# SPATIAL PATTERNS AND FLOODPLAIN CONTRIBUTIONS OF MINING-RELATED CONTAMINANTS IN CHAT CREEK WATERSHED, SOUTHWEST MISSOURI

A Thesis

Presented to

the Graduate Faculty of the Department of

Geography, Geology and Planning

Southwest Missouri State University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Resource Planning

By

Jimmy C. Trimble

December 2001

SPATIAL PATTERNS AND FLUVIAL SEDIMENT CONTRIBUTIONS OF MINING RELATED CONTAMINANTS IN CHAT CREEK
WATERSHED, SOUTHWEST MISSOURI

Department of Geography, Geology and Planning

Southwest Missouri State University, December 2001

Degree of Master of Science in Resource Planning

Jimmy C. Trimble

## ABSTRACT

Past mining activities have left a legacy of water quality problems in the Tri-State Mining District. Contemporary environmental risks stem from the release of lead and zinc from mine tailings previously dispersed far downstream in alluvial deposits as well as abandoned tailings piles. This study examines mining-related heavy metal contamination in the Chat Creek Watershed. Chat Creek drains the area near Aurora, Missouri on the eastern edge of the Tri-State District where mining occurred from 1886 to about 1930. This study identifies the spatial distribution of metal contamination in fluvial sediments and quantifies the role of bank erosion as a secondary source of contamination to the watershed. The three objectives of this study are to: (1) determine the spatial distribution of lead and zinc contamination in the watershed; (2) determine erosion rates due to lateral stream migration; and (3) develop a sediment-metal budget for floodplain erosion. Sediment samples were taken from active channel and floodplain deposits to determine the current distribution of metals. Historical aerial photographs are used to determine lateral migration rates. Sediment-metal concentration data were combined with migration rates to determine a short-term sediment-metal budget for the 5.5 km study area. Lead concentrations in active channel sediment range from 60 ppm to 2,068 ppm. Zinc concentrations range from 286 ppm to 19,666 ppm. Average floodplain lead concentrations range from 59-643 ppm while zinc ranges from 191 ppm to 5,377 ppm. Bank erosion releases 929 Mg of sediment into Chat Creek each year. Floodplain erosion also releases 84 kg/yr of lead and 321 kg/yr of zinc into Chat Creek. This study provides resource managers, in charge of Total Maximum Daily Load determination, with data concerning metal contamination in Chat Creek and the amounts of metals being introduced into the system due to reworking of floodplain deposits.

This abstract is approved as to form and content

Chairperson, Robert T. Pavlowsky
Southwest Missouri State University

# SPATIAL PATTERNS AND FLUVIAL SEDIMENT CONTRIBUTIONS OF MINING RELATED CONTAMINANTS IN CHAT CREEK WATERSHED, SOUTHWEST MISSOURI

By

Jimmy C. Trimble

A Thesis
Submitted to the Graduate School
of Southwest Missouri State University
in Partial Fulfillment of the Requirements
for the Degree of Master of Science in Resource Planning

December 2001

Approved:

Robert T. Pavlowsky, Ph.D., Chairperson

Rex Cammack, Ph.D., Member

Elias Johnson, Ph.D., Member

Frank Einhellig, Ph.D., Associate Vice
President for Academic Affairs
and Dean of the Graduate College

# ACKNOWLEDGMENTS

I would like to acknowledge many people who contributed to the completion of this thesis research. First I would like to thank my committee members. Special thanks to my thesis advisor and mentor Dr. Robert T. Pavlowsky, who guided my learning and understanding throughout this process. My committee members, Dr. Rex Cammack and Dr. Elias Johnson, also deserve many thanks for their technical advice and encouragement. I would also like to thank the faculty and staff of the Department of Geography, Geology, and Planning Department at Southwest Missouri State for their support and assistance. Thanks to Deana Gibson for her editorial work and insight. My fellow graduate students also deserve acknowledgment for their help and support. Thanks to Ryan Wyllie who gave many hours of his own time to my fieldwork. Brian Fredrick and Marc Owen also deserve thanks for their GIS related advice. I also appreciate the willingness of landowners to allow access to Chat Creek on their properties.

Two sources provided funding for this thesis research: (1) SMSU Faculty Research Grant to Dr. Robert T. Pavlowsky entitled, "Geography and Geochemistry of Metal Contamination in River Sediments, Spring River Watershed, Tri-State Zn-Pb District" for $6,640; and (2) SMSU Graduate College MS Thesis Grant to Jimmy Trimble for $500.

I would also like to express a special thanks to my family and friends who have supported and encouraged me throughout this process. My parents and sisters deserve many thanks for their never-ending support.

## TABLE OF CONTENTS

## TABLE OF CONTENTS CONTINUED

## TABLE OF CONTENTS CONTINUED

# LIST OF TABLES

Page

## LIST OF FIGURES

## LIST OF FIGURES CONTINUED

# CHAPTER 1

# INTRODUCTION

## Mining –Related Water Quality Concerns

Metal contaminants released from active and abandoned base-metal mines to river systems represent a major environmental problem worldwide (Hawes-Davis, 1993; Forstner, 1995; USEPA, 1995; Carroll *et al.,* 1998; Caruso and Ward, 1998; Marcus *et al.*, 2001). Of concern are the effects that mining-related pollution has on water quality (Barks, 1977; Spruill, 1987; Hawes-Davis, 1993; Peterson *et al.*, 1998) and the dispersal of these metals throughout river systems (Warren, 1981; Marcus, 1987; Bradley, 1989, James, 1989; Foster and Charlesworth, 1996; Miller, 1997). The contamination problem can originally stem from several different sources associated with mining activities. Most of these sources such as mill effluents, acid mine drainage, and tailings input are point sources concentrated in close proximity to the active or abandoned mines (Salomons, 1995). However, the release of metals from previously contaminated alluvial deposits has drawn much recent investigation (Bradley, 1989). Contaminated alluvial deposits can be spatially diffuse and act as pollution sources to receiving waters for long periods of time due to erosion and chemical weathering, and thus are considered nonpoint sources of pollution. Researchers have worked to gain an understanding of the transport of metals from the time of initial introduction to the time of exit from the watershed.

Mining-derived contaminants undergo several depositional and erosional cycles before ultimately being transported out of the watershed. The timing and duration of these cycles may mean that these contaminants remain in the watershed for decades if not centuries (Pavlowsky, 1996; Marcus *et al.*, 2001). Once introduced into the stream system, these contaminants are subsequently carried downstream and are usually deposited in channel deposits and floodplain deposits before being completely flushed from the system (James, 1989). Contaminants deposited in the stream channel may be entrained by subsequent floods and carried downstream where it is either again deposited in the channel, in floodplain deposits, or washed from the system (James, 1989). Floodplain deposits act as water quality buffers storing contaminants away from the active stream system (Bradley and Cox, 1990; Lecce and Pavlowsky, 1997; Lecce and Pavlowsky, 2001). The effectiveness of this buffering mechanism depends on the rate at which the channel migrates laterally and erodes the contaminated floodplain deposits. Floodplain stored contaminants remain in storage until lateral stream migration erodes these deposits and re-releases the metals into the stream (Bradley and Cox, 1990; Rowan *et al.,* 1995; Lecce and Pavlowsky, 1997; Smith *et al.*, 1998). Thus, floodplain deposits become secondary non-point sources of contaminants (Lewin *et al.*, 1977; Rowan *et al.*, 1995; Smith *et al.*, 1998).

Watershed-scale contamination relating to mining waste is a concern in the Tri-State Mining District of southwest Missouri. To date, studies have been conducted to understand mining contaminant effects on water quality (Barks, 1977; Peterson *et al.*, 1998) but little is known about the spatial distribution and transport of these contaminants in sediments. Barks (1977) examined the water quality in the Joplin, Missouri area as a result of abandoned lead and zinc mines. He found that tailings pollution increased zinc concentrations in bottom sediment from 100 µg/g to ~2,500 µg/g and lead concentrations from 20 µg/g to ~450 µg/g. A study completed in cooperation with the National Water-Quality Assessment Program determined that lead and zinc concentrations (both dissolved and sediment-bound) are elevated above background levels downstream of abandoned mining sites in the Tri-State Mining District (Petersen *et al.*, 1998). Sediment-bound lead and zinc concentrations downstream of historical mining sites were determined to be above threshold guidelines for possible adverse affects on biota. Carlson (1999) investigated zinc and lead concentrations in active stream sediments downstream of mining areas in the Honey Creek watershed in southwest Missouri. Zinc concentrations directly downstream of past mining sites average 163 times background levels. Zinc levels remain elevated at a distance of 24 km downstream of mining sites where levels are over three times higher than background (Carlson, 1999). Carlson (1999), also found that lead concentrations are not as elevated as zinc. Lead concentrations in active stream sediments are 21 times higher than background immediately downstream of mining and fall to two times background 2 km downstream.

The Chat Creek watershed near Aurora, Missouri is an area that suffers from the legacy of past mining activities. Abandoned mining operations in the headwaters of this stream have created contemporary water quality concerns. The Missouri State Department of Natural Resources recognizes Chat Creek as having impaired water quality due to zinc from mining activities. A study in an adjacent watershed, Honey Creek, showed that high levels of lead and zinc are contained in the channel and bank sediments (Carlson, 1999).

## Scope of Study

This study focuses on understanding the effects of mining-related zinc and lead pollution on sediment quality in the Chat Creek Watershed, which is located along the eastern boundary of the Tri-State Mining District in the Upper Spring River Basin. Chat

Creek has been heavily impacted due to past mining activities in the Aurora sub-district of the Tri-State Mining District. The contamination concern is well known, but to date, no studies have been completed to determine the spatial extent, severity, and non-point sources of the contamination. The Missouri Department of Natural Resources (MDNR) recognizes Chat Creek on its state 303d list of waters that have water quality concerns (EPA, 1998). The degradation of water quality in Chat Creek is attributed to zinc from abandoned mining operations. Under the Clean Water Act of 1977, the MDNR must establish a management plan for restoring water quality in the degraded body of water. One of the main stipulations is that the MDNR must develop a Total Maximum Daily Load (TMDL) for the responsible contaminant. The established TMDL will then be used to allocate release rates of the contaminant from different portions of the watershed and including both point or non-point sources (USEPA, 1999). This study also examines lead contamination in Chat Creek because of its hazardous nature in general and strong association with zinc in the contaminated sediments.

Even though mining ceased over seventy years ago there still remains a threat of lead and zinc contamination into Chat Creek. This threat mainly stems from erosion of abandoned tailings piles and the release of metals from previously contaminated alluvial deposits, specifically floodplain deposits. Most of the remnant tailings piles are now subdued features on the landscape covered in vegetation, therefore, eroding floodplain deposits may be a significant source of lead and zinc.

## Purpose Statement

Chat Creek has impaired water quality due to past mining activities, but little is known about the spatial distribution of this contamination and how it is being transported through the watershed. These factors must be better understood in order to improve the water quality in Chat Creek. The MDNR's protocol for developing TMDLs stipulates that an initial step in determining an appropriate TMDL is to identify the sources of contaminants and their relative contribution of contaminants (USEPA, 1999). The purpose of this study is to gain an understanding of the distribution of contamination in Chat Creek and to determine the importance of floodplain erosion as a non-point source. Past studies have recognized a need for quantitative information on sediment- bound contaminant transport between the time of original release and when the contaminant is ultimately flushed from the system (Meade, 1982; Walling, 1983). The quantitative knowledge generated by this study concerning the metal contamination in Chat Creek and its transport will allow for better management decisions.

## Research Questions

The goal of this research is to address two main questions concerning metal contamination in Chat Creek. Each research question contains two sub-questions to be addressed.

1. **What is the geographic distribution of metal contamination in the fluvial sediments of Chat Creek?**
    - What are the levels of contamination?
    - What portions of the stream system are most heavily contaminated?

In order to make effective management decisions concerning water quality improvement in Chat Creek, the patterns of contamination must be understood. It is also important to identify less contaminated areas so that limited restoration resources are not wasted.

2. **Are floodplain deposits acting as pollution buffers, storing metals out of the active stream system?**
    - What are the bank erosion rates and downstream trends along Chat Creek?
    - How much metals are being released into the system from the reworking of floodplain deposits?

Mining sites and remnant tailings piles are easily identified on historic maps or by scars on the landscape. Since these areas are relatively easy to locate, they get the most attention as contamination sources. The erosion of stream banks is a subdued, natural process that may go unrecognized as a possible significant non-point source of metals into Chat Creek.

## Objectives

There are three major objectives in this thesis research:

1. **Determine the spatial distribution and magnitude of mining-related metal contamination in both active channel and bank sediments within the Chat Creek watershed.**

No previous studies have been conducted on active channel or bank sediments to monitor lead and zinc contamination within these two fluvial environments. Initial assessments of lead and zinc levels and distributions are a vital first step to identify problem areas. Management efforts may then be focused on high priority areas.

2. **Determine lateral bank erosion rates for the stream.**

The importance of this objective is twofold. It is important to this investigation because lateral erosion rates are an important variable in determining amounts of material released into the stream due to erosion. Therefore, the third objective will not be realized without determining rates of migration. In addition, the Water Restoration Action Strategy (WRAS) report for the Upper Spring River identifies sediment introduction into Chat Creek as a concern of local citizens (WRAS, 2000). Areas with high erosion rates can be targeted for restoration projects to limit sediment release into the stream.

**3. Calculate a sediment-metal budget for the floodplain erosion system.**

It is important to identify the important possible sources of lead and zinc within the watershed. Modeling the downstream relationship of deposition and erosion of metals will identify problem areas within the watershed. This budgeting procedure will also allow for a general determination of the amount of metals released into the Spring River from Chat Creek due to floodplain erosion.

## Hypothesis

It is hypothesized that contamination patterns in Chat Creek will be similar to other watersheds that have been impacted by past mining activities. Due to selective sorting, deposition, and mixing and dilution with uncontaminated sediments, metal contamination levels in sediments tend to decay downstream of mining sites (Marcus, 1987; Pavlowsky, 1995).

Secondly, it is hypothesized that Chat Creek, like other mining impacted streams, will have a large proportion of current contamination entering the stream from lateral channel migration and erosion of previously contaminated floodplain deposits (Rowan *et al.*, 1995; Smith *et al.*, 1998). Some watersheds that have had mining waste sites and milling sites removed or remediated receive a large proportion of current contamination from erosion of floodplain deposits. Therefore, metal levels in stream sediments remain high even though upstream sources have been eliminated (Rowan *et al.*, 1995; Smith *et al.*, 1998).

## Benefits of Study

In order to improve the water quality of Chat Creek, the degree and location of contamination as well as sources of the metals must be better understood. This study will facilitate this understanding. This research will contribute to the source load assessment process for establishing TMDL criteria for Chat Creek. In order for state agencies to establish an appropriate TMDL, all sources and contributions of the contaminant must be quantified. By better understanding the spatial distribution of the metal contamination and processes acting to transport it, management efforts can be focused and thus more effective. Additionally, this study will improve the overall understanding of fluvial processes in Ozark streams since little is presently known about sediment release rates from floodplain deposits in Ozark streams.

On a broader-scale, this study will shed light on fluvial processes that shape the earth's surface. Watersheds with past mining activities provide valuable natural laboratories in which to study sedimentation patterns and sediment transport. Metals that attach to sediment and are referenced spatially and temporally provide valuable tags for which to trace sediment as it is dispersed through fluvial systems (Knox, 1987; Marcus, 1987; Bradley, 1989).

This thesis research also provides a unique approach combining field-based investigations with geospatial technologies to evaluate environmental problems. With the increasing availability of inexpensive high quality digital data such as aerial photographs, researchers are fusing empirical field-based studies with digital analysis.

This study is an extension of this research approach. Geographic Information Systems allow the integration of field data and geospatial data to solve complex environmental problems. Most prior similar studies focus on large study areas. Both the study by Smith *et al.* (1998) and the study by Rowan *et al.* (1995) combine digital spatial analysis with field investigations on relatively large streams. The current research tests this approach by applying it to a very small-scale area. Advances in software technology and higher resolution geospatial data have allowed researchers to investigate small-scale environmental issues such as stream bank erosion. These studies utilize terrestrial photogrammetry to develop detailed large-scale digital terrain models (DTMs), which are used to evaluated changes in stream bank form over time (Barker *et al.*, 1997; Heritage *et al.*, 1998). These studies are aimed at improving techniques used to budget sediment transport at reach–scale levels.

# CHAPTER 2

# TRANSPORT AND DISTRIBUTION OF MINING RELATED CONTAMINANTS IN FLUVIAL SYSTEMS

The Chat Creek Watershed has been greatly impacted by past zinc and lead mining activities. Erosion and leaching of abandoned mining sites have released zinc and lead into the stream where fluvial processes distribute the metals downstream. Thus, channel and floodplains deposits along Chat Creek are heavily contaminated with mining-related zinc and lead. Presently, some of the contaminated floodplain deposits are being reworked by fluvial processes and are secondarily entering the stream system as non-point source contaminants. Metals derived from abandoned mining sites have been distributed throughout the watershed by various fluvial processes. This chapter discusses sediment bound metal contamination in fluvial systems as well as geomorphic processes that initially distribute these sediment bound contaminants within a watershed. Fluvial processes that are responsible for secondary introduction of metal contamination such as lateral channel migration and floodplain reworking will also be addressed. Next, the use of digital technologies to analyze lateral channel migration in watersheds that have not been previously surveyed will be discussed. Lastly, this chapter will discuss studies conducted on mining contamination in other Ozark streams.

## Metal Contaminants in Fluvial Systems

In water quality studies, research is concerned with contaminants that are both dissolved and attached to sediment and how these contaminants are delivered to and dispersed through watersheds. Since, research has shifted from focusing on a lack of nutrients in soil to problems with contaminants in the soils (Holmgren *et al.*, 1993;

Forstner, 1995), the emphasis in recent years has focused on understanding the effects of heavy metal contamination on water resources. Metals can move up the biological food chain until ultimately ending up in the blood stream of humans (Forstner, 1995). Of particular importance to this study, a body of literature has developed that examines heavy metal contamination from abandoned mining sites. Bradley (1989) reviewed an early study examining low zinc and lead from mining operations had an adverse affect on a water supply in the United Kingdom. More recent investigations on contaminants from mining areas began in the early 1970s. Many of these studies focused on metal contaminant distribution and transport in areas of the Upper Mississippi Valley (Knox, 1987; Pavlowsky, 1995; Lecce and Pavlowsky, 1997; Lecce and Pavlowsky, 2001), European mining areas (Bradley, 1989; Rowan *et al.*, 1995), and mining areas of the western U.S. (Marcus, 1987; James, 1989; Smith *et al.*, 1998).

Certain amounts of trace metals occur naturally in soil and water systems, but when these amounts become elevated and toxic to organisms it is of great concern to natural resource managers (Holmgren *et al.*, 1993). Many recent studies have found that areas with past mining operations have elevated levels of lead and zinc in the local fluvial environments (Swennen *et al.*, 1994; USEPA, 1995; Rowan *et al.*, 1995; Lecce and Pavlowsky, 1997; Smith *et al.*, 1998;). Research has focused on the terrestrial and alluvial sources of metals, such as lead and zinc and how these metals are transported through fluvial systems (Rowan *et al.*, 1995; Foster and Charlesworth, 1996; Smith *et al.*, 1998). These types of studies involve an understanding of sediment transport and sediment geochemistry since metals tend to attach more readily to sediment than dissolve in water (Steele and Wagner, 1975; Forstner and Muller, 1981; Warren, 1981; Foster and

Charlesworth, 1996; Helgen and Moore, 1996). It is not unusual for 90-99% of metal loads in a fluvial system to be transported attached to sediment (Miller, 1997). This observation creates a two-pronged research need. First, fluvial sediment transport processes must be better understood in order to analyze transport and dispersion of metal contaminants (Miller, 1997). Second, using metal contaminants as temporal tracers allows fluvial geomorphologists to expand the understanding of fluvial process involved with sediment transport through researching mined watersheds.

## Geomorphic Response to Land Use Changes

Many studies have addressed channel changes that have resulted from changes in land use or watershed surface cover. Knox (1977, 1987) has done an extensive investigation of channel changes due to land use changes and the resulting sedimentation rates in the Upper Mississippi Valley area of southwestern Wisconsin and northwestern Illinois. Other studies have also examined the hydrologic effects of land use changes on stream channels (Trimble, 1983; Jacobson, 1995; Jacobson and Gran, 1999). Studies have also investigated the recovery of rivers after the removal of preturbation. Magilligan and Stamp (1997) investigated the geomorphic response to changing hydrologic conditions induced by land clearing. The authors also examined the hydrologic and geomorphic response to the removal of the disturbance by revegetation. Magilligan and Stamp (1997) concluded that flood peak hydrographs and sedimentation rates have declined since revegetation. Flood peaks and sedimentation rates have stabilized but remain higher than modeled pre-settlement measurements indicating the establishment of a new hydrologic and geomorphic equilibrium.

Initial land clearing for settlement and agriculture along with poor agricultural practices increases runoff rates and sediment available for transport (Knox, 1977; Knox, 1987; Ruhlman and Nutter, 1999). The increased runoff and erosion creates more overbank flow events in lower order tributaries (Knox, 1987). This creates a situation in which overbank flow events deposit large amounts of sediment in the low energy floodplain areas; the floodplain subsequently aggrades increasing channel depth (Knox, 1987; Odemerho, 1992). Subsequent flood events are then contained and concentrated on downstream areas thus increasing bank and bed erosion rates. A second geomorphic response to land use change is a widening of the stream channel, especially in streams with relatively small drainages (<155 km$^2$)(Knox, 1977; Grant and Goddard, 1980). The result is that streams can now hold all but the largest of flow events within its banks. Ruhlman and Nutter (1999) also concluded that the Upper Oconee River in the Georgia Piedmont has undergone a period of channel enlargement since land clearing resulting in lower overbank flood frequencies.

Due to an improvement in agricultural practices, soil conservation practices and an increase in impervious surface, the sediment supply is reduced but runoff remains high. This situation results in less floodplain aggradation but an increase in channel size since the channel begins to expend its energy by eroding its banks (Odemerho, 1992). The stream migrates laterally because of this erosion, thus adding more sediment and attached pollutants to the stream.

