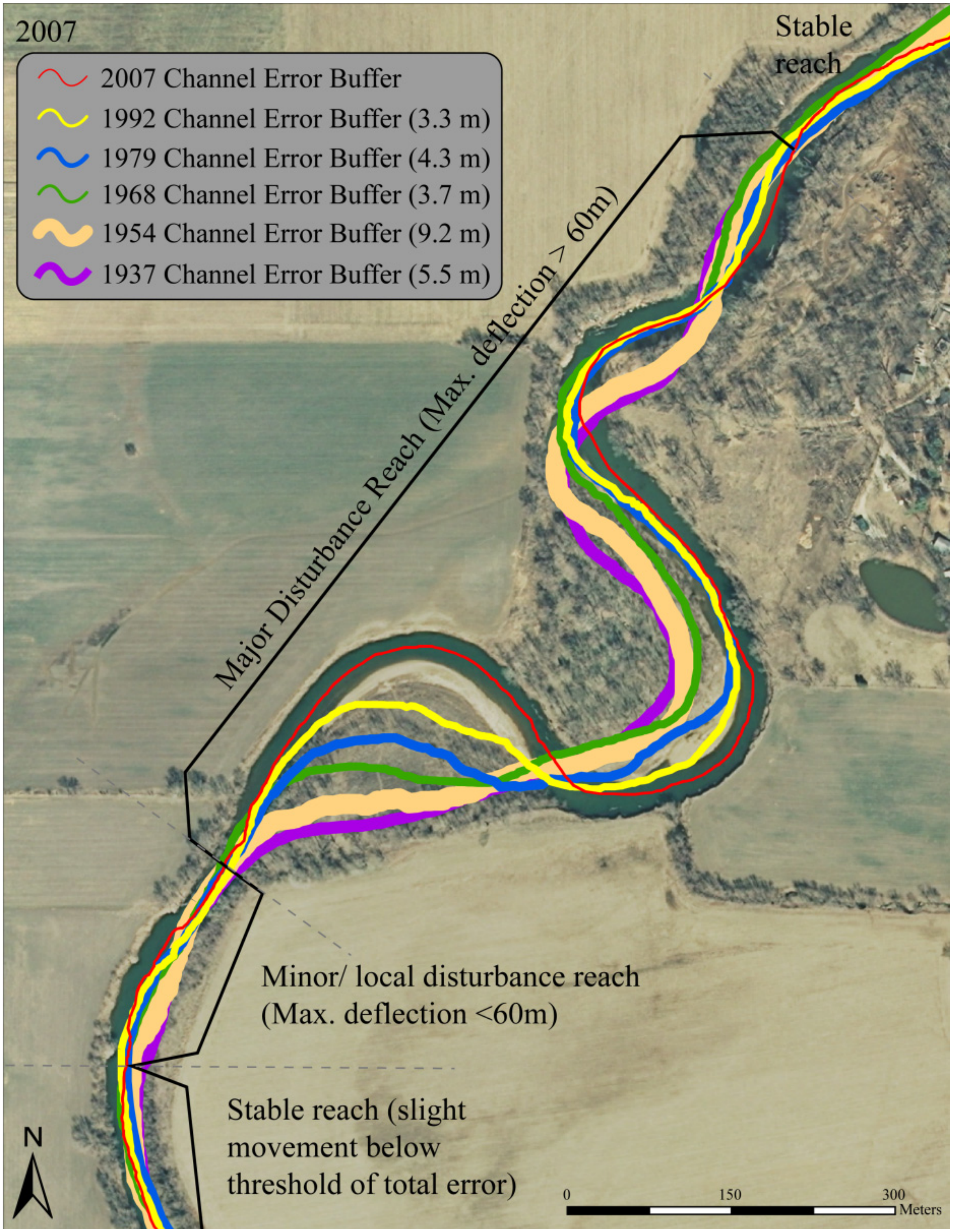


Figure 12. Superimposed channel centerline error buffers used to identify channel disturbances.

Gravel bar patterns. The same historical aerial photographs that were used to quantify historical channel change and map channel disturbance reaches were also used to determine the spatiotemporal patterns in gravel bar deposition (Table 3). Visible bars were easily recognized on historical aerial photography as a relatively bright, homogenous area often times forming on the inside of meander bends. Longitudinal, point, and center bars are most frequently observed in the Big River (Rosgen, 1996). Bar complexes or mega-bars are also found in disturbance areas. All bar deposit outlines were digitized for each set of aerial photographs using the same heads-up digitizing method that has been previously described for the identification of channel disturbance reaches. Bar deposits were digitized separately as stable and active based off the amount of visually identifiable vegetation on the bar surface (Fig. 13).

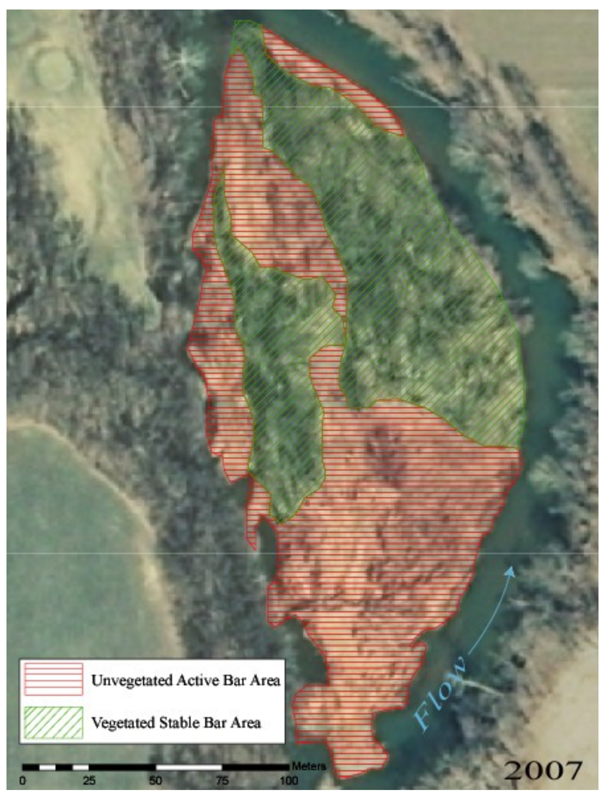


Figure 13. Digitized vegetated and un-vegetated bar outlines.

Stable bars showed obvious, thick, vegetation growth forming on the bar surface and appeared to have darker colors than those bars that had no obvious vegetation growth or minimal vegetation not able to be identified on aerial photography. Active bars, on the other hand, have little identifiable vegetation on the bar surface and are light colored due to the light tan color of chert gravel in the region (Fig. 13).

Digitized gravel bar deposits were analyzed at 200 meter intervals. Each 200 meter active channel area is hereinafter referred to as a channel cell. Boundaries of each 200 meter active channel cell are based on river kilometer from the mouth (Appendix A). Channel cells that are 200 meters in length represents approximately half of a riffle spacing along the Big River and are of sufficient spacing to resolve downstream gravel bar changes at the reach scale of one meander cycle or 3 successive riffle (Rosgen, 1996). Total bar area per each 200 meter channel cell was determined using the Identity tool in ArcMap 9.3, and exported into a table for data analysis.

Errors in gravel bar analysis. River stage can affect the location of channel boundaries and bar area on aerial photography. Daily mean discharge and gage height of the Byrnesville gage, the furthest upstream extent of the study reach, were analyzed to address discrepancies in channel boundaries due to river stage. All sets of aerial photographs had a daily mean discharge record for the given date the image was taken. However, there were no gage heights prior to 1982 on record, so gage heights were estimated from a known daily mean discharge vs. gage height relationship.

A channel cross section closest to the Byrnesville gage was calibrated to known data from the Byrnesville gage and hydrologic modeling software was used to determine wetted widths for earlier aerial photograph dates. The highest flow conditions occurred in

1992, with a daily mean discharge of 24.9 m^3/s (Table 4). Under these conditions, the wetted width was nearly 200% larger than that at average flow conditions and the high bar was fully submerged. All other river stages did not inundate the high bar and wetted width changes were minimal. It is therefore safe to assume that for all years, except for the highest flows in 1992, that bar measurements and bank boundaries are not significantly impacted by water depth and are safe to use for comparative analysis. Therefore, bar areas for 1992 are expected to be underestimated due to high water levels, and but will still be used in bar analysis to show patterns. Furthermore, aerial photographs from 1992 are used for center line and bank erosion analysis as well.

GIS based erosion and deposition areas and bank erosion rates. Areas of floodplain erosion and deposition were created in a similar fashion that has been used for channel disturbance reach analysis. Error buffers equivalent to the maximum point to point error for each respective aerial photograph year were applied to the previously digitized individual channel banks (both left and right).

Individual channel banks and associated error buffers were merged and aggregated together using the dissolve tool in ArcMap for consecutive aerial photograph years (i.e.- right bank for 2007 and right bank for 1992). Merged buffers were converted to coverages, the single channel coverage was selected and inverse selection highlighted all areas of change between individual channel banks, in which these areas were exported as a shapefile. The resulting output shapefile contained polygons of both erosion and deposition for each bank between successive aerial photograph years and were individually classified as either erosion or deposition. Floodplain erosion and deposition were summed and analyzed at every 200 meter channel cell throughout.

In an attempt to account for all inherent rectification error, this study applies full error buffers to individual banks. However, erosion and deposition areas were analyzed using half the point to point error buffer and no error buffer to essentially do a sensitivity analysis and quantify how much erosion and deposition polygons may be over or under predicted if little to no error is accounted for. Error buffer analysis was conducted on a sub-reach from river kilometer 11-17, a reach that is longer than one meander cycle and has both disturbance and stable reaches throughout. The results will be described later in this study, however, full error buffers equivalent to the maximum point to point error that account for the greatest error were used for each bank throughout this study. Results therefore will be conservative, and tend to not over predict erosion and deposition rates.

Bank erosion rates were calculated at the at every 200 meter channel cell along the study reach. Polygons areas created from the aforementioned analysis were individually classified as erosion (or deposition) and summed according to individual channel cells. Total floodplain erosion area (m^2) was divided by length (200 m) and again divided by years between successive aerial photograph years to yield a rate (m/yr) of bank erosion at every 200 meters downstream within the study reach.

All floodplain erosion polygons were assigned a soil/ landform being eroded into based off of aerial photography and the Jefferson County Soil Survey. However, polygons identified as deposition were all assigned the same soil unit. This is because the sediment-Pb budget analysis is only assessing the last 28 years, so it is safe to assume that all GIS based deposition within the study reach consists of most recent floodplain deposits mapped as Kaintuck soil series with related geomorphic and geochemical characteristics. Therefore, all floodplain deposition polygons identified using individual banks were assumed to be Kaintuck soil and were assigned the same bulk density throughout.

Field Methods

Geomorphic assessments of channel. Channel geometry assessments were conducted at sites every 400 meters of the channel downstream from the Byrnesville gage (river km=24.2) to the mouth of the Big River (river km=0) during the spring and summer of 2010. Geomorphic assessments were collected at every 400 meter channel cell rather than the aforementioned 200 meter cells because of time constraints but. Geomorphic assessment at every 400 meters downstream allowed data to be collected in 3-4 separate trips but at a still at a relatively fine scale. At each assessment site, prominent geomorphic landform heights were measured and topographic surveys were conducted to determine channel dimensions and soil samples were collected depending on accessibility.

Thalweg water depth was measured using a metric stadia rod being held by a field worker usually over the side of a canoe, as the thalweg was most of the time too deep to wade. Also at the thalweg, depth of channel bed to refusal was measured using an AMS steel tile probe. At each assessment site, the elevations of high bar, benches, floodplain, and terraces of both the left and right banks were also measured and recorded if present. Elevations of these landforms were measured visually using a metric stadia rod from different landforms in the field and were referenced to the thalweg elevation. Although this rapid assessment of landform heights using a stadia rod is not exact, field workers were trained to be as precise and consistent as possible. Rapid assessments and height measurements of landform heights allowed for the collection of relatively large amounts of data in a short period of time.

Channel surveys. In addition to rapid geomorphic assessments, nine channel cross-sectional surveys were conducted throughout the study reach to further determine channel dimensions and verify relative heights of prominent geomorphic landforms relative to the active channel bed (Appendix B and C). Seven of those cross sections were conducted at a glide-riffle transition area, and the remaining two were conducted at the apex of meander bends. Topographic surveys were performed using either a Topcon GTS electronic total station with a prism rod or a Topcon Autolevel with a metric stadia rod. One person generally operated the survey equipment while the other would hold the prism or stadia rod. Landforms and monuments were included in the cross-sectional survey including the location of instrument, terrace elevation, slump scars, floodplain height, bar and bench elevations for each bank, water edge, bank toe, thalweg location, and known referenced field monuments. Height above the thalweg was plotted against distance across the channel for each prominent landform included in the survey. On average, 22 points were collected per survey but ranged from 17-28 points over 62-135 meters of the active channel width, yielding approximately one point every 4 meters along the cross-sectional survey.

Flood frequency analysis using channel surveys. Topographic cross sectional surveys and field notes were used to relate mapped NRCS soil series to associated landforms and create a proper nomenclature to be used in the future for alluvial soils along the Big River. Each of the nine cross sections was input into the hydrological modeling software HydraFlow Express, which can be used to change channel slope, roughness, discharge, and depth of flow within a cross section. Slope used for this study is based off of the slope at the Byrnesville gage (0.0636%) and Manning's roughness coefficient (n) used for this analysis is typical for Ozark streams (0.038). Depth of flow input values were adjusted in order to inundate prominent landforms within a cross section such as the high bar, floodplain and terrace surfaces. The hydrologic modeling software then calculated discharge for each depth of flow depending on the landform height above the thalweg. The maximum annual flood record for the Byrnesville gage was used to plot annual maximum floods over recurrence interval, or the time in years between similar flow events (Fig. 8). Using this relationship, stream discharges calculated by the hydrological modeling software that inundate specific landforms within cross sections are used to determine the recurrence interval of that landform. Recurrence intervals of specific landforms determine how often these surfaces get inundated and help determine exactly what these fluvial landforms are, rather than making educated guesses while in the field.

Sediment sampling and geochemical characterization. A total of 102 sediment samples were collected at the same sites used for geomorphic assessments located every 400 meters depending on accessibility: 31 from channel banks, 48 from bars, 23 from the channel bed. Bank samples were collected in bulk increments ranging from 50-100 cm to a depth of 3-4 meters below the top bank surface until the water surface limited sample collections. Bank samples were collected using a hand trowel and were bagged in standard sandwich bags with river kilometer, location, date, and depth collected at already recorded on the bag. Bar and bed samples were collected with a perforated shovel and simply drained and bagged in standard freezer bags for transport back to the laboratory for further textural and geochemical analysis. All samples were dried in an oven at 60° C in the laboratory and manually sieved and weighed at specific size classes in preparation for geochemical analysis. In some cases, a mortar and pestle was used to disaggregate samples. Samples were manually sieved to <2mm, 2-4 mm, 4-8 mm, 8-16 mm, 16-32 mm, 32-64 mm and 64+ mm fractions (Appendix D). After sieving and weighing each specific size class, a 2% Hydrochloric acid (HCl) solution was used to 'sanitize' each sieve such that cross contamination of samples did not occur. In this study, the <2mm sub-fraction was transferred to metal-free bags and used for further geochemical analysis. Heavy metal concentrations were determined using an X-Met3000TXS+ Handheld XRF Analyzer (OEWRI, 2011) of the <2mm sub-fraction (Appendix D). Concentrations of lead (Pb), zinc (Zn), Calcium (Ca), Iron (Fe), Manganese (Mn) and Copper (Cu) were of particular interest in this study, but the main interest is Pb concentrations. For every twentieth sample analyzed by the XRF, two laboratory duplicates, one known standard and one bag blank were also analyzed to further determine the precision and accuracy of the XRF.

Floodplain Sediment-Pb Budget

The aforementioned areas of erosion and deposition created in the GIS were used to create a sediment-Pb budget. Erosion and deposition polygons were created using the active channel banks based off of the aerial photographs from 1979 and 2007, which is the time period since cessation of mining operations in the Big River watershed. During this time, the Big River is responding geomorphically to changes in sediment regimes from the mining period to post mining. Twenty-eight years is a long enough time period to model the geomorphic changes going on and determine how the Big River is attempting to recover from disturbance.

Soil surveys for Jefferson County were used in conjunction with aerial photographs to determine the soil type and inherent landform that each GIS created floodplain and terrace polygon is eroding into. Each erosion area polygon was assigned a soil/ landform being eroded into, based off of the closest proximity soil series to an eroding floodplain polygon. Once floodplain erosion polygons were assigned a soil/ landform that each polygon is eroding into, landform depth was needed to calculate a volume for floodplain erosion at each bank. Field based channel geometry assessments were used to determine relative depths of associated landforms above the thalweg in order to calculate volumes of eroded and deposited floodplain areas.

A bulk density, or the ratio of mass of material to the total sample volume, was assigned to each landform being eroded based off of the Jefferson County soil survey (NRCS, 2006). Bulk densities were reported in the county soil survey as moist values and differed according to depth of the soil. However, this study simply used the median value for each landforms bulk density. The mass of sediment being eroded or deposited per floodplain or bar is calculated by multiplying GIS based erosion and deposition polygons by the landform depth by the median unit bulk density and can be determined by:

$$Mg_{sediment} = (A \text{ x } D_l)*B/1000 \qquad \text{Equation 1}$$

where $Mg_{sediment}$ is the mass of sediment (in Mg-Megagrams), A is the GIS based erosion or deposition areas (m^2), D_l is the depth of the landform (m) and B is the median bulk density (kg/m^3). Geochemical analysis of collected soil samples is further needed to create a bank contamination model which then can be used to determine the lead load of the river.

A total of 31 bank samples were collected to determine floodplain Pb contamination throughout the study reach, however, these samples usually were collected from the top of the bank and did not account for Pb concentrations throughout the entire landform to the thalweg depth. Therefore, a depth-weighted average Pb concentration was used hereinafter. A depth-weighted Pb concentration approach takes into account geochemical variations based on depth of bank thickness and is important because an assumption used throughout this study is if a landform is being eroded, the entire 'slice' of landform is eroded and introduced to the channel, rather than small, separate sub-fractions of the entire landform. The average Pb concentration for banks can be calculated by:

$$\sum(D_s * C_d)/D_t \qquad \text{Equation 2}$$

where D_s is sampled depth interval from top of bank (m), C_d is the concentration of Pb within the depth interval (ppm), and D_t is the total depth of the landform from top of bank to thalweg.

Average-depth weighted Pb concentrations for each landform was then used to determine the amount of Pb being stored or released from floodplains. The mass of Pb being eroded or deposited per floodplain unit is calculated by multiplying the mass of sediment by a depth-weighted Pb concentration and dividing by 1, 000,000 to convert to Megagrams and can be determined by:

$$Mg_{Pb} = (Mg_{sediment} \text{ x } C_{Pb})/ 1{,}000{,}000 \qquad \text{Equation 3}$$

where Mg_{pb} is the mass of lead (Pb) (in Mg- Megagrams), $Mg_{sediment}$ is the mass of sediment (in Mg- Megagrams) and C_{pb} is the depth weighted Pb concentration (in ppm).

Accounting for overbank deposition. Recall that GIS based floodplain erosion areas were assigned a soil unit that each polygon was eroding into, but all GIS based deposition areas were assumed to occur within the last 28 years and therefore assumed to be the active floodplain. These GIS based deposition areas are limited to areas of meander belts and do not account for over bank sedimentation. Therefore, total Pb deposition estimates from the valley floor are needed. Pavlowsky et al. (2010) used a truck mounted giddings rig to collect 11 floodplain cores. Cores were analyzed to determine the depth of detectable Cs-137, and its half life of 30.17 years was used to determine a range of floodplain sedimentation rates. Average Pb concentration from these 11 floodplain cores collected by Pavlowsky et al. (2010) will be used with sedimentation rates to account for Pb in overbank sedimentation. Floodplain sedimentation data was collected 80+ kilometers upstream of the study reach of interest in this research, but this is the best data available. Overbank sedimentation depth can be calculated based off of sedimentation rates and the 28 year period of study in the sediment-Pb budget and will be applied to deposition polygons to calculate volumes of overbank deposits.

Gravel Bar Sediment- Pb Budget

Stable and active gravel bar surface areas were digitized from the 1979 and 2007 aerial photographs. Bar surface areas were merged together for each respective aerial photograph year for the sediment-Pb budget analysis. Net bar surface area was calculated per 200 meter channel segment and similar methods as those described for floodplain erosion and deposition polygons were used to determine net Pb mass within gravel bar deposits. Net bar area was coupled with field surveys that measured the height of bar units, and a NRCS bulk density was applied to determine a mass of bar sediment being eroded or deposited.