## Sediment-Metal Dispersion in Mined Watersheds

### *Tracing Dislodged Sediment*

The metals released by mining operations to streams can be used as stratigraphic markers to trace the path of sediment as it is cycled through fluvial systems (Knox, 1987; Marcus, 1987; Bradley, 1989; Pavlowsky, 1995; Rowan *et al.*, 1995; Sear and Carver, 1996; Graf, 1996; Lecce and Pavlowsky, 1997; Carlson, 1999). Once the metals are introduced into the stream system via tailings release, they are deposited in one of three basic areas: (1) as colluvium; (2) deposited as alluvium in channel or on floodplains; or (3) flushed from system (Trimble, 1983). The spatial distribution of mining-related metals in the fluvial system depends on the location and number of mining sites in the watershed as well as how the sediment is sorted, the manner in which contaminated sediment is mixed with uncontaminated sediment, and how the sediment is deposited and stored on the floodplain (Foster and Charlesworth, 1996).

Other studies were completed utilizing metal tags to examine downstream sediment transport and dispersion. Marcus (1987) tested downstream dispersion models and the difference between dispersion of heavy metals attached to suspended loads as opposed to heavy metals contained in bedload. Marcus (1989) tested whether sediment bound metal loads from monitored tributaries can be successfully translated to unmonitored tributaries. Another study used dispersion models to quantify metal loads both before mining and after mining. This was done in an attempt to create better background knowledge in order to improve understanding of elevated contamination levels (Helgen and Moore, 1996). Other "tracer" studies have quantified post settlement floodplain sedimentation rates using metal tracers (Knox, 1987; Lecce and Pavlowsky, 1997; Carlson, 1999). These studies are expanded in a later section.

After quantifying the downstream distribution of metals in the Allen basin, Goodyear *et al.* (1996) tested the Hawkes' model for its applicability in contamination source studies. Hawkes' model is used to estimate downstream dispersion of lead and zinc as a function of dilution by clean sediment input (Pavlowsky, 1995). This estimation was compared to actual levels, determined by sampling, to determine the reliance of Hawkes' model in this application. Hawkes' model estimations resembled actual levels when the concentrations were near background levels, as contamination increased Hawkes' model lost accuracy (Goodyear *et al.*, 1996). Other studies have examined geochemistry and natural sorting and mixing processes to determine spatial distribution of mining derived contaminants (Pavlowsky, 1995; Sear and Carver, 1996; Graf, 1996). Combest (1991) studied spatial distribution of metals in an urban stream but did not focus specifically on mining derived metals. He concluded that sediment-bound zinc introduced to an urban stream did not decay downstream. Combest (1991) also concluded that lead levels actually increase downstream possibly due to the response of increased lead input from nonpoint sources.

James (1989) tested Gilbert's sediment wave model on the Bear River in California by using quartz vein mineral tracers. James concluded that sediment transport in the Bear River may not follow the symmetrical wave Gilbert proposed instead it was asymmetrical. This asymmetrical wave, skewed to the right, is the result of remobilization of sediment stored in and along the channel margin in floodplain and terrace deposits (Figure 2.1) (James, 1989). Even after sediment remains in storage over fifty years the storage may not necessarily be permanent. Decreasing downstream sediment yields are usually due to this storage, but if upland areas are stabilized main channels may begin to erode and increase sediment yield downstream. Thus, ultimately this released the stored sediment and associated metals (James, 1989).

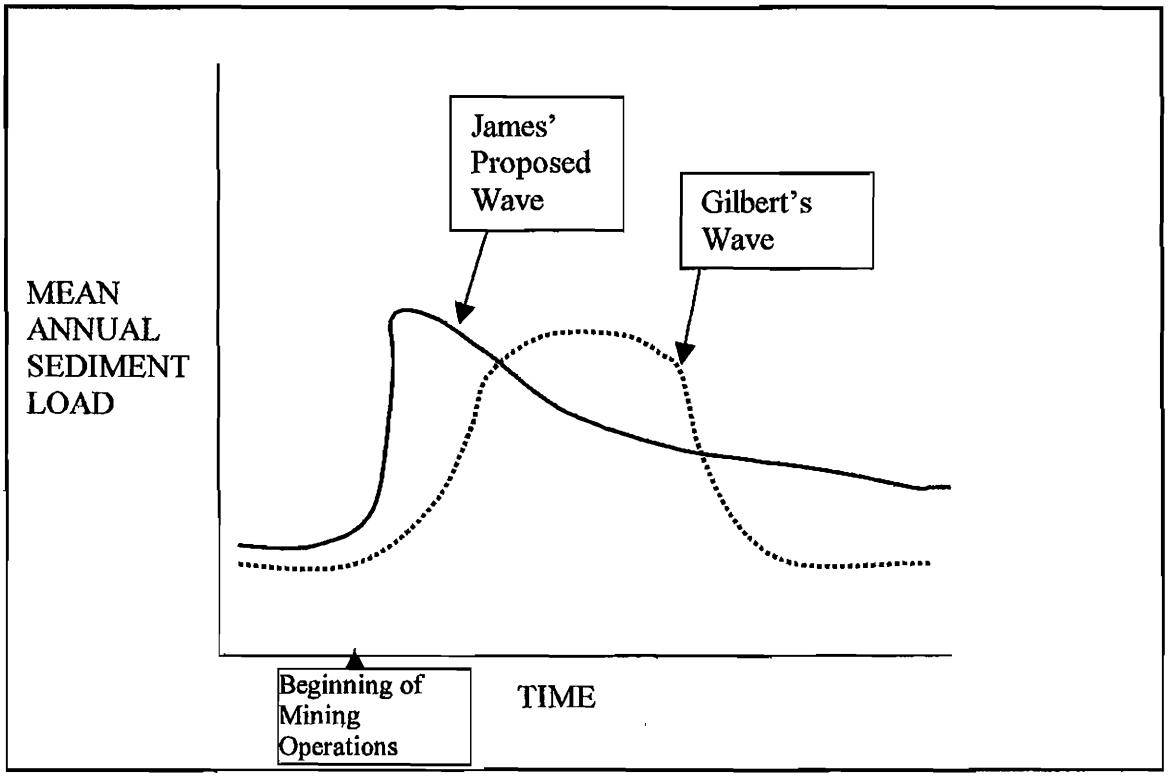


**Figure 2.1** James' proposed asymmetrical sediment. Remobilization of sediment temporarily stored in and along channel margins skews the curve representing sediment loads . (Figure adapted from James, 1989).

These findings may shed light on the idea of how sediment waves move through stream systems. Even though mining ended in the study area more than seventy years prior to the study, the majority of the contamination may still be in the upper reaches of the watershed nearer to mining areas. It will most likely take centuries before the sediment-metal concentrations return to pre-mining conditions and the longitudinal downstream decay of contamination is reversed (James, 1989). The lengthy residence times of mining/land clearing induced sediment-metal in the study area is due to the fact that portions of the sediment-metal wave are stored in floodplain and terrace deposits along the stream. This sediment releases as these deposits erode over time.

### ***Sediment Transport***

Several studies have developed watershed scale sediment budgets to examine sediment yield and sediment storage. Trimble (1983) described sediment yield in the Coon Creek Basin of Wisconsin as a function of "conveyance capacity." He combined three sediment budget methods to get one over all picture of sediment storage and transport patterns in Coon Creek. In the case of Coon Creek, over fifty percent of historical sediment has gone into storage with only seven percent of introduced sediment leaving the drainage (Trimble, 1983). The author concluded that the stream would carry sediment equal to its conveyance capacity. If sediment load exceeds conveyance capacity, storage occurs, but when the sediment load falls below this level sediment will be eroded from the bed and/or banks and released downstream (Trimble, 1983).

Trimble (1993) conducted a subsequent study on sediment budgets for different areas in the same stream system. The results indicate that the upper valley of the main channel is contributing much sediment while tributaries and the lower main channel are providing very little sediment (Trimble, 1993). Trimble advises that management efforts concerning soil erosion should be focused in the upper main stem where cut banks are exposed -- this location may correspond to the middle reach of Chat Creek where large cut banks of historical sediment are exposed.

Several studies have been completed on channel changes and sediment transport in various Ozark streams (McKenney *et al.*, 1995; Jacobson and Pugh, 1995; Jacobson, 1995; Jacobson and Gran, 1999). Most of these studies address channel changes as a result of low impact land uses as well as gravel waves that move through Ozark streams. Jacobson and Gran (1999) concluded that historically a large gravel wave created by headword erosion has moved through Ozark streams and presently much smaller waves may be passing through these systems.

## Floodplains: Contaminant Sinks and Secondary Sources

### *Floodplains as Temporary Pollutant Sinks*

Several studies have used metal tracers to investigate storage patterns and sedimentation rates in floodplain deposits. These studies have combined channel change characteristics, sediment transport and dispersion, and geochemical properties to analyze floodplain deposition. Knox (1987) quantified floodplain sedimentation rates by referencing metal concentrations in soil horizons to dates of mining activity. Many studies have examined floodplains as sinks and future sources for metal contamination and how these metals are concentrated and spatially distributed within the floodplain (Leenaers *et al.*, 1988; Rang and Schouten, 1989; Bradley and Cox, 1990; Swennen *et al.*, 1994; Rowan *et al.*, 1995; Lecce and Pavlowsky, 1997; Smith *et al.*, 1998; Carlson, 1999). These studies utilize geochemical analysis to determine longitudinal distribution of metals within the floodplain (Lecce and Pavlowsky, 1997; Carlson, 1999) as well as lateral and vertical distribution (Swennen *et al.*, 1994; Lecce and Pavlowsky, 1997; Carlson, 1999).

### ***Erosional Potential and Lateral Stream Migration***

Floodplains become secondary sources of mining-related metals through the process of lateral migration. There are several factors that influence the rates at which streams migrate laterally. One of the main factors affecting channel stability is stream bank composition. Thorne and Tovey (1981) examined the stability of composite stream banks, which are similar to the structure of stream banks in Chat Creek. Composite riverbanks consist of lower layers of sand and gravel that are overlain by cohesive layers of silt/clay. The authors concluded that erosion occurs by a process of fluvial transport of the lower sand and gravel that creates cantilevers in the upper cohesive layer. This upper layer gives way and collapses into the stream where it is transported downstream by subsequent flow events.

Other factors that influence lateral migration, which are relevant to Chat Creek, include the role of riparian forest and vegetation buffers and barriers such as valley and artificial structures that may reduce erosion rates.

A study by Burckhardt and Todd (1998) examined the effects of riparian forests on lateral migration in northern Missouri. They concluded that meander bends with forest buffers migrate more slowly than bends without forest buffers. A similar study by Beeson and Doyle (1995) concluded that streams in British Columbia migrate more slowly at bends that have riparian vegetation than at bends without riparian vegetation. The middle reach of Chat Creek can be characterized as having alternating stretches of forest with stretches of livestock pastureland. Depending on rates of erosion, floodplains can become significant secondary sources of contaminants or can act as buffers by storing high levels of contamination and slowly releasing them into the stream via slow migration rates.

Valley walls and artificial structures are important impedances to lateral migration in Chat Creek. In some cases, Chat Creek is confined against the valley wall and prevented from migrating laterally at any significant rate. Where Chat Creek is slowly eroding into the pre-historic hillside, relatively "clean" sediment is being released and diluting downstream metal concentrations. The Burlington Northern railroad that parallels Chat Creek is also a deterrent to migration in some reaches.

### *Determining Lateral Migration Rates*

Analysis of aerial photographs is an accurate way to measure stream migration over time. This is one of only a few options for streams that have not been previously surveyed. Three previous studies provide models for determining migration patterns from historic air photos (Rowan *et al.*, 1995; Barry *et al.*, 1996; Smith *et al.*, 1998). In each study, air photographs were used from several different years to determine migration rates. The air photos were digitized and then input into a GIS so that the stream channels from different years could be overlain and the changes in position quantified (Rowan *et al.*, 1995; Barry *et al.*, 1996; Smith *et al.*, 1998).

### *Lateral Migration and its Non-point source contamination contribution*

Two previous studies provide models for quantifying the amount of nonpoint source metal contamination contributed by lateral stream migration. These studies by

Smith *et al.* (1998) and Rowan *et al.* (1995) combined spatial distribution of metal contaminants with rates of lateral migration in designated reaches of two streams to quantify amounts of contamination entering the stream system from lateral migration. Each study divided their respective streams into segments, established a level of floodplain contamination and a rate of migration for each segment. The authors were then able to quantify the amount of contaminated sediment being eroded. The study by Smith *et al.* (1998) establishes that on the Clark Fork River, Montana contamination from various sources remains relatively constant through time. Even though mining has ceased and tailings piles and mining sites have been remediated, the relative percentage of contaminants released from these sites as compared to contaminants released from floodplain erosion remains constant (Smith *et al.*, 1998).

After mining operations cease floodplains can become the major source of mining related contaminants to fluvial systems (Rowan *et al.*, 1995). Rowan *et al.* (1995) concluded that levels of metal concentration may continue to decay longitudinally downstream due to the fact that most of the contamination was in fact coming from upper floodplains where primary contamination was highest and where the stream is most actively migrating. Another study alludes to the difficulty in quantifying the amounts of contamination being released by lateral migration. In some instances, even though mining has ceased, metal input from "on site" locations may drown out the effect of metal inputs from floodplain deposits on sediment-metal concentrations in the channel system (Pavlowsky, 1995).

## Mining Contamination in Ozark Streams

Various studies have been completed addressing mining contaminants in Ozark streams, however no such studies exist on Chat Creek. Steele and Wagner (1975) examined trace metals in sediments of the Buffalo River, Arkansas. The authors used geochemical analysis to locate the affect ore bodies had on metal concentrations. Steele and Wagner (1975) found that due to mixing with sediment from tributaries, peak zinc levels can return to background levels within a mile or two from the confluence. Carroll *et al.* (1998) examined geochemical data of sediment and water samples to determine controls of trace metal distribution in mining areas of the Tri-State Mining District. The authors concluded that metals attached to sediment could become bioavailable because of active exchange between particulate metals and dissolved metals. A study conducted by Barks (1977) examined dissolved metal concentrations in the Joplin, Missouri area. He determined that the dissolved fraction of zinc was elevated in Joplin, but the lead levels were high only at runoff sites from tailings piles.

A recent study by Carlson (1999) examined spatial distribution of contamination in floodplain deposits of the Honey Creek Watershed in Southwest Missouri. He also quantified post settlement floodplain sedimentation rates using metal tracers. Carlson (1999) found that present day sources of mining-related metals into Honey Creek are related to inputs of both "pure" tailings from past mining sites as well as nonpoint introduction through erosion of contaminated floodplain deposits.

## Chapter Summary

Historical land uses have a lasting affect on stream water quality. Agricultural land clearing and urbanization cause geomorphic changes in stream channels and at the same time may introduce contaminants into the same streams. Upon the initial release of contaminants from mining activities, their distribution within the watershed is largely dependent on deposition and mixing processes. Due to geomorphic controls, many of these contaminants are originally deposited in floodplains and other alluvial deposits. Presently, these floodplain deposits may be the major non-point source of contaminants due to reworking by erosion.

In the case of Chat Creek, past land uses including land clearing, agriculture, urbanization, and mining have changed the channel characteristics and introduced large amounts of sediment and heavy metals into the watershed. Due to the initial floodplain aggradation much of this sediment and associated metals were deposited in floodplains (Knox, 1987). Since mine closure, tailings piles have been removed or covered by vegetation and sediment loads have been reduced. Hydrologic energy is being expended through erosion of cut banks and it is quite possible that this erosion is introducing large amounts of nonpoint source metals into Chat Creek.

Distribution and transport of sediment-bound metals have been examined thoroughly in some areas of the world. However, this research is lacking in the Ozarks region. Besides the study by Carlson (1999) and a few studies completed in the Joplin, Missouri area, little is known about metal contamination in Ozark streams. This knowledge is key for watershed managers who are in charge of improving the water quality in Chat Creek.

# CHAPTER 3

# CHAT CREEK WATERSHED

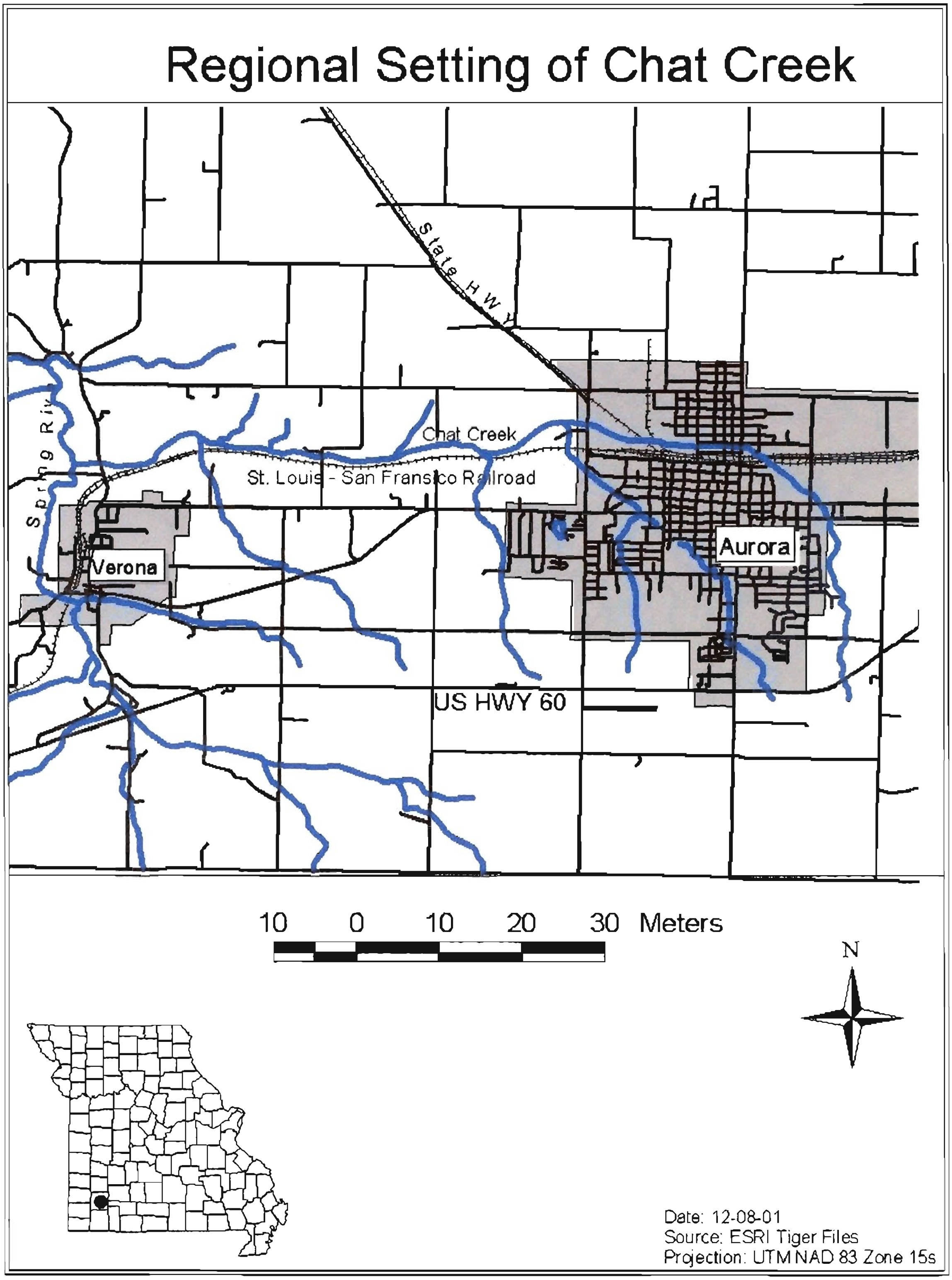
## Regional Setting

The Chat Creek watershed is located Lawrence County, Missouri. Lawrence County is a part of the Ozarks region of Southwest Missouri in Lawrence County (Figure 3.1). The watershed is located at the edge of the Springfield plateau physiographic province. Chat Creek drains the town of Aurora (population 7,104), which was historically an important mining sub-district at the eastern edge of the Tri-State mining district (Figure 3.1) (Missouri Census Data Center, 2000; Winslow, 1894).

Chat Creek is an intermittent tributary of the Upper Spring River and joins the river just north of the town of Verona. Chat Creek runs for nearly 12.08 km from its headwaters southeast of Aurora and drains approximately 32 square kilometers before entering the Spring River. Chat Creek begins at 439 m above sea level and falls to about 378 m above sea level where it enters the Spring River.

Past mining activities between 1880 and 1930 were centralized in an area just north and east of Aurora where much of the metal contaminants were originally introduced in association with tailings and other mill wastes (Figure 3.2). Since the mines have been shut down remediation efforts have been attempted in this area. Most of the original tailings piles have either been cleaned up or covered by vegetation.

Chat Creek has also been channelized and greatly disrupted in the urban area of Aurora. Due to these anthropogenic disturbances this study focuses largely on the lower 5.5 km of Chat Creek. All work involving floodplain analysis and channel morphology is limited to this lower reach where most sediment storage occurs.



Date: 12-08-01
Source: ESRI Tiger Files
Projection: UTM NAD 83 Zone 15s

**Figure 3.1** Map of regional location of the Chat Creek Watershed.

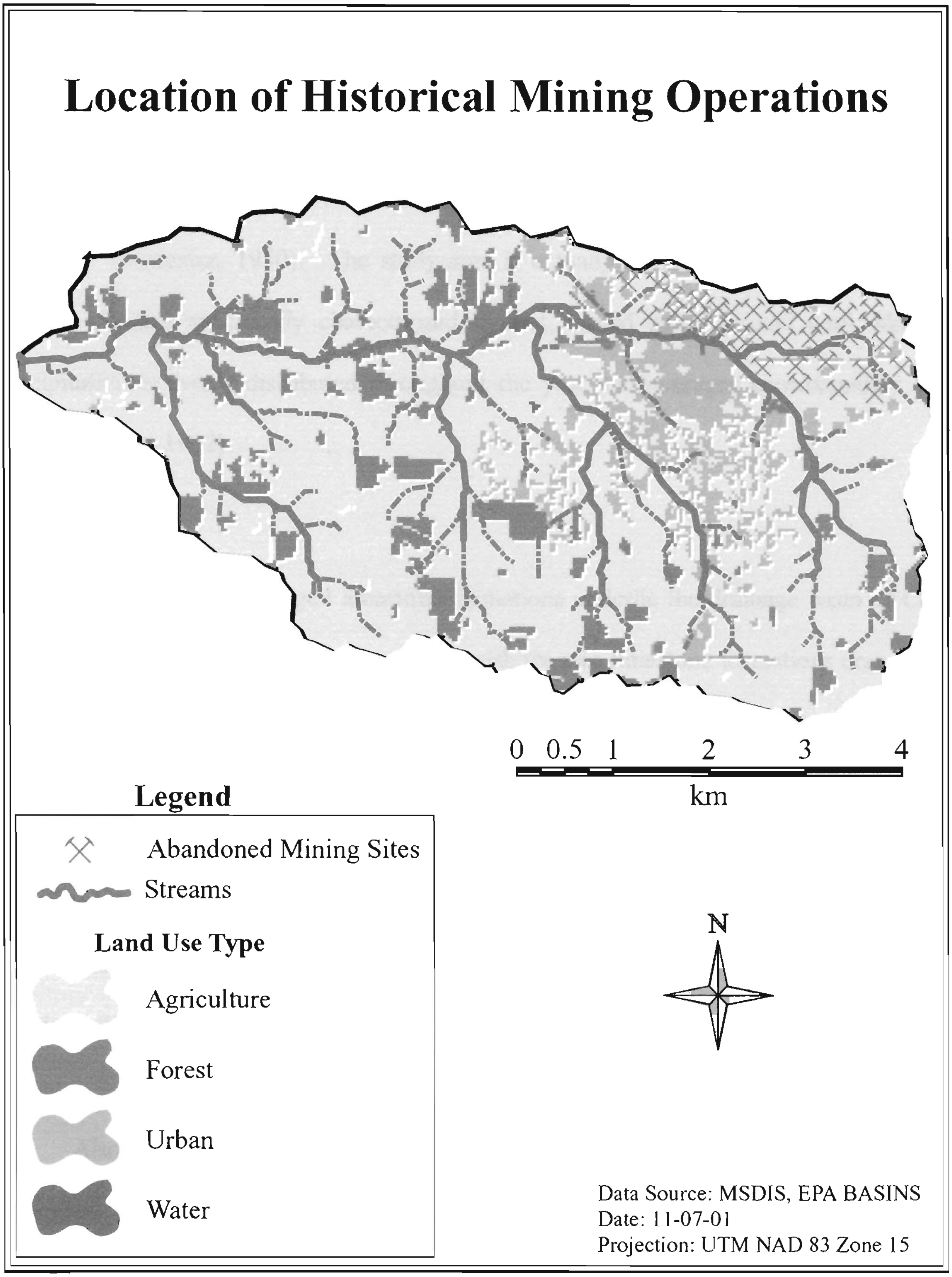


**Figure 3.2** Location of historical mining operations northeast of the town of Aurora.

## Physical Setting

### *Climate*

Its mid continent, mid-latitude location, determines the climate of Missouri as a whole. Changes in altitude and local relief are not sufficient to alter climate (Rafferty, 1983). Missouri's climate is technically categorized as a "humid continental with long summers" (Forrester, 1950). The study area is actually a mix of continental and sub-tropical climates specifically characterized by hot, humid summers and cool winters. Precipitation is evenly distributed throughout the year and averages approximately 106 cm/yr (Hughes, 1982).

### *Geology*

Two Mississippian-aged limestone formations underlie the drainage basin of Chat Creek. Age and chert nodule content distinguish the two limestone formations drained by the stream. The older unit is the Elsey/Reeds Springs Formation, which is very cherty. The younger unit is the Burlington/Keokuk formation, and it contains less chert than the underlying Elsey/Reeds Springs Formation. The Elsey/Reeds Springs formation underlies the stream for approximately five kilometers upstream from its mouth representing most of the study area for the bank erosion study. From the head of Chat Creek to five kilometers from its mouth, the Burlington/Keokuk Formation underlies the stream.

Also typical of most Ozark regions, the hydrology of the Chat Creek watershed is influenced by karst features. Sinkholes and underground streams pirate surface flow from area streams. Chat Creek itself is a losing stream in the last four miles of flow (Kiner *et al*, 1997).

### *Soils*

Soils in the study area, form from unconsolidated surficial materials of residuum, loess, colluvium, and alluvium (Hughes, 1982). There are several different fluvial soils that make up the Chat Creek drainage area. Some of the mapped soils on the Soil Survey of Greene and Lawrence Counties are actually soil complexes. These complexes consist of different soils that are arranged in such a manner that makes mapping them as individual units difficult at the scale of the survey. The descriptions of the soils give some idea of where they are located in relation to each other. The Chat Creek valley largely consists of four mapped soil units, while two more soil types make up a small portion of the drainage (Figure 3.3).

The major soil of the Chat Creek valley floor is the Cedargap series. Cedargap soils are deep, well drained soils that exist on the floodplains of small streams. Cedargap soils have an "A" horizon and a "C" horizon, but lack a "B" horizon due to the lack of maturity. The soils are silt loams with varying amounts of chert fragments that increase with depth (Hughes, 1982). Cedargap soils are mapped with two other soils as soil complexes. The first of these soils is the Waben series (mapped as Waben-Cedargap). Waben soils are deep, well drained soils on terraces and alluvial or colluvial fans. Waben soils are relatively old, cherty silt loams that consist of an "A" horizon and a "B" horizon. Chert in this soil occurs near the surface. A large portion of the "B" horizon has clay accumulation. The Waben-Cedargap complex makes up the majority of the soils of Chat Creek from 1.2 km from its mouth to approx. 6 km upstream. The other soil complex is

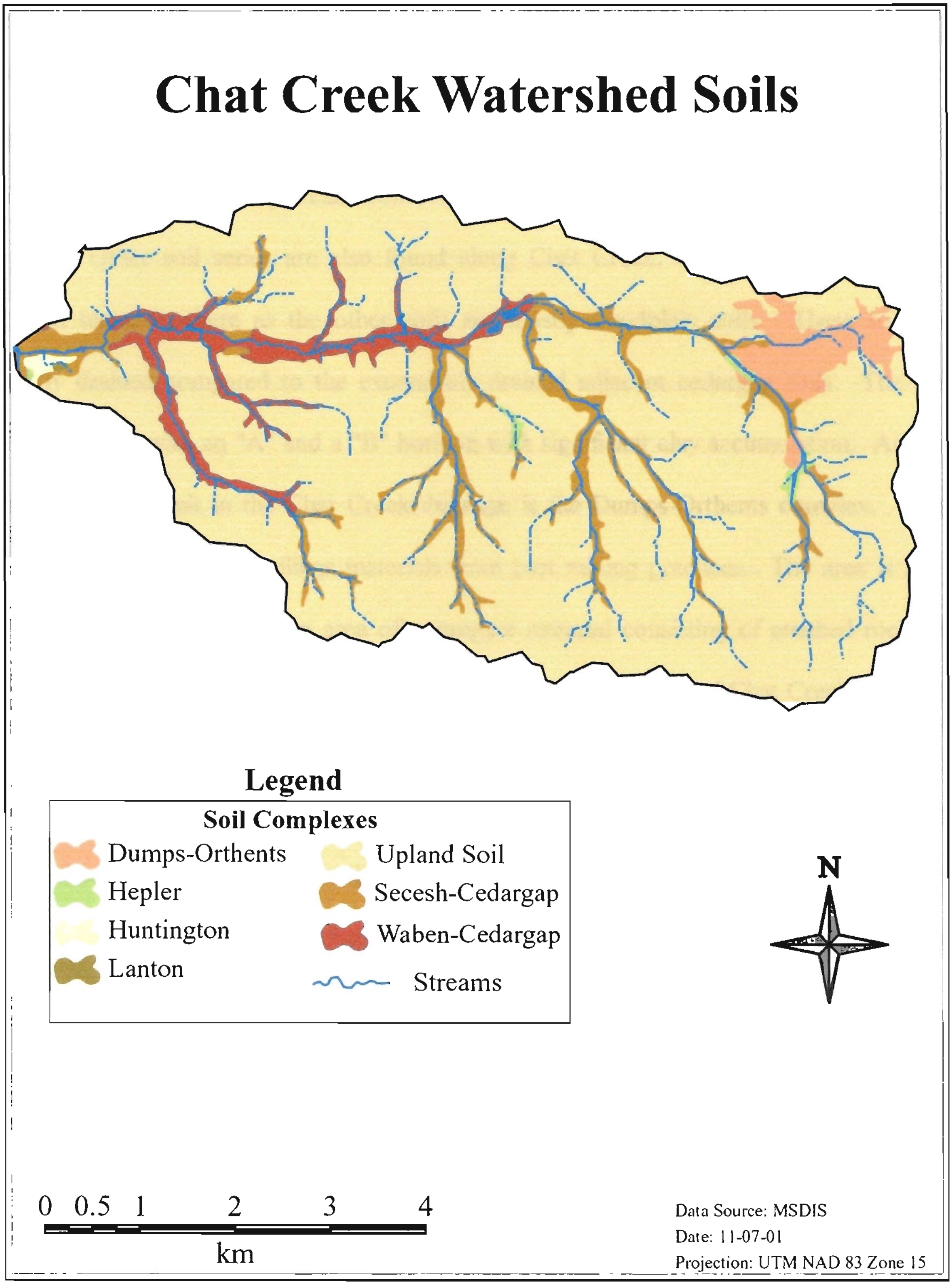


**Figure 3.3** Map of major soils of the Chat Creek alluvial valley.

the Secesh-Cedargap complex. Secesh soils are located on low terraces and consist of an "A" horizon and a "B" horizon with clay accumulation. Secesh soils are also silt loams with chert fragments appearing at greater depths than the Waben soils (Hughes, 1982). Secesh-Cedargap soils make up the larger tributaries that drain the town of Aurora and portions of the drainage upstream from Aurora.

Other soil series are also found along Chat Creek. Hepler soils exist on low stream terraces where as the other soils are mostly floodplain soils. These soils are poorly drained compared to the excessively drained adjacent cedargap soils. The soils are silt loams with an "A" and a "B" horizon with significant clay accumulation. Another major mapped unit in the Chat Creek drainage is the Dumps-Orthents complex. These areas consist largely of tailings materials from past mining practices. The area is not a developed soil, but rather an area of aggregate material consisting of crushed rock and metal ores. This complex comprises a large area of the drainage of Chat Creek and is the main original source of metal contamination to Chat Creek (Hughes, 1982).

There are also a couple of minor soil units that have been mapped in the watershed. These are the Huntington and Lanton series and they exist mainly in the Spring River valley at the confluence of Chat Creek and Spring River. Huntington soils are old deep soils of floodplains. Huntington soils are silt loams that contain an "A", "B", and a "C" horizon (Hughes, 1982). Lanton soils are also found on floodplains, drainages, and low points. Lanton soils lack a "B" horizon and are very clayey in nature (Hughes, 1982).

### *Land Use History*

Topography and relief influence land use patterns in the Chat Creek Watershed (Kiner *et al.*, 1997). Agriculture represents ~85% of the present land use which consists mostly of pasture with some limited row cropping (Kiner *et al.*, 1997). A large portion of the current contamination concern is due to historical land uses.

Three main land disturbances greatly affected the current situation in Chat Creek. The first was the initial clearing of land for European settlement, which began in the early 1800s. Forest clearing involves cutting down trees for housing and fuel as well as for clearing fields for agriculture. The second major land use was clearing of entire forests for railroad construction beginning around 1870. Thousands of acres were cleared for building materials for the railroad. Stream channel change was the main result of the first two land uses. Forest clearing and agriculture resulted in increased water run off and increased sediment loading into the stream systems. These results most certainly changed the character of channels of the local streams by depositing higher banks, widening tributaries and scouring to bedrock in some places (Knox, 1977; Trimble, 1983; Carlson, 1999).

The third significant historical land disturbance was mining. Mining activities were in the form of heavy base metal mining for lead and zinc covering about 12% of the watershed. Mining became significant in 1886 in the Aurora sub-district of the Tri-State Mining District and lasted until the 1920s (Winslow, 1894; Rafferty, 1970). Peak mining production was in 1916 (Kilsgaard and Hayes, 1967). Due to the lack of environmental concern and the lack of efficient extraction and recovery techniques large portions of the processed rock contained high levels of metals. This rock waste or tailings (locally known as “Chat”) were essentially dumped in piles into Chat Creek or on its banks. Tailing material typically contained greater than 0.5% Zn and 0.2% Pb. The present concern over poor water quality is a result of these past practices.

# CHAPTER 4

# METHODS

Spatial assessment of metal pollutant distribution and determination of metal input from bank erosion requires a combination of field methods and laboratory methods. Field methods consist of active channel and cut bank sediment monitoring and analysis. Lab methods consist of sediment sample processing, GIS and aerial photograph analysis, and data analysis.

## Field Methods

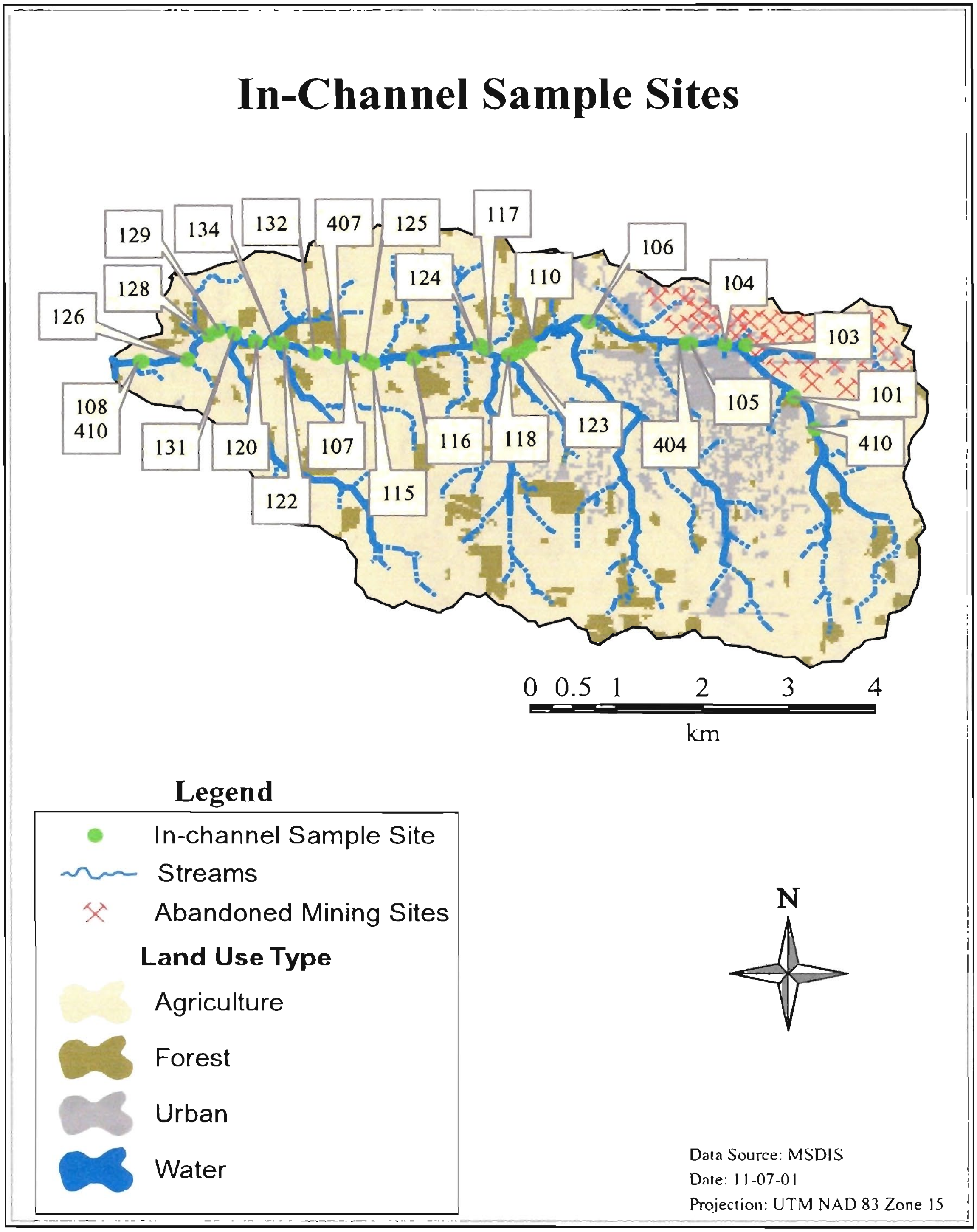
Fieldwork for the current study was conducted to determine metal concentrations in channel and bank sediments throughout the watershed and to physically assess the stream channel morphology at various locations. A total of 120 sediment samples were collected in order to assess the distribution of lead and zinc. Sixty-five in-channel sediment samples were collected from 29 sites. Thirty-six samples were collected from 10 cut bank sites. Background concentrations of lead and zinc were determined from eight samples collected from one site on the Upper Spring River. A stratified random sampling scheme was used for in-channel sediment sampling. In-channel sampling was distributed throughout the watershed to assess present-day contaminant transport patterns. Six tributary sampling sites were chosen in major tributaries where access was not limited; eleven total samples were collected at these sites.

In order to assess channel geometry, floodplain metal content, and composition, ten 100-meter reaches were chosen for analysis. These study reaches were chosen downstream of the confluence with major tributaries in order to account for dilution from clean sediment, changes in land use and discharge. Floodplain profile samples were collected within each of these reaches to understand metal variability with depth. Cross section surveys were collected at the meander bend location of floodplain profile sampling and at a straight segment directly upstream or downstream of the bend.

### *Sediment Sampling*

In-Channel. Active channel samples were spaced throughout the entire length of the mainstem of Chat Creek in order to represent contemporary contamination within the entire watershed. Active sediment samples were taken in accordance with Goodyear *et al.* (1996). Sixty-five in-channel sediment samples were taken from twenty-nine sites to determine the spatial distribution of lead and zinc in the active stream system (Figure 4.1). At 18 sites, triplicate samples were collected one meter apart in order to statistically analyze with-in site concentration variability. All in-channel samples were collected in low energy areas at the tails of point bars in order to sample the fine-grain deposits. The top five cm of sediment was collected in order to sample recent deposition. These samples were also used to represent the metal concentration of the sediment that is being actively deposited and stored in point bar features within the channel. Appendix A provides information for in-channel sample sites including location and naming nomenclature.

Floodplain. Floodplain profile (cut bank) deposits were also sampled to determine zinc and lead concentrations in the eroding floodplains. Ten reaches were chosen from the lower 5.5 km of the stream for floodplain profile sampling and other analysis (Figure 4.2). A description of the sampling at these reaches can be found in Appendix B. The floodplain sampling focuses on the lower Chat because of


In-Channel Sample Sites

Data Source: MSDIS
Date: 11-07-01
Projection: UTM NAD 83 Zone 15

**Figure 4.1** Twenty-nine in-channel sample sites on the mainstem of Chat Creek. Site identification numbers are in tan boxes. Sites with two identification numbers represent sites where two samples were collected in close proximity to each other. Sample site descriptions are given in Appendix A.