Additionally, Pb concentrations are needed to determine the amount of Pb contaminated sediment being stored and released from bar complexes along the lower Big River. As previously stated, 48 bar sediment samples were collected from both bar heads and bar tails, but were combined to represent bar composition for textural and geochemical analysis. Pavlowsky et al. (2010) found that bar and bed samples had similar characteristics and appeared to be from the same population of contaminated sediment, albeit bed samples were slightly coarser than bars. Bar sediment samples were sieved and weighed at different size classes, but only the less than 2 mm fraction was used for geochemical analysis, so geochemistry and subsequent Pb concentrations found in bars only represented that portion of the bar that was of the <2 mm subfraction. It is assumed that bar deposits are well-mixed geochemically, so Pb concentrations of bar sediment that is coarser than the 2mm subfraction need to be accounted for. All bar sediment that is coarser than the 2 mm subfraction in this study is assumed to have a Pb concentration of 15 ppm. To account for geochemical variations, a bulk concentration of bar sediment can be determined by:

$$C_{bulk} = ((C_{pb<2mm} \text{ x } P_{<2mm}) + (P_{>2mm} \text{ x } C_{coarse})) / 100 \qquad \text{Equation 4}$$

where C_{bulk} is corrected bulk Pb concentration (in ppm), $C_{pb<2mm}$ is the concentration of less than 2 mm bar sediment subfraction (in ppm), $P_{<2mm}$ is the percentage of bar sample less than 2 mm (in %), $P_{>2mm}$ is the percentage of bar sample greater than 2 mm (in %)

and C_{coarse} is the concentration of sediment coarser 2 mm (in ppm) assumed to be 15 ppm.

An average bulk Pb concentration of the collected samples, which accounts for geochemical variations in the coarse and fine sediment fractions of bar deposits, will be used in conjunction with bar area, bar depth, and an associated bulk density to calculate the amount of Pb being released and stored in bar formations. Floodplain and bar sediment mass as well as Pb mass were calculated for each 200 meter channel segment downstream in order to review downstream variations in erosion and deposition of floodplains and bars. Additionally, floodplain and bar sediment and Pb erosion and deposition trends were categorized by either historical disturbance or stable reaches to determine the role that disturbance reaches play in the storage and release of Pb. A general schematic flow chart can be used to simplify methods and help show how GIS and field methods are combined to calculate the final sediment-Pb budget (Fig. 14).

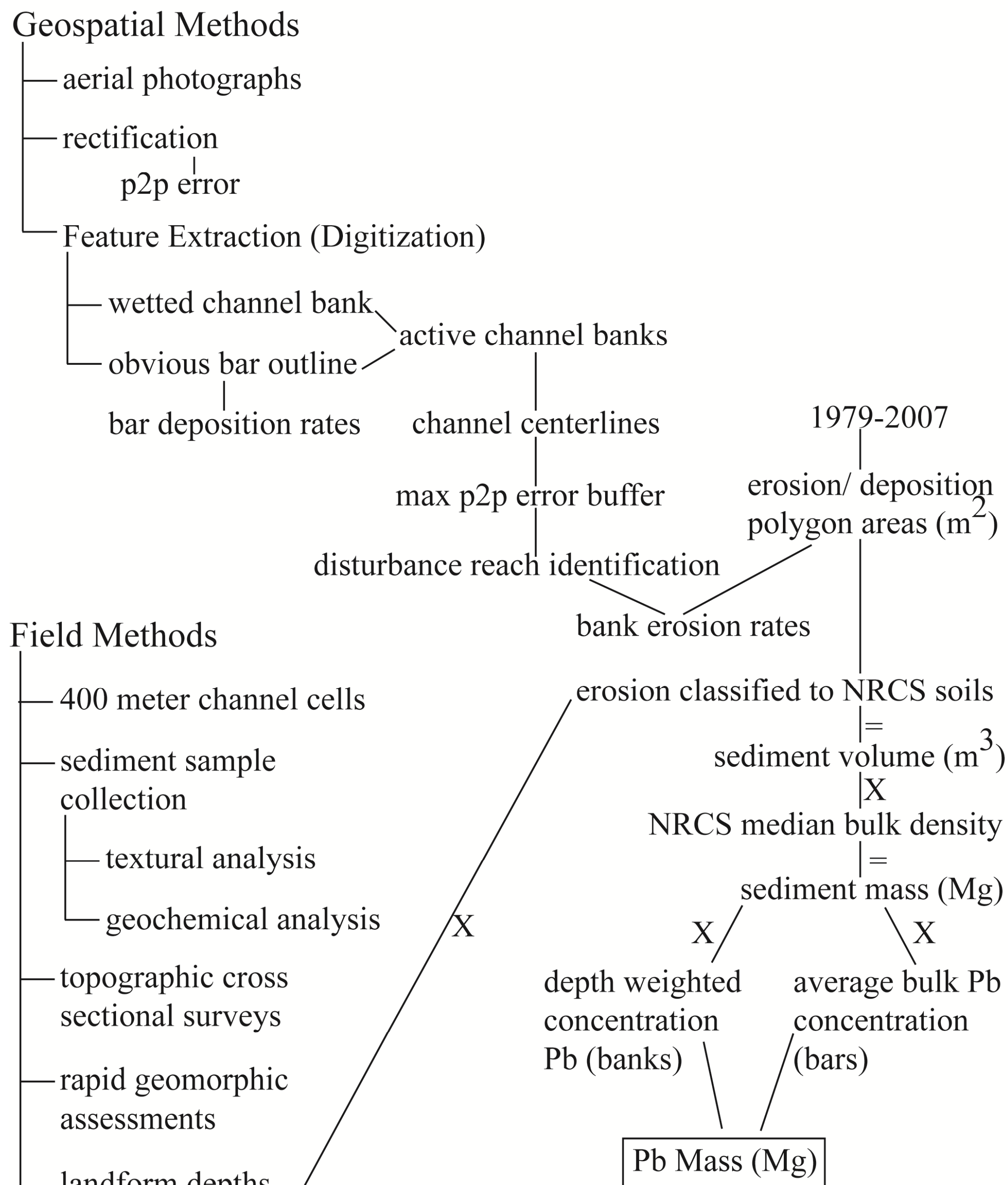


Figure 14. Flow chart simplifying methods used to calculate sediment-Pb budget.

CHANNEL AND FLOODPLAIN GEOMORPHOLOGY

Channel Morphology and Floodplain Features

Active channel width and valley-scale controls. Active channel width varies over time and space, but historical active channel widths tend to coincide with wider portions of the channel historically occuring near river kilometer 8 and 16 (Fig. 15a). Average active channel widths measured from the 2007 set of aerial photographs is approximately 43 meters, but ranges from 25 meters at river kilometer 12.8 to 75 meters at river kilometer 8 (Fig. 15a). Historically, average active channel width for the entire study area ranges from approximately 37-43 meters, but most variability in active channel widths is measured from the oldest sets of historical aerial photographs from 1937 and 1954. This could be due to poor image resolution in those images compared to newer aerial photographs or more variability caused by more intense land use disturbance during those years (Fig 9). Valley widths on the other hand range from 0.80 to 2 kilometers but average approximately 1.2 kilometers (Table 5, Fig. 15b).

Table 5. Historical active channel and valley widths (in meters).

	1937	1954	1968	1979	1992	2007	Valley
avg	38.7	37.1	41.9	37.7	42.9	43.4	1180.1
St. Dev	13.0	10.8	7.8	8.9	6.9	8.1	271.5
CV%	33.6	29.1	18.7	23.6	16.0	18.6	23.0

Each 200 meter channel cell was analyzed to determine the closest proximal distance to the valley wall or bedrock outcrop. Based off of the 2007 set of aerial photographs, ten individual channel cells were confined within 50 meters of the valley wall or a bedrock outcrop, representing approximately 8% of the total channel cells along the lower Big River (Fig. 15b). An additional 17 channel cells, or a total of 27 channel cells were found to be within 100 meters of valley or bedrock confinement, representing

22% of the total. These 27 'confined' locations correspond directly to or are slightly upstream or downstream of disturbance reaches.

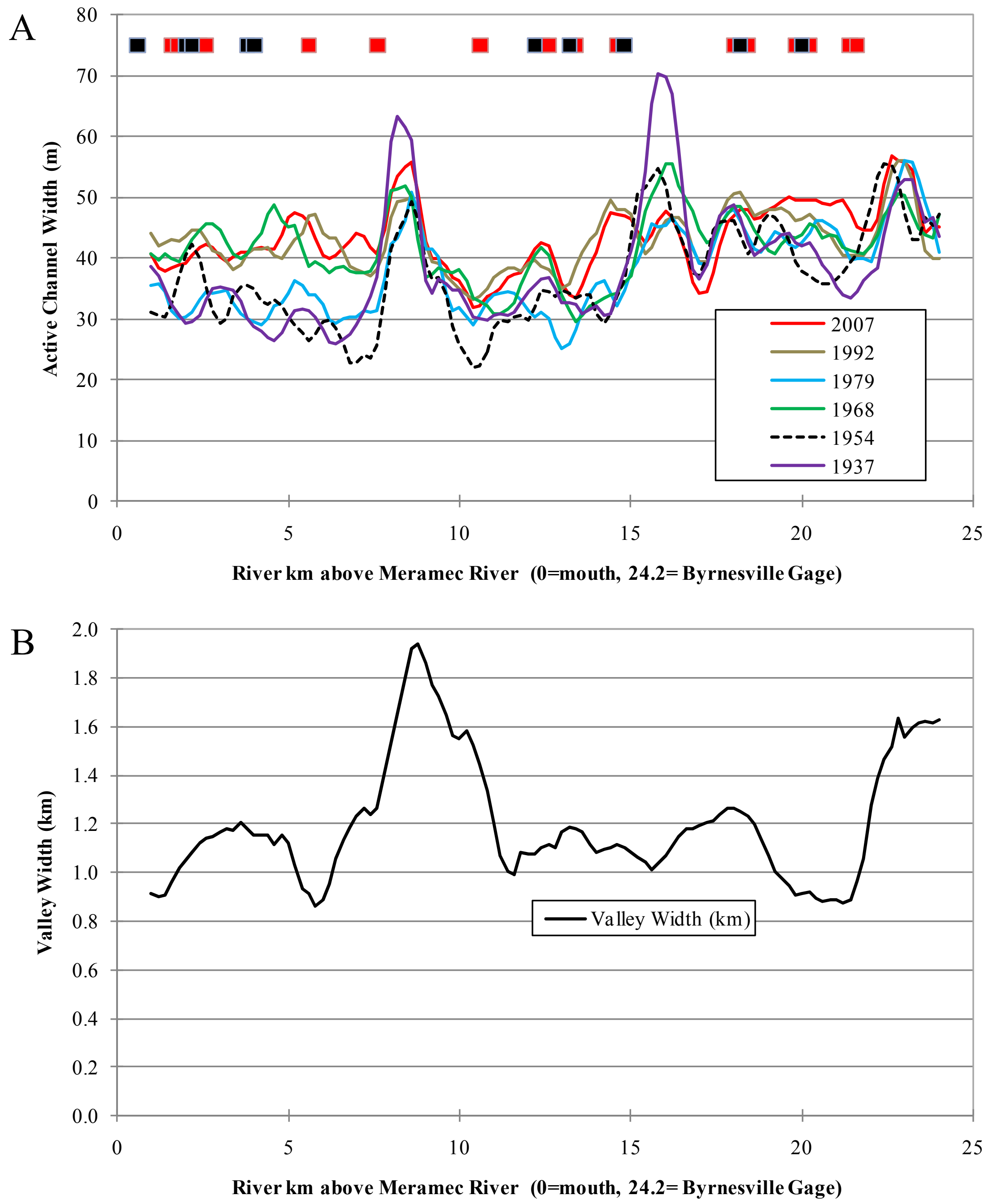


Figure 15a-b. Downstream trends in active channel (A) and valley (B) widths. Black boxes indicate confinement within 50 meters of valley wall or bedrock outcrop and red boxes indicate confinement within 100 meters.

Nine cross sectional surveys were used to classify NRCS soils to associated landforms and distinguish between bars, in-channel benches, floodplains, and terraces. Recurrence intervals for the channel at which bank tops with Kaintuck series on it (NRCS, 2006), range from 1.14-1.38 years and therefore will be referred to as the active floodplain (Table 6). Floods with recurrence intervals of 1.2-1.5 years is said to be the bankfull event, or the event in which flow tops the channel bank and spills onto the floodplain (Knighton, 1998). This bankfull channel is also assumed to represent the geomorphic control of discharge and sediment load on the river channel. Haymond, Wilbur, and Sturkie series soils recurrent intervals ranging from 1.62- 3.74, but all recurrence intervals are slightly to moderately above the bankfull event, so these soils will be called low terraces (Table 6). Soils of Horsecreek, Gabriel, Moniteau, and Freeburg have recurrence intervals all greater than 5.16 and rarely get inundated by flood waters and therefore will be called high terraces (Table 6).

Table 6. Recurrence intervals and nomenclature of specific landforms along the lower Big River.

	Q (m^3/s)					Recurrence Interval (years)				
River Km	High Bar	Low Bench	Floodplain	Low Terrace	High Terrace	High Bar	Low Bench	Floodplain	Low Terrace	High Terrace
0.9			262.2	632.5	1,071.9			1.2	3.4	11.8
2.8	47.5		284.0	471.4		0.7		1.3	2.2	
3.7		198.6	266.3	369.8			1.0	1.2	1.6	
5	33.7	71.0	270.6	477.0		0.6	0.7	1.2	2.2	
8.6		75.6		665.6	1,005.1		0.7		3.7	9.8
10.2		40.5	311.2	415.5	854.3		0.6	1.4	1.9	6.4
13.8	67.3		316.6	498.4		0.7		1.4	2.3	
15.9	88.5	110.2	242.6	600.2		0.7	0.8	1.1	3.1	
16.1	108.1	178.9			779.3	0.8	1.0			5.2
n	5.0	6.0	7.0	8.0	4.0	5.0	6.0	7.0	8.0	4.0
avg	69.0	112.5	281.9	499.7	816.8	0.7	0.8	1.3	2.4	7.1
St. Dev	30.1	63.4	28.2	102.4	53.0	0.1	0.2	0.1	0.7	2.4
CV%	43.6	56.4	10.0	20.5	6.5	8.7	20.7	7.9	30.6	33.6

Thalweg refusal and high bar depth. Thalweg refusal depth is relatively shallow throughout the study reach, varying from approximately 0-2.5 meters below the thalweg throughout (Fig. 16). However, it is apparent that mill dams, specifically the Byrnes Mill Access (Rkm~14.5) and the Rockford Beach Access (Rkm~17.4), are influencing localized channel bed aggradation resulting in a 1-2 meter thickening of substrate above refusal depth directly upstream of mill dams (Fig. 16).

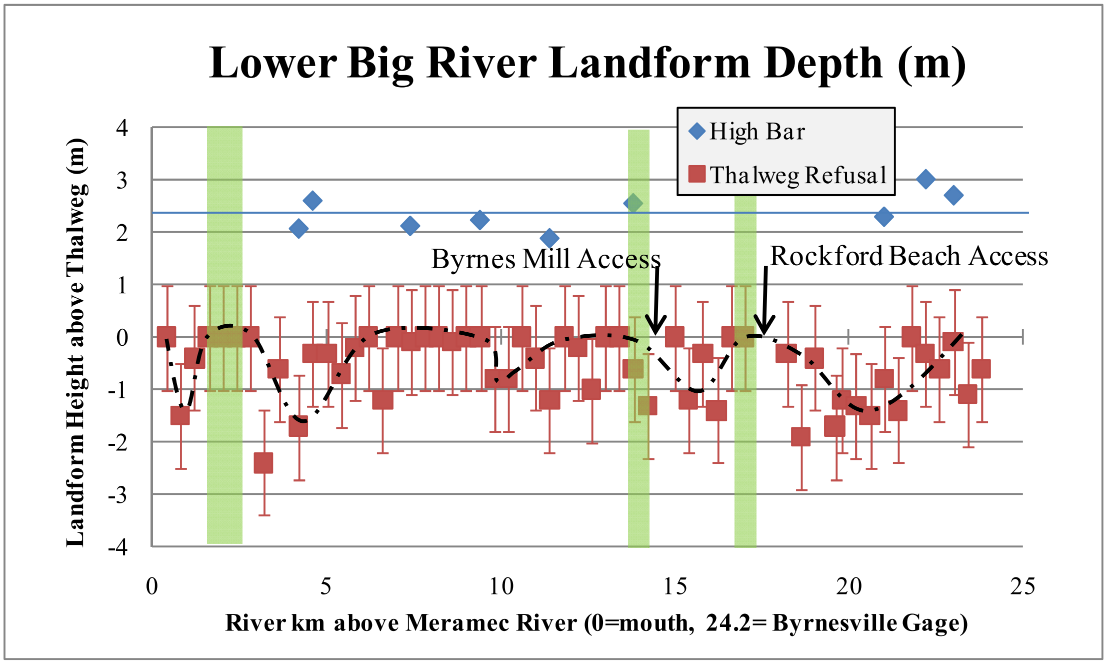


Figure 16. Downstream variations in thalweg refusal depth and high bar height above the thalweg. Dotted black line indicates patterns in thalweg refusal depth, solid blue line indicates average high bar height above thalweg, green vertical areas indicate location of endangered mussel beds identified by U.S. Fish and Wildlife Service.

Throughout the study reach, average high bar height is approximately 2.4 meters above the thalweg (Fig. 16). There is little variation in downstream trends in high bar height, possibly indicating this area of the Big River is dominated more by floodplain processes than high bar formation and development.

In-channel bench and active floodplain depth. Average in-channel bench height is 3 meters above the thalweg, but ranges from approximately 2-4 meters above the thalweg (Fig. 17). These landforms are assumed to be minor sources of sediment storage and release and are assumed to go into larger storage, like active floodplains throughout time. In some places, the in-channel bench may be grading into the active floodplain and it is difficult to discern between the two. In-channel benches were measured and recorded in the field, however, warrant no further analysis as larger landforms such as active floodplains will be examined in greater detail. Active floodplains, or those associated with the Kaintuck soil series, typically occur approximately 4.4 meters above the thalweg, but range from approximately 3.5-5.5 meters above the thalweg (Fig. 17). There is slight variation in active floodplain height; however, average active floodplain height above the thalweg (4.4 meters) will be used in the sediment-Pb budget analysis later on.

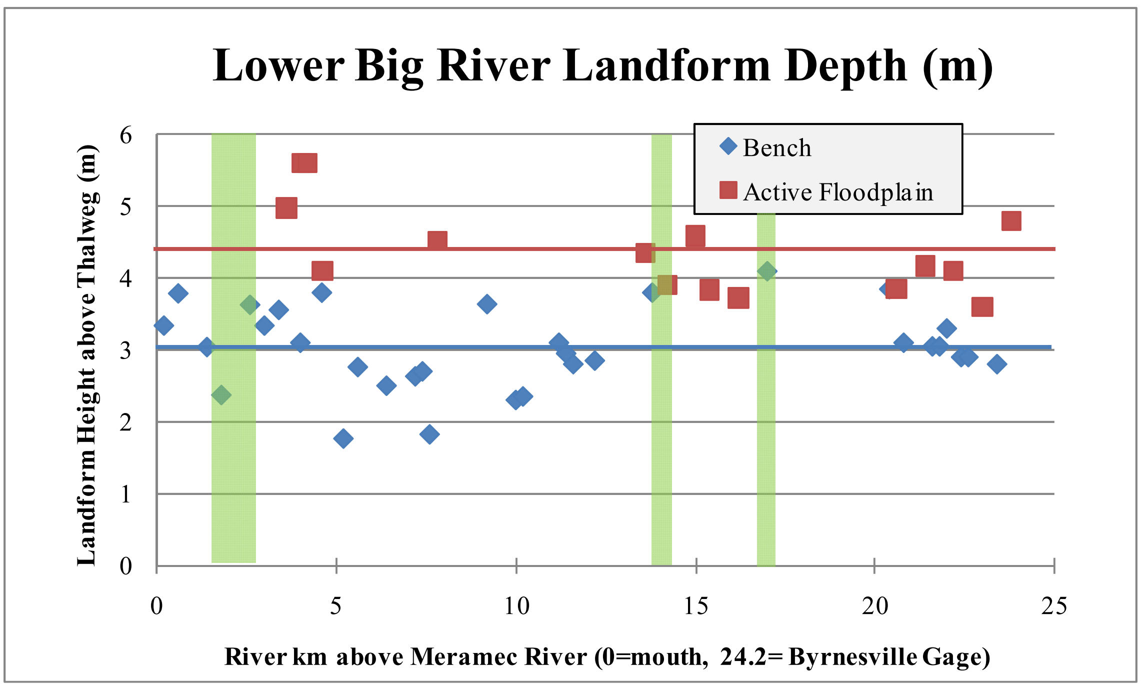


Figure 17. Downstream variations in bench and active floodplain heights above the thalweg. Blue line indicated average bench height and red line idicates average active floodplain height above the thalweg.