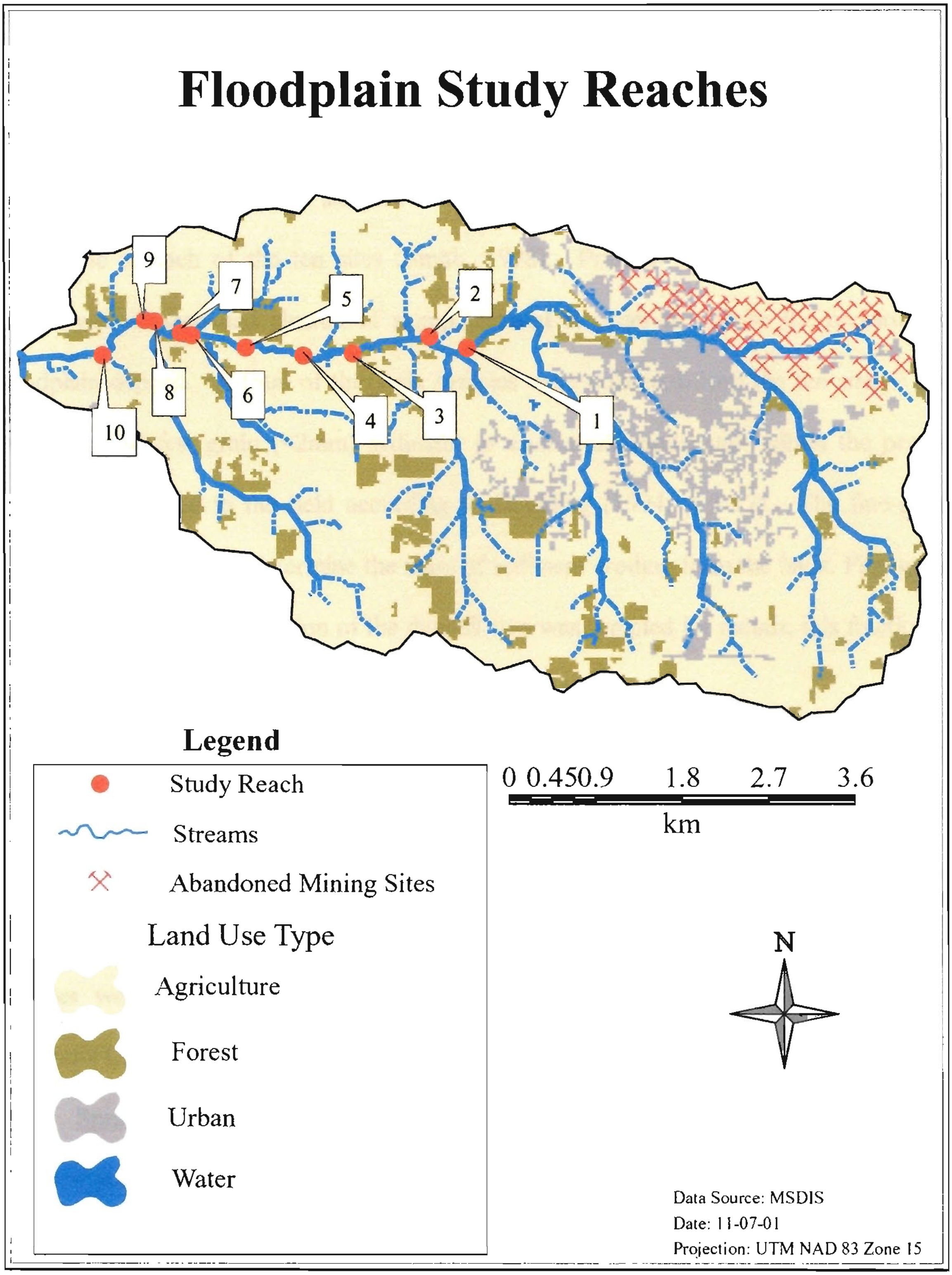
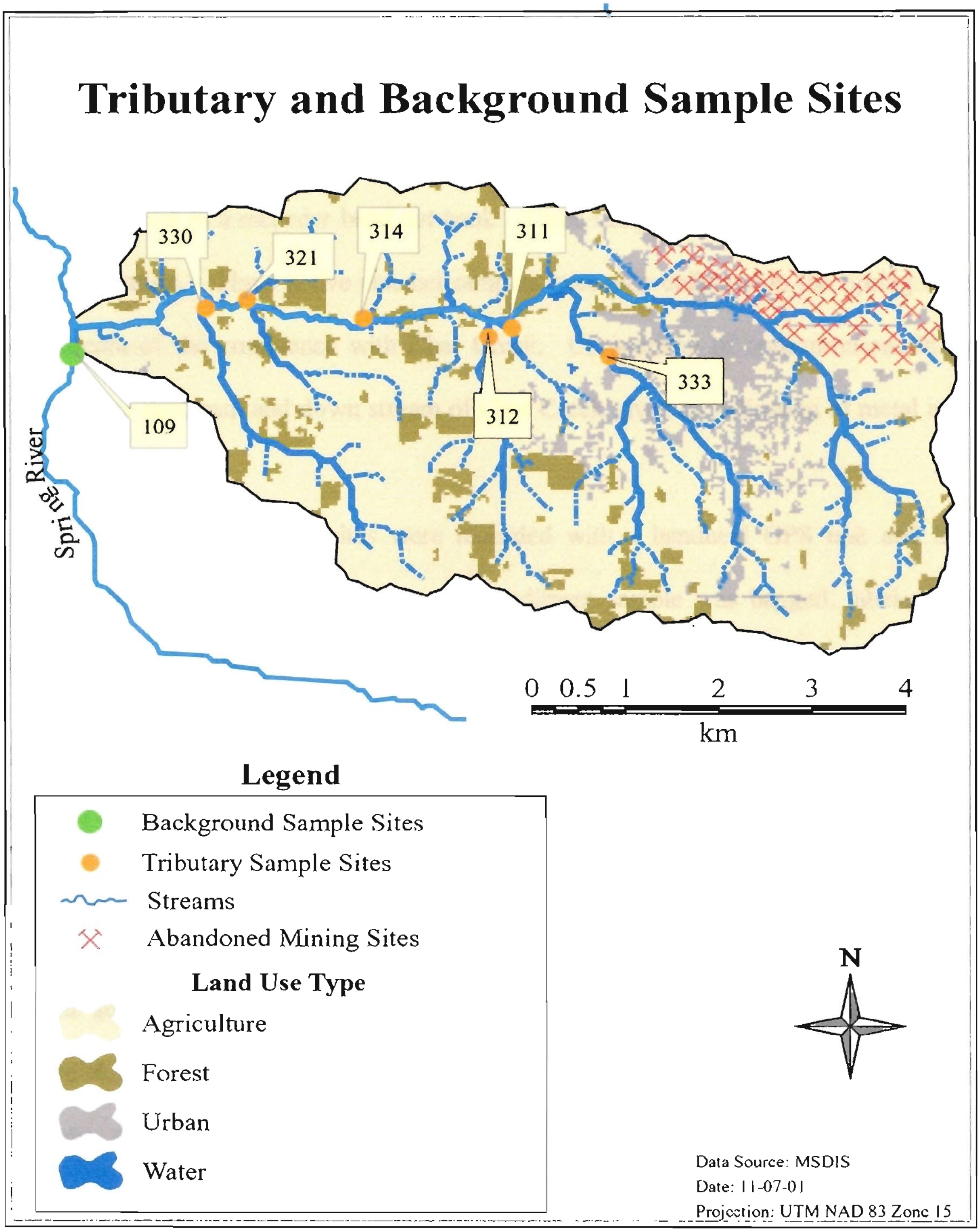


**Figure 4.2** Reaches for floodplain sampling, cross section surveys, and floodplain composition analysis. Site identification numbers are in tan boxes. Site descriptions and locations are in Appendix B.

anthropogenic disturbance in the upper section. These 100-meter reaches were chosen downstream of main tributaries. A cut bank exposure was sampled within each of these ten reaches. In order to get an accurate representation of the floodplain metal concentrations, sediment grab samples were collected from each stratigraphic unit within the profile at each of the ten sites (Smith, 1998). Prior to collection, the floodplain profile was scraped and cleared of slump material in order to expose the undisturbed floodplain deposit. A total of thirty-six samples were collected from the ten sites. The percentage of fine grain (<2mm) sediment in each stratigraphic unit within the profile was also evaluated in the field according to Boulding (1994; p 3-17). The fine-grain percentage was used to determine the mass of sediment eroding from the bank. Fine-grain sediment represents the portion of the deposit that was sampled for metals, this fraction is the most easily transported and most heavily contaminated.

Tributaries. Unnamed tributaries were also sampled in order to represent their contribution of metals into Chat Creek (Figure 4.3). Six tributaries were sampled upstream of their confluence with Chat Creek. Tributary sites were chosen according to their location in the watershed and according to the landuses that were drained. Eleven samples were collected in all. Information concerning tributary sample sites is in Appendix C.

Spring River Sediment Sampling. In order to determine background or natural levels of lead and zinc, sediment samples were collected in areas away from the influence of past mining operations (Figure 4.3). Due to the relatively high abundance of sphalerite and galena in the local bedrock, the study area is expected to have higher metal concentrations than non-mineralized areas. Since mining was so prevalent in the Chat



Data Source: MSDIS
Date: 11-07-01
Projection: UTM NAD 83 Zone 15

**Figure 4.3** Sites sampled to determine zinc input into Chat Creek from various land uses and areas. Samples that begin with "3" are tributary samples, samples that begin with "1" are Spring River Background samples. Sample site information is given in Appendix C.

Creek watershed, a sampling site was chosen on the Upper Spring River to determine background concentrations. This site is less than 100 meters upstream of the confluence with Chat creek. This area has the same physical setting as Chat creek with the exception of the mining influence. Five sediment grab samples were collected from each stratigraphic unit in a meander bend cut bank. Three samples were also collected from a point bar feature. Three active channel samples were also collected in the Spring River downstream of the confluence with Chat Creek. Comparison of concentrations in the Spring River upstream and down stream of Chat Creek given an indication of metal input from Chat Creek.

General. All sample sites were recorded with a handheld GPS unit and later entered into a GIS. Upon collection each sediment sample was bagged, labeled, and sealed for transport back to the lab for processing.

### Channel Morphology

Twenty cross section surveys were conducted in the lower 5.5 km of Chat Creek. Within each study reach, one cross section survey was conducted at the cut bank sampling site (designated as "bend" segments) and one cross section was surveyed at a straight segment directly upstream or downstream from the cut bank sampling site (Figure 4.2). Cross section surveys were conducted in order to measure channel geometry and floodplain height. Cross-section surveys were measured by stretching a tape across the channel at each of the study reaches. A stadia rod was placed along the tape at every change in topography to measure the depth from the tape to the land surface. A surveying level was used to read the depth on the rod. The depth and lateral distance from the tape was recorded in a field book. Measurements were made from one floodplain surface to the adjacent floodplain surface (Schilling and Wolter, 2000). Each of the cross section locations was recorded with a GPS unit. Each of the 100-meter study reaches was assessed for point bar fine-grain (<2 mm) composition. Several estimates were made at each study reach, depending on point bar structures, and averaged to determine the mean fine-grain sediment stored in the reach. This assessment was used to determine the volume of sediment-metal deposited in point bar features. Estimates of the percentage of fine-grain sediment were made according to Boulding (1994, p 3-17).

## Lab Methods

### *Sample Analysis*

After transport to the laboratory, each sample was allowed to air dry for several days. The samples were then completely dried in a convection oven at 55-65 degrees Celsius. Once the samples were completely dried, each was disaggregated with a mortar and pestle, and passed through a two mm screen sieve. Five grams of each sample were then bagged, labeled, and sealed for transport to Chemex Labs Incorporated in Sparks, Nevada for geochemical analysis. The concentrations of thirty-two elements were analyzed through the use of inductively coupled plasma-atomic emission spectroscopy (ICP-AES). The metals were extracted using a hot acid mixture of 3:1 $HCl:HNO_3$ (aqua regia) (Carlson, 1999). This extraction does not dissolve all elements equally, but tests show that it releases >90% of lead and zinc in fluvial sediments from mined watersheds (Pavlowsky, 1995; Lecce and Pavlowsky, 1997).

Organic Matter Composition. The author in the geomorphology lab at Southwest Missouri State University analyzed the organic matter content of each sample. The organic Loss on Ignition (LOI) method was used to determine percent organic matter in each sample (Dean, 1974; Pavlowsky, 1995). The LOI method is a measurement of the percent weight loss after burning each sample in a muffle furnace at 500°C for six hours. Before placing in the muffle furnace, 5 g of the pre-sieved sample was weighed and placed in a (pre-weighed) ceramic crucible. Each sample was then placed in a convection oven at 105°C for two hours to remove moisture within the sample. The samples were then placed in a dessicator to cool. Upon cooling each sample and crucible was weighed and the pre-burn weight was recorded. After the required six hours of ignition, each sample was again placed in the dessicator to cool and was subsequently weighed. Organic matter was determined from the following equation:

$$OM = A - B, \quad \text{(Eq. 4.1)}$$

Where:
A = Preburn Sediment and Crucible Weight (g).
B = Dry Crucible and Sediment Postburn Weight (g).

Percent Organic Matter LOI was determined according to the following equation:

$$OM\%\ LOI = OM / \text{Preburn Sediment Weight (g)} \quad \text{(Eq. 4.2)}$$

Anthropogenic Enrichment Factor. To assess the level of anthropogenic induced metal contamination for all sampling sites, a ratio was computed for sample concentration to background concentration. To account for effects of variable sediment properties on metal sorption, each sample and background metal concentration were divided by the aluminum percentage of the sample (Pavlowsky, 1989). The following equation was used to calculate the anthropogenic enrichment factor (AEF) for each sample:

$$AEF = (CM/CAR) / (BM/B_{AR}) \quad \text{(Eq. 4.3)}$$

Where:

AEF = Anthropogenic Enrichment Factor

CM = Sample Metal Concentration (ppm)
CAR = Sample Aluminum Content (%)
BM = Background Metal Concentration (ppm)
BAR = Background Aluminum Content (%)

## Aerial Photograph Analysis

Lateral channel migration can be an important source of metals into the stream system (Rowan *et al.*, 1995; Smith *et al.*, 1998). Due to the fact that Chat Creek has not been previously surveyed, migration rate measurements are dependent upon examining changes in planform position through evaluation of historical aerial photographs. Aerial photographs from 1990 and two digital ortho quarter-quads (DOQQ) from 1997 were used to determine migration rates. An aerial photograph from 1939 was also used to visually assess major channel changes such as channelization. Do to the size of the stream and photo resolution, only the centerline of the stream was digitized and changes in position were measured. Studies such as Smith (1998) and Rowan *et al.* (1995) also measured stream channel migration by digitizing the stream centerline and measuring changes in planform position from the overlain centerlines.

Aerial Photograph Rectification. The initial step in analyzing the aerial photographs was to register the raw images to real world (map) coordinates utilizing the 1997 DOQQ. The air photos were scanned, saved as ".tiff" images and saved to a CD-ROM. The air photos were scanned at a resolution of 500 dots per inch (d.p.i.). The air photo images were then registered (rectified) to map coordinates using two 1997 DOQQs (Aurora 7.5 NW and Verona 7.5 NE). The DOQQs are geospatially-referenced images (geoTIFF) with a header file that stipulates the map coordinate information for the

DOQQ. The coordinate system and datum used for the DOQQs are Universal Transverse Mercator (UTM), NAD 83, Zone 15.

The rectification process involves selecting common identifiable ground control points (gcp) in both the raw scanned image and the registered DOQQ. These gcps are used to "snap" the raw image to the registered images, assigning the coordinates of the gcps in the registered image to the same point in the raw image. Two different rectification processes were used to register the 1939 and 1990 photos. This was necessary in order to gain geometrically accurate images. A polynomial quadratic rectification process was used to register the 1939 air photo to the map coordinates. Eighteen common ground control points were used to rectify the air photo. The root mean square (RMS) error for each point was maintained below 0.2. An orthorectification process was used to rectify the 1990 air photos. A complete description of rectification and a comparison of each type can be found in Novak (1992). Orthorectification utilizes ground control points, elevation data, and camera calibration data to produce a rectified image that is corrected for terrain and camera tilt. Seven GCPs were used to rectify the 1990 photos. The average RMS error for the seven points is 0.124 and the total RMS error is 0.870. The rectified images were then exported as raster band interlent by line (bil) files for digitization. The images were then displayed and examined for accuracy.

Prior to digitizing the channel centerlines, each photo was enhanced to improve visual interpretability. The image contrast was enhanced in order to better detect channel boundaries. Once scanned, each photo has a 16-bit brightness resolution. This resolution results in 256 (0-255) possible brightness values for each raster pixel. The image enhancement involved using a majority of these values to represent the densest cluster of pixels. Examination of each histogram indicated that a majority of the pixels occurs in the center of the 0-255 brightness range. By clipping off the tails of the distribution and eliminating the extreme pixel values, more of the 0-255 range could be used for the majority of the pixels. This density slicing technique ultimately improves the resolution and distinguishes the pixels in terms of gray tones (Figure 4.4) (Campbell, 1996).

Vector line files were created for the 1990 and 1997 images. One centerline file was created for each of the two photo years. Each of these line files was built through digitization of the two sets of images. Once digitized, the channel centerline files for 1990 and 1997 were input into a GIS and overlain to determine migration rates for 1990-1997. During the migration rate measurement, each 20-meter segment was also designated as either a "Bend" segment or a "Straight" segment.

Channel Migration Measurement. Lateral migration through cut-bank erosion and point bar deposition is a natural process in meandering rivers (Leopold *et al.*, 1964). In order to determine metal input from this process, lateral migration rates must be determined. The digitized channels were divided into 275, 20-meter segments for determination of changes in centerline position. The segments were divided by transects oriented perpendicular to the 1997 digitized channel. Five measurements were made in each segment to determine the average change in position for that segment. A point was located in the center of each segment to represent the average migration per segment. The yearly migration rate was determined to be the average of the total migration for the time period (1990-1997).

Due to an inaccuracy in the rectification process the 1990 and 1997 images were slightly offset in some areas. This offset did not occur throughout the entire study reach

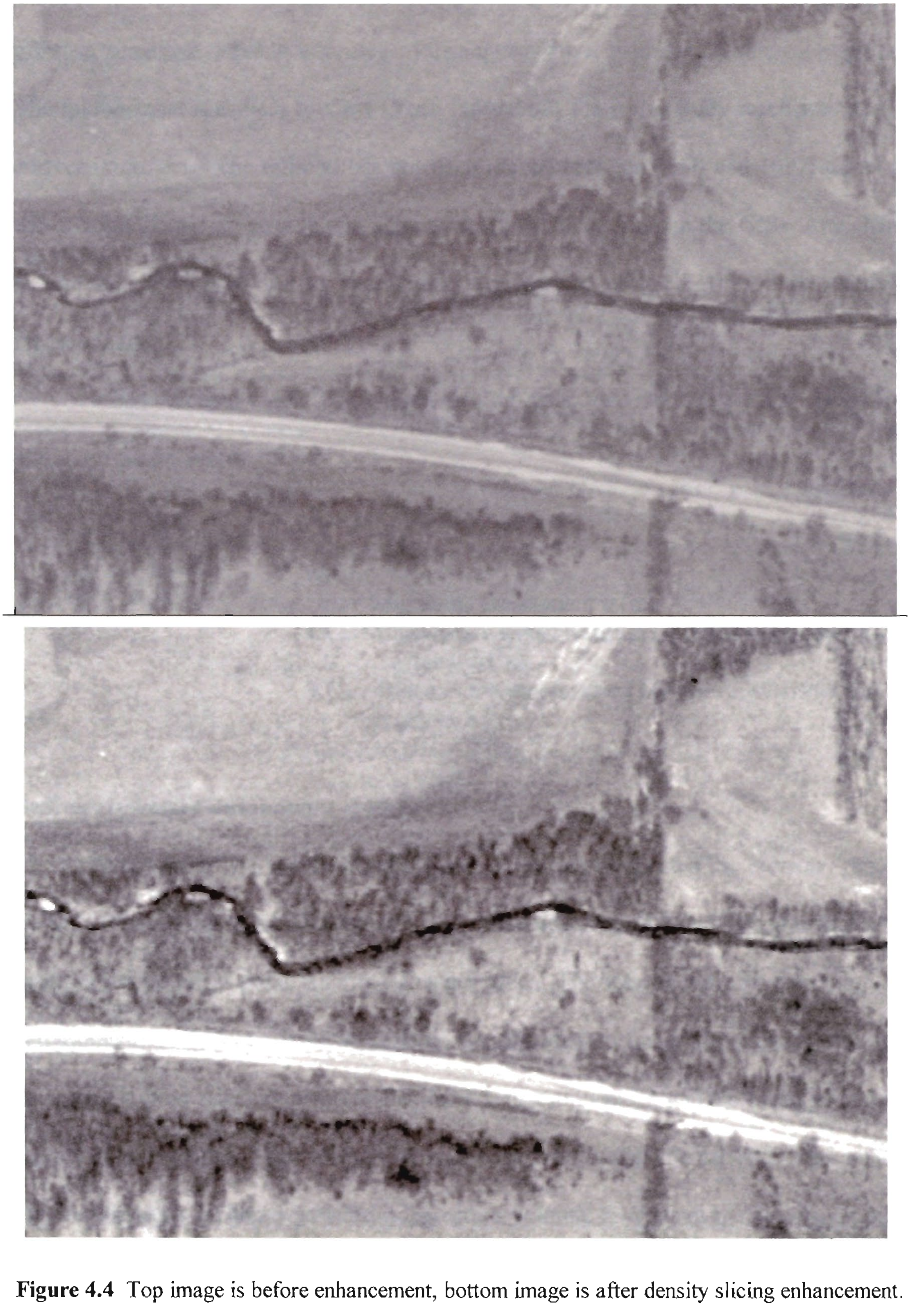


**Figure 4.4** Top image is before enhancement, bottom image is after density slicing enhancement.

and was not consistent in distance throughout its occurrence. To correct this geometric offset, a surrogate variable was used to distinguish offset from actual channel migration. The railroad that runs next to Chat Creek throughout the entire study reach was used to correct the offset. The railroad has not been moved between 1990 and 1997; therefore, the railroad from each year should align perfectly when overlain in the GIS. Any change in railroad position is due to photo-offset and can be used to correct the migration measurement.

When necessary the following equation was used to correct the 1990-1997 migration for geometric offset:

$$M_n = (CC_n) - (RC_n) \quad \text{(Eq.4.4)}$$

Where:
$M_n$ = Migration for segment $n$ (m)
$CC_n$ = Change in channel position between 1990-1997 for segment $n$ (m)
$RC_n$ = Offset in railroad position between 1990-1997 for segment $n$ (m)

## Sediment-Metal Contaminant Budget

Determining a sediment-metal budget for lateral stream erosion requires quantification of the mass of sediment-metals released from cut banks and the mass of the material deposited in point bars and channel beds. The introduction of metals into the active channel of Chat Creek at each of the ten study reaches depends on the metal concentrations in the floodplain profile, lateral migration rates, and thickness or mass of eroded bank material. The amount of metals deposited in point bar and other channel features depends on three variables; deposition volume, in-channel metal concentration, and in-channel percent fine-grain material. Subtracting the mass of material deposited on point bar features and channel beds from the mass of eroded sediment-metal yields the amount of material released to downstream reaches. Figure 4.5 is a schematic of the budget equation. This net release/storage of material was calculated for all 275 twenty-meter segments.

### *Sediment-Metal Release Calculation*

Each floodplain profile is composed of several stratigraphic units that were identified in the field and analyzed separately for metal contamination. The metal content in each floodplain profile depends on the metal concentration in each stratigraphic unit, the thickness of the stratigraphic unit, and the total height of the floodplain profile. The following equation was used to determine weighted bank metal concentrations at each of the 10 study reaches:

$$C_x = \sum[z_1/z_{total}(c_1)+\ldots+ z_n/z_{total}(c_n)] \quad \text{(Eq. 4.5)}$$

Where:

$C_x$ = weighted average concentration (ppm) of metal x in floodplain profile
$z_n$ = thickness (m) of stratigraphic unit n
$c_n$ = concentration (ppm) of metal x in stratigraphic unit n
$z_{total}$ = total height (m) of floodplain profile

The weighted floodplain metal concentrations at the ten study reaches were used to model floodplain concentrations of the remaining 275 stream segments. The ten weighted concentrations were plotted against distance from the confluence with the Spring River and an exponential function was used to construct a best-fit line through the data points.