Low and high terrace height. Approximately 1.5 meters above the active floodplain are low terraces, averaging 6.0 meters above the thalweg, but range from approximately 5-7 meters above the thalweg (Fig. 18). High terrace heights range from approximately 8-12+ meters and average terrace height is 8.9 meters above the thalweg. Among all the landform heights previously described, terrace height has the highest variability with 17.6% coefficient of variation. Terrace height is fairly uniform at approximately 8 meters above the thalweg until river kilometer 5, when terrace height gets steeper and subsequently abruptly increases to 12+ meters above the thalweg (Fig. 18). This pattern of increasing terrace height near the mouth of the Big River occurs because the lower Big River is grading into an older set of higher terraces associated with the Meramec River.

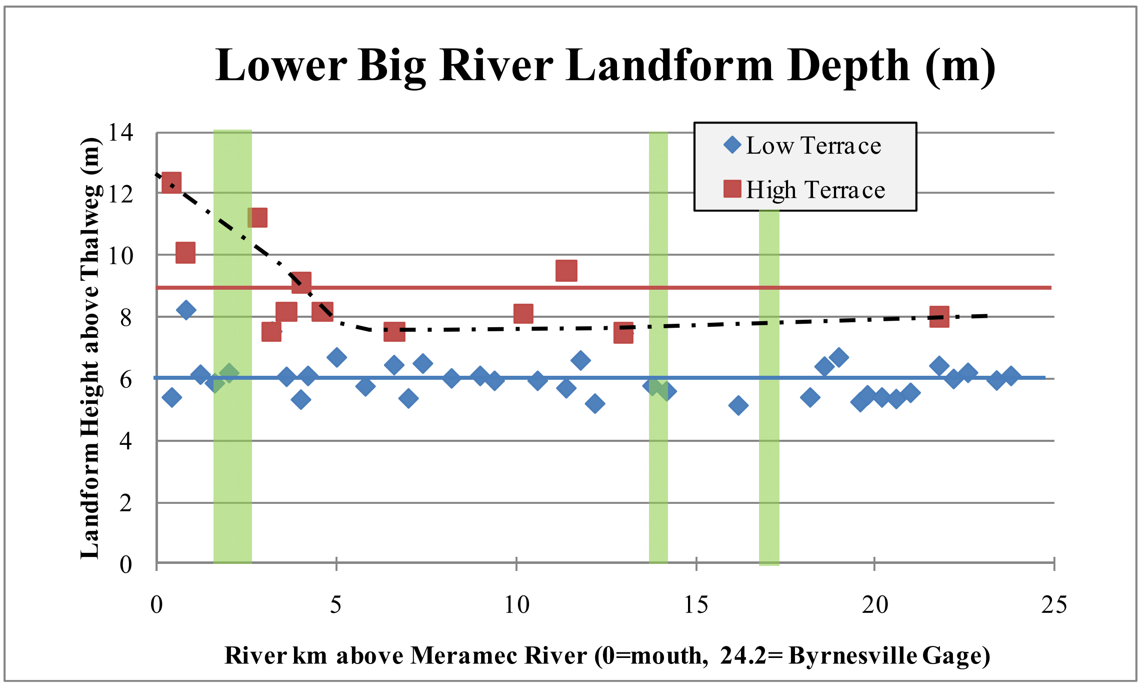


Figure 18. Downstream variations in low and high terrace height above the thalweg. Blue line indicates average low terrace height, red line indicates average high terrace height above the thalweg.

Although Figures 16-18 show downstream variations in landform heights above the thalweg, field surveys determining landform heights were not analyzed at the reach scale to see downstream variability, which is outside the scope of this study. More data on specific landform height is needed to be collected in the future if downstream variations in landform height above the thalweg are to be used in the sediment-Pb analysis. Therefore, this study uses the average landform height to quantify sediment and Pb sources and sinks (Table 7).

Table 7. Average landform height above thalweg (in meters).

	Probe Refusal Depth	High Bar	Active Floodplain	Low Terrace	High Terrace
average (m)	0.3	2.4	4.4	6.0	8.9
st dev (m)	0.5	0.3	0.6	0.7	1.6
CV%	194	14.6	14.5	11.2	17.6

Disturbance Reach Characteristics

Spatial distribution. In this study, a disturbance reach is defined where the location of the channel centerline has shifted laterally beyond the range of rectification errors introduced over a given aerial photograph time interval. Over the past 70 years (1937-2007), the lower Big River has been relatively stable, with channel bank and floodplain erosion occurring in discrete disturbance reaches along the lower Big River. In the lower Big River, major disturbance reaches represent approximately 21% of the study reach from 1937-2007, while local or minor disturbance reaches represent approximately 11%. Recall that disturbance reaches with maximum deflection less than 60 meters between 1937 and 2007 were classified as minor or local disturbance reaches (Table 8).

Disturbance reaches with maximum deflection greater than 60 meters than were classified as major disturbance reaches (Table 8). Regardless of maximum deflection within disturbance reaches, the channel patterns observed in this study exhibit a typical Ozark channel pattern described by Jacobson (1995) and others as alternating stable and disturbance reaches.

Table 8. Maximum deflection within disturbance reaches (in meters).

	minor/local	major
n	17	6
avg	37.4	98.3
st. dev	9.3	45.7
CV %	25	47

Disturbance reach location and attributes. Throughout this thesis, references will be made to river kilometer, which is distance along the thalweg upstream from the mouth (river km=0) to the Byrnesville gage (river km= 24.2) (Appendix A). The longest continuous disturbance reaches are located between river km 8-9, upstream of river km 14, downstream of the Rockford Beach mill dam, and between river km 22-23.4 downstream of the Brynesville gage.

The spatial distribution of disturbance reaches along the lower Big River shows a particular, non-random pattern. Disturbance reach location along the lower Big River can be attributed to valley wall morphology, presence of old mill dams, and tributary inputs. Most, if not all major disturbance reaches occur as the channel flows towards or away from the valley walls (Fig. 19). Long, straight, stable reaches of the lower Big River tend to flow along one side of the valley parallel to the valley bluff line. Major disturbance reaches then occur when the channel begins to bend back across the valley floor, but is confined by the opposite valley wall (Fig. 19). Minor or local disturbance reaches on the other hand can occur at meander bends or where excessive deposition forces the thalweg to the side of the channel. (Fig. 19).

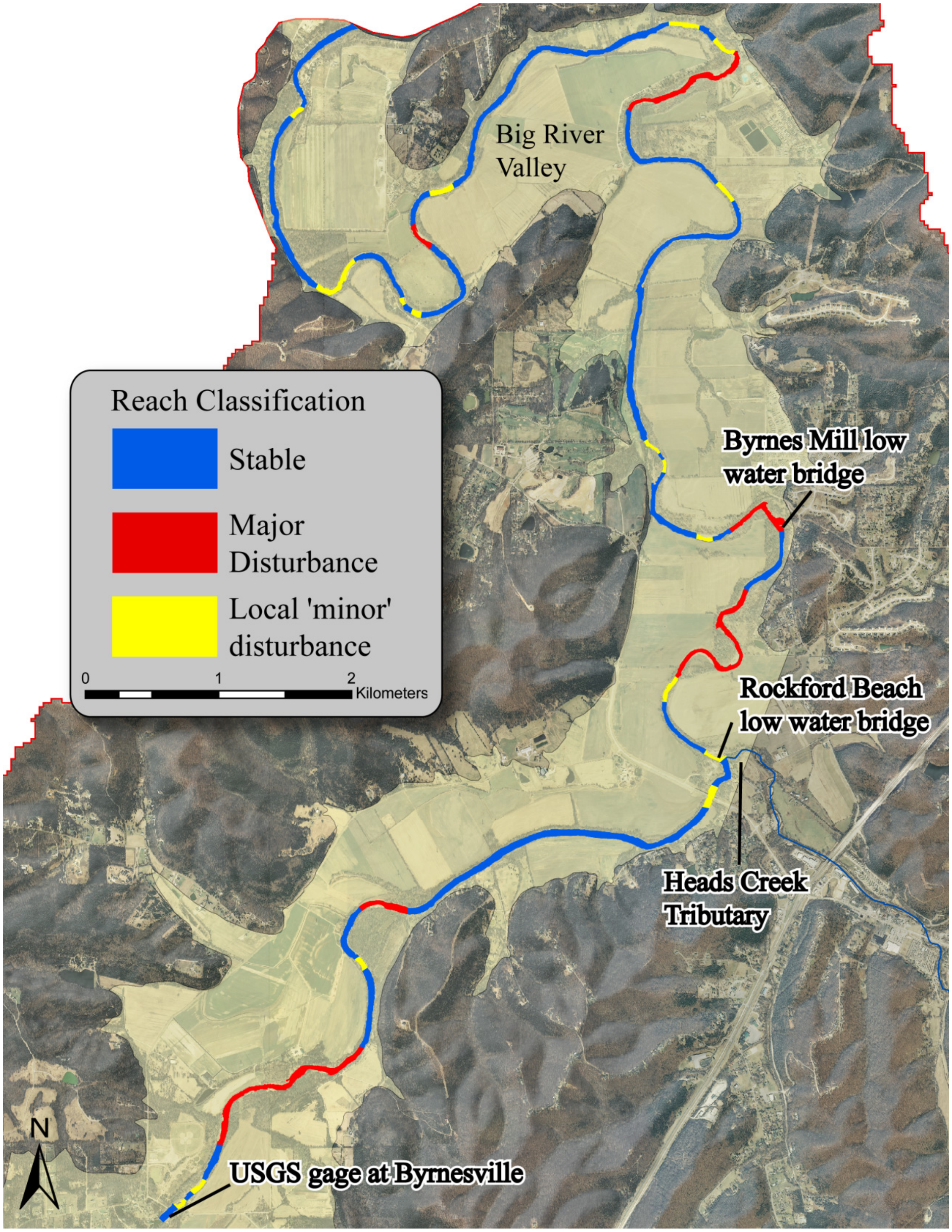


Figure 19. Spatial distribution of disturbance reaches along the lower Big River.

Old mill dam crossings may affect the spatial distribution of disturbance reaches, but not to the extent of valley wall confinement. Mill dams alter channel hydraulics, which essentially affect erosion and deposition patterns, typically causing sedimentation upstream and bed scour downstream. Byrnes Mill, Rockford Beach and Byrnesville dams, the only mill dam crossings within the study reach, have disturbance reaches occurring less than one river kilometer downstream of them. Tributary input may also affect the spatial distribution of disturbance reaches. The largest disturbance reach in the study area in terms of bank erosion and lateral channel migration rates is located slightly downstream of Heads Creek, the only major tributary (third order or greater) input in the study reach which flows into the Big River immediately downstream of the Rockford Beach mill dam.

Few reaches throughout the lower Big River show complete channel stability throughout the past 70 years (Fig. 20). In fact, only one reach from approximately river km 6-7 shows complete channel stability over the entire period of record. Other reaches, for example between river kilometers 0-1, 3-4, 9.5-10, and 19-20 are mostly stable throughout the 70 year aerial photograph record but show numerous, short disturbance reaches interrupting the stable reaches. On the other hand, few reaches also show complete historical disturbance throughout the study period. Channel reaches of complete historical disturbance occur between river kilometer 15-16 and 22-23 (Fig. 20).

Many of the historical disturbance reaches are relatively short in length and probably are small, localized disturbance reaches (Fig. 20). Therefore, it is possible that many more historical reaches are either classified as completely stable or disturbance, with localized disturbance reaches often interrupting historically stable reaches. If these localized disturbance reaches were removed or ignored, more reaches would be classified as historically completely stable or disturbance.

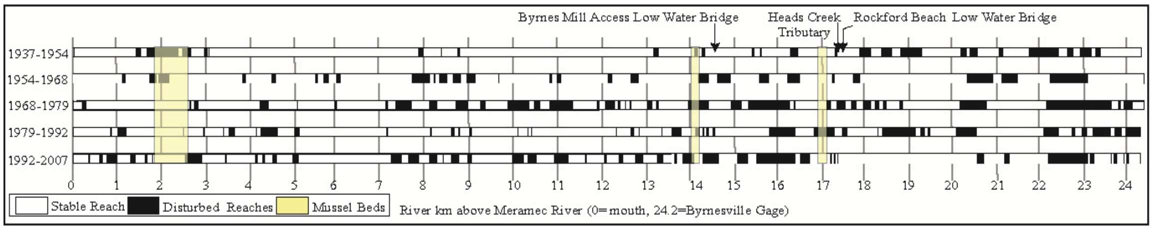


Figure 20. Location and length of historical channel disturbances.

Disturbance reach number and length. From 1937-2007, the number of disturbance reaches identified in the lower Big River generally increases (Table 9). There are 27 disturbance reaches that were identified from 1937-1954 and 44 were identified from 1992-2007. Relative frequency of disturbance reaches per river kilometer gradually increases over time from 1.1 disturbance reaches per river kilometer from 1937-1954 to 1.8 disturbance reaches per river kilometer from 1992-2007. This may be due to the fact the more recent aerial photographs (1992, 2007) have better resolution and therefore the banks are easier to see and digitize in a GIS compared to those older aerial photographs with poor resolution (1937-1954). However, the trend of increasing disturbance reaches may also indicate a change in channel behavior related to variations in sediment loads or watershed factors.

Table 9. Historical trends in disturbance reach number and length.

	Disturbance Reach No.	Mean Disturbance Reach Length (m)	% of Study Reach Length Disturbed
1937-1954	27	164	18
1954-1968	28	182	21
1968-1979	38	214	34
1979-1992	40	150	25
1992-2007	44	178	32
1937-2007	21	350	32

Stable reaches are characterized by rather long, straight reaches averaging approximately 745 meters and range from 20-2,520 meters in length. This mean length of 745 meters or 16 channel widths represents 1-2 meander cycles. Major disturbance reaches on the other hand are characterized by shorter, sinuous reaches averaging approximately 350 meters and range from 60-1,500 meters in length. Mean disturbance reach length has historically increased since 1937 when mean length was approximately 165 meters and peaked from 1968 to 1979 when mean length was 214 meters (Table 9). Historical increases in both number and mean length of disturbance reaches possibly indicate a period of increased channel instability throughout the aerial photograph record. The biggest changes in channel disturbance, therefore, occur after the active mining period when there is a possible reduction in the release of historical gravel delivery (Jacobson, 1995).

Gravel Bar Trends

Spatiotemporal trends in gravel bar surface area are essential to help quantify the amount of bed material stored in each 200 meter channel cell. Both vegetated stable bars and non-vegetated active bar formations were digitized from aerial photographs. Although the actual channel bed-material will not be able to be quantified from aerial photographs, gravel bar surface area is assumed to be a good indicator of storage and transport of excess bed material in the lower Big River. Bar area measurements can be affected by the depth of flow in the river at the time of aerial photography. Higher floods will decrease the visible bar area as stage rises and bars become inundated. Due to flooding during the 1992 set of aerial photographs, bar surface area for that year is drastically (~200%) underestimated and therefore will not be used in analysis (Fig. 21a-b).

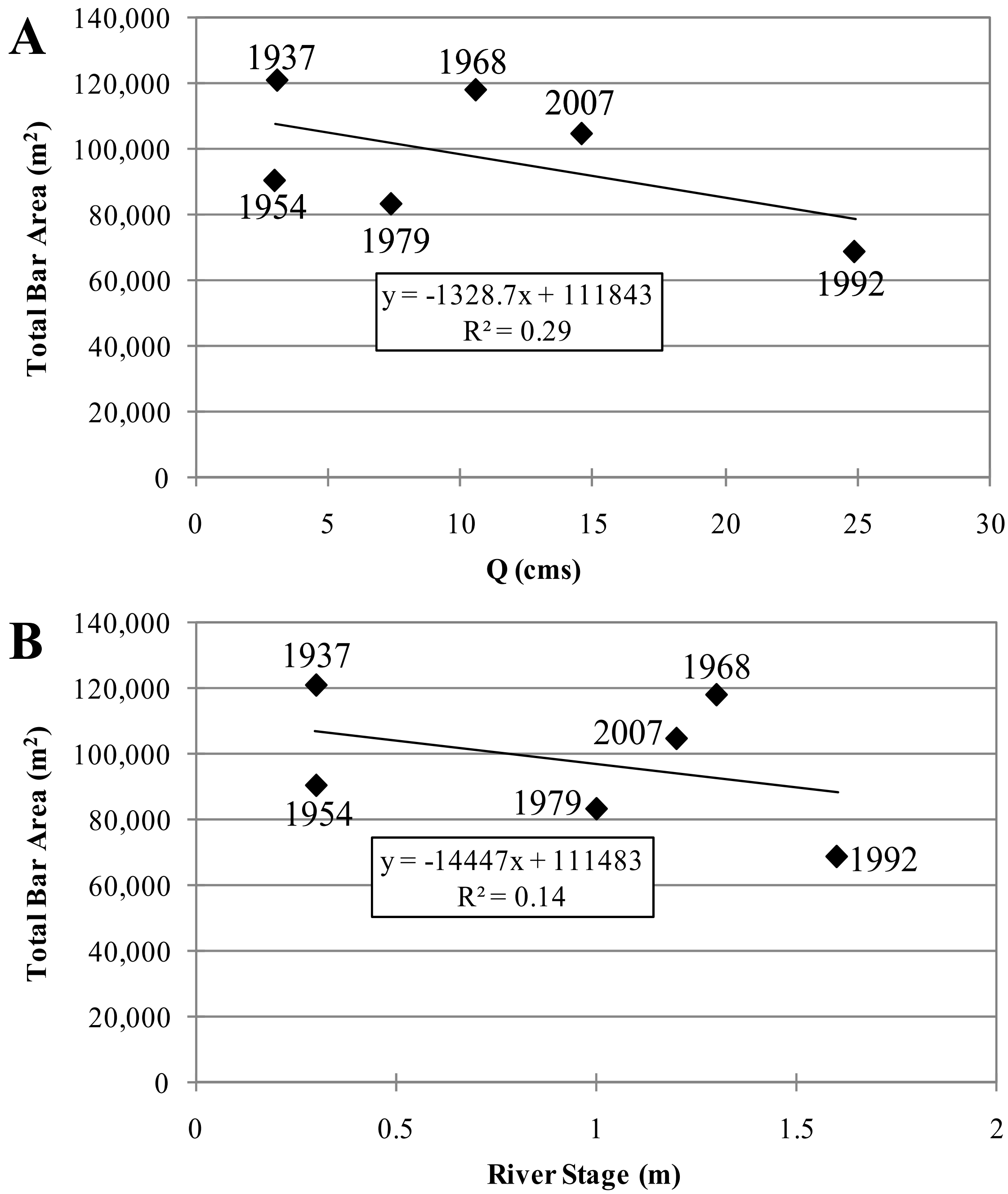


Figure 21a-b. Flow conditions effect on bar area measurements.

Gravel bar surface areas throughout the study reach show similar patterns to that of disturbance reaches, varying over space and time (Fig. 22). Total bar surface area within the specific study reach varies from approximately 70,000- 120,000 m^2 throughout the 70 year aerial photograph record. Although total bar surface area varies throughout time, it is apparent that total vegetated stable bar surface area is historically decreasing. Although several factors could explain this phenomena, decreasing vegetated stable bar area may be attributed to vegetation age, as gravel bar stability decreases with increasing age of vegetation on the bar (McKenney et al., 1995). However, determining the age of vegetation was not able to be determined based off of aerial photograph interpretation and is outside the scope of this study.

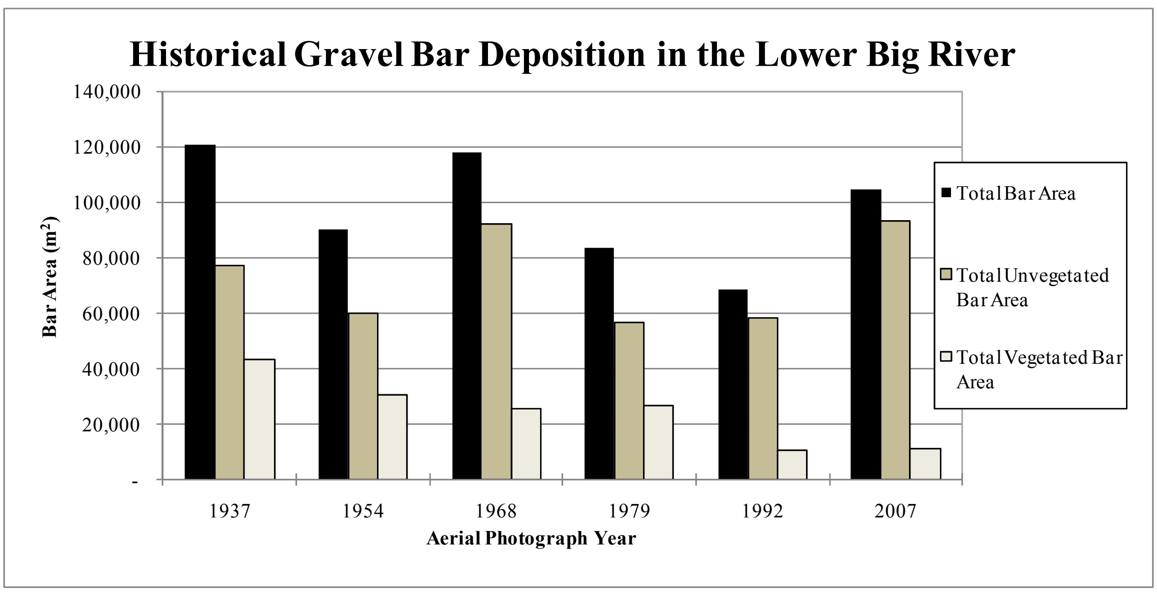


Figure 22. Historical gravel bar patterns in the lower Big River.