Fine-grained sediment is considered the primary mobile carrier of contaminants. Bank and channel deposits in the region tend to contain significant but variable amounts

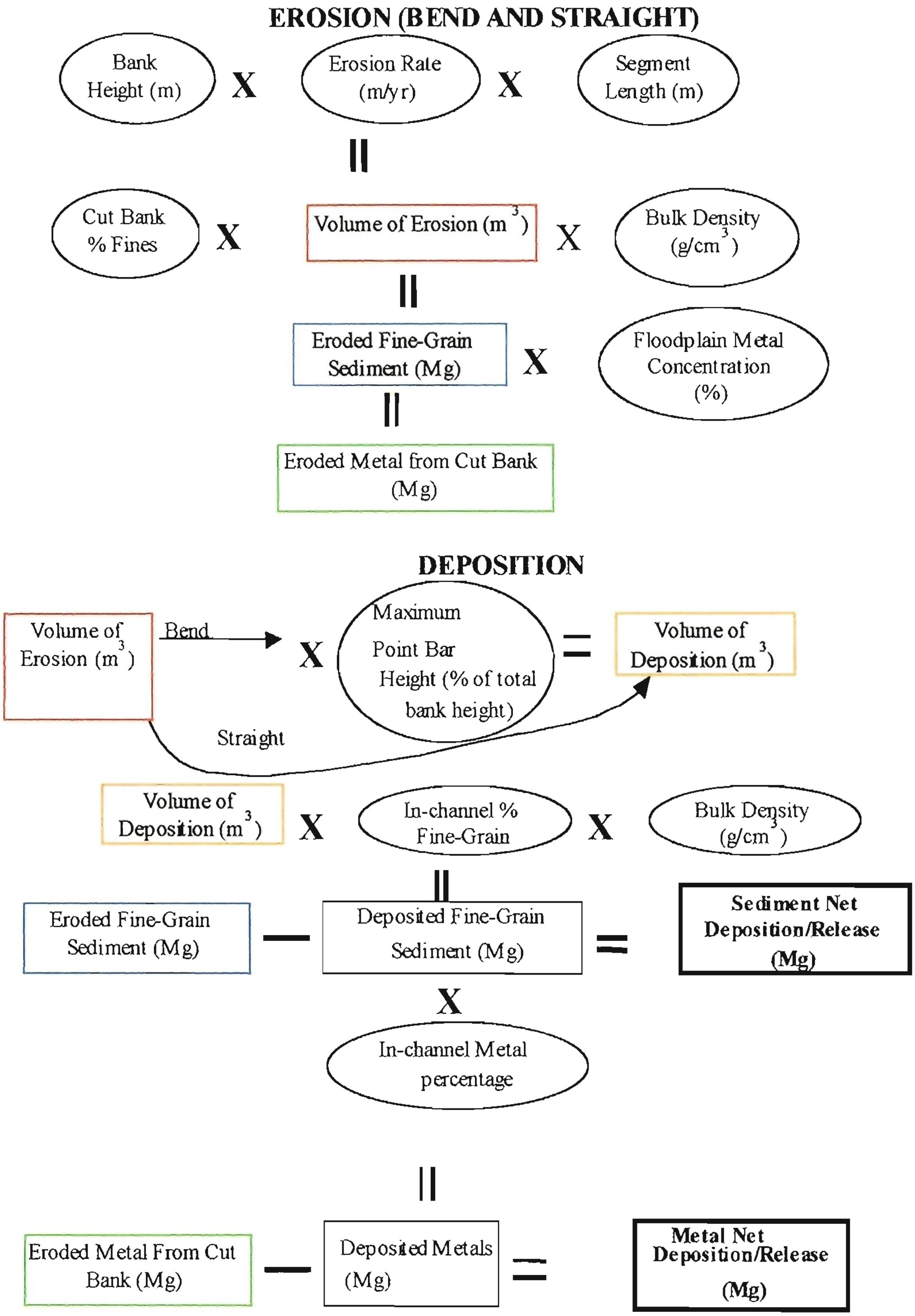


**Figure 4.5** Schematic of sediment-metal budget due to floodplain erosion.

of chert and carbonate gravels. Hence, sediment-metal budget calculations must account for these variations in composition since gravels are assumed not to contribute to Zn and Pb contaminant transport and storage. Equation 4.5 was also used to determine fine-grain sediment composition in the floodplain profile at each of the study reaches. However, fine-grain percentage was substituted for metal concentrations.

The computed weighted fine-grain composition percentage for each study reach cut bank was used to determine the floodplain fine-grain percentage for the remaining 275 segments. The fine-grain percentage at each study reach was plotted against distance from the confluence with the Spring River. A straight line was fit between each point and the adjacent point downstream. The slope of this line was determined and used to calculate the fine-grain percentage for each segment occurring between the two points.

Another important variable in determining the amount of sediment-metals eroded from floodplain deposits is bank height. Bank height was modeled separately for "bend" and "straight" reaches. Bend segment bank heights were interpolated from the ten cross section surveys completed at each study reach, likewise straight segment bank heights were interpolated from cross section surveys completed at each of the ten study reaches. In each case, interpolation was computed using the same method as for fine-grain percentage.

The mass of metals released from each of the 275 segments was determined by multiplying the modeled weighted metal concentration in the floodplain profile by the volume of material eroded due to lateral migration.

The mass of eroded fine-grained material was determined as follows:

$$S_n = (L_n * W_n * H_n) * (B_d) * (F_n) \qquad \text{(Eq.4.6)}$$

Where:

$S_n$ = Mass (Mg) of eroded fine-grained sediment at segment *n*
$L_n$ = 20 meters, length of study segment *n*
$W_n$ = Migration rate (m/yr) at study segment *n*
$H_n$ = Height (m) of floodplain profile at segment *n*
$B_d$ = Average Bulk density of soil assumed to be 1.4 (g/cm$^3$) after Hughes (1982)
$F_n$ = Mean weighted percent fines at segment *n*

Quantification of metal release at the 275 segments was determined by the following equation:

$$RM_n\,(\mathrm{Mg}) = S_n(PM * 10^{-6}) \quad (\text{Eq.4.7})$$

Where:

$RM_n$ = Release metal (Mg) at segment *n*
$S_n$ = Mass (Mg) of eroded fine-grained sediment at segment *n*
PM = Weighted metal (ppm) in floodplain profile at segment *n*

### *Sediment - Metal Deposition Calculation*

The other major component of the sediment-metal budget is the mass of sediment-metal deposited in point bars and other channel features. There are several variables that have to be modeled in order to determine mass of deposition. One of these variables is the volume of deposition. Volume of deposition was determined separately for "bend" segments and "straight" segments. The volume of deposition for bends was determined as the percentage of maximum point bar height to the total cut bank height. This was calculated for each of the ten study reaches and the remaining segments were interpolated using the same method as the "floodplain fine-grain" percentage and "bank height" variables mentioned previously. For straight reaches, the volume of deposition was assumed to equal the volume of erosion calculated for the respective segments. Percentage of in-channel fine-grain sediment was determined in the field at each study reach. The gravel content of fluvial deposits may vary, thus changing the proportion of fine-grained sediment in each unit volume of bank or channel material. Relationships between the percentage of fine-grained sediment and downstream distance were used to interpolate for the remaining segments. The method of interpolation was the same as mentioned previously.

### *Assumptions for Sediment-Metal Budget Calculations*

Given the time, financial limitations and the complex nature of the processes involved, three assumptions were made for the current study to facilitate the calculation of the sediment budget. The first assumption was made largely because of the lack of previous survey data for Chat Creek. Since the only cross section data available for Chat Creek were surveyed for the current study, it is assumed that the channel geometry remains constant in the short term. As the channel migrates laterally the shape of the channel remains constant and the only variable that changes is the position of the channel. Smith et al. (1998) also made the assumption of constant channel geometry in a similar study.

The second assumption marginalized the role of overbank deposition in the budget. It is assumed that the mass of overbank deposition of sediment and attached metals is negligible in the short term. In other words, released sediment-metal is either deposited in point bar features or is transported downstream. This assumption is supported by the findings of Carlson (1999). Carlson (1999) concluded that overbank sedimentation rates for Elm Branch (a tributary to Honey Creek draining the Aurora mines to the north) generally ranged from 0.03 to 0.27 cm per year between 1916 and 1998. Further, his research suggests that annual rates were higher in the beginning of this time period and were <1 mm/yr. during the 1990s.

The third assumption is that the average floodplain or bank metal concentrations remain constant in the short term. Since it was not possible to sample the lateral distribution of metals across the valley floor, it must be assumed that for the time interval between aerial photographs of 7 years the metal concentrations sampled from cutbanks remain constant at decadal time scales. This generally represents a valley floor segment of <10 meters within a total valley width ranging from 100m to 500m.

**Data Maintenance**

Several software packages were used to store, manage, analyze, and display the data for the current study. All sample sites and study reaches were recorded with a handheld GPS unit and later downloaded into a GIS so that precise locations could be recorded and analyzed. ER Mapper remote sensing software was used to create the digital orthophotos through the rectification of raw digital aerial photographs. ArcGIS was used to display the digital orthophotos and to measure channel migration rates. ArcGIS was used to map sample site locations, study reach locations, and metal concentrations at the sample sites. Adobe Illustrator 8.1 was used for graphical enhancement of cartographic products. Watershed Delineator, an Arcview 3.2 extension, was used to delineate the watershed above each sample site. Drainage area was determined for each of these sub –watersheds. Microsoft Office products were used for data storage, analysis and word processing. MS Excel was used to store migration and geochemical data. MS Excel was also used to plot trends for metal concentrations at the sample sites. MS Word was used for all word processing requirements for the current study. SPSS 10-1 statistical software was used for Pearson correlation analysis.

# CHAPTER 5

## IN-CHANNEL DISTRIBUTION OF LEAD AND ZINC

The first objective of the current study is to determine the spatial distribution of mining-derived contamination in Chat Creek. This chapter addresses three major points concerning the distribution of lead and zinc in the Chat Creek watershed. First, concentrations of the two metals will be described spatially. This section also addresses the influence of tributaries on the concentration of lead and zinc in the stream. The enrichment of lead and zinc due to anthropogenic activities is quantified. Secondly, important geochemical relationships between lead and zinc and other elements are described. These relationships can indicate the association of lead and zinc with specific sediment size fractions or source points in the watershed. Although not a direct focus of this study, the spatial distribution and concentration of sediment-bound phosphorous is also evaluated. Phosphorus is of local concern because of its detrimental affects on receiving waters when concentrations are abnormally high and is of concern to local environmental managers. Finally, this chapter will quantify downstream pollution trends to help determine a lead and zinc budget for floodplain erosion in Chat Creek. Using the twenty-nine in-channel sample sites, a spatial model is calculated for in-channel lead and zinc concentrations for each of the two hundred seventy-five, 20-meter stream segments. This model will allow for the calculation of the mass of lead and zinc deposited in and along the active channel of Chat Creek.

The spatial distribution of lead and zinc is determined by sampling in-channel bed sediments. In-channel bed sediments indicate the contemporary patterns of transport in the watershed and represent the aggregate of metals introduced from all upstream sources. These samples were collected along the inside of meander bends from point bar features above the low flow stage of the stream. A table with geochemical data for all in-channel samples can be found in Appendix D.

## Lead and Zinc Concentrations

### *Downstream Trends*

Lead concentrations in active stream sediments rise sharply immediately downstream of the abandoned mining area and generally decrease downstream from this area. At seventeen of the 29 sampling sites, triplicate samples were collected in order to quantify the range of local scale variability of metal-sediment concentrations by calculating standard deviations and coefficient of variation percentages (CV%) (Table 5.1). Coefficient of variation values, an expression of the standard deviation as a percentage of the mean, greater than 100% indicates extreme values and scatter in the data. The mean coefficient of variation for within-site variability in lead concentration is twenty-seven percent. Two data points higher than the minimum CV% (R10) is eight and two data points lower than the maximum (R90) is 53. Zinc concentrations in the active stream sediments of Chat Creek have the same general pattern as lead concentrations. However, zinc concentrations are much higher than lead concentrations, at times an order of magnitude higher (Table 5.1 and 5.2). Again the C.V.% is relatively high for zinc but generally decreases downstream (Table 5.2). The mean CV% for zinc is 30 while the median is 25 (Table 5.2). The R10 CV% for zinc is 10 and the R90 CV% value is 62 (Table 5.2). The coefficient of variation for the triplicate sites is relatively high throughout the watershed for both metals but generally decrease with increasing

**Table 5.1** Lead concentrations in active channel sediments at this study's twenty-nine sample sites.

| Site # (*mean of triplicate) | Distance from Confluence (meters) | Drainage Area (km$^2$) | Pb (ppm) | Std. Deviation (ppm) | Coefficient of Variation (%) |
|---|---|---|---|---|---|
| *401 | 9,765 | 3.91 | 80 | 9 | 11 |
| *101 | 9,276 | 4.66 | 786 | 414 | 53 |
| *103 | 8,373 | 6.73 | 981 | 301 | 31 |
| *104 | 8,130 | 6.93 | 2068 | 336 | 16 |
| *105 | 7,724 | 7.15 | 880 | 634 | 72 |
| *404 | 7,676 | 7.18 | 782 | 252 | 32 |
| *106 | 6,483 | 8.83 | 1172 | 270 | 23 |
| 119 | 5,687 | 16.02 | 1365 | - | - |
| *110 | 5,583 | 16.07 | 476 | 336 | 70 |
| 123 | 5,504 | 16.09 | 1065 | - | - |
| *118 | 5,452 | 16.10 | 794 | 25 | 3 |
| 117 | 5,117 | 16.50 | 206 | - | - |
| *124 | 5,030 | 16.50 | 314 | 69 | 22 |
| *116 | 4,149 | 22.71 | 373 | 158 | 42 |
| 115 | 3,645 | 22.77 | 300 | - | - |
| 125 | 3,556 | 23.71 | 310 | - | - |
| *107 | 3,264 | 24.26 | 367 | 37 | 10 |
| *407 | 3,187 | 24.39 | 369 | 29 | 8 |
| 132 | 2,870 | 24.40 | 384 | - | - |
| 122 | 2,358 | 25.90 | 60 | - | - |
| 134 | 2,287 | 27.40 | 256 | - | - |
| 120 | 2,018 | 27.55 | 160 | - | - |
| *131 | 1,704 | 30.57 | 256 | 121 | 47 |
| 128 | 1,288 | 30.83 | 194 | - | - |
| *129 | 1,407 | 30.83 | 212 | 30 | 14 |
| 126 | 850 | 31.33 | 214 | - | - |
| 127 | 840 | 31.40 | 148 | - | - |
| *108 | 295 | 31.47 | 158 | 12 | 8 |
| *410 | 279 | 31.91 | 170 | 4 | 2 |

| | Mean | Median (R50) | R10 | R90 |
|---|---|---|---|---|
| CV% | 27 | 22 | 8 | 53 |

**Table 5.2** The zinc concentrations in Chat Creek's active stream sediments.

| Site # (*mean of triplicate) | Distance from Confluence (meters) | Drainage Area (Km$^2$) | Zinc (ppm) | Std. Deviation (ppm) | Coefficient Of Variation (%) |
|---|---|---|---|---|---|
| *401 | 9,765 | 3.91 | 878 | 185 | 21 |
| *101 | 9,276 | 4.66 | 14,780 | 9,225 | 62 |
| *103 | 8,373 | 6.73 | 6,563 | 2,004 | 31 |
| *104 | 8,130 | 6.93 | 19,666 | 2,871 | 15 |
| *105 | 7,724 | 7.15 | 7,946 | 5,606 | 71 |
| *404 | 7,676 | 7.18 | 6,566 | 1,990 | 30 |
| *106 | 6,483 | 8.83 | 7,500 | 821 | 11 |
| 119 | 5,687 | 16.02 | 7,030 | - | - |
| *110 | 5,583 | 16.07 | 3,040 | 2,472 | 81 |
| 123 | 5,504 | 16.09 | 6,910 | - | - |
| *118 | 5,452 | 16.10 | 5,380 | 171 | 3 |
| 117 | 5,117 | 16.50 | 916 | - | - |
| *124 | 5,030 | 16.50 | 1,765 | 704 | 40 |
| *116 | 4,149 | 22.71 | 2,410 | 602 | 25 |
| 115 | 3,645 | 22.77 | 1,570 | - | - |
| 125 | 3,556 | 23.71 | 1,590 | - | - |
| *107 | 3,264 | 24.26 | 2,123 | 318 | 15 |
| *407 | 3,187 | 24.39 | 1,645 | 298 | 18 |
| 132 | 2,870 | 24.40 | 1,305 | - | - |
| 122 | 2,358 | 25.90 | 286 | - | - |
| 134 | 2,287 | 27.40 | 994 | - | - |
| 120 | 2,018 | 27.55 | 1,095 | - | - |
| *131 | 1,704 | 30.57 | 884 | 223 | 25 |
| 128 | 1,288 | 30.83 | 538 | - | - |
| *129 | 1,407 | 30.83 | 780 | 323 | 41 |
| 126 | 850 | 31.33 | 1,270 | - | - |
| 127 | 840 | 31.40 | 940 | - | - |
| *108 | 295 | 31.47 | 1,161 | 118 | 10 |
| *410 | 279 | 31.91 | 1,430 | 50 | 3 |

|  | Mean | Median (R50) | R10 | R90 |
|---|---|---|---|---|
| CV% | 30 | 25 | 10 | 62 |

distance downstream of the mining area (Figure 5.1). The CV% for both metals is highly correlated from 9,765 meters from the confluence with the Spring River downstream to 5,583 meters from the confluence (Figure 5.1). Downstream of this site the relationship between lead and zinc within-site concentration variability diminishes (Figure 5.1). Decreasing CV% downstream and the relationship of the CV% for both metals may be the result of the influence of mining-derived sediment characteristics on transport processes. In upper watershed reaches with higher more correlated CV% values, samples may contain pieces of metaliferous ore that have not been transported far from the mining source area due to its higher density. Thus, concentrations may change drastically over short distances, meters or less, due to density sorting and selective transport. Further downstream, sediment- bound lead has been sorted and is more uniform in concentration resulting in lower local variation.

Both concentrations of lead and zinc are elevated downstream of the abandoned mining area and generally decrease downstream. Site #401, the only sample site above the mining area, has a mean lead concentration of 80 ppm which is the second lowest concentration in the stream (Table 5.1). The lead concentration rises sharply at the next downstream sample site, #101, to 786 ppm. This site is directly adjacent to a portion of the abandoned mining area. The highest lead concentration in the watershed of 2,068 ppm was sampled at site #104 directly downstream of the mining area. From this point downstream to the confluence with the Spring River, lead concentrations in active stream sediments generally decrease. The lowest lead concentration in the watershed, 60 ppm, is found at site #122, which is a little less than 7,000 meters downstream of the mining area (Table 5.1). This low concentration could be the result of dilution erosion of the by the

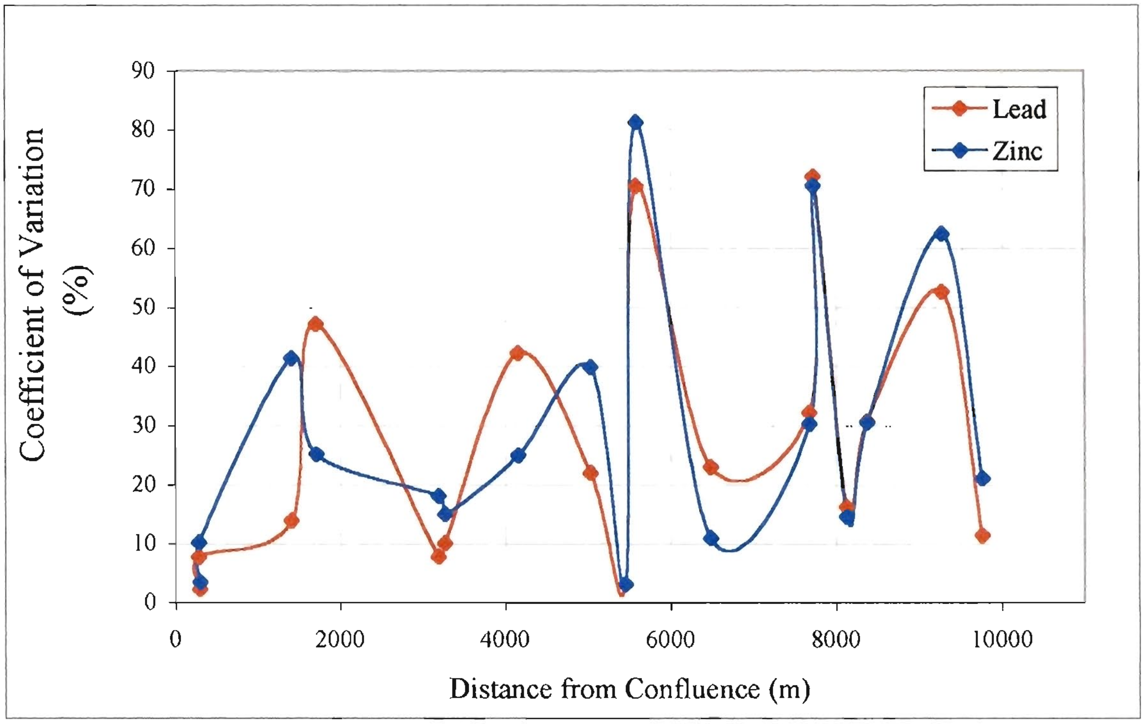


**Figure 5.1** Downstream trend of CV% for lead and zinc.

limestone residuum soil materials, which is relatively uncontaminated in terms of metals compared to mining-contaminated sediment deposits. However, concentrations increase slightly downstream of site #122 (Table 5.1). The zinc concentration above the mining area is 878 ppm (site #401) and rises to 14,780 ppm (site #101) adjacent to the abandoned mining area. Zinc concentrations remain high throughout the watershed but generally decrease downstream to a concentration of 1,430 ppm at site #410, 279 m upstream of the confluence with the Spring River (Table 5.2). Site #122 has the lowest zinc concentration in the watershed at 286 ppm.

A plot of lead and zinc concentrations against distance from the confluence with the Spring River reveals that there are three clusters of similar concentrations for each metal within the mainstem of Chat Creek (Figure 5.2). The downstream relationship of lead and zinc concentrations is similar due to the metals originating from the same source. The geometric mean was calculated for each cluster and used for modeling downstream trends in concentrations of lead and zinc (discussed in a subsequent section). The resulting pattern is a step-like decline downstream (Figure 5.2). The first major step down in metal concentrations is directly downstream of a major tributary that is away from the influence of mining and thus delivers relatively clean sediment into Chat Creek (Figure 5.2). The next step down is downstream of site #122 where the stream cuts into the pre-historical colluvium containing limestone residuum (Figure 5.2).