Un-vegetated, vegetated, and total bar area deposition patterns are variable throughout time (Fig. 22). Total bar surface area patterns within the lower Big River follow a repeated pattern of a decrease in total bar area followed by an increase in bar area between successive aerial photographs (Figs. 22-23). From 1937 to 1954 there was a 25% decrease in total bar surface area, indicating that channel transport capacity was high relative to channel storage supply (Figs. 23). This period of high transport and lower deposition rates was followed by a 30% increase in total bar area between 1954 and 1968.

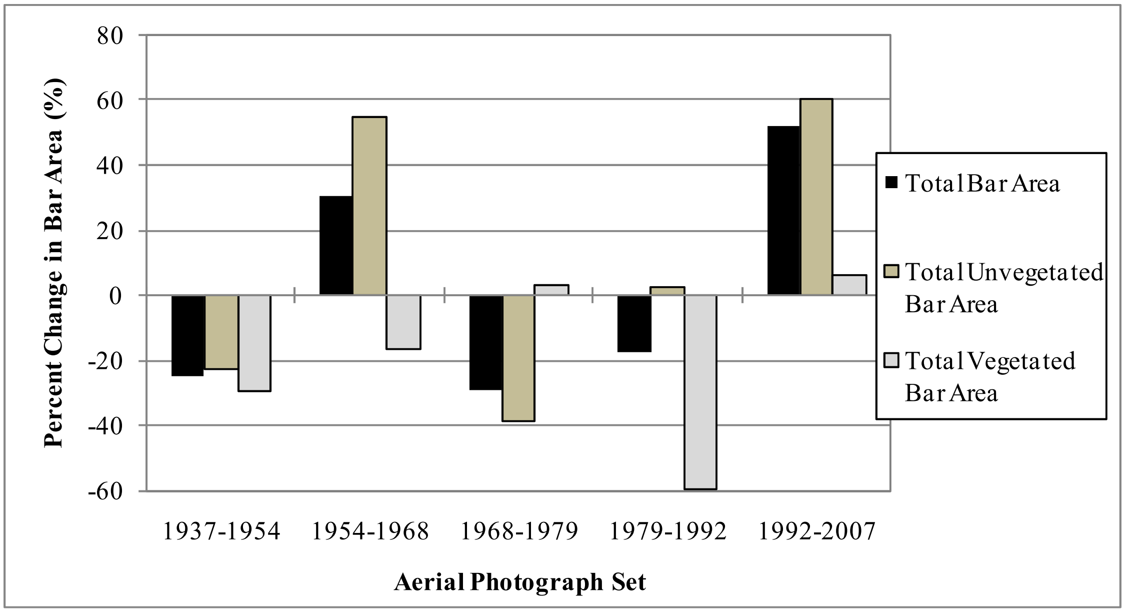


Figure 23. Percent change in historical bar area between aerial photographs.

The lower Big River exhibits this pattern of fluctuating gravel bar surface areas throughout the study period and percent change in total bar surface area is approximately +/- 45% between successive aerial photographs (Fig. 23). While there may be a relatively large percent decrease in vegetated bar area between successive aerial photograph years, the total bar area percent change may not fluctuate that much (Fig. 23). For example, between 1979 and 1992, there was an approximate 60% decrease in total vegetated bar area, but only a 17% decrease in total bar area (Fig. 23).

Relative high variability over time of total gravel bar surface area indicates the lower Big River may have variable source inputs. Gravel bars deposited in the lower Big

River can be formed with sediment from both natural and anthropogenic sources. Channel instability in the form of disturbance reaches can potentially cause rapid channel migration, bank erosion, and bed scour as the channel deepens in response to a new sediment load. As the channel deepens or widens, gravel may be released from the banks that were once a buried channel deposit formed by historical lateral accretion. Also, tributary inflow may have an effect on gravel deposition. As the Big River watershed continues to become increasingly urban, an increase in impervious surface causes major tributaries feeding the Big River to adjust to changing hydrologic and sediment regimes. In response to these imbalances in the fluvial system, tributaries can incise and head-cut erosion occurs, which may release gravel to some segments of the channel.

Large areas of gravel bars ranging from approximately 4,000-15,00 m^2 are concentrated at distances of approximately 5, 8, 14, 17, and 22 kilometers upstream from the mouth of the Big River, which correspond to locations of disturbance reaches (Fig. 24). Total gravel bar surface area that is completely within a disturbance reach ranges from 63-73% with the largest percentage of bar area completely within a disturbance reach occurring during the 2007 set of aerial photographs. While gravel bar deposits are concentrated and correspond with the locations of historical channel disturbance reaches, not all gravel deposition occurs exclusively within disturbance reaches and some gravel deposition does occur in stable reaches. However, gravel bar deposition is not as pronounced in stable reaches compared to disturbance reaches.

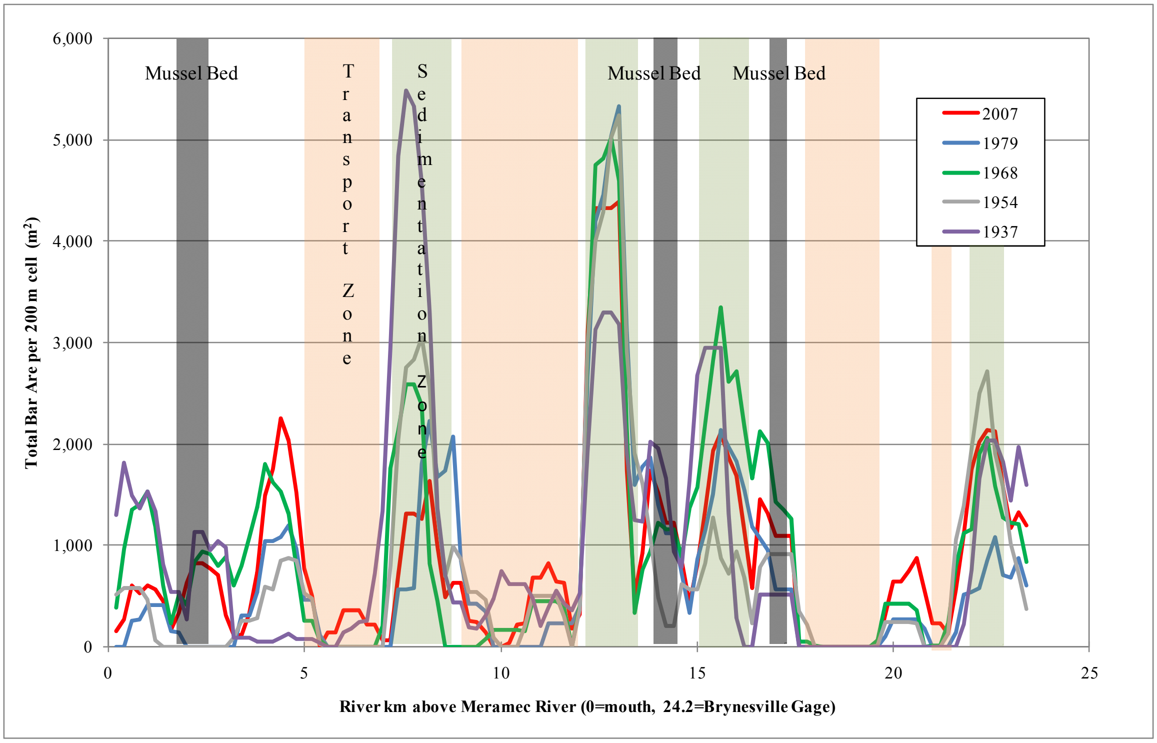


Figure 24. Historical downstream variations in total gravel bar deposition. A five point moving average, which creates a series of averages of subsets of data to 'smooth' trendlines, was used here.

Transport and sedimentation zones. Distinct sedimentation and transport zones of gravel bars are located throughout the lower reaches of the Big River. Transport zones occur in reaches where relatively little gravel bar area has historically been present and are located between river kilometers 5-7.5, 9-12, 18-20 and near river kilometer 22 (Fig. 24). These locations are all relatively straight reaches approximately 2-3 kilometers long and are mapped as stable reaches, with the exception being near river kilometer 22. Total bar area in transport is approximately 500 m^2 per 200 meter channel segment. Historical sedimentation zones occur where peaks of gravel deposits greater than 1,000 m^2 and occur between river kilometer 7.5-9, 12-14, 15-16, and near 22.5 (Fig. 24). These locations occur in areas of increased sinuosity, as gravel bar are being formed historically on point bar surfaces. All sedimentation zones seem to be slightly shorter than transport zones, as transport zones are 3+ kilometers long and sedimentation zones range from 1-2 kilometers in length.

Bank Erosion Rates

Bank erosion rates within disturbance reaches (1937-2007) of the lower Big River range from 0.11-0.30 m/yr/disturbance (Fig. 25). Bank erosion rates are greatest between 1968 and 1979 and the lowest bank erosion rates occur from between 1937 and 1968. Bank erosion rates within disturbance reaches are relatively low in the older sets of aerial photographs, peak in 1968-1979 and decline thereafter till the present (Fig. 25).

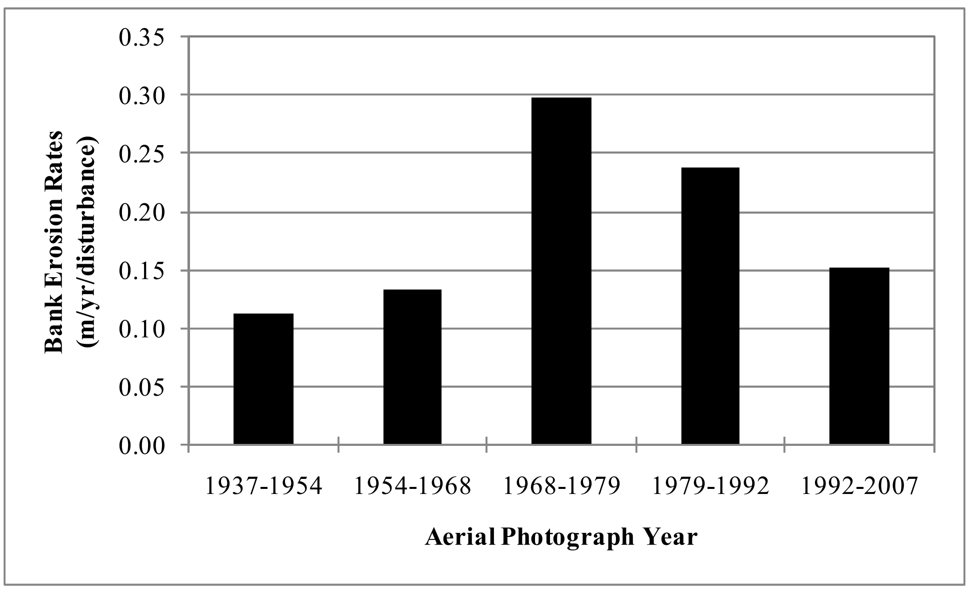


Figure 25. Historical bank erosion rates within disturbance reaches.

As expected, bank erosion rates vary in the downstream direction over time but the greatest bank erosion rates occur within channel segments classified as disturbance reaches (Fig. 26). In the period from 1937-1954 and from 1968-1979, bank erosion rates peak upstream of river kilometer 20, however other years do not show the same pattern. When examining bank erosion rates from 1992-2007, bank erosion is typically greatest in areas where valley sinuosity is relatively high, containing more channel bends and cut-bank areas that increase the potential for bank erosion due to scour and mass wasting. Locations of low bank erosion rates from 1992-2007 on the other hand occur where the channel is confined by one side of the valley wall. The valley wall acts as a barrier to bank erosion and essentially limits bank erosion compared to a channel section meandering across the valley floor. More recent bank erosion rates are typically smaller than historical bank erosion rates, but exceed historical rates at river kilometer 7.5, 13 and 16 (Fig. 26)

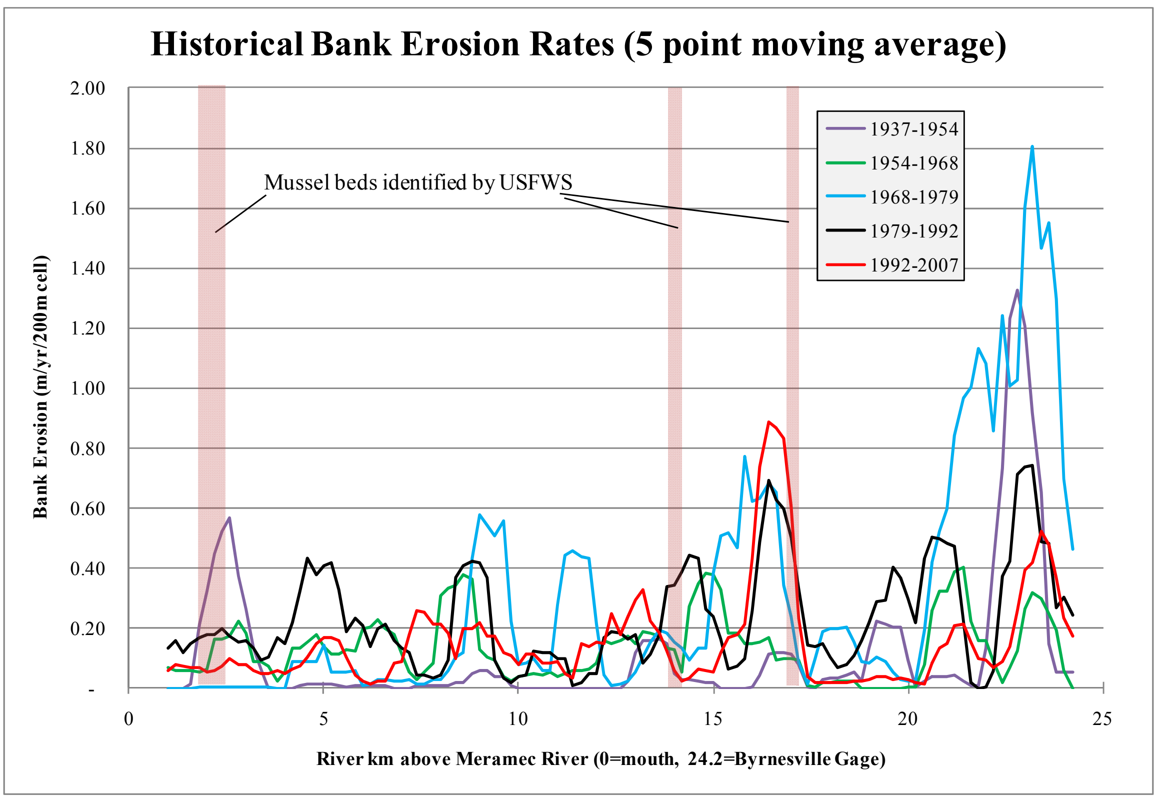


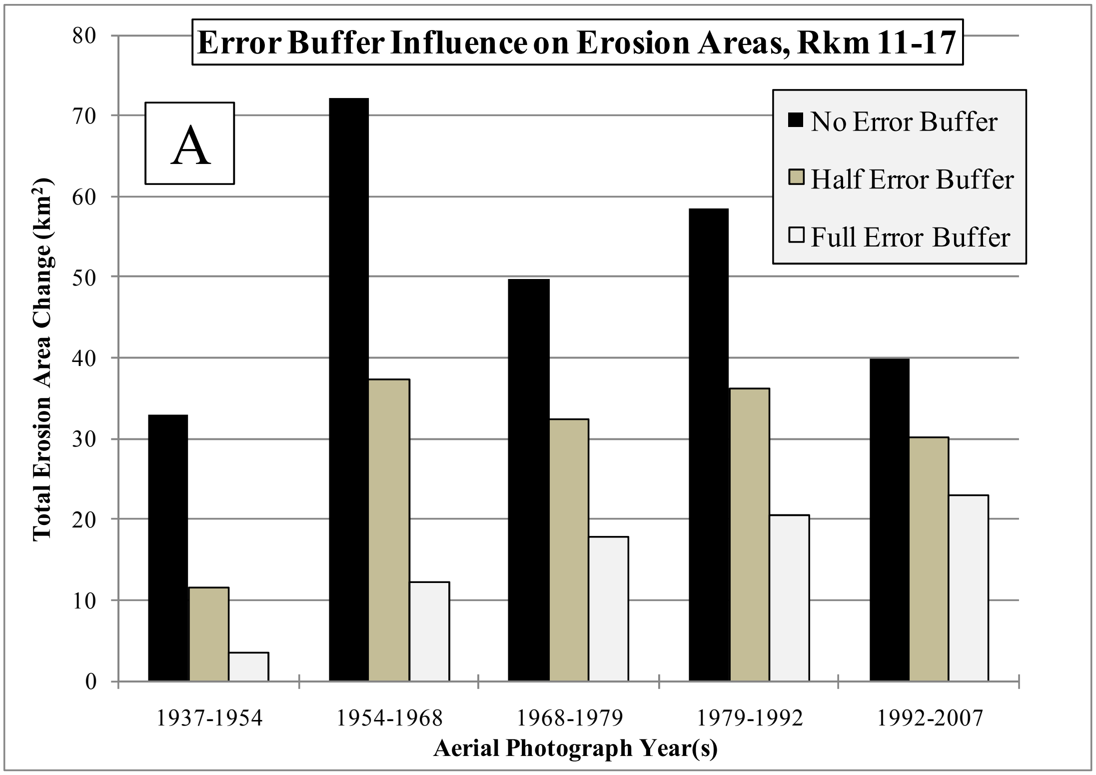
Figure 26. Downstream variations in historical bank erosion trends.

Between 1979 and 2007, a relatively small length of the channel is responsible for the majority of erosion and sediment introduction to the lower Big River. Approximately 32% (7,693 meters) of the total channel length between river kilometers 4-5, 8.4-9, 12-

14, 16-16.4, and 19-23 is responsible for 50 percent of the total erosion between 1979 and 2007. That leaves approximately 68% (16.3 kilometers) of the total channel length responsible for the other 50% of total erosion between 1979 and 2007.

Erosion and Deposition Error Buffer Influence

Different error buffers applied to individual channel bank boundaries can affect measurements of erosion and deposition areas throughout time (Fig 27a-b**.** Total area of erosion and deposition in the 6 kilometer sub-reach where different error buffers were analyzed follow similar patterns as time progresses. Differences between error buffers (full, half and none) are larger in the oldest sets of historical aerial photographs compared to more recent aerial photographs (Fig. 27a-b). For example, between 1937 and 1954, total bank erosion areas yield 3, 11.5, and 33 km^2 for full, half and no error buffers respectively (Fig. 27a).



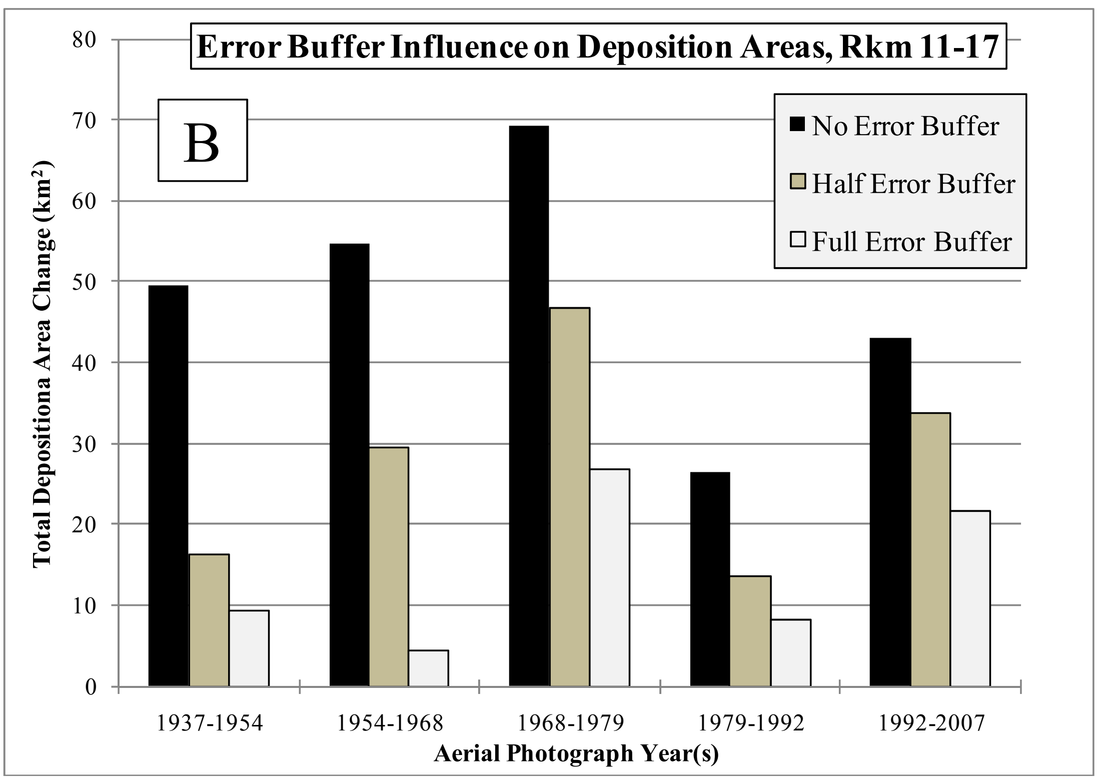


Figure 27a-b. Full, half, and no error buffer influence on total erosion (A) and deposition areas (B) between river kilometer 11-17.