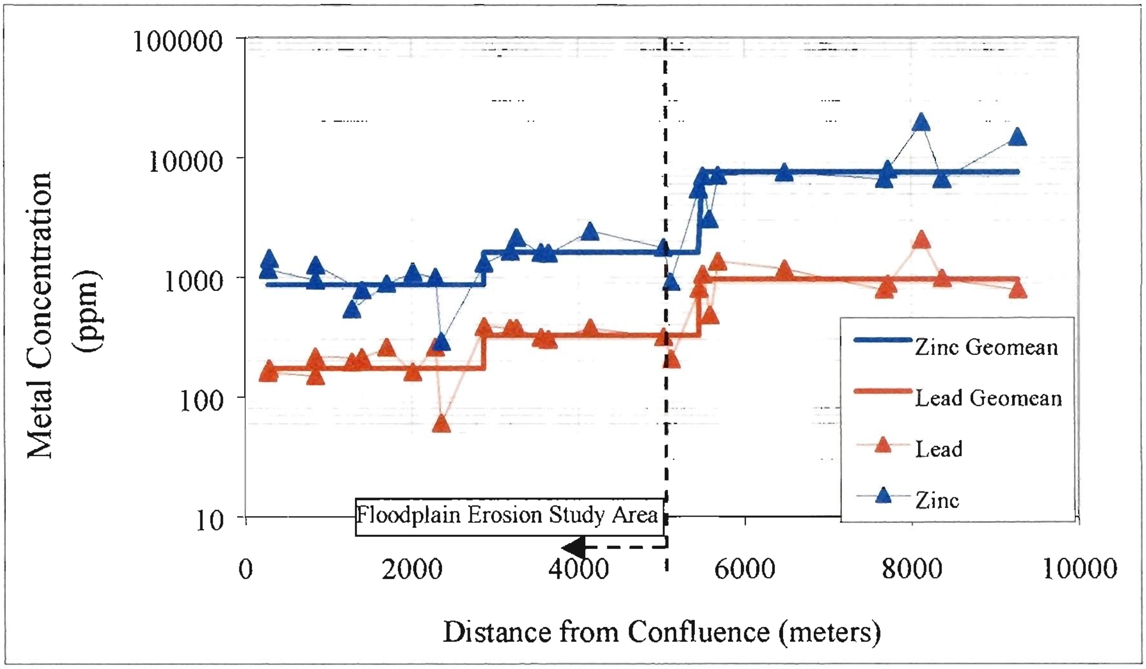


**Figure 5.2** Chat Creek's downstream distribution of lead and zinc.

### *Tributary Inputs*

Complete evaluation of the spatial distribution of lead and zinc in the Chat Creek Watershed requires the analysis of tributary inputs. Tributaries away from major mining sources of lead and zinc should have low metal concentrations and deliver relatively uncontaminated sediment to Chat Creek, thus, mixing with and diluting the lead and zinc in the stream. It is important to point out that the main mining area is not the only source of lead and zinc into the stream. Urban activities can also release relatively large amounts of lead and zinc into the natural environment (Marsalek, 1986; Pitt and Barron, 1989; Bannerman, 1991; Xanthopolous and Hahn, 1993). Furthermore, it is also highly probable that due to the abundance and low-cost of chat material around the mining sites it would be highly desirable to use this material as road fill and other construction fill. If this material were used for such functions it would represent another diffuse source on the landscape. In addition, scattered mining in some tributaries suggest that small mining operations or natural weathering of in-place ore deposits may represent additional source of lead and zinc to tributaries.

Tributary concentrations of lead are highest at sites #333 and #314 with 208 ppm and 232 ppm, respectively (Figure 5.3 and Table. 5.3). Site #333 drains the town of Aurora and its related sources of lead (Figure. 5.3). Concentrations in the active sediments of Chat Creek remain high and are not diluted by the tributary (Figure. 5.3). Site #314 drains a rural area that may have been the location of a few small, isolated mining operations (Figure. 5.3). The remaining four tributary sites have drastically lower lead concentrations than sites #333 and #314 (Table 5.3). Sites #311 and #312 have low concentrations 63 and 39 ppm, respectively. These sites are directly upstream of the location of the first step like decrease in lead concentrations and are acting to dilute the lead concentrations in the main channel (Figure 5.2 and Figure 5.3).

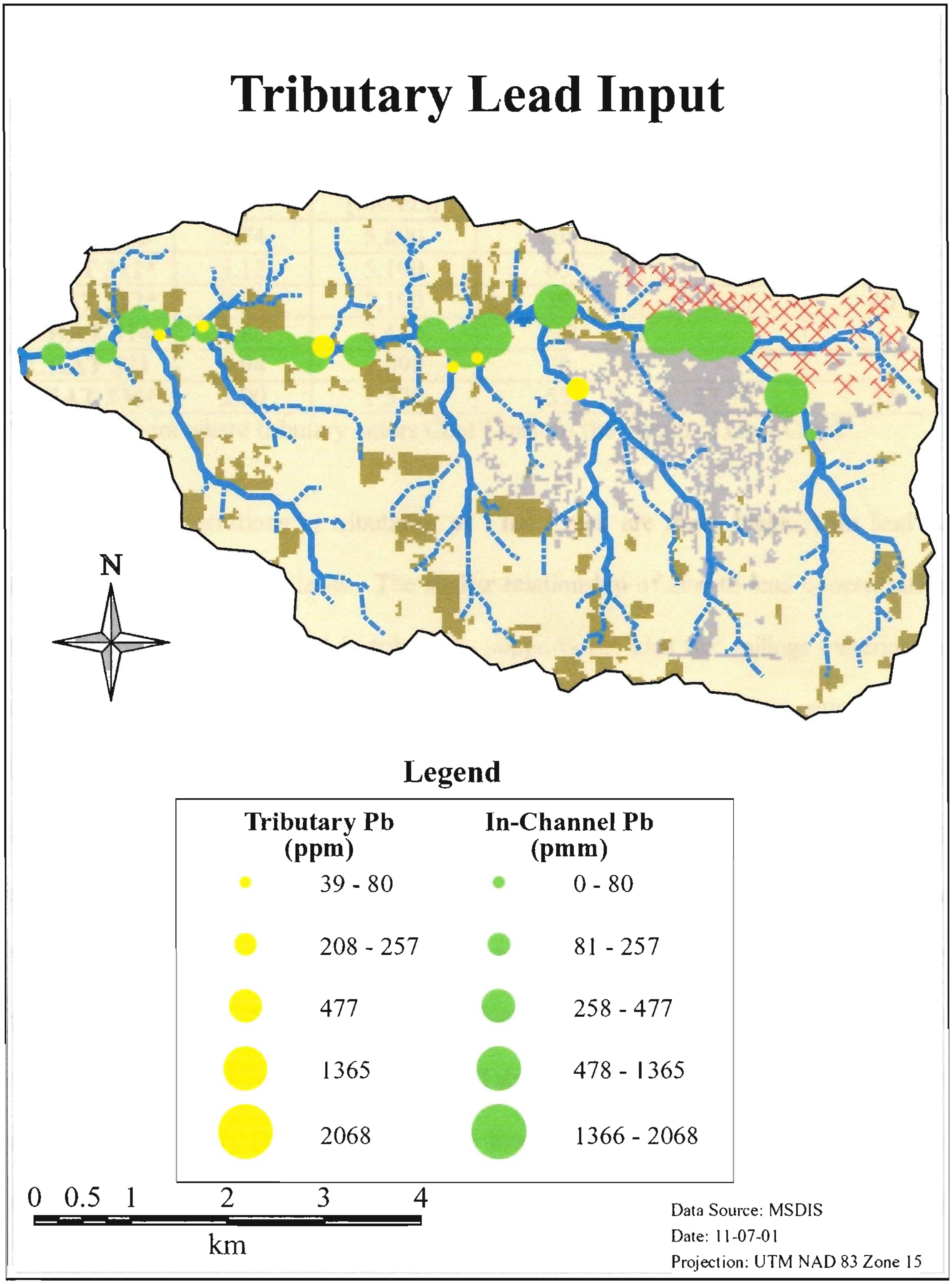


**Figure 5.3** Map illustrating in-channel and tributary concentrations of lead.

**Table 5.3** Tributary concentrations for lead in the Chat Creek Watershed study area.

| Sample # (* triplicate site) | $A_d$ ($km^2$) | **Distance Upstream of Spring R. Confluence (meters) | Pb (ppm) | Std. Dev. (ppm) | Coefficient Of Variation (%) |
|---|---|---|---|---|---|
| **CHAT 333** | 5.74 | 5,890 | 208 | - | - |
| **CHAT 311*** | 3.12 | 5,190 | 63 | 1.15 | 2 |
| **CHAT 312*** | 0.51 | 5,190 | 39 | 15.56 | 40 |
| **CHAT 314** | 0.86 | 3,450 | 232 | - | - |
| **CHAT 321** | 0.94 | 2,090 | 78 | - | - |
| **CHAT 330*** | 2.90 | 1,370 | 53 | 27.59 | 52 |

** Distance from where tributary enters Chat Creek to the mouth of Chat Creek

Zinc concentrations in tributaries of Chat Creek are much higher than lead but have similar distribution patterns. The similar relationship of zinc to lead concentrations in active stream sediments and in tributaries supports the idea that tailings material may have been used for construction fill material. Typically, urban and other sources do not yield such a drastic difference in concentration. The highest zinc concentration of the six tributaries is 1,260 ppm in the tributary that drains Aurora (Table 5.4). Site #314 has the second highest concentration with 844 ppm zinc. In-channel concentrations downstream of these sites do not show evidence of dilution and remain similar to concentrations upstream (Figure 5.4). Sites #311 and #312 have relatively low concentrations and dilute concentrations in the Chat Creek mainstem (Table 5.4 and Figure 5.4). It is important to note that the tributary at site #312 has the lowest zinc concentration and the smallest drainage area of 0.51 $km^2$. In addition, this tributary consists of pastureland with isolated

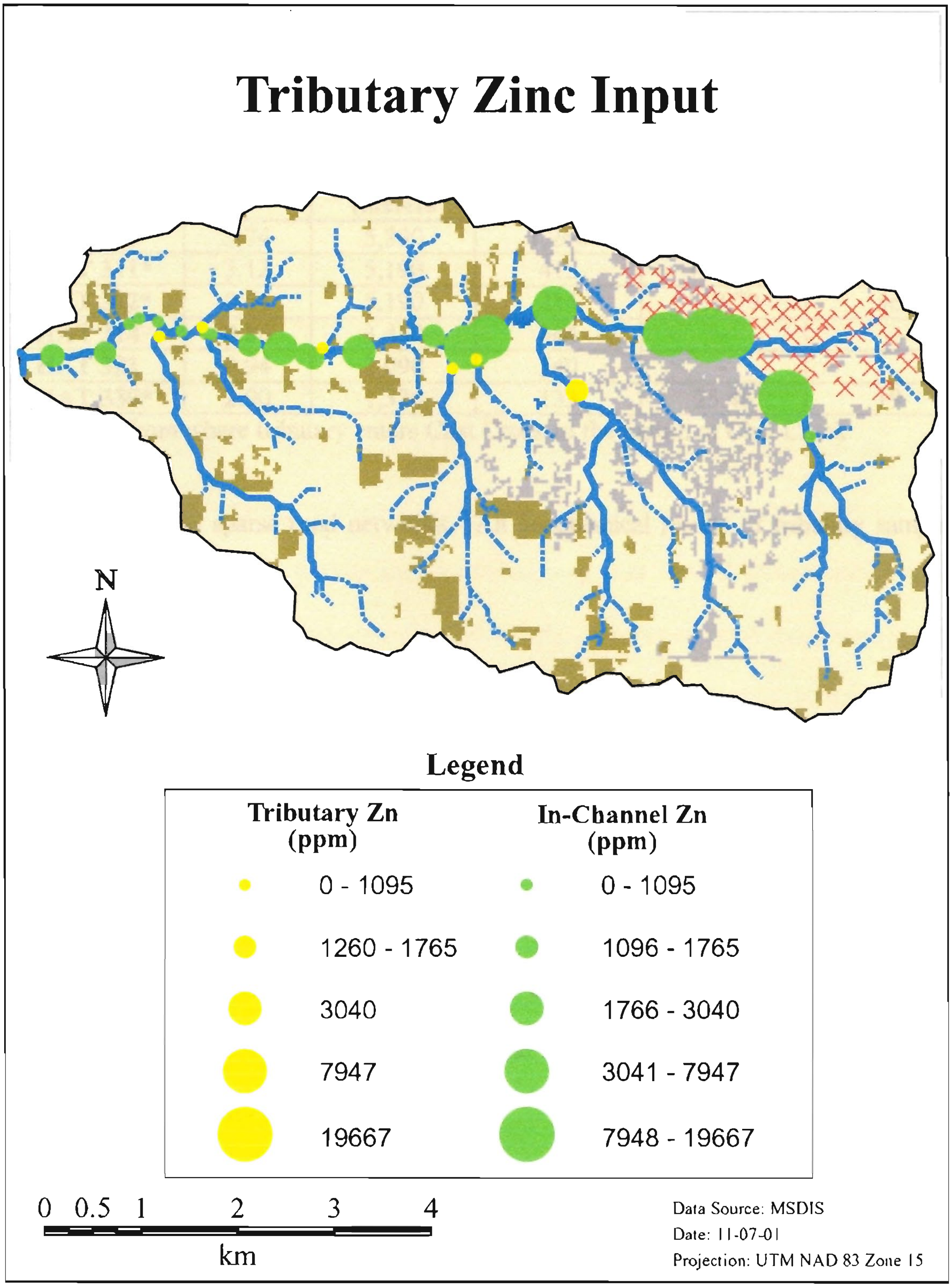


**Figure 5.4** In-channel and tributary zinc concentrations in the Chat Creek Watershed.

**Table 5.4** Tributary concentrations for zinc in the Chat Creek Watershed study area.

| Sample # (* triplicate site) | $A_d$ ($km^2$) | **Distance Upstream of Spring R. Confluence (meters | Zn (ppm) | Std. Dev. (ppm) | Coefficient Of Variation (%) |
|---|---|---|---|---|---|
| **CHAT 333** | 5.74 | 5,890 | 1,260 | - | - |
| **CHAT 311*** | 3.12 | 5,190 | 415 | 121.15 | 29 |
| **CHAT 312*** | 0.51 | 5,190 | 214 | 118.79 | 56 |
| **CHAT 314** | 0.86 | 3,450 | 844 | - | - |
| **CHAT 321** | 0.94 | 2,090 | 540 | - | - |
| **CHAT 330*** | 2.90 | 1,370 | 133 | 25.48 | 19 |

** Distance from where tributary enters Chat Creek to the mouth of Chat Creek

residential lots and sparse road networks. All geochemical results of tributary samples can be found in Appendix F.

### *Anthropogenic Enrichment Factor*

In lead and zinc, mining areas like Chat Creek, natural or background concentrations of these metals will obviously be higher than in other areas. It is expected that natural sources will contribute lead and zinc into the environment as galena and sphalerite weather out of the mineralized bedrock units. The amount of contamination is the degrees of lead and zinc enrichment above this natural background level. A ratio between sampled concentrations and background concentrations was used to determine this Anthropogenic Enrichment Factor (AEF).

Background concentrations are determined from sample sites that are similar in physical setting as the other sample sites but are not downstream of urban, mining, or any other anthropogenic source to minimize the effects of human activities. Site #109 sampled on the Spring River upstream of the confluence with Chat Creek represents background concentrations of sediment-bound lead and zinc (Figure 4.3). Three in-channel and five floodplain profile samples were collected from this site. The in-channel concentrations were slightly elevated as compared to the floodplain samples, this may be due to the effects of isolated suburban inputs and diffuse mining or tailings used in construction of roads. The floodplain samples more accurately represent natural inputs and were therefore used for background levels. The lead and zinc concentrations for each of the floodplain profile samples were divided by the aluminum percentage in the respective sample. Normalizing the metal concentrations with aluminum percentage removes the effects of background sediment geochemistry and grain size on metal concentration. The average of these five ratios is used for the background ratio for each metal (Table 5.5). The background lead/aluminum and zinc/aluminum ratios were determined to be 13 and 55 respectively (Table 5.5). The uncorrected mean background concentrations of each metal are also important when assessing the mass of metals being transported out of the Chat Creek watershed. The uncorrected background concentrations can be used to separate natural metal delivery from mine contaminant delivery. These raw background concentrations are 18 ppm Pb and 78 ppm Zn (Table 5.5). The uncorrected background concentrations used for this study are comparable to those derived for a similar study conducted in the nearby Honey Creek Watershed of 17-ppm lead and 64-ppm zinc (Carlson, 1999).

Like the background samples, lead and zinc concentrations were divided by aluminum percentages for the in-channel sample sites. The resulting concentrations were then divided by the background concentration to determine the AEF for each metal

**Table 5.5** Concentrations used for background determination from the Spring River.

| Lab # | Aluminum (%) | Lead (ppm) | Lead/Aluminum | Zinc (ppm) | Zinc/Aluminum |
|---|---|---|---|---|---|
| **1094** | 1.32 | 20 | 15.15 | 90 | 68.18 |
| **1095** | 1.30 | 20 | 15.38 | 74 | 56.92 |
| **1096** | 1.35 | 20 | 14.81 | 76 | 56.30 |
| **1097** | 1.43 | 14 | 9.79 | 66 | 46.15 |
| **1098** | 1.80 | 18 | 10.00 | 84 | 46.67 |
| **Mean** | | **18** | **13** | **78** | **55** |

(Tables 5.6 and 5.7). Tables 5.6 and 5.7, column #5, shows that Chat Creek is contaminated with lead and zinc throughout its length. Site #104, directly downstream of the abandoned mining area, is the most contaminated with lead concentrations 124 times background levels and zinc concentrations 279 times background levels (Tables 5.6 and 5.7). The step-like downstream distribution of lead and zinc is also evident in the AEF of each metal. At the first step decline at site #117, directly downstream of tributary sites #311 and #312, the lead AEF declines from 47 to 8 while the zinc AEF declines from 75 to eight. The second step decline at site #122, where Chat Creek is eroding into the pre-historical clay unit, the lead AEF declines from 24 to three and zinc AEF declines from 20 to three. The step-like distribution is also evident in Figure 5.5.

Tributary lead and zinc anthropogenic enrichment factors show similar patterns to concentrations of these metals in the tributaries. Sites #333 and #314 again have high AEFs for both lead and zinc (Tables 5.8 and 5.9). Sites #311, #312, and #330 that drain rural pasture and forested areas have the lowest AEFs for lead and zinc.

**Table 5.6** Chat Creek's lead anthropogenic enrichment factor for each in-channel sample site.

| (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|
| **Site #<br>(*mean of triplicate)** | **Al (%)** | **Pb (ppm)** | **Sample Pb/ Sample Al {(3) / (2)}** | **AEF {(4) / 13}** |
| ***401** | 1.24 | 80 | 64.34 | 5 |
| ***101** | 1.04 | 786 | 743.35 | 58 |
| ***103** | 2.22 | 981 | 441.89 | 34 |
| ***104** | 1.28 | 2,068 | 1611.43 | 124 |
| ***105** | 1.02 | 880 | 865.57 | 67 |
| ***404** | 0.77 | 782 | 1011.21 | 78 |
| ***106** | 1.41 | 1,172 | 834.16 | 64 |
| **119** | 1.62 | 1,365 | 842.59 | 65 |
| ***110** | 1.43 | 476 | 333.64 | 26 |
| **123** | 1.27 | 1,065 | 838.58 | 65 |
| ***118** | 1.3 | 794 | 609.21 | 47 |
| **117** | 1.98 | 206 | 104.04 | 8 |
| ***124** | 1.52 | 314 | 206.13 | 16 |
| ***116** | 1.51 | 373 | 246.48 | 19 |
| **115** | 1.11 | 300 | 270.27 | 21 |
| **125** | 1.23 | 310 | 252.03 | 19 |
| ***107** | 1.37 | 367 | 267.88 | 21 |
| ***407** | 1.13 | 369 | 326.55 | 25 |
| **132** | 1.21 | 384 | 317.35 | 24 |
| **122** | 1.62 | 60 | 37.04 | 3 |
| **134** | 1.22 | 256 | 209.84 | 16 |
| **120** | 1.58 | 160 | 101.27 | 8 |
| ***131** | 1.48 | 256 | 172.58 | 13 |
| **128** | 1.64 | 194 | 118.29 | 9 |
| ***129** | 1.99 | 212 | 106.53 | 8 |
| **126** | 1.54 | 214 | 138.96 | 11 |
| **127** | 1.64 | 148 | 90.24 | 7 |
| ***108** | 2.07 | 158 | 76.45 | 6 |
| ***410** | 1.72 | 170 | 99.03 | 8 |

**Table 5.7** Chat Creek's zinc anthropogenic enrichment factor for each in-channel sample site.

| (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|
| **Site # (*mean of triplicate)** | **Al (%)** | **Zn (ppm)** | **Sample Zn/ Sample Al {(3) / (2)}** | **AEF {(4) / 55}** |
| ***401** | 1.24 | 878 | 706.17 | 13 |
| ***101** | 1.04 | 14,780 | 14,166.13 | 258 |
| ***103** | 2.22 | 6,563 | 2,956.31 | 54 |
| ***104** | 1.28 | 19,666 | 15,324.16 | 279 |
| ***105** | 1.02 | 7,946 | 7,815.74 | 142 |
| ***404** | 0.77 | 6,566 | 8,490.52 | 154 |
| ***106** | 1.41 | 7,500 | 5,338.08 | 97 |
| **119** | 1.62 | 7,030 | 4,339.51 | 79 |
| ***110** | 1.43 | 3,040 | 2,130.84 | 39 |
| **123** | 1.27 | 6,910 | 5,440.95 | 99 |
| ***118** | 1.3 | 5,380 | 4,127.88 | 75 |
| **117** | 1.98 | 916 | 462.63 | 8 |
| ***124** | 1.52 | 1,765 | 1,158.64 | 21 |
| ***116** | 1.51 | 2,410 | 1,592.51 | 29 |
| **115** | 1.11 | 1,570 | 1,414.41 | 26 |
| **125** | 1.23 | 1,590 | 1,292.68 | 24 |
| ***107** | 1.37 | 2,123 | 1,549.64 | 28 |
| ***407** | 1.13 | 1,645 | 1,455.75 | 26 |
| **132** | 1.21 | 1,305 | 1,078.51 | 20 |
| **122** | 1.62 | 286 | 176.54 | 3 |
| **134** | 1.22 | 994 | 814.75 | 15 |
| **120** | 1.58 | 1,095 | 693.04 | 13 |
| ***131** | 1.48 | 884 | 595.96 | 11 |
| **128** | 1.64 | 538 | 328.05 | 6 |
| ***129** | 1.99 | 780 | 391.96 | 7 |
| **126** | 1.54 | 1,270 | 824.68 | 15 |
| **127** | 1.64 | 940 | 573.17 | 10 |
| ***108** | 2.07 | 1,161 | 561.77 | 10 |
| ***410** | 1.72 | 1,430 | 833.01 | 15 |