Bank deposition areas between 1937 and 1954 show a similar pattern of areas found using the full error buffer are approximately 3-4 times less than areas with half error buffers and a full order of magnitude less than those deposition areas with no error buffers applied. Specifically between 1937 and 1954, total bank deposition areas are approximately 9, 16, and 49 km^2 for full error buffer, half error buffer and no error buffer respectively (Fig. 27b). Large differences in the total bank erosion and deposition areas prevalent in the earlier sets of aerial photographs are not present in newer sets of aerial photographs (Fig. 27a-b). Between 1992 and 2007, there is only a 16 and 12 km^2 total area difference between full error buffers, half buffers, and no buffers applied to bank erosion and deposition areas respectively. Smaller differences in total bank erosion and deposition area could be due to the better resolution of newer aerial photographs, which subsequently allows for more accurate rectification of images and a reduced point to point error which determines the error buffer size applied to the channel banks.

Throughout this study, full error buffers are applied to individual channel bank boundaries to calculate erosion and deposition areas. Full error buffers account for errors in the rectification process in every direction of the aerial photograph and take a conservative approach to future analysis. If no error buffers were applied, bank erosion and deposition areas used in the sediment-Pb budget analysis could be overestimated by up to an order of magnitude.

SEDIMENT TEXTURE AND Pb CONCNETRATIONS

Sediment Textural and Geochemical Properties

Sediment samples collected from the bank all consist of fine-grained sediment and there is little variation in the size class. Bank samples range from 99.2-100% finer than 2 mm with a median value of 99.8 % (Table 10a). Median bank concentration of the 31 samples collected is 181 ppm Pb, but varies with depth and among differing landforms, which will be examined in the future.

Table 10a-b. Bank (A) and bar (B) sediment textural and geochemical properties.

A

n=31	Percentile						
	Min	5th	25th	50th	75th	95th	Max
Percent <2mm (%)	99.2	99.3	99.6	99.8	100	100	100
Percent 2-32mm (%)	0	0	0	0.2	0.4	0.7	0.8
<2 mm Pb (ppm)	20	42.5	66	181	960	2,074.6	2,902

B

n=48	Percentile						
	Min	5th	25th	50th	75th	95th	Max
Percent <2mm (%)	23.6	25.3	49.2	71.8	95.9	100	100
Percent 2-32mm (%)	0	0	4.1	28.2	50.8	74.7	76.4
<2 mm Pb (ppm)	40	42.2	66.5	82	168	403	751
Avg. Bulk Pb (ppm)	29.9	31.8	43.3	62.3	117.9	329.9	749

Bed and bar sediment samples are coarser than bank sediment samples and range from 24-100% of the entire sample finer than 2 mm with a median value of 71.8% (Table 10b). Bar contamination in the less than 2 mm fraction ranges from 40-751 ppm Pb with a median value of 82 ppm Pb. However, bar deposits are assumed to be mixed well geochemically, so the entire deposit needs to be geochemically accounted for, not just the less than 2 mm fraction. Therefore, in this study, coarse sediments (>2mm) in bar deposits are assumed to contain 15 ppm Pb, and will be used to determine the bulk Pb concentration in bar deposits that will be explained later in this thesis.

Pb concentrations in bank samples range from 250-3,000 ppm lead, depending on depth of sample and associated landform being sampled (Fig. 28). In general, samples with the most contamination were collected from 0-2 meters below the top of bank. Average Pb bank concentration is approximately 618 ppm and 39% of the bank samples collected exceed the terrestrial soil probable effect cause (PEC) used by the U.S. Fish and Wildlife Service of 400 ppm Pb. More than half (~52%) (16 of 31) of the bank samples collected exceed the aquatic sediment probable effect cause of 128 ppm Pb while 39% (12 of 31) of bank samples exceed the terrestrial probable effect cause of 400 ppm Pb. Pb concentrations in bar samples range from 50-425 ppm. Approximately 6% (3 of 21) of bar samples collected are contaminated above the terrestrial probable effect cause while approximately 44% (21 of 48) of bar samples exceed the aquatic probable effect cause.

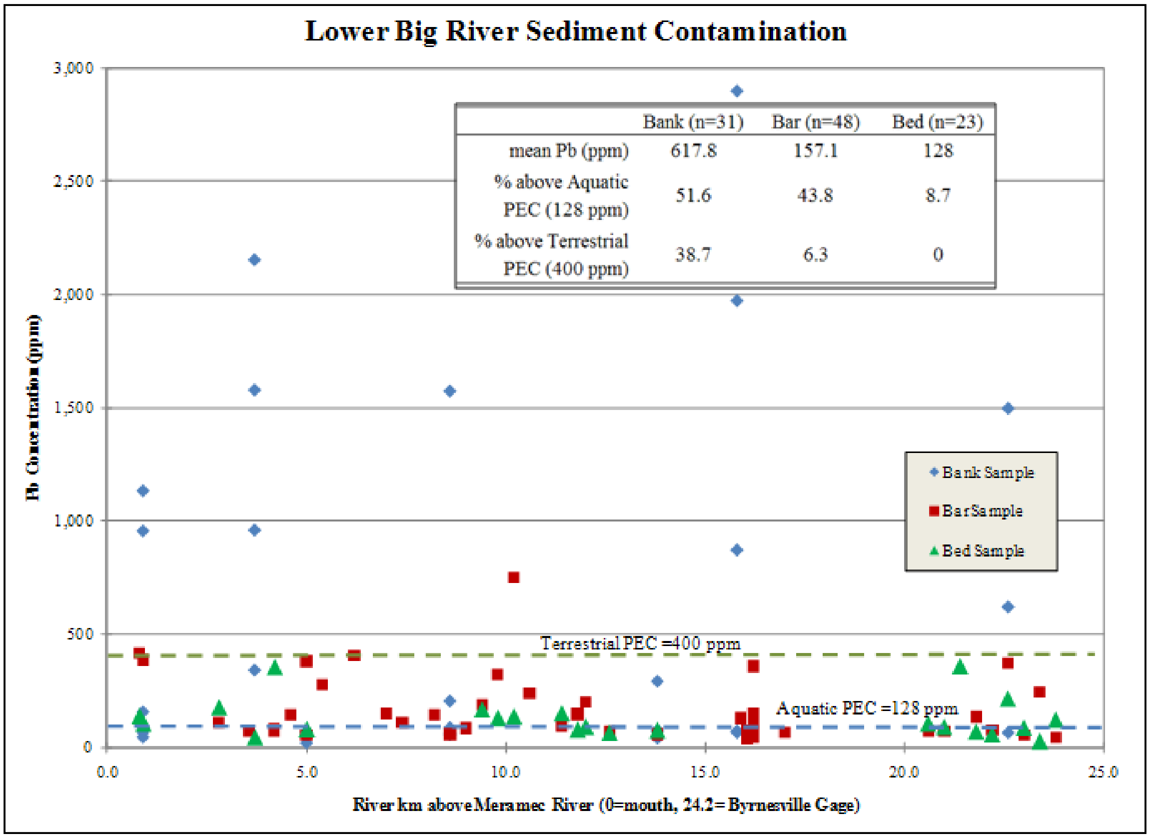


Figure 28. Collected sediment samples and associated contamination levels.

Bulk Densities

Bulk densities used in the sediment-Pb budget analysis ranged from 1.3-2.0 g/cc depending on soil series and associated landform (NRCS, 2006) (Table 11). Within each soil series, bulk density varied according to depth, but this study used the median bulk density value for each NRCS soil series and landform in the sediment-Pb budget analysis (Table 11).

Table 11. Bulk densities used in sediment-Pb budget (NRCS, 2006; Pavlwosky et al., 2010). Bulk densities of gravel are not reported in the NRCS (2006) soil survey but was found in Pavlowsky et al. (2010) and are therefore denoted by an *.

Soil Name	Landform	Depth (in)	NRCS Moist Buk Density (g/cm^3)	Median bulk Density (kg/m^3)
gravel bars		n/a	2.0*	2,000
Kaintuck	Active Floodplain	0-6	1.3-1.5	1,350
		6-80	1.2-1.5	
Haymond	Low Terrace	0-6	1.3-1.5	1,375
		6-41	1.3-1.5	
		41-80	1.3-1.4	
Wilbur		0-8	1.3-1.5	1,400
		8-36	1.3-1.5	
		36-80	1.3-1.5	
Sturkie		0-8	1.2-1.4	1,300
		8-28	1.2-1.4	
		28-80	1.2-1.4	
Freeburg	High Terrace	0-65	1.3-1.5	1,350
Moniteau		0-80	1.3-1.5	1,350
Horsecreek		0-60	1.5-1.7	1,350
Gabriel		0-80	1.3-1.5	1,325

Depth-Weighted Bank Contamination

Fine grained contamination. Bank and bar samples were collected in the field, but only represented a portion of the total landform being sampled and did not account for geochemical variations of Pb concentrations with depth. Therefore, depth-weighted contamination were needed to account for variations of Pb contamination according to depth. Active floodplain deposits associated with Kaintuck series soils are contaminated above the terrestrial probable effect (400 ppm) to a depth of approximately 2 meters above the thalweg, where Pb concentrations are at or near background concentrations (Fig. 29a). Contamination is relatively constant throughout the active floodplains at approximately 500 ppm Pb until 2 meters above the thalweg. Average Pb concentration in active floodplains is 513.1 ppm Pb (Table 12).

Table 12. Landform depth to thalweg-weighted Pb concentration (ppm).

	Active Floodplain	Low Terrace	High Terrace
n	4	9	1
min	208	68	21
max	976	1086	21
average	513	699	21
st. dev	328	403	-----
CV%	64	58	-----

Contamination levels in low terraces mainly associated with Haymond series soils, but also Wilbur and Sturkie series soils, show a unique pattern compared to active floodplains. These deposits are generally thicker, and have greater Pb concentrations. Pb contamination in low terraces is slightly below the aquatic probable effect (128 ppm) for approximately one meter below the top of the landform, where concentrations rapidly spike to nearly 7,000 ppm Pb (Fig. 29b). Pb Concentrations thereafter decrease back to background levels approximately 3 meters above the thalweg and remain near background levels until the thalweg. Average Pb concentration for low terraces is 699 ppm Pb (Table 12).

High terrace landforms associated with Horsecreek, Moniteau, Freeburg, and Gabriel soils are uncontaminated, with Pb concentrations remaining below 75 ppm Pb throughout the entire profile (Fig. 29c). Average Pb contamination of high terrace is 21 ppm Pb (Table 12).

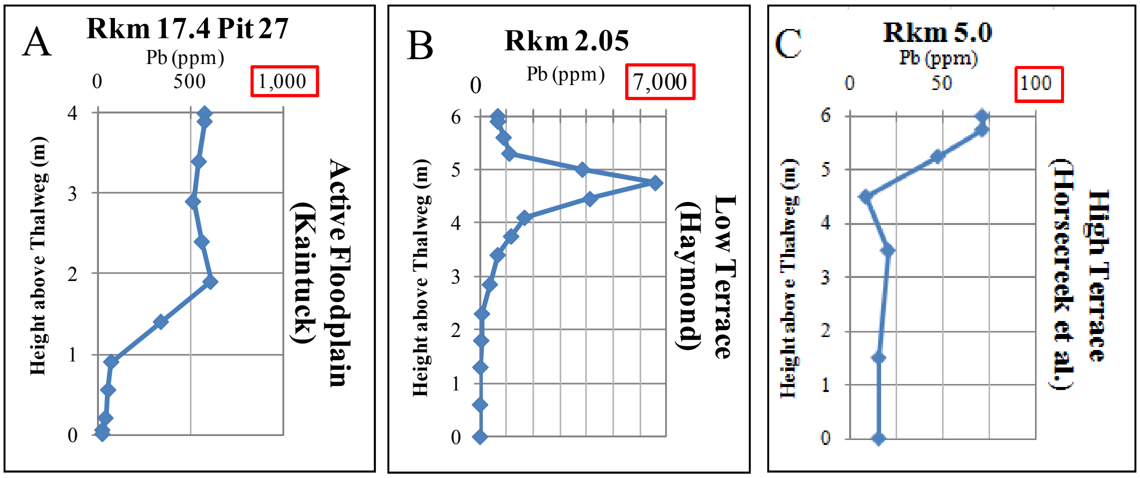


Figure 29a-c. Pb contamination variability with landform depth.

Contamination patterns according to landform can be explained based off on the history of mining operations and the time in which each landform formed. During the active mining period in the Old Lead Belt Mining District, ultra-fine material called slimes were produced in the milling process of Pb ore and were concentrated in Pb. Slimes were discharged directly into the Big River, as no environmental regulations had been put in place yet to stop this. Pb rich slimes were probably transported far downstream and reached the study reach of this study (Pavlowsky et al., 2010. Floods were able to distribute Pb-rich slimes onto the floodplain as vertical over-bank accretion deposits, and Pb-rich slimes were deposited above un-contaminated sediment. In recent past, strict environmental regulations put in place have reduced Pb-rich slime discharge into the channel, therefore natural sediment is able to be deposited overbank above the Pb-rich slimes on low terraces, which is why there is a distinct spike in contamination levels in the low terraces.

Active floodplains do not have the same magnitude of contamination as low terraces. Active floodplains are formed under the current hydrologic regime, but were probably forming during the end of mining operations as well. Active floodplains are inundated more frequently than low terraces, so more Pb contaminants are released from storage and subsequently remobilized. Also, active floodplains of the lower Big River generally have a fining-upward sequence, evidence of vertical accretion deposits. Recently deposited active floodplains were formed near the end and after mining operations. They are composed of mixed mining and natural sources of sediment and therefore are more uniformly contaminated but at a lower peak concentration than older historical floodplain deposits.

High terraces on the other hand require larger flows to be inundated compared to active floodplains and low terraces. Larger flows needed to inundate high terraces are rare, so little to no Pb contaminants are able to be deposited on these surfaces, resulting in minimal contamination throughout.

Coarse grained contamination. Bar deposits are assumed to be well-mixed geochemically, but depth-weighted averages of Pb contamination similar to floodplains and terraces were not analyzed in this study. Concentrations of Pb bar sediment range from 40-751 ppm Pb, but since geochemical analysis was only completed on the <2mm fraction of bar sediment, coarser sediment needed to be accounted for. Bar sediment coarser than 2 mm was assumed to have a background concentration of 15 ppm. Bulk Pb concentration in bar sediment then ranges from approximately 30 to 750 ppm and the average bulk concentration of bar material is approximately 62 ppm Pb (Table 10b).

SEDIMENT AND PB BUDGET (1979-2007)

Floodplain Budget

Sediment mass. The lower Big River has an overall negative sediment budget as net floodplain erosion is typically an order of a magnitude greater than floodplain deposition. Approximately 866,174 more Mg of sediment is being released from floodplains than what is being deposited within the study reach, accounting for approximately 31,000 Mg of net floodplain erosion per year. Floodplain erosion throughout the study reach ranges from 100 to approximately 2,100 Mg of sediment per 200 m river segment per year and varies in the downstream direction with no distinct pattern (Fig. 30). Distinct peaks in floodplain release of sediment occur in reaches upstream of river kilometer 20, near river kilometer 16, 9, and 4.5, all of which are mapped as historical channel disturbance reaches (Fig. 30). Although floodplain deposition is minimal throughout the study reach, floodplain deposition peaks in areas of the channel that have high floodplain erosion as well, with the exception being near river kilometer 4.4 (Fig. 30). Reaches with high bank erosion also tend to have high floodplain deposition rates on the opposite banks or inside meander bends.

Floodplain Pb budget. Pb sources and sinks were identified in the lower Big River based on GIS based erosion rates, channel surveys, and sediment geochemistry. Pb being released from banks in the lower Big River ranges from approximately 0 to 1.2 Mg per year in 200 meter channel segments. Approximately 575 more Mg of Pb is being eroded from floodplains than what is being deposited between 1979-2007, equivalent to 21 Mg per year being released from floodplains. Most of the erosion of floodplain Pb occurs in upstream portions of the study reach, specifically upstream of river kilometer 16 to the USGS gage at Byrnesville (Fig. 31). There is not a distinct spatial trend in floodplain Pb release but floodplain Pb erosion tends to range from 0.1 – 0.6 Mg per year downstream from river kilometer 16 (Fig. 31).

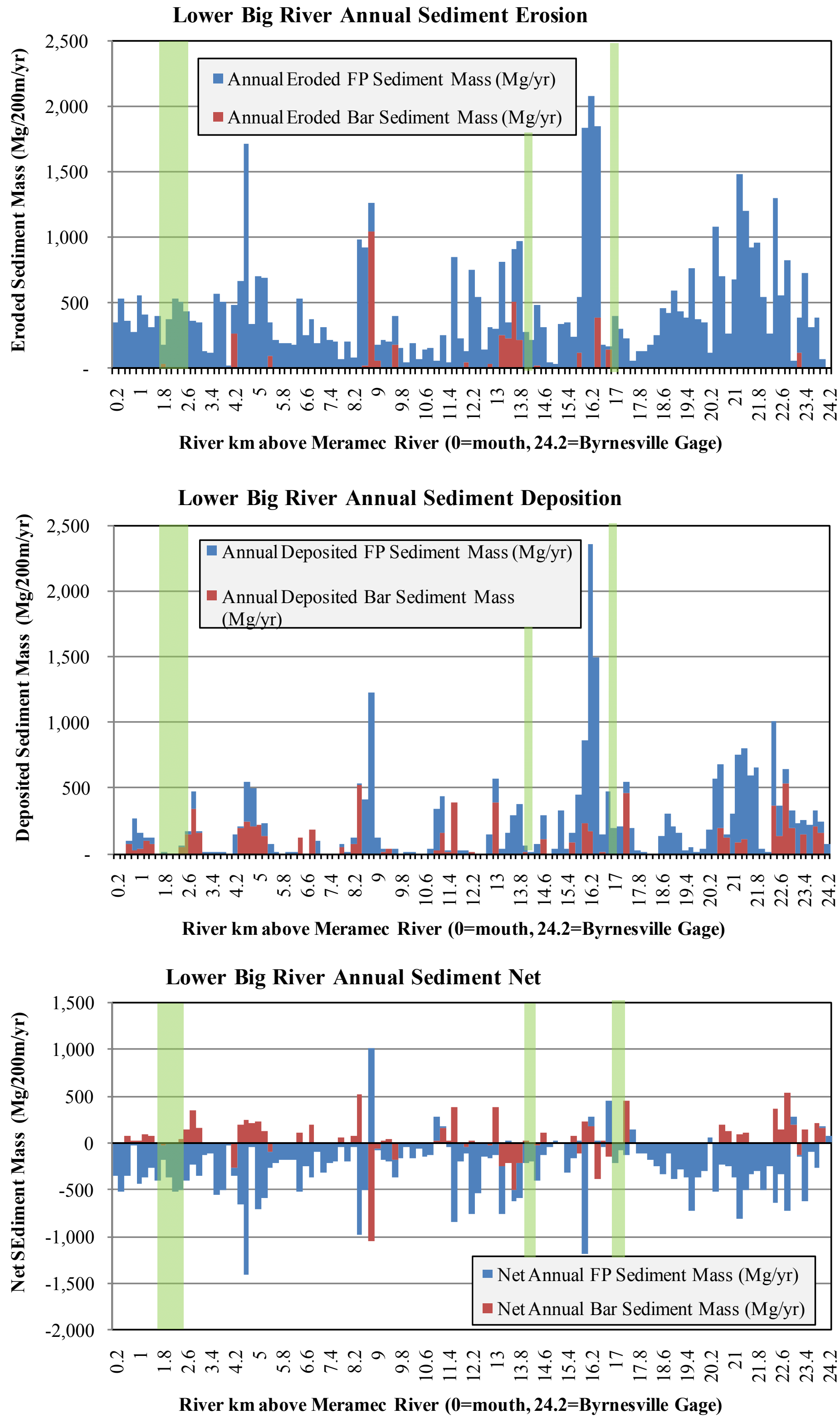


Figure 30. Unit length sediment erosion, deposition and net mass. Green areas indicate locations of mussel beds identified by USFWS.

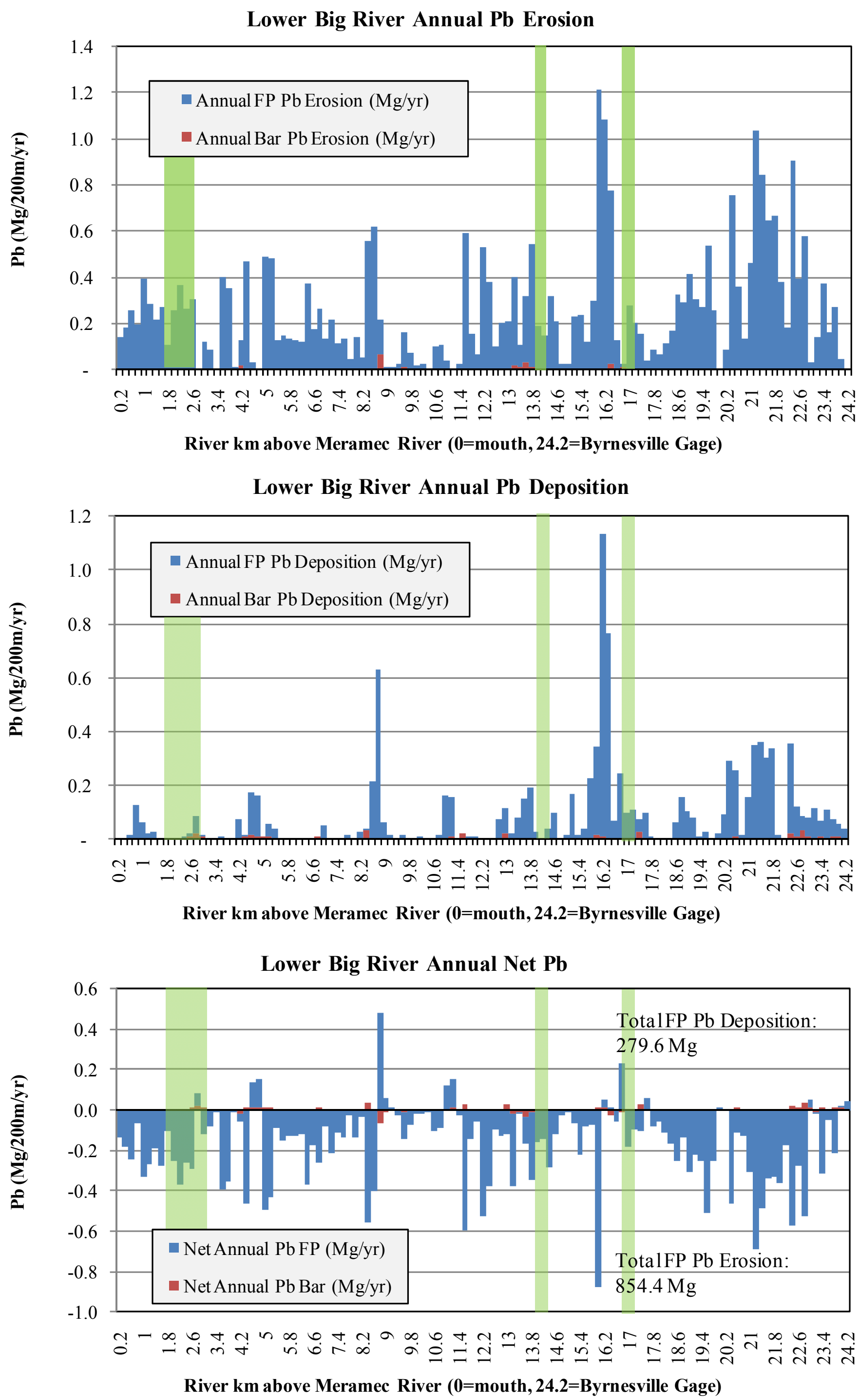


Figure 31. Unit length Pb erosion, deposition, and net mass.

Overbank sedimentation. All fine-grained deposition between 1979 and 2007 only accounted for deposition between individual channel banks and was assumed to be associated with active floodplain sedimentation, not taking into account overbank sedimentation. Floodplain cores and Cs-137 data collected at Washington State Park approximately 80+ kilometers upstream indicate an average floodplain sedimentation rate from 3-5 mm per year or approximately 0.14 meters of vertical accretion throughout that past 28 years on floodplain and low terrace surfaces (Pavlowsky, personal communication, 2011). Average Pb concentration from 11 floodplain cores is 747 ppm Pb. Using equation 3, 17,743 Mg of sediment is being deposited within the study reach as overbank sedimentation. Of the approximate 18,000 Mg of sediment being overbank sedimentation, 13.25 Mg (0.07%) of it is Pb, yielding an annual overbank Pb sedimentation rate of 0.47 Mg per year.

Bar Budget

Sediment mass. While floodplains in the lower Big River have an overall negative budget, gravel bars generally show the opposite trend. Gravel bars are acting as a net sediment sink and possibly are being incorporated into floodplain storage, due in part to the lower Big River attempting to recover from channel disturbance by channel widening and floodplain formation over bar platforms. There is a positive net bar mass where approximately 100,000 more Mg of sediment is being deposited within gravel bars throughout the study reach than what is being eroded. This yield is equivalent to approximately 3,600 Mg of sediment being deposited in bar formations per year since 1979. Similar to floodplain trends bar erosion and deposition patterns also vary downstream, but are generally concentrated in areas of historical channel disturbance. Eroded bar sediment is minimal throughout the study reach but peaks of bar erosion are located directly in the same location as peaks in floodplain erosion, mainly near river kilometers 4.4, 9.4, 13.4, and 16.2 (Fig. 30). All bar deposition per 200 meter channel segment is approximately 500 Mg per year or less.

Bar Pb budget. Deposition of Pb contaminants in bar formations throughout the lower Big River is minimal, but almost three times more Pb is being deposited in bars than what is being released from bars. Net bar deposition is approximately 6 Mg equaling more than 0.22 Mg of Pb per year being deposited in bars than being released. Deposition of Pb in bar formations is less than 0.05 Mg per year in every 200 meter channel cell throughout the entire study reach. Although bar Pb deposition varies downstream, approximately 83% of total bar Pb deposition is occurring downstream of river kilometer 9 to the confluence of the Big and Meramec Rivers (Fig. 31).

Overall Budget

Total floodplain Pb release is approximately 855 Mg while total Pb release within bar formations is 6.53 Mg giving a subtotal of all Pb being released in the lower Big River of 861 Mg Pb, or approximately 31Mg Pb annually (Table 13). Total Pb storage is 280 Mg and 12.73 Mg for floodplain and bars respectively. Accounting for overbank sedimentation, 13.25 more Mg Pb is being deposited overbank within the lower Big River, and adding this value to the total Pb deposition, 306 Mg Pb or approximately 11 Mg Pb annually is being deposited within the last 28 years (Table 13). Using these totals, the lower Big River is releasing a net of approximately 555 Mg Pb over the past 28 years, equivalent to 20 Mg per year. Also, the fate of these contaminated sediments is of future concern, as 20 Mg Pb per year is being transported to the Meramec River and eventually the Mississippi River. There has been little documentation as to how Pb contamination from the Big River is contaminating the Meramec and Mississippi Rivers, but this study suggests increased amounts of Pb are being introduced to both river systems and further polluting subsequently larger areas.

Table 13. Alluvial sediment and Pb mass erosion and deposition (1979-2007). Percent occurring in disturbance reaches in parentheses.

	Alluvial Sediment Mass (Mg)	Pb Mass (Mg)
Total FP Erosion	1,411,174.2 (54.6%)	854.4 (52.8%)
Total Bar Erosion	104,779.8 (53.4%)	6.5 (53.4%)
Erosion Subtotal	**1,515,954.75**	**860.91**
Total FP Deposition	545,000.44 (64.5%)	279.6 (64.5%)
Total Bar Deposition	204,405.1 (77.3%)	12.7 (77.3%)
Total Overbank Deposition	17,742.70	13.25
Deposition Subtotal	**767,148.26**	**305.62**
Total Net	**-748,806.49**	**-555.29**

Additionally, sediment- Pb storage and release from banks and bars can be apportioned between stable and disturbance reaches along the lower Big River. Disturbance reaches are characterized by rapid lateral channel migration, deposition of broad un-vegetated gravel bars, and channel instability (Jacobson, 1995; McKenney et al., 1995; Jacobson and Gran, 1999). One would expect that the majority of bank and bar sediment-Pb erosion and deposition would occur within channel disturbance reaches, however, this is not always be the case in the lower Big River. Only slightly more alluvial sediment and Pb are being released from bank and bar storage within disturbance reaches compared to stable reaches (Table 13). Approximately 53-55% and of total bank and bar erosion of alluvial sediment and Pb respectively occurs within disturbance reaches of the lower Big River (Table 13). However, approximately 65% and 77% of sediment and Pb deposition within banks and bars respectively occurs in disturbance reaches. Since sediment and Pb erosion from banks and bars is occurring about evenly between stable and disturbance reaches, there is more going on from a geomorphic standpoint along the lower Big River than what previously thought.

Mussel Bed Implications

As described previously, mussels prefer a stable substrate, and thus two of three endangered mussel beds occur within 400 meters downstream of mill dam crossings at or near bedrock (Fig. 16). Mussel beds may be recruited to these areas because of lower fine grained sedimentation, which has been shown to be trapped upstream of mill dams, reducing potential supply to mussel beds. The third mussel bed is located between river km 1.85-2.5 directly on a bedrock reach where thalweg refusal depth is zero.

Bar sediment remobilization through release and storage within the lower Big River probably has more of an impact on endangered mussel channel bed recruitment as bar erosion and deposition directly affect the channel bed that mussels inhabit. Two of the three mussel beds identified throughout the study reach are located just upstream of locations of bar erosion at river kilometer 13.8 and 16.8 (Fig. 30). Mussel bed location in relation to bar deposition is similar to floodplain sediment deposition in that mussel beds are located in areas where there is little to no bar deposition, but mussels are found directly downstream of bar deposits at each of the three sites (Fig. 30).

Two of the three endangered mussel beds identified by the U.S. Fish and Wildlife Service are located in reaches where there are relatively low bank erosion rates below 0.1 meters per year for the most recent time period between 1992 and 2007 (Fig. 24). The lone exception is the mussel bed located near river kilometer 17, where bank erosion rates are approximately 0.6 meters per year. Bank erosion may not be a very good indicator of mussel population locations, as mussels are affected more by direct changes in the channel bed and bar deposits. However, mussel beds are affected by fine grained sedimentation and contaminants in the water column, so bank erosion rates of approximately 0.6 meters per year may adversely affect the mussel populations near river kilometer 2, 14 and 17 in the future.

Those two same mussel beds identified by the U.S. Fish and Wildlife Service in the lower Big River are located slightly upstream of relatively large areas of floodplain erosion and deposition at river kilometer 14.1 and 17.01, both of which occur less than 0.5 kilometers from mill dams (Fig. 30). All three mussel beds are located in areas of the channel where floodplain release of sediment is approximately 500 Mg/yr or less and in areas where floodplain deposition is less than 250 Mg/ yr from 1979 to 2007 (Fig. 30).

All three of the mussel beds located in the lower Big River are located in areas where increased amounts of Pb is being released from floodplains. However, all mussel beds are located in channel segments where floodplain Pb release is less than 0.4 Mg per year (Fig. 31). Average floodplain Pb erosion rates at the locations of the three mussel beds are 0.25, 0.17, and 0.28 Mg Pb per 200 meter channel segment per year respectively (Fig. 31). Approximately 20 Mg Pb per year poses an immediate threat to endangered mussel beds along the Big River.

Target Recommendations

Contaminated floodplain deposits represent potential sources of future pollution and water quality degradation due to Pb remobilization along the lower Big River. Relatively high concentrations of Pb in banks along the lower Big River are an important non-point source of present and potential future pollution. Therefore, it is crucial for resource management officials to understand the role and magnitude of floodplain erosion as a contemporary source of fine grained sediment and Pb in the lower Big River in order to make management decisions to remediate some or the entire Pb load inputs.

While resource management officials may target any number of combinations of reaches to reduce the current Pb loads, specific reaches with the most Pb being released from floodplain storage must be targeted. If resource management officials were to reduce the present Pb loads in the lower Big River by 25%, there are nine channel cells (200 meters) upstream of river kilometer 16 that are responsible for top 25% of the current Pb load and should be targeted: river kilometers 16, 16.2, 21.2, 22.4, 21.4, 20.4, 16.4, and 21.8, in that order (Fig. 32). This is assuming that vertical overbank accretion and floodplain storage remain the same. Targeting the top 25% of Pb being eroded from floodplains would represent 1.8 kilometers (7.4%) of the total 24.2 kilometer study reach. Of the aforementioned reaches that are responsible for the top quarter of Pb erosion from floodplains, the top two reaches (river kilometer 16 and 16.2) and another (16.4) are located in between the present location of mussel beds populations. In order to reduce present Pb loads by 50%, an additional 15 reaches, or 23 total reaches, need to be targeted throughout the lower Big River (Fig. 32). Therefore, 23 (19%) of the 121 total channel cells of 200 meters, or 4.6 kilometers, are responsible for the top 50% of the present Pb loads from bank erosion in the lower Big River.

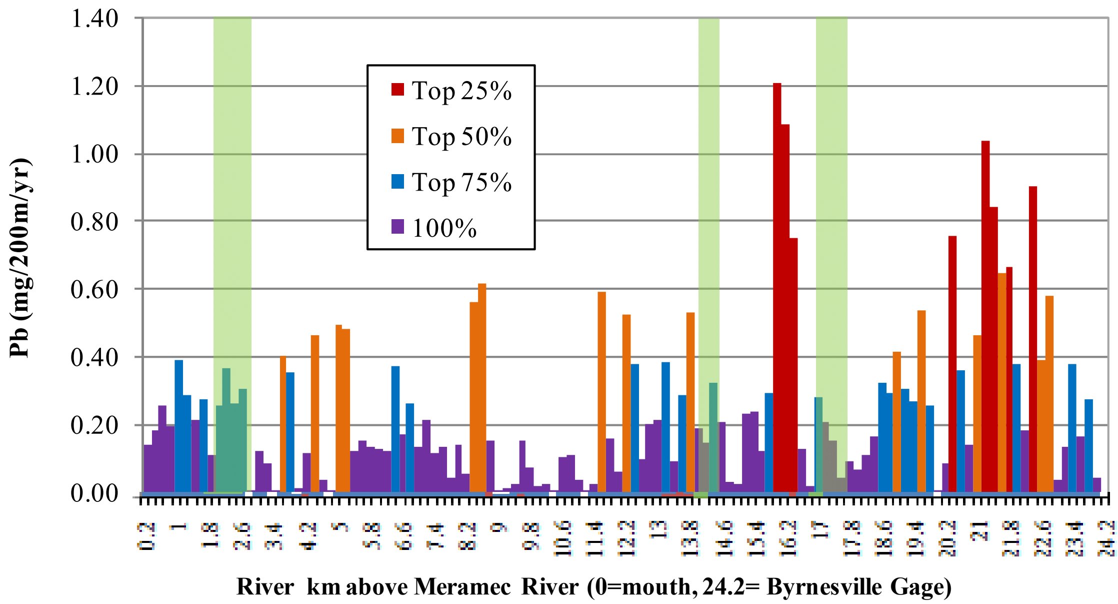


Figure 32. Lower Big River Pb-bank target recommendations.

CONCLUSIONS

It is critical for resource management officials to understand the geomorphic response of river systems to human disturbances for effective management and conservation practices of rivers. Understanding geomorphic responses of river systems to human-induced disturbances is essential to determine possible causes of channel change and assess channel recovery after disturbance. From a resource management standpoint, trends in channel disturbances in relation to geomorphic, geologic, climatic, and anthropogenic factors must be understood to properly manage and protect streams affected by disturbance.

Since the mid to late 1800's, dramatic human-induced land use changes in the Missouri Ozarks have caused stream instability due to changing hydrology and sediment loads (Jacobson and Primm, 1994; Jacobson, 1995; Jacobson and Pugh, 1995; Jacobson and Gran, 1999). In eastern Missouri, historical mining operations within the Old Lead Belt Mining District have delivered large amounts of contaminated sediment to the Big River. Lead (Pb) and other non-volatile metals are stored as both channel deposits and floodplain deposits within the Big River (Pavlowsky et al., 2010), but may be released from storage and remobilized as bank erosion occurs in reaches of channel instability in disturbance reaches. Both federal and state officials are concerned about the long-term environmental risk that contaminated alluvium poses to endangered mussel beds in the lower reaches of the Big River.

Six sets of aerial photographs spanning 70 years were used to identify, classify, and characterize areas of channel disturbance along the 24 kilometer segment of the lower Big River. Although the study segment has been relatively stable over time, increased bank erosion and bar deposition occurs within discrete, localized disturbance reaches which represents approximately 32% of the study reach. Both the number and length of disturbance reaches appears to have been increasing since 1937. GIS based bank erosion rates within disturbance reaches vary from 0.11-0.19 meters per year and represent an important source of metal contaminants to the river as bank concentrations range from approximately 250-3,000 ppm lead in these eroding banks.

GIS based erosion and deposition rates were used in conjunction with field surveys and sediment geochemistry to calculate a sediment-Pb budget for the lower Big River study reach, the first of its kind created at such a small scale. Approximately 749,000 Mg more of sediment is being released from banks than being deposited along the lower Big River, as the channel shows an overall negative net sediment budget releasing sediment from banks. However, bar deposits along the lower Big River are acting as net sediment and Pb sinks that may become incorporated into long-term storage in the future as the channel attempts to recover from disturbance by widening and depositing new floodplains. Although Pb values being released from banks and stored in bar deposits may seem relatively small compared to total sediment being released and deposited, Pb inputs can't be ignored by resource management officials.

Contaminated floodplain deposits represent potential sources of future pollution to the channel due to remobilization in disturbance reaches. High concentrations of Pb are stored in the banks and combined with relatively high rates of bank erosion make bank deposits an important non-point source of future pollution, which could affect native mussel beds that are already endangered. Furthermore, the fate of 555 Mg Pb being released over the past 28 years from the study reach is unknown, as this contaminated sediment is introduced to the Meramec River and eventually the Mississippi River.

In order to reduce the present Pb loads of the lower Big River by 25%, resource management officials would need to target a total of 1.8 kilometers of the study reach upstream of river kilometer 16 for control measures. To reduce Pb loads from bank erosion by 50%, an additional 2.8 kilometers need to be targeted throughout the lower Big River study reach. Also, it should be of interest to resource management officials in the future to determine the contribution of Pb to the Meramec River into which the Big River flows. There have been no studies yet that examine the sediment and Pb erosion and deposition patterns of the Meramec River and essentially the potential delivery of pollutants to the Mississippi River.

This study demonstrates the use of a sediment-Pb budget approach to evaluate environmental fate and risk of Pb on a 24 kilometer segment of the Big River, which represents approximately 11% of the entire main stem of the Big River. The framework of this research could potentially be used as a case study and the sediment-Pb budget approach used in this research can be applied to the entire Big River basin in the future to get a better understanding of the role remobilized contaminated alluvium plays in the present-day contamination of the river system and further pollution of the Big, Meramec and eventually the Mississippi River.