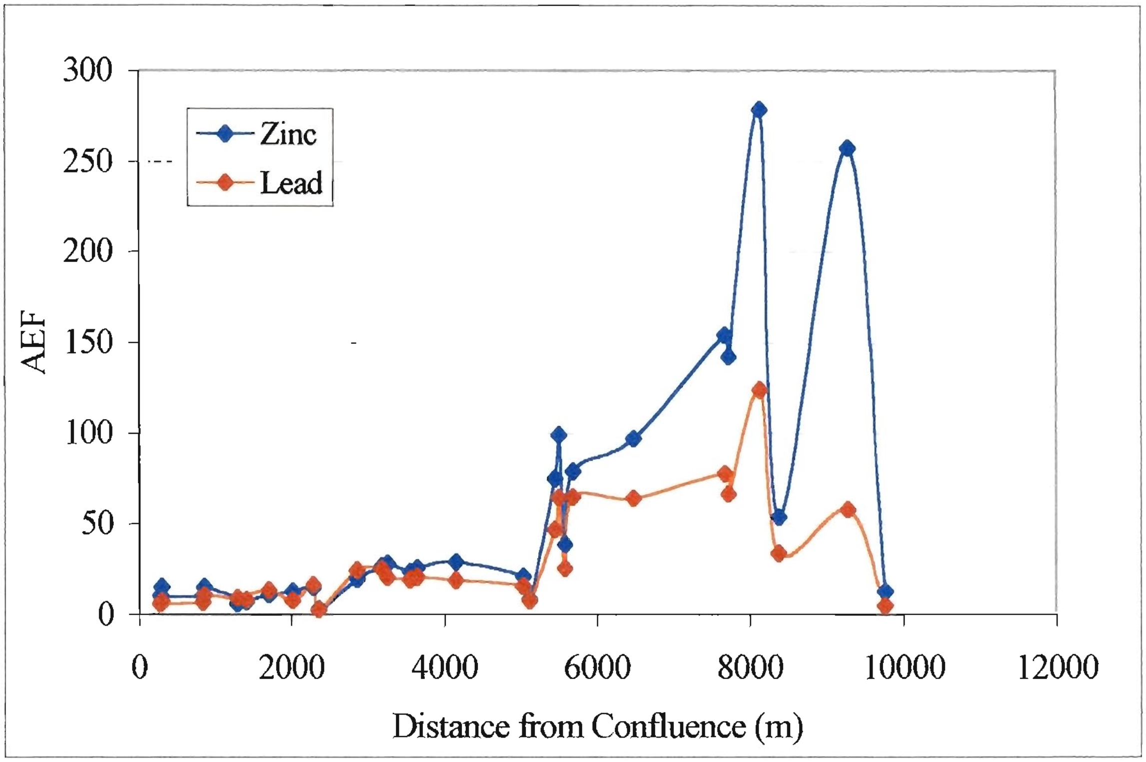


**Figure 5.5** Chat Creek's downstream distribution of lead and zinc AEF.

**Table 5.8** Chat Creek sample sites tributary lead AEF.

| (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|
| **Sample # (*mean of triplicate)** | **Al (%)** | **Pb (ppm)** | **Sample Pb/Sample Al {(3) / (2)}** | **AEF {(4) / 13}** |
| **CHAT 333** | 1.23 | 208 | 169 | 13 |
| **CHAT 311*** | 1.32 | 63 | 47 | 4 |
| **CHAT 312*** | 1.98 | 39 | 20 | 2 |
| **CHAT 314** | 1.37 | 232 | 169 | 13 |
| **CHAT 321** | 1.01 | 78 | 77 | 6 |
| **CHAT 330*** | 1.71 | 53 | 31 | 2 |

**Table 5.9** Chat Creek's sample site tributary zinc AEF.

| (1) | (2) | (3) | (4) | (5) |
|---|---|---|---|---|
| **Sample # (*mean of triplicate)** | **Al (%)** | **Zn (ppm)** | **Sample Zn/Sample Al {(3) / (2)}** | **AEF {(4) / 55}** |
| **CHAT 333** | 1.23 | 1,260 | 1024 | 19 |
| **CHAT 311*** | 1.32 | 415 | 314 | 6 |
| **CHAT 312*** | 1.98 | 214 | 108 | 2 |
| **CHAT 314** | 1.37 | 844 | 616 | 11 |
| **CHAT 321** | 1.01 | 540 | 535 | 10 |
| **CHAT 330*** | 1.71 | 133 | 78 | 1 |

### *Lead and Zinc Geochemical Relationships*

Many researchers investigate the relationship between lead/zinc and other geochemical elements in order to understand the mobility and forms of these metals in the environment (Warren, 1981; Leenaers *et al.*, 1989; Mantei and Sappington, 1994; Pavlowsky, 1995; Swennen and Van der Sluys, 1998). Source and sediment characteristics can often be explained by strong relationships between lead/zinc and other elements. Researchers often use correlation or regression analysis of these relationships in order to predict metal concentrations. While this is not the main focus of this study, Pearson correlation analysis is used to test for relationships between lead and zinc and other geochemical components (Table 5.10). The Pearson correlation coefficient indicates the strength of linear relationships and is expressed as a number between one and minus one. A Pearson correlation coefficient of one is a perfect positive linear relationship between the two elements in question while a Pearson correlation coefficient of minus one is a perfect negative linear relationship. A Pearson correlation coefficient of zero indicates that there is no linear relationship between the two variables under

**Table 5.10** Pearson Correlation Matrix for plotting geochemical relationships.

**Geochemical Relationships**

| | | PB | ZN | P | AL | FE | CA | MN | OM |
|---|---|---|---|---|---|---|---|---|---|
| PB | Pearson Correlatio | 1 | .889** | -.022 | -.192 | .014 | .548** | .368** | .252* |
| | Sig. (2-tailed) | . | .000 | .848 | .093 | .904 | .000 | .001 | .041 |
| | N | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 66 |
| ZN | Pearson Correlatio | .889** | 1 | -.173 | -.273* | -.115 | .589** | .196 | .156 |
| | Sig. (2-tailed) | .000 | . | .130 | .015 | .316 | .000 | .086 | .211 |
| | N | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 66 |
| P | Pearson Correlatio | -.022 | -.173 | 1 | -.011 | .352** | -.266* | -.022 | .290* |
| | Sig. (2-tailed) | .848 | .130 | . | .924 | .002 | .019 | .851 | .018 |
| | N | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 66 |
| AL | Pearson Correlatio | -.192 | -.273* | -.011 | 1 | .113 | -.493** | .267* | -.004 |
| | Sig. (2-tailed) | .093 | .015 | .924 | . | .326 | .000 | .018 | .976 |
| | N | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 66 |
| FE | Pearson Correlatio | .014 | -.115 | .352** | .113 | 1 | -.263* | .475** | -.270* |
| | Sig. (2-tailed) | .904 | .316 | .002 | .326 | . | .020 | .000 | .028 |
| | N | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 66 |
| CA | Pearson Correlatio | .548** | .589** | -.266* | -.493** | -.263* | 1 | .100 | .165 |
| | Sig. (2-tailed) | .000 | .000 | .019 | .000 | .020 | . | .382 | .187 |
| | N | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 66 |
| MN | Pearson Correlatio | .368** | .196 | -.022 | .267* | .475** | .100 | 1 | .015 |
| | Sig. (2-tailed) | .001 | .086 | .851 | .018 | .000 | .382 | . | .902 |
| | N | 78 | 78 | 78 | 78 | 78 | 78 | 78 | 66 |
| OM | Pearson Correlatio | .252* | .156 | .290* | -.004 | -.270* | .165 | .015 | 1 |
| | Sig. (2-tailed) | .041 | .211 | .018 | .976 | .028 | .187 | .902 | . |
| | N | 66 | 66 | 66 | 66 | 66 | 66 | 66 | 66 |

**. Correlation is significant at the 0.01 level (2-tailed).

*. Correlation is significant at the 0.05 level (2-tailed).

examination. The strongest linear relationship is between lead and zinc, indicating the same source (mining area) for both metals (Table 5.10). Another important relationship that emphasizes the mining area as a source for lead and zinc is the relationship of lead and zinc with calcium, which indicates the calcium carbonate bedrock source of the mine tailings (Table 5.10). The relationship of lead and zinc with iron, manganese, and organic matter (OM) are also important relationships to examine since these components may accumulate pollutants. Organic matter and iron-manganese oxide coatings usually concentrate lead and zinc by sorption processes in aquatic systems (Horowitz, 1991).

However, there is only a weak relationship between lead and manganese and organic matter and even poorer trend with zinc (Table 5.10). It is quite possible that these typical aquatic geochemical relationships are largely overwhelmed by the dominant influence of the mine tailings contribution and its physical transport downstream (Table 5.10). Understanding the association of lead and zinc with particular sediment size fractions is also important for researchers. Sediment fraction analysis can indicate transport patterns and source environments. Research has indicated that aluminum is closely associated with clay particles and can be used as a surrogate for the clay fraction (Horowitz, 1991; Aslan and Autin, 1998). Strong relationships between lead and zinc with aluminum would indicate that these metals are concentrated in the clay fraction and could aid in determining transport processes of these metals. However, this relationship does not exist in the sediment of Chat Creek (Table 5.10). It is probable that due to the milling and processing of mining ore that the metals are distributed throughout several different sediment size fractions and are not concentrated in any particular fraction.

## Phosphorus Distribution

An important water quality issue in southwestern Missouri is the excessive level of nutrients, especially phosphorus, in recreational waters. Excessive phosphorus levels cause high rates of algal growth, which in turn allows increased growth of bacteria that feed on dying algae. The bacteria generation depletes dissolved oxygen levels resulting in eutrophic conditions. Eutrophication results in fish kills and degraded water appearance and smell. Different sources are associated with excessive phosphorus introduction including both point and nonpoint sources. Point source introduction is mostly linked to waste water treatment facilities. Nonpoint sources include urban and suburban functions and agricultural activities. All of these possible sources are present in the Chat Creek watershed. Aurora, its surrounding subdivisions, and the outlying agricultural areas are possible nonpoint sources. The outflow of Aurora's wastewater treatment facility enters directly into Chat Creek and is a point source of phosphorus.

### *Downstream Trends*

Concentrations of sediment-bound phosphorus in active sediments of Chat Creek are relatively low and then gradually increase downstream to site #119, which is directly downstream of the wastewater treatment facility outflow to 1,370 ppm (Table 5.11 and Figure 5.6). The gradual increase just upstream of the wastewater treatment facility could be attributed to other urban industrial inputs from Aurora or the result of sewage sludge applications. Four hundred meters downstream from the wastewater treatment facility outflow (5,900 meters from confluence with Spring River) at site #123 phosphorus concentration increases to a high of 3,080 ppm. (Table 5.11 and Figure 5.6). Downstream from this site, concentrations gradually decrease with the exception of two minor spikes (Figure 5.6). Concentrations do not decrease drastically because of the extremely high concentrations from the wastewater treatment facility. From the wastewater treatment facility to the confluence with the Spring River, (5.9 km) concentrations are below 1,000 ppm only twice (Table 5.11 and Figure 5.6). The mean concentration for all 29-sample sites is 1,268 ppm. A possible reason for phosphorus concentrations remaining high throughout the length of Chat Creek is the abundance of nonpoint sources. The lower 5.2 km of Chat Creek is composed almost exclusively of pasture and livestock operations, which could be introducing significant amounts of phosphorus into the stream.

**Table 5.11** Phosphorus concentration levels in the active stream sediment of Chat Creek.

| Site # (*mean of triplicate) | Distance from Confluence (meters) | Drainage Area (km$^2$) | P (ppm) | Std. Deviation (ppm) | Coefficient of Variation (%) |
|---|---|---|---|---|---|
| ***401** | 9,765 | 3.91 | 270 | 10 | 4 |
| ***101** | 9,276 | 4.66 | 493 | 49 | 10 |
| ***103** | 8,373 | 6.73 | 310 | 108 | 35 |
| ***104** | 8,130 | 6.93 | 413 | 67 | 16 |
| ***105** | 7,724 | 7.15 | 410 | 92 | 22 |
| ***404** | 7,676 | 7.18 | 417 | 60 | 14 |
| ***106** | 6,483 | 8.83 | 838 | 112 | 13 |
| **119** | 5,687 | 16.02 | 1,370 | - | - |
| ***110** | 5,583 | 16.07 | 1,757 | 649 | 37 |
| **123** | 5,504 | 16.09 | 3,080 | - | - |
| ***118** | 5,452 | 16.10 | 2,320 | 79 | 3 |
| **117** | 5,117 | 16.50 | 1,510 | - | - |
| ***124** | 5,030 | 16.50 | 1,670 | 235 | 14 |
| ***116** | 4,149 | 22.71 | 1,747 | 405 | 23 |
| **115** | 3,645 | 22.77 | 1,770 | - | - |
| **125** | 3,556 | 23.71 | 2,050 | - | - |
| ***107** | 3,264 | 24.26 | 1,523 | 31 | 2 |
| ***407** | 3,187 | 24.39 | 1,640 | 10 | 0 |
| **132** | 2,870 | 24.40 | 2,080 | - | - |
| **122** | 2,358 | 25.90 | 760 | - | - |
| **134** | 2,287 | 27.40 | 1,300 | - | - |
| **120** | 2,018 | 27.55 | 950 | - | - |
| ***131** | 1,704 | 30.57 | 1,323 | 231 | 17 |
| **128** | 1,288 | 30.83 | 1,010 | - | - |
| ***129** | 1,407 | 30.83 | 1,233 | 110 | 9 |
| **126** | 850 | 31.33 | 1,080 | - | - |
| **127** | 840 | 31.40 | 1,050 | - | - |
| ***108** | 295 | 31.47 | 1,103 | 119 | 11 |
| ***410** | 279 | 31.91 | 1,307 | 59 | 5 |

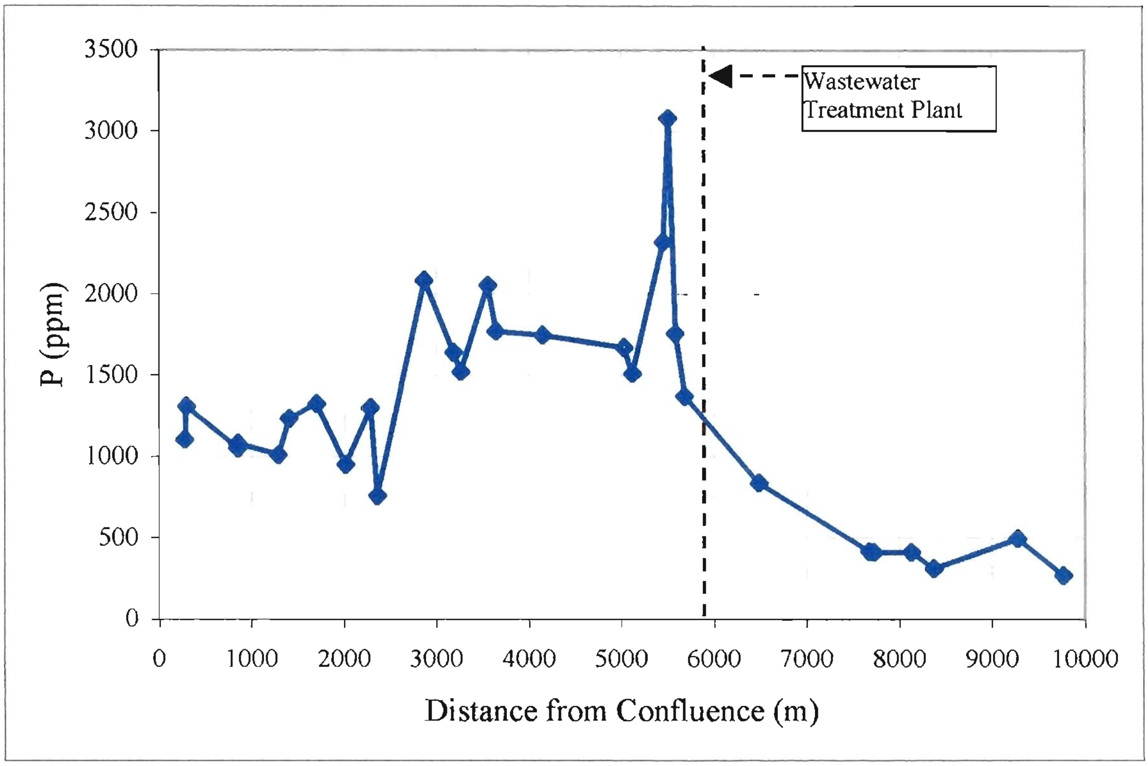


**Figure 5.6** Downstream distribution levels of sediment-bound phosphorous in Chat Creek.

The concentrations of sediment-bound phosphorus in Chat Creek are generally higher than concentrations found in similar studies. White (2001) investigated phosphorus in the sediment of the King's River Watershed in northwestern Arkansas. The highest concentration sampled, downstream of a wastewater treatment facility, was 1,280 ppm which is 1,800 ppm less than the highest concentration in the Chat Creek watershed (White, 2001). Concentrations in the King's River watershed away from point sources averaged 170 ppm, the lowest concentration sampled in the Chat Creek watershed was 270 ppm. Fredrick (2001) assessed sediment-bound phosphorus concentrations in the James River Basin, Southwest, Missouri. He determined through the analysis of 80 samples that the mean phosphorus concentration in active channel sediments of the James River was 366 ppm and the range was 100 – 1,960 ppm (Fredrick, 2001). The mean value is 900 ppm lower than the mean for the 29 samples in Chat Creek. The highest concentration sampled in Chat Creek is 1,120 ppm higher than in the James River Basin. The highest concentration for both studies was sampled downstream of a wastewater treatment facility. However, the wastewater treatment facility in the James River study serves the urban area of Springfield, Missouri and is much larger than the wastewater facility that serves Aurora, Missouri. Sub-watersheds consisting mostly of forestland and some agriculture that were sampled by Fredrick have much lower concentrations than the Chat Creek watershed. The largely undisturbed Flat Creek and Crane Creek, in the James River Basin, have sediment-phosphorus concentrations that range from 100 – 300 ppm.

### *Tributary Inputs*

High phosphorus concentrations in tributaries may be another reason there is not a longitudinal decay of concentrations in the mainstem of Chat Creek. While tributary concentrations are low as compared to the rest of the Chat Creek drainage, they are still considered high when compared to the findings of White (2001) (Table 5.12). The highest tributary concentrations were found at sites #314 (930 ppm) and #321 (780 ppm), these sites drain the pasture/livestock area of the lower Chat Creek (Table 5.12 and Figure 5.7). The only predominantly urban tributary, site #333, has the third lowest concentration with 400 ppm P (Table 5.12). There is some evidence of the dilution of Chat Creek sediment phosphorous below tributary sites #311 and #312 (Figure 5.7). At site #118, upstream of this confluence, the P concentration is 2,320 and at site #117, downstream of this confluence, the P concentration is 1,510 ppm (Table 5.11).

**Table 5.12** Phosphorus concentration levels in the tributaries of Chat Creek.

| **Sample #** **(* triplicate site)** | **$A_d$ ($km^2$)** | ****Distance Upstream of Spring R. Confluence (meters)** | **P (ppm)** | **Std. Dev. (ppm)** | **Coefficient Of Variation (%)** |
|---|---|---|---|---|---|
| CHAT 333 | 5.74 | 5,890 | 400 | - | - |
| CHAT 311* | 3.12 | 5,190 | 417 | 124.23 | 30 |
| CHAT 312* | 0.51 | 5,190 | 265 | 49.50 | 19 |
| CHAT 314 | 0.86 | 3,450 | 930 | - | - |
| CHAT 321 | 0.94 | 2,090 | 780 | - | - |
| CHAT 330* | 2.90 | 1,370 | 390 | 79.37 | 20 |

** Distance from where tributary enters Chat Creek to the mouth of Chat Creek

***Phosphorus Geochemical Relationships***

Just as with lead and zinc, it is important to examine the relationship or lack of a relationship between phosphorus and other geochemical elements. In a natural setting phosphorus has a strong affinity for organic matter and the fine-grain sediment fraction (Horowitz, 1991). Again, aluminum is used as a surrogate for fine-grain sediment. High aluminum percentages indicate high fine-grain composition in the sample. The samples for the current study do exhibit a poor relationship between phosphorus and aluminum and a moderate relationship between phosphorus and organic matter (Table 5.10). Again this may indicate the complete disruption of any natural relationships because of the overwhelming influence of the wastewater treatment facility. It is of importance to also examine the relationships between phosphorus and lead and zinc. There is no relationship between phosphorus and these metals indicating that the wastewater treatment facility is not an important source of either lead or zinc (Table 5.10). The strong relationship between phosphorus and iron suggests that iron oxides are

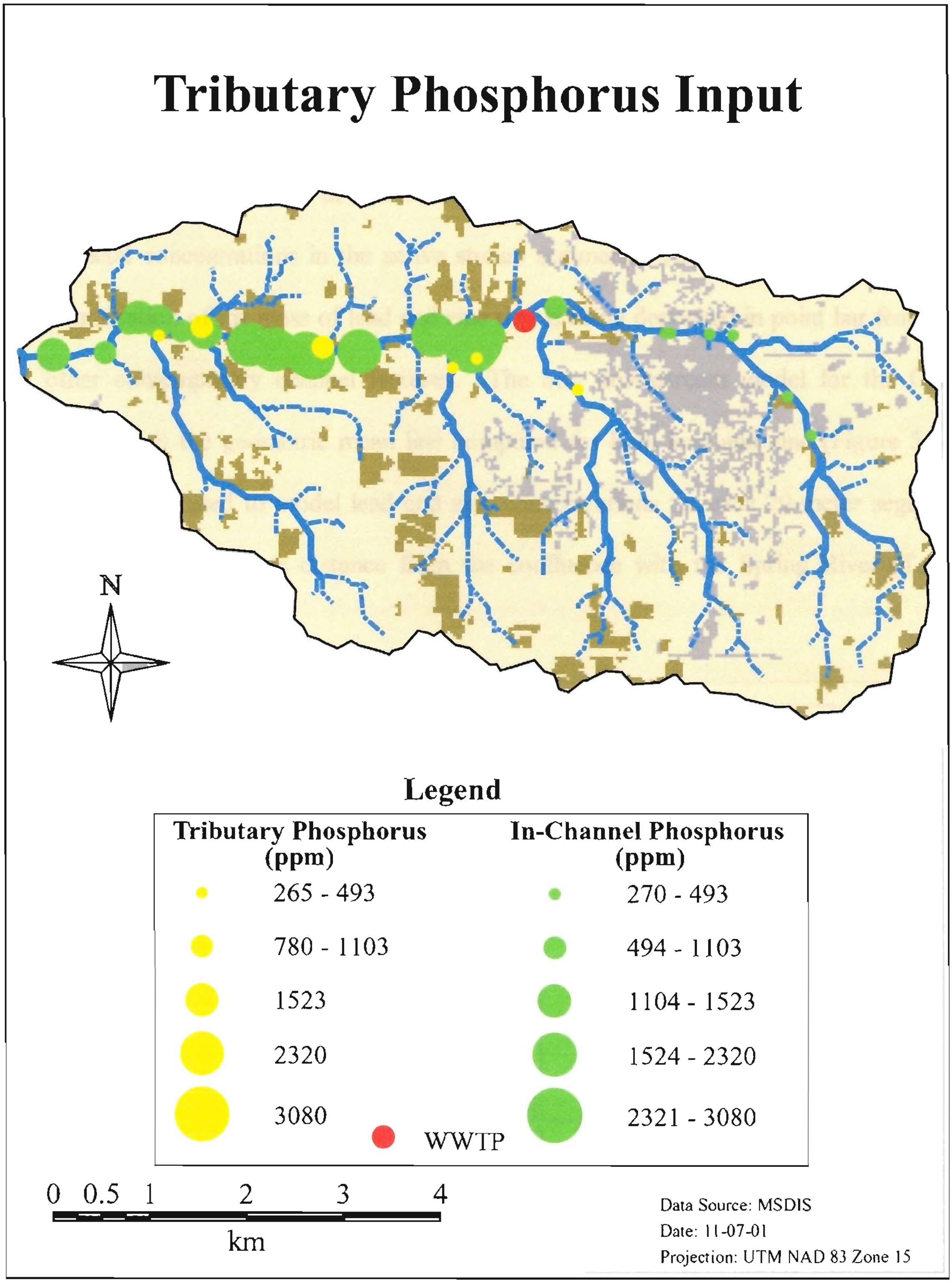


**Figure 5.7** Tributary influence on mainstem phosphorus concentrations in the study area.

Accumulating phosphorous from the wastewater effluent or that iron is found in relatively high levels in the effluent too.