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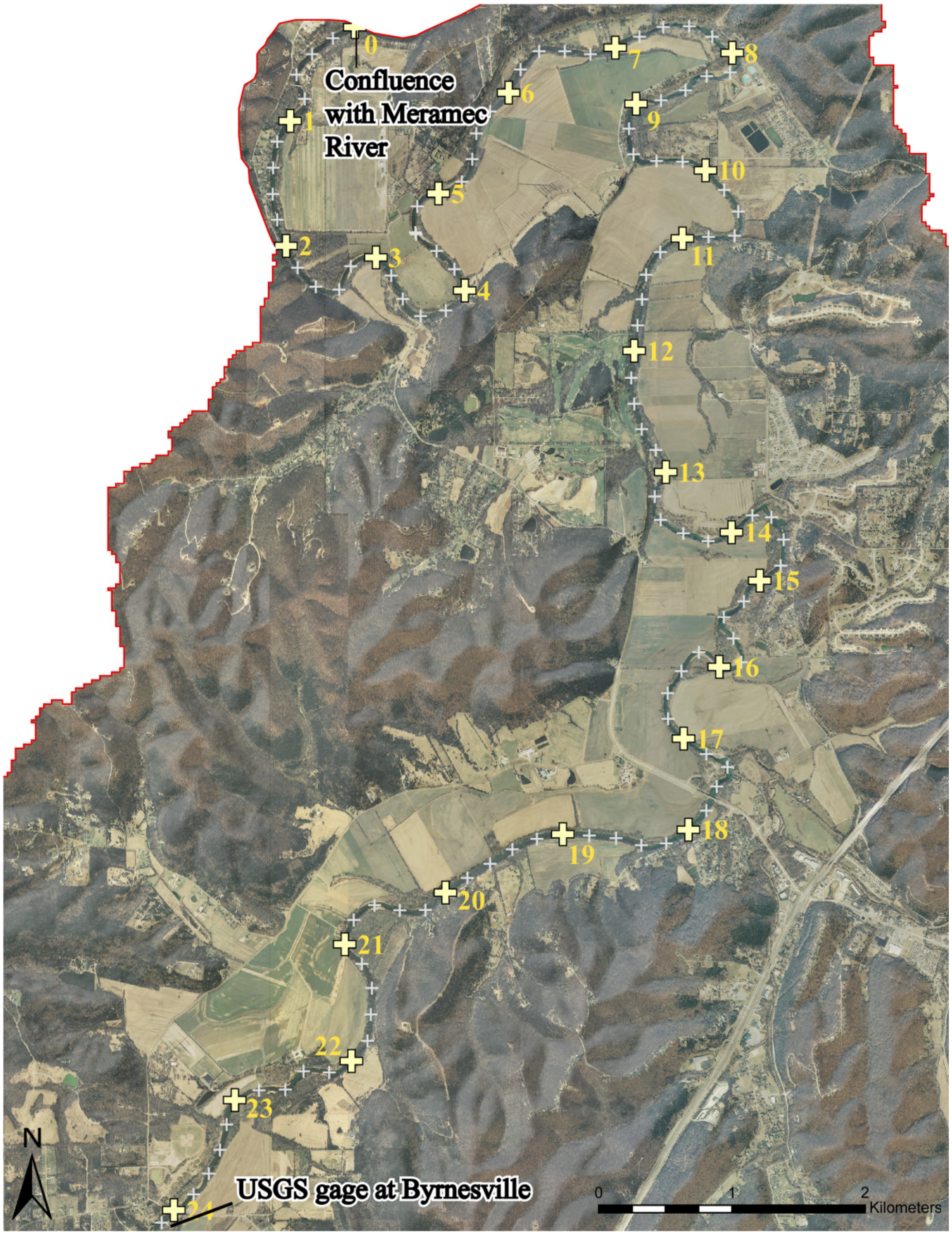
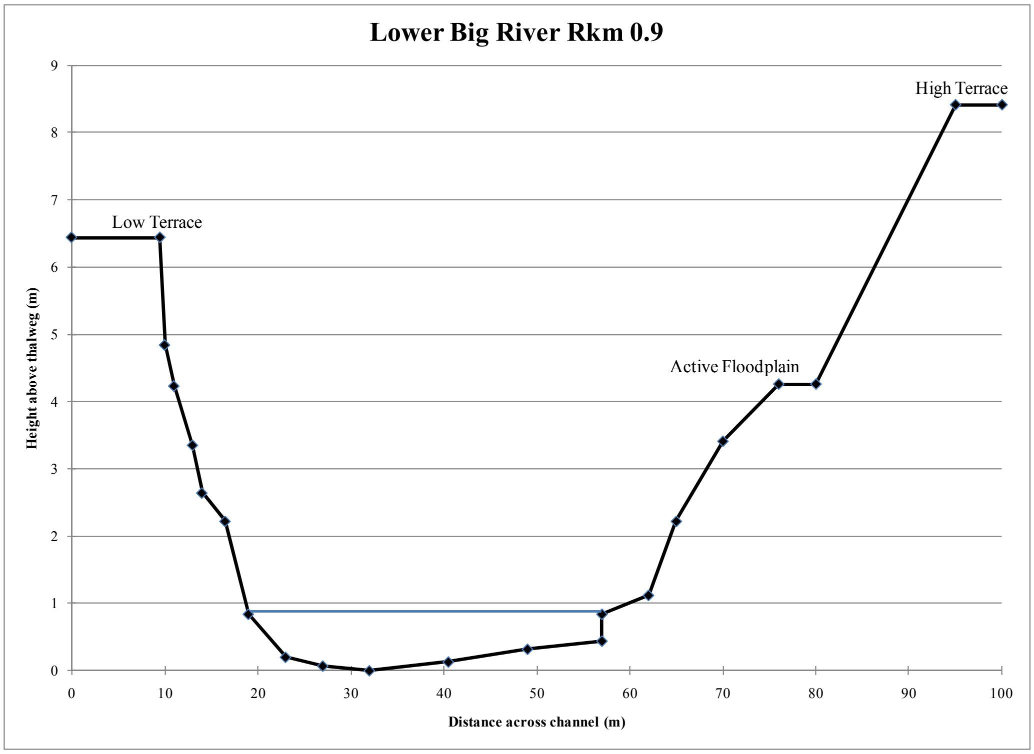
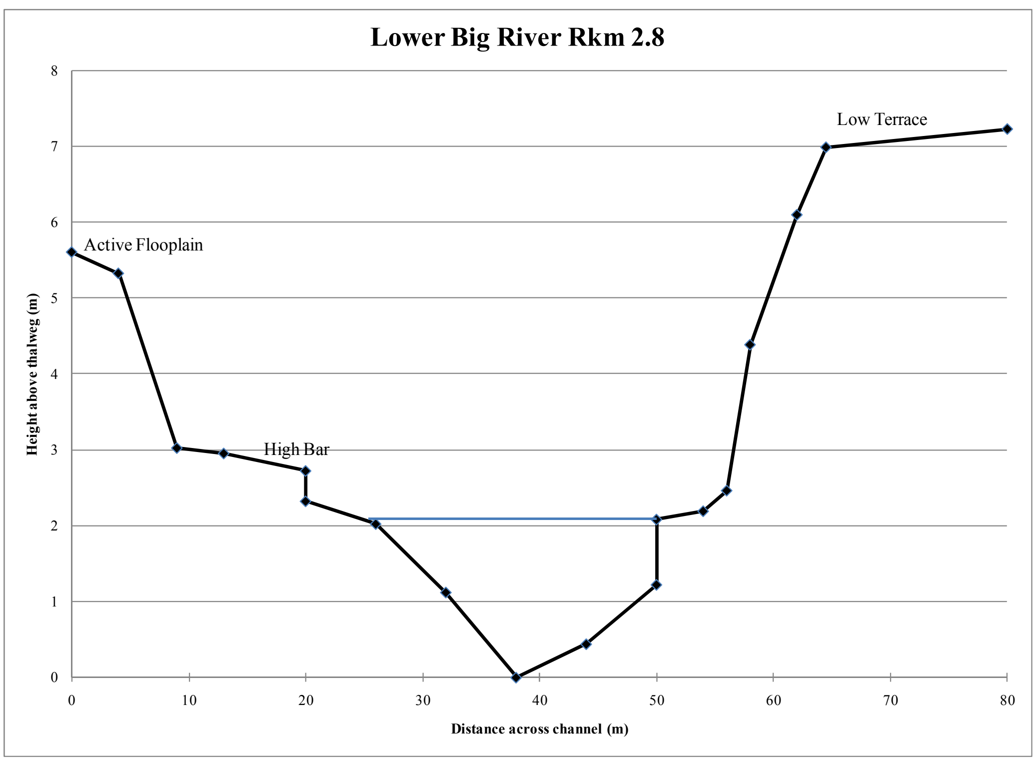
APPENDICES

Appendix A. River Kilometer Reference



Appendix B. Cross Sections





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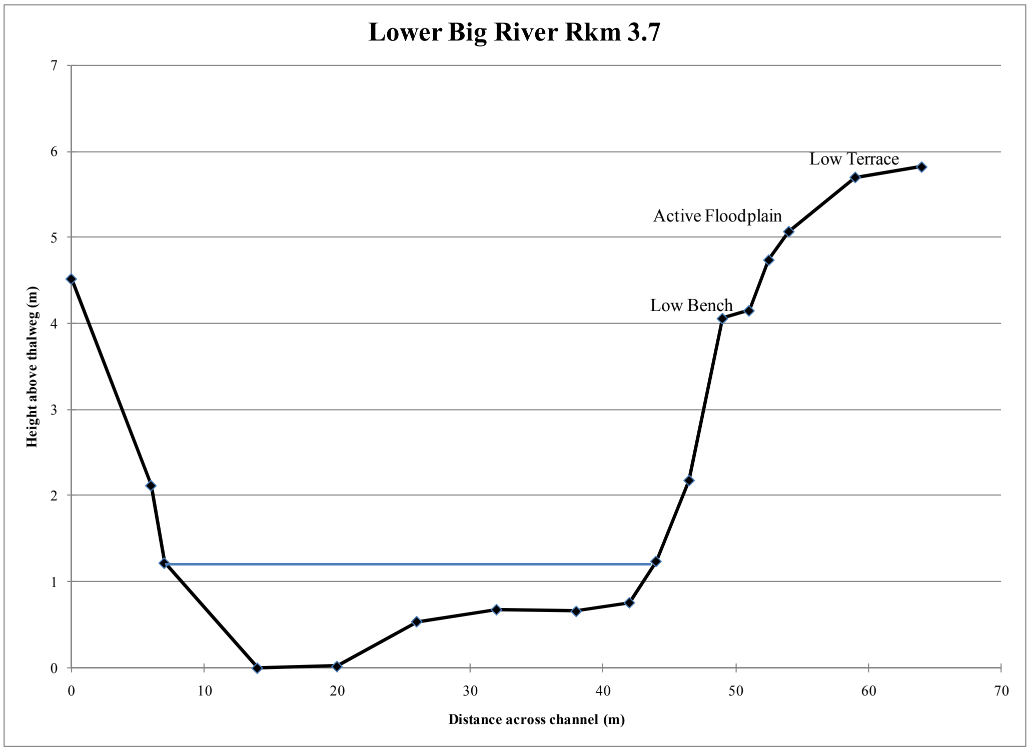

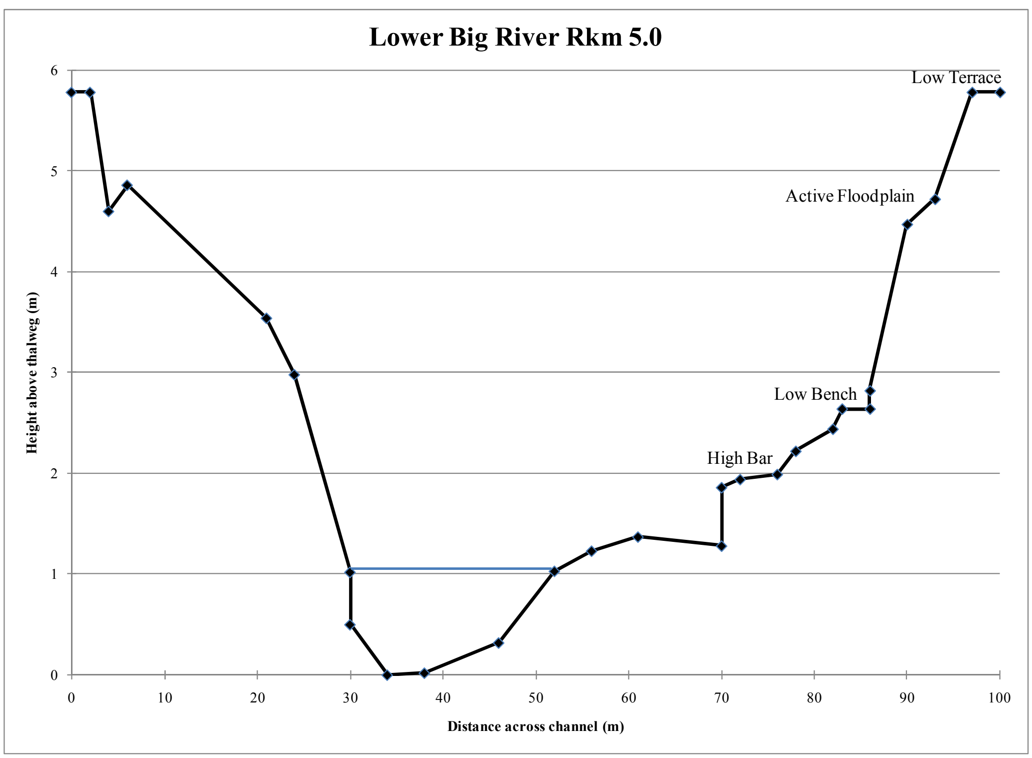

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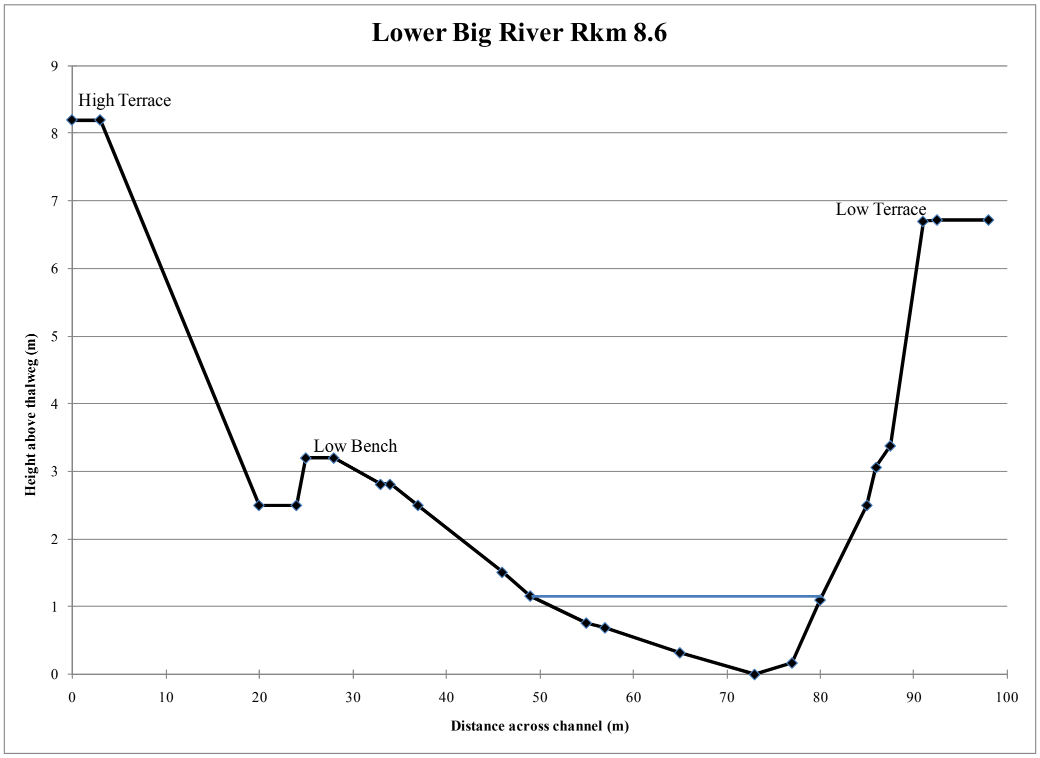
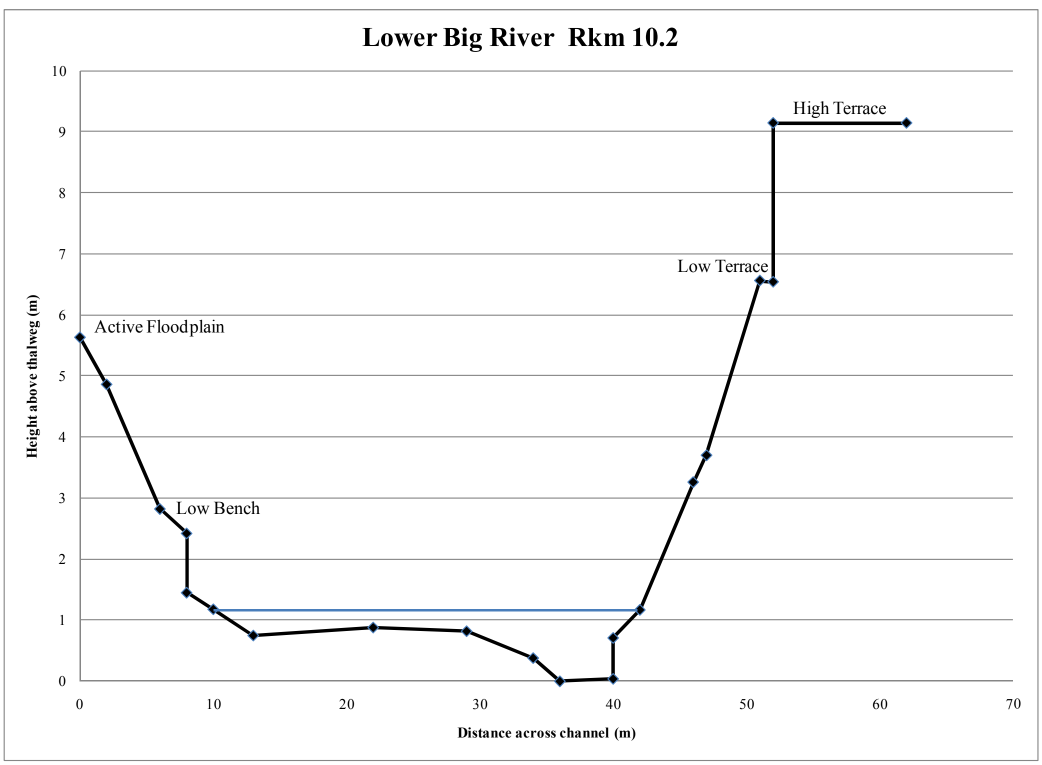
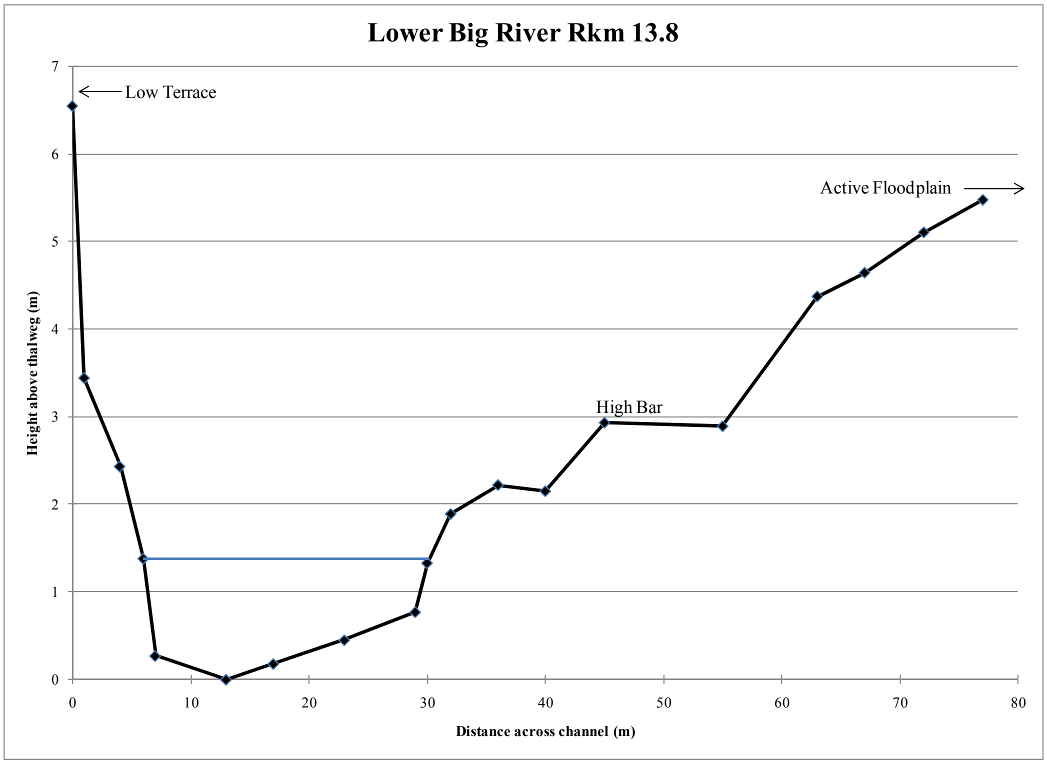
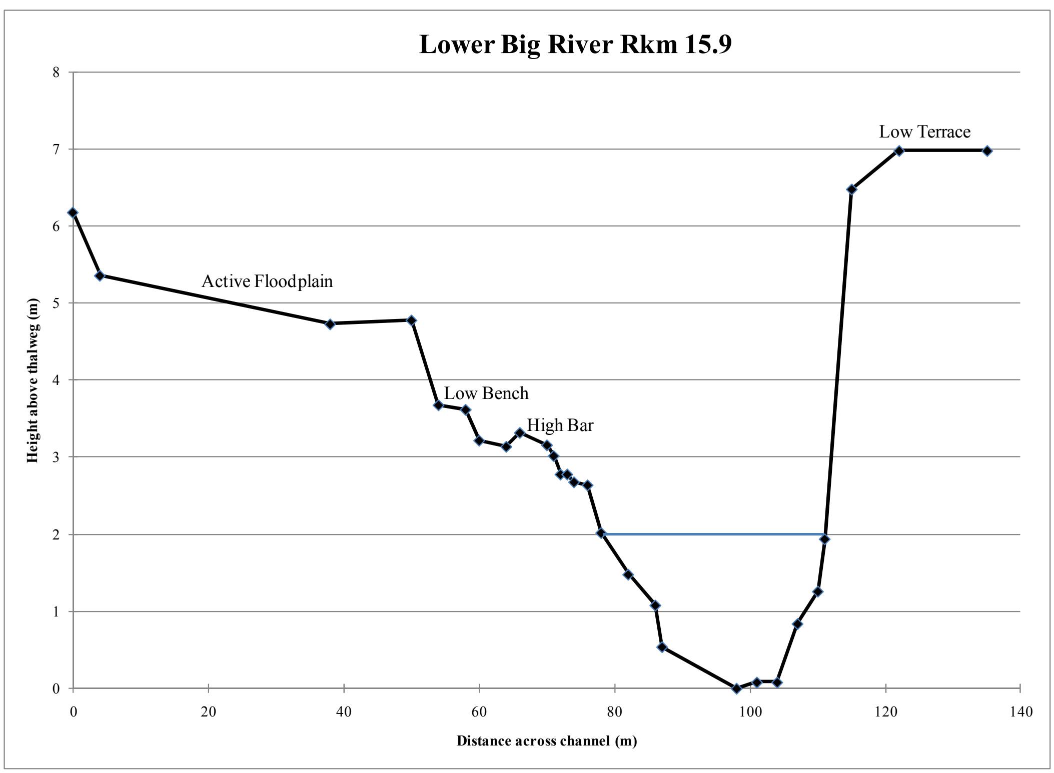


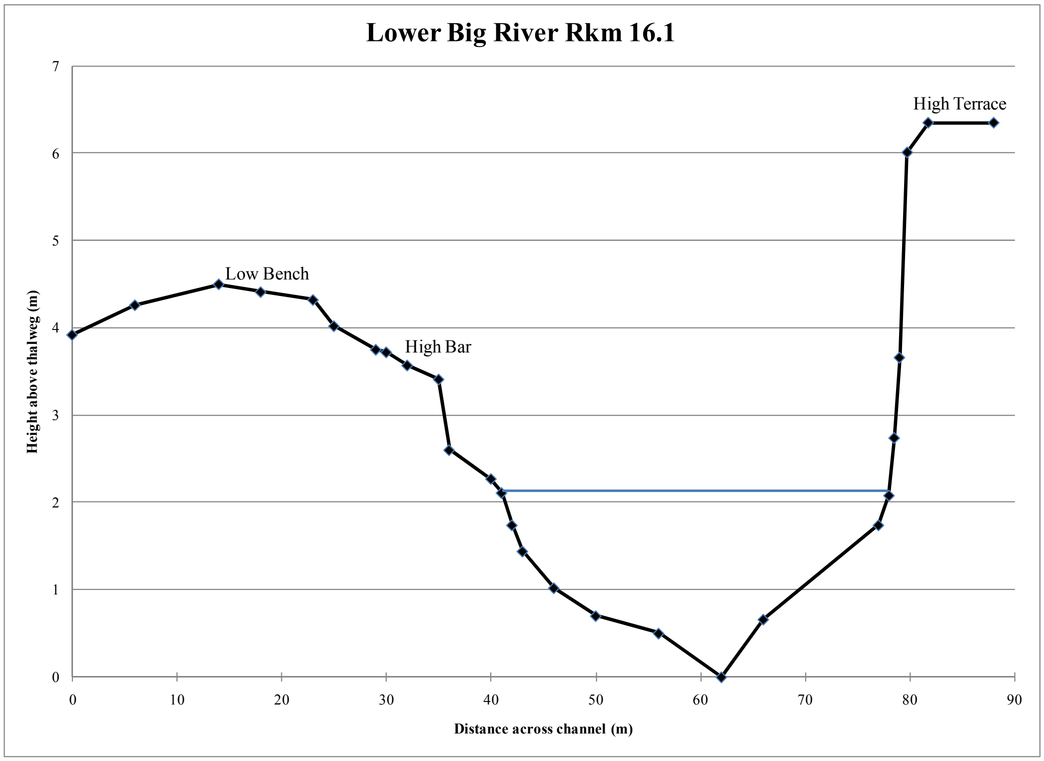


Appendix B Continued. Cross Sections





Appendix B Continued. Cross Sections



Appendix C. Cross Sectional Data

Rkm 0.9 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
100	8.41	high terrace
95	8.41	
80	4.26	
76	4.26	instrument
70	3.41	
65	2.22	
62	1.12	we-R
57	0.84	toe
57	0.44	bed
49	0.32	bed
40.5	0.13	bed
32	0	bed
27	0.07	toe
23	0.2	we-L
19	0.84	
16.5	2.22	
14	2.64	
13	3.35	
11	4.23	
10	4.84	
9.5	6.44	TOB
0	6.44	

Appendix C Continued. Cross Sectional Data

Rkm 2.8 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0	5.6	instrument
4	5.32	low fp edge
9	3.02	bank toe
13	2.95	high bar
20	2.72	
20	2.32	
26	2.02	we-L
32	1.12	bed
38	0	
44	0.44	
50	1.22	toe
50	2.08	
54	2.19	
56	2.46	
58	4.38	
62	6.09	
64.5	6.98	
80	7.22	terrace

Appendix C Continued. Cross Sectional Data

Rkm 3.7 Data		
Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0	4.52	
6	2.12	bank/ slump block
7	1.22	bank/ slump block
14	0	we-L
20	0.02	toe
26	0.54	bed
32	0.68	bed
38	0.66	bed
42	0.76	bed
44	1.24	bed
46.5	2.18	we-R
49	4.06	bank
51	4.15	bench
52.5	4.74	
54	5.07	tob
59	5.7	at instrument
64	5.82	

Appendix C Continued. Cross Sectional Data

Rkm 5.0 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
103	5.78	
100	5.78	
96	4.72	instrument
93	4.47	bench
89	2.82	
89	2.64	
86	2.64	
85	2.44	
81	2.22	high bar
79	1.99	edge high bar
75	1.94	low bar
73	1.86	
73	1.28	
64	1.37	we-R
59	1.23	
55	1.03	
49	0.32	
41	0.02	toe
37	0	we-L
33	0.5	slump deposit
33	1.02	slump deposit
27	2.98	slump deposit
24	3.54	
9	4.86	
7	4.6	
5	5.78	terrace
3	5.78	
0	5.78	

Appendix C Continued. Cross Sectional Data

Rkm 8.6 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
98	6.72	
92.5	6.72	TOB
91	6.7	instrument
87.5	3.38	
86	3.06	top of low bank
85	2.5	slump scar
80	1.1	we-R
77	0.17	toe
73	0	
65	0.32	
57	0.69	
55	0.76	toe
49	1.16	we-L
46	1.51	
37	2.5	edge of fp bench
34	2.81	surface of bench
33	2.81	
28	3.2	FP
25	3.2	backswamp
24	2.5	
20	2.5	terrace
3	8.2	
0	8.2	

Appendix C Continued. Cross Sectional Data

Rkm 10.2 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0	5.63	TOB
2	4.86	mid bank
6	2.82	bench-bank break
8	2.42	top of bench
8	1.45	
10	1.18	we-L
13	0.75	toe
22	0.88	bed
29	0.82	bed
34	0.38	bed
36	0	thalweg
40	0.04	toe
40	0.71	
42	1.17	we-R
46	3.26	lower bank top
47	3.7	
51	6.56	
52	6.54	
52	9.14	
62	9.14	terrace

Appendix C Continued. Cross Sectional Data

Rkm 13.8 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
77	5.47	terrace
72	5.1	
67	4.64	instrument
63	4.37	
55	2.89	bank toe to bar
45	2.93	high bar
40	2.15	low bar
36	2.22	
32	1.89	low bar (mid)
30	1.33	we-R
29	0.77	toe (bar)
23	0.45	bed
17	0.18	
13	0	
7	0.27	toe
6	1.38	we-L
4	2.43	
1	3.44	
0	6.54	TOB

Appendix C Continued. Cross Sectional Data

Rkm 15.9 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0	6.18	
4	5.36	
38	4.73	
50	4.78	in line with station
54	3.68	
58	3.62	
60	3.22	
64	3.14	
66	3.32	
70	3.16	
71	3.02	
72	2.78	
73	2.78	
74	2.68	
76	2.64	
78	2.02	water edge L
82	1.48	
86	1.08	
87	0.54	
98	0	
101	0.08	
104	0.08	
107	0.84	
110	1.26	toe
111	1.94	water edge R
115	6.48	
122	6.98	TOB
135	6.98	

Appendix C Continued. Cross Sectional Data

Rkm 16.1 Data

Distance Across Channel (m)	Height Above Thalweg (m)	Notes
0.0	3.9	
6.0	4.3	
14.0	4.5	
18.0	4.4	
23.0	4.3	instrument
25.0	4.0	
29.0	3.8	
30.0	3.7	high bar
32.0	3.6	high bar
35.0	3.4	high bar
36.0	2.6	high bar
40.0	2.3	
41.0	2.1	
42.0	1.7	water edge L
43.0	1.4	
46.0	1.0	
50.0	0.7	
56.0	0.5	
62.0	0.0	
66.0	0.7	
77.0	1.7	
78.0	2.1	toe
78.5	2.7	water edge R
79.0	3.7	
79.7	6.0	
81.7	6.4	TOB
88.0	6.4	FP/ Terrace

Appendix D. Collected Sample Textural and Geochemical Properties

Unique ID	Landform sampled	Particle Size Distribution (grams)							
		<2mm	2-4mm	4-8mm	8-16mm	16-32mm	32-64mm	>64mm	Total
BY-1	bar	152	76	124	187	65	0	0	604
BY-2	bed	144	90	121	86	16	0	0	457
BY-3	bar	281	34	2	0	0	0	0	317
BY-4	bed	259	143	219	392	334	0	0	1347
BY-5	bank	413	1	0	0	0	0	0	414
BY-6	bank	450	2	0	0	0	0	0	452
BY-7	bank	458	1	0	0	0	0	0	459
BY-8	bank	461	1	0	0	0	0	0	462
BY-9	bank	424	2	0	0	0	0	0	426
BY-12	bar	452	48	53	32	15	0	0	600
BY-13	bed	133	49	130	265	225	33	0	835
BY-14	bar	617	25	7	1	0	0	0	650
BY-16	bed	569	112	90	86	28	59	0	944
BY-17	bank	246	1	0	0	0	0	0	247
BY-18	bank	232	0	0	0	0	0	0	232
BY-19	bank	246	2	0	0	0	0	0	248
BY-20	bank	128	1	0	0	0	0	0	129
BY-22	bar	343	73	118	134	56	0	0	724
BY-23	bar tail	303	91	177	344	286	0	0	1201
BY-24	bed	360	0	0	0	0	0	0	360
BY-25	bar	449	89	62	44	43	0	0	687
BY-28	bed	308	87	152	255	336	75	0	1213
BY-29	bank	485	1	0	0	0	0	0	486
BY-30	bank	334	0	0	0	0	0	0	334
BY-31	bank	482	1	0	0	0	0	0	483
BY-32	bank	335	1	0	0	0	0	0	336
BY-33	bar	112	56	83	0	0	0	0	251
BY-34	bar	159	59	99	0	0	0	0	317
BY-35	bar	550	1	3	0	0	0	0	554
BY-36	bar	349	72	109	133	39	0	0	702
BY-38	bar	207	80	112	234	245	0	0	878
BY-39	bar	802	30	26	0	0	0	0	858
BY-40	bank	495	1	0	0	0	0	0	496
BY-41	bank	272	1	0	0	0	0	0	273
BY-42	bank	478	1	0	0	0	0	0	479
BY-43	bank	173	1	0	0	0	0	0	174
BY-44	bar	308	30	29	40	0	60	0	467
BY-45	bar	399	149	187	85	0	0	0	820
BY-46	bed	584	106	114	91	11	0	0	906
BY-48	bed	89	58	122	88	35	0	0	392

Appendix D Continued. Collected Sample Textural and Geochemical Properties

Unique	Landform	Particle Size Distribution (grams)							
ID	sampled	<2mm	2-4mm	4-8mm	8-16mm	16-32mm	32-64mm	>64mm	Total
BY-49	bar	369	1	0	0	0	0	0	370
BY-50	bed	893	18	26	11	0	0	0	948
BY-53	bar	563	46	76	98	1	0	0	784
BY-54	bed	307	94	153	359	304	0	0	1217
BY-55	bed	489	36	126	236	265	88	0	1240
BY-56	bar	161	59	94	198	111	0	0	623
BY-57	bar	161	59	94	198	111	0	0	623
BY-58	bed	255	107	248	364	145	0	0	1119
BY-59	bed	81	39	131	337	232	0	0	820
BY-62	bed	369	108	213	375	328	0	0	1393
BY-63	bar	603	132	122	64	80	0	0	1001
BY-64	bank	284	1	0	0	0	0	0	285
BY-65	bank	207	1	0	0	0	0	0	208
BY-66	bank	358	1	0	0	0	0	0	359
BY-67	bank	396	0	0	0	0	0	0	396
BY-68	bank	372	0	0	0	0	0	0	372
BY-75	bar	140	31	60	134	56	57	0	478
BY-76	bed	273	106	178	333	54	0	0	944
BY-77	bar	991	44	46	23	0	0	0	1104
BY-78	bed	566	234	295	285	228	0	0	1608
BY-79	bar	690	112	155	193	267	0	0	1417
BY-80	bed	331	0	0	0	0	0	0	331
BY-81	bed	409	145	243	335	214	0	0	1346
BY-82	bar	1203	21	16	2	0	0	0	1242
BY-83	bed	317	92	247	535	347	0	0	1538
BY-84	bar	663	154	266	358	264	0	0	1705
BY-85	bed	267	101	180	251	176	0	0	975
BY-86	bar	988	10	0	0	0	0	0	998
BY-87	bank	205	1	0	0	0	0	0	206
BY-88	bank	557	1	0	0	0	0	0	558
BY-89	bank	420	0	0	0	0	0	0	420
BY-90	bank	289	1	0	0	0	0	0	290
BY-91	bed	433	174	319	273	83	0	0	1282
BY-92	bar	1198	100	134	210	7	0	0	1649
BY-93	bed	787	63	140	154	73	0	0	1217
BY-94	bar	802	36	16	39	37	0	0	930
BY-95	bed	364	136	255	468	159	0	0	1382
BY-96	bar	1282	33	43	29	41	0	0	1428
BY-97	bar head	293	184	258	162	54	0	0	951
BY-98	bar head	166	0	1	0	0	0	0	167

Appendix D Continued. Collected Sample Textural and Geochemical Properties

Unique	Landform	Particle Size Distribution (grams)							
ID	sampled	<2mm	2-4mm	4-8mm	8-16mm	16-32mm	32-64mm	>64mm	Total
BY-99	bar head	447	200	104	50	0	0	0	801
BY-100	bar head	710	33	74	126	95	67	0	1105
BY-101	bar head	397	49	99	143	78	0	0	766
BY-102	bar head	623	23	51	79	66	0	0	842
BY-103	bar head	693	37	58	75	101	0	0	964
BY-104	bar head	519	56	103	203	138	0	0	1019
BY-105	bar head	511	31	72	135	124	49	0	922
BY-106	bar head	585	0	0	0	0	0	0	585
BY-107	bar tail	645	0	0	0	0	0	0	645
BY-108	bar tail	731	0	0	0	0	0	0	731
BY-109	bar tail	569	0	0	0	0	0	0	569
BY-110	bar tail	689	0	0	0	0	0	0	689
BY-111	bar tail	703	0	0	0	0	0	0	703
BY-113	bank	471	0	0	0	0	0	0	471
BY-114	bank	322	0	0	0	0	0	0	322
BY-115	bank	439	0	0	0	0	0	0	439
BY-116	bank	528	0	0	0	0	0	0	528
BY-117	bank	589	0	0	0	0	0	0	589

Appendix D Continued. Collected Sample Textural and Geochemical Properties

Unique ID	Landform sampled	Element Concentration (ppm)			
		Pb <2mm	Zn <2mm	Ca <2mm	Fe <2mm
BY-1	bar	415	98	2686	12123
BY-2	bed	138	76	ND	8152
BY-3	bar	385	136	7790	12613
BY-4	bed	106	68	2737	5836
BY-5	bank	1134	6757	19826	996
BY-6	bank	957	5493	16447	815
BY-7	bank	66	3158	17599	836
BY-8	bank	157	3026	15784	728
BY-9	bank	45	2508	15967	910
BY-12	bar	111	80	ND	7904
BY-13	bed	177	85	5819	11072
BY-14	bar	74	49	934	4940
BY-16	bed	46	29	909	3052
BY-17	bank	961	6179	21184	1036
BY-18	bank	1580	9616	23139	1094
BY-19	bank	2156	7598	19356	981
BY-20	bank	342	5202	17812	916
BY-22	bar	73	77	ND	8411
BY-23	bar tail	82	76	1120	7803
BY-24	bed	354	130	11425	13316
BY-25	bar	142	105	ND	11082
BY-28	bed	81	65	1087	7348
BY-29	bank	71	2183	18091	746
BY-30	bank	47	1938	15820	652
BY-31	bank		1725	14406	658
BY-32	bank	20	1588	9366	322
BY-33	bar	277	99	8618	9947
BY-34	bar	405	130	7571	11313
BY-35	bar	148	65	2516	6508
BY-36	bar	110	72	1461	6652
BY-38	bar	143	98	1044	12182
BY-39	bar	56	39	2072	6174
BY-40	bank	205	2411	9132	372
BY-41	bank	1575	4620	21281	1103
BY-42	bank	87	2254	17736	717
BY-43	bank	58	2592	15374	692
BY-44	bar	84	45	4004	5669
BY-45	bar	188	83	3540	9634
BY-46	bed	168	95	1466	9807
BY-48	bed	130	76	6632	8150

Appendix D Continued. Collected Sample Textural and Geochemical Properties

Unique ID	Landform sampled	Element Concentration (ppm) Pb <2mm	Zn <2mm	Ca <2mm	Fe <2mm
BY-49	bar	751	186	14292	15401
BY-50	bed	137	61	2614	6314
BY-53	bar	93	50	ND	5752
BY-54	bed	151	95	1202	9657
BY-55	bed	79	36	ND	4215
BY-56	bar	198	73	2096	7301
BY-57	bar	198	73	2096	7301
BY-58	bed	92	37	ND	4334
BY-59	bed	65	25	ND	3185
BY-62	bed	77	36	ND	5188
BY-63	bar	57	29	ND	3374
BY-64	bank	292	3340	18825	866
BY-65	bank	76	2915	19901	864
BY-66	bank	69	2766	20641	993
BY-67	bank	42	2858	18083	791
BY-68	bank	43	2342	17472	790
BY-75	bar	66	35	34789	4568
BY-76	bed	106	60	3755	5664
BY-77	bar	70	47	2135	4874
BY-78	bed	92	56	867	6686
BY-79	bar	69	53	ND	5726
BY-80	bed	359	123	7321	9905
BY-81	bed	71	53	919	6708
BY-82	bar	135	65	1223	7240
BY-83	bed	59	38	1078	5049
BY-84	bar	77	43	1105	4839
BY-85	bed	215	78	5185	8004
BY-86	bar	372	102	5704	10028
BY-87	bank	1499	9230	20689	1096
BY-88	bank	621	3713	18510	956
BY-89	bank	65	2808	15008	594
BY-90	bank	478	3552	27782	2033
BY-91	bed	87	48	1272	4486
BY-92	bar	55	46	ND	6137
BY-93	bed	28	11	ND	2517
BY-94	bar	244	84	5348	7046
BY-95	bed	122	81	5383	8739
BY-96	bar	42	26	3582	2753
BY-97	bar head	356	99	5348	9223
BY-98	bar head	146	91	19643	20750

Appendix D Continued. Collected Sample Textural and Geochemical Properties

Unique ID	Landform sampled	Element Concentration (ppm)			
		Pb <2mm	Zn <2mm	Ca <2mm	Fe <2mm
BY-99	bar head	359	133	2395	13124
BY-100	bar head	67	34	1627	4697
BY-101	bar head	77	49	2200	6650
BY-102	bar head	96	52	1802	5481
BY-103	bar head	75	44	1432	7240
BY-104	bar head	48	32	ND	4640
BY-105	bar head	44	27	ND	3886
BY-106	bar head	46	33	1800	4191
BY-107	bar tail	55	40	ND	5559
BY-108	bar tail	41	24	869	3171
BY-109	bar tail	75	52	1272	6480
BY-110	bar tail	71	44	4871	5498
BY-111	bar tail	40	28	ND	3374
BY-113	bank	873	7379	20430	1021
BY-114	bank	1975	11144	22688	1293
BY-115	bank	2902	10551	20578	1111
BY-116	bank	72	2905	17726	892
BY-117	bank	66	4213	16812	738