### Downstream Model of In-Channel Lead and Zinc

An important variable in determining a budget for floodplain erosion of lead and zinc is metal concentrations in the active stream sediment. These concentrations aid in the quantification of the mass of lead and zinc that is being deposited in point bar features and other contemporary channel features. The best downstream model for the Chat Creek dataset is the geometric mean line computed for both lead and zinc (Figure 5.8). These lines were used to model lead and zinc concentrations for each 20-meter segment according to the segments distance from the confluence with the Spring River (Table 5.13).

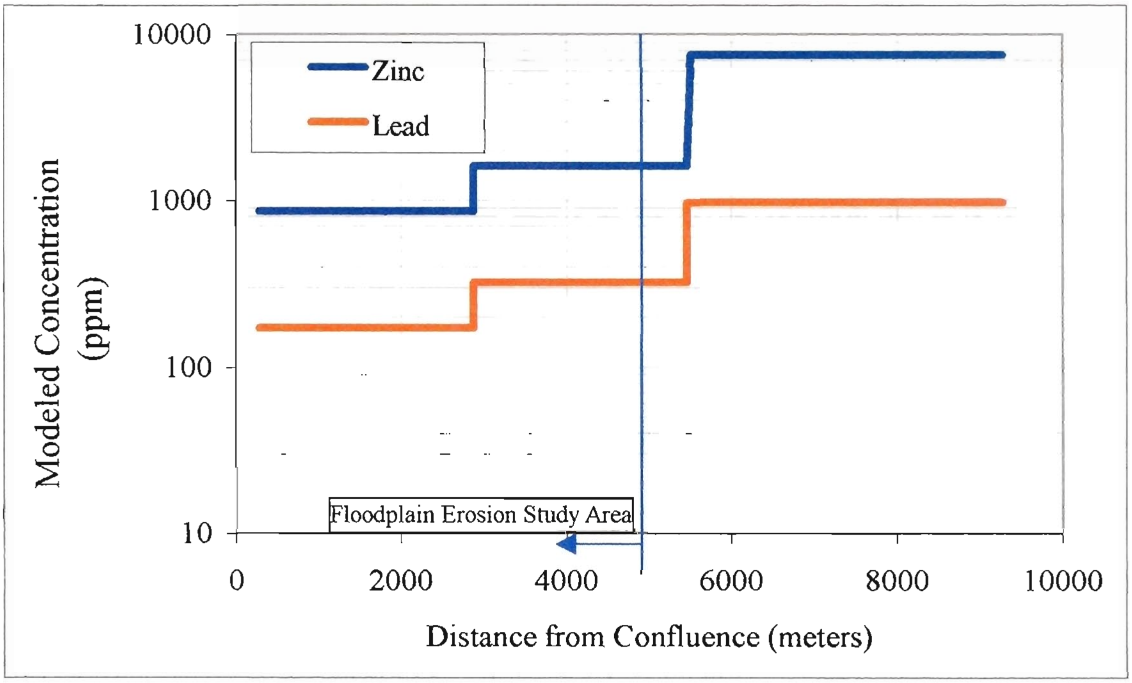


**Figure 5.8** Geometric mean line used model lead and zinc concentrations in active channel sediment of Chat Creek.

**Table 5.13** Lead and zinc concentrations applied to each 20-meter segment.

| Distance from Confluence (meters) | Modeled Zinc (ppm) | Modeled Lead (ppm) |
|---|---|---|
| 5,500-5,452 | 7,539 | 966 |
| 5,451-2,870 | 1,606 | 322 |
| 2,869-0 | 863 | 172 |

## Chapter Summary

Knowing that high lead and zinc concentrations are present in the active stream sediment of Chat Creek is important to watershed managers. Metal concentrations in the active stream sediment of Chat Creek are extremely elevated downstream of the abandoned mining areas. Lead concentrations directly downstream of the mining area are as high as 2,068 ppm, which is elevated 124 times above background levels. The highest zinc concentration, at the same site, is 19,666 ppm, which is elevated 279 times above background levels.

The downstream trends of both lead and zinc concentration are best represented by the geometric mean of three different reaches of the stream. The line yielded by the geometric mean is a stair-step pattern decreasing in the downstream direction. The two steps in each dataset are created by two different phenomena. The first step down is the result of the introduction of “clean” sediment from a relatively uncontaminated tributary. The second step down in each case is the result of erosion of slope soils or colluvium of the clayed limestone residuum unit. The lines formed by the geometric means of each metal were used to quantify the trends of in-channel concentrations. These concentrations are equivalent to the concentration of metals deposited in the active channel from upstream sources. For lead, these concentrations are: (1) 966 ppm for segments occurring between 5,500 and 5,452 meters from the confluence; (2) 322 ppm for segments occurring between 5,451 and 2,870 meters from the confluence; and (3) 172 ppm for segments occurring between 2,869 meters from the confluence to the confluence with the Spring River. For zinc, these concentrations are: (1) 7,539 ppm for segments between 5,500 and 5,452 meters from the confluence; (2) 1,606 ppm for segments between 5,451 and 2,870 meters from the confluence; and (3) 863 ppm for segments occurring between 2,869 meters from the confluence to the confluence with the Spring River.

Phosphorus levels in Chat Creek are also high compared to other studies. The highest phosphorus concentrations are downstream of the wastewater treatment facility. The highest concentration sampled in the stream was 3,080 ppm while the lowest was 270 ppm upstream of the wastewater treatment facility. Phosphorus concentrations gradually decrease downstream of the wastewater treatment facility but remain high throughout the length of the stream and probably provide a source of phosphorus to the Spring River.

# CHAPTER 6

# CHANNEL MIGRATION RATES

The annual migration rate for each 20-meter segment is an important variable in determining a budget for sediment, lead, and zinc since channel migration results in floodplain erosion. Since no previous surveys exist for Chat Creek, these rates were determined through analysis of contemporary and historical aerial photographs. Channel centerlines were digitized for aerial photographs from 1990 and 1997 and the migration rate was determined by the change in platform position for the time span using a GIS. This rate was averaged over the seven-year period to derive the yearly migration rate, which was input directly into the budget calculation. The migration rate is used to determine erosion volume ($m^3$) and deposition volume ($m^3$).

Error propagation is an important consideration when using digital spatial datasets, therefore this chapter begins with a discussion on quantifying and minimizing error associated with determining migration rates for each of the 20-meter segments. The remaining discussion focuses on two sets of results, raw migration rates and migration rates that have been filtered through the determined error limits. Downstream trends are discussed as well as patterns for "bend" reaches and "straight" reaches.

## Error Analysis

Spatial investigations utilizing digital data must attempt to understand error in the digital data that can be propagated throughout subsequent analysis. Several methods were utilized in this study to quantify and to minimize error. The errors examined in this study mainly fall into one of two types. The first type of error is introduced during the aerial photograph rectification process. Even though RMS errors were kept to a minimum during rectification, the 1990 photograph does not match perfectly in two-dimensional space with the 1997 DOQQ to which it was rectified. This poses obvious problems when evaluating stream channel migration since rectification error can result in the apparent change in channel position even though no change has actually taken place. Two steps were taken to try to first quantify the amount of offset and then to minimize as much of the offset as possible without sacrificing the integrity of the data. The second type of error is the placement of the digitized centerlines for the 1990 and 1997 channels. Although each channel centerline was thoroughly checked and edited to improve the location of the line in regards to the center of the channel, the consistent placement of the line is of concern.

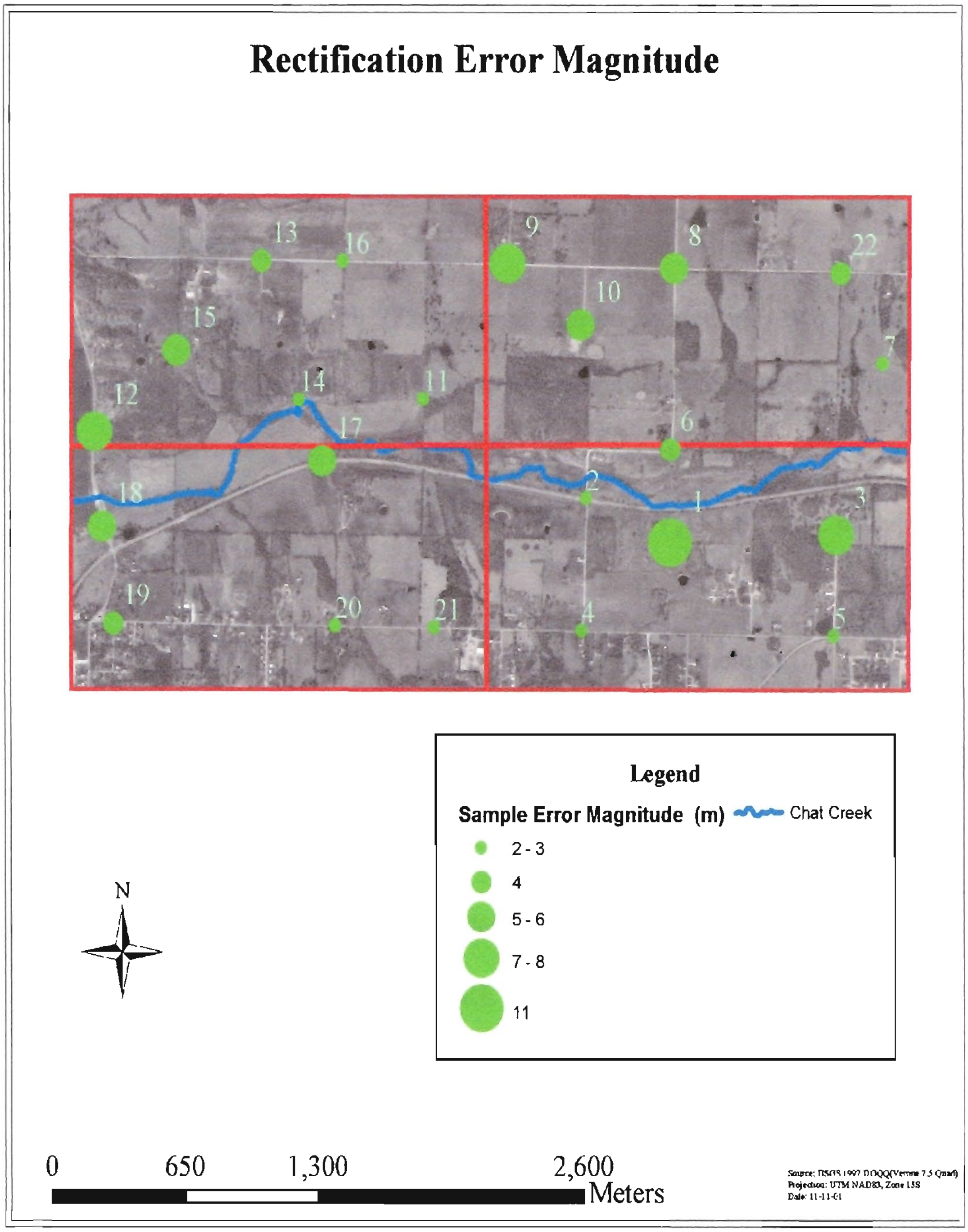
The National Standard for Spatial Data Accuracy (NSSDA) developed by the Federal Geographic Data Committee (FGDC) provides a statistical methodology to evaluate the accuracy of digital spatial datasets (FGDC, 1998). Rectification (horizontal) accuracy of the 1990 aerial photograph in relation to the 1997 DOQQ was evaluated using the NSSDA guidelines similar to Greenfield (2001). Coordinates (Easting and Northing) of 22 common points were evaluated between the photos and the amount of deviation from the DOQQ to the 1990 photo was recorded. The analysis results of rectification error are listed in Table 6.1. The mean horizontal error in points on the 1990 photograph is 4.6 meters away from the same points on the 1997 DOQQ. While this appears to be a large amount of offset, when averaged over the seven-year study period, it is only 0.66 meters per year. It is also important to note that these points were selected from various points not necessarily near Chat Creek where rectification efforts were focused. A majority of the points near Chat Creek have displacement between 2-4

**Table 6.1** Results of adjustment showing statistics for quantifying and minimizing error in digital spatial dataset.

| | n | Mean (meters) | Std. Deviation (meters) | Median (meters) | 95% Confidence Interval(meters) |
|---|---|---|---|---|---|
| **Rectification Error** | 22 | 4.6 | 2.3 | 4.1 | -- |
| **Railroad Adjustment** | 214 | 4 | 2.47 | 3.8 | -- |
| **1990 Line Placement Error** | 45 | 0.52 | 0.42 | 0.45 | $0.40 \leq \mu \leq 0.64$ |
| **1997 Line Placement Error** | 45 | 0.49 | 0.39 | 0.37 | $0.38 \leq \mu \leq 0.60$ |

meters (Figure 6.1). Another step was taken to minimize, where possible, this offset error. This measure entails using the railroad that runs adjacent to Chat Creek to adjust for offset (discussed in Chapter 4) and 214 20-meter segments were adjusted a mean horizontal distance of 4 meters (Table 6.1). This adjustment reduces the total mean offset error to 0.6 meters in errors where this methodology was used (Table 6.1). Not all portions of Chat Creek were adjusted using the railroad; the adjustment was not applicable to 61 of the 275 segments, these segments are indicated in Appendix J. Also of importance, the area near Chat Creek that contains some of the highest offset values (point #1) was adjusted using the railroad offset (Figure 6.1).

The line placement error was assessed by triplicate digitization of three 100-meter segments in both the 1990 photo and the 1997 DOQQ and differences in line placement measured. Each of the three lines was digitized in separate settings with only the stream channel displayed on screen. The data for line placement difference for each year were recorded, summarized, and used to determine a 95% confidence interval for the difference in line placement for each year (Table 6.1). The overall mean for the difference for 1990 occurs between 0.40 meters and 0.64 meters at the 95% confidence level (Table 6.1). Dividing this interval by the seven-year study period reduces the



Source: USGS 1997 DOQQ(Version 7.5 Quad)
Projection: UTM NAD83, Zone 15S
Date: 11-11-01

**Figure 6.1** Rectification error magnitude at 22 sample points. Numbers next to point indicates sample number.

interval to a yearly difference of 0.06 – 0.09 meters. The 95% confidence interval for the overall mean of the 1997 difference in line placement is 0.38 – 0.60 meters (Table 6.1). Allocating this interval over the seven-year study period reduces it to 0.05 – 0.09 meters. The interval for the total difference in line placement, 0.11 – 0.17 meters, was computed by summing the 1990 and 1997 intervals.

Cumulative error for all 275 segments can be divided into two broad categories. The first category consists of the segments that were adjusted with the railroad offset. The cumulative error for the first category is determined as follows:

$$TE_{rr}(m) = \left[(RE \div 7) - (RA \div 7)\right] + LPI \quad \text{(Eq. 6.1)}$$

where:

$TE_{rr}$ = Total error of segments adjusted with railroad offset (meters)
RE = Mean total rectification error (meters)
RA = Mean total railroad adjustment (meters)
LPI = Confidence interval for total difference in line placement (meters)

The second category is the 61 segments not adjusted with the railroad offset. The cumulative error for the first category is determined as follows:

$$TE(m) = (RE \div 7) + LPI \quad \text{(Eq. 6.2)}$$

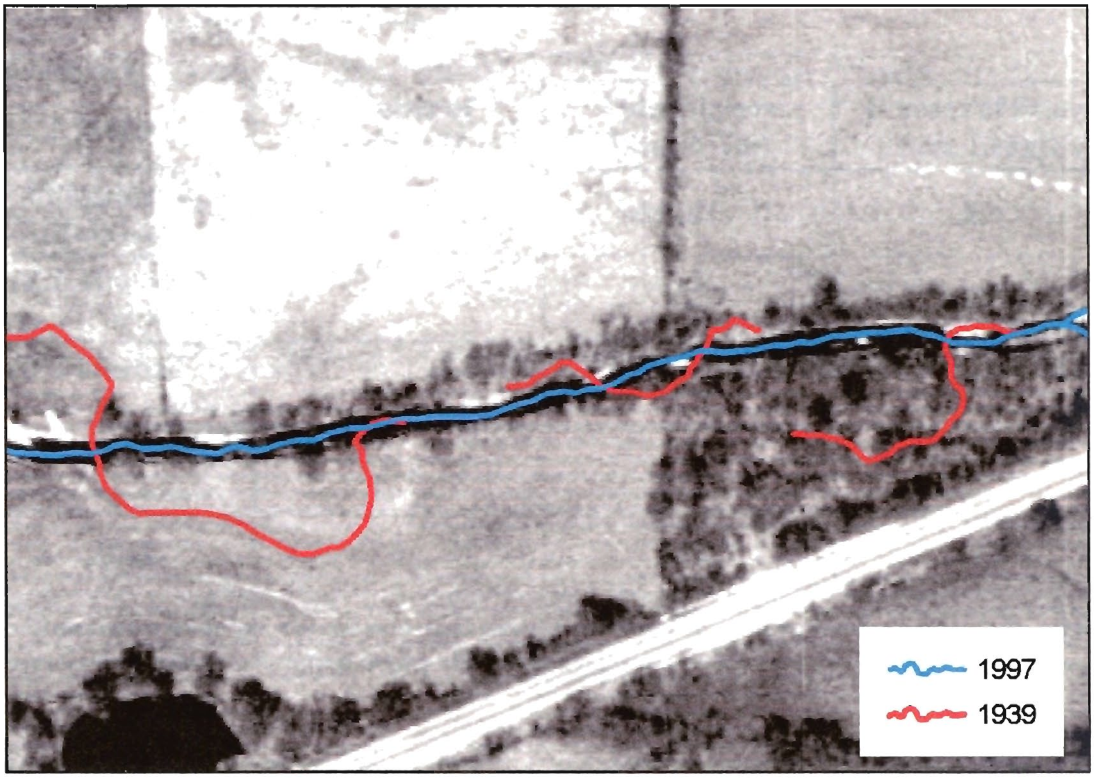
where:

TE = Total error of segments adjusted with railroad offset (meters)
RE = Mean total rectification error (meters)
LPI = Confidence interval for total difference in line placement (meters)

The mean cumulative error for the 214 segments that were adjusted using the railroad offset occurs between 0.2 and 0.26 meters/yr 95% of the time. Likewise, the 95% confidence interval for the mean cumulative error for the segments not adjusted with the railroad is between 0.77 and 0.83 meters/yr. This cumulative error was used to create an "error-filtered" dataset. For segments that were adjusted with the railroad, the filter value is 0.3 meters/yr. For segments not adjusted with the railroad, the filter value is 0.85 meters/yr. These filter values were subtracted from the raw annual migration rate of each appropriate creating the "error-filtered" dataset. All resulting negative migration rates for 205 segments were placed at 0 m/yr.

### Reach – Scale Migration Classification

All two hundred seventy-five, 20-meter segments were classified according to lateral migration between 1990 and 1997. Segments were classified in an effort to identify potential problem areas and high priority reaches for monitoring and stabilization. Three types of identifiable segments in Chat Creek are: "Channelized", "Disturbed", and "Typical". Channelized segments were identified by comparing the 1939 rectified aerial photograph with the 1997 DOQQ (Figure 6.2). These segments were identified separately to analyze how Chat Creek has migrated since channelization. Twenty-four segments were identified as being previously channelized (Table 6.2). Channelized segments comprise a small part of the study area, 9%, and largely exist within one reach in the lower portions of Chat Creek. Channelized segments average 2.32 meters of total migration from 1990-1997 or 0.33 cm of migration annually using the raw data (Table 6.3). Average annual migration rates filtered for error for these same segments is 0.09 meters (Table 6.3). After the channelized segments were identified and isolated from the dataset, the remaining segments were sorted according to the total migration from 1990 to 1997. Segments that ranked in the 95th percentile or higher were identified as "disturbed". The threshold value for a segment being categorized as "disturbed" is 8.6 meters migration in seven years. Segments that exceeded this value for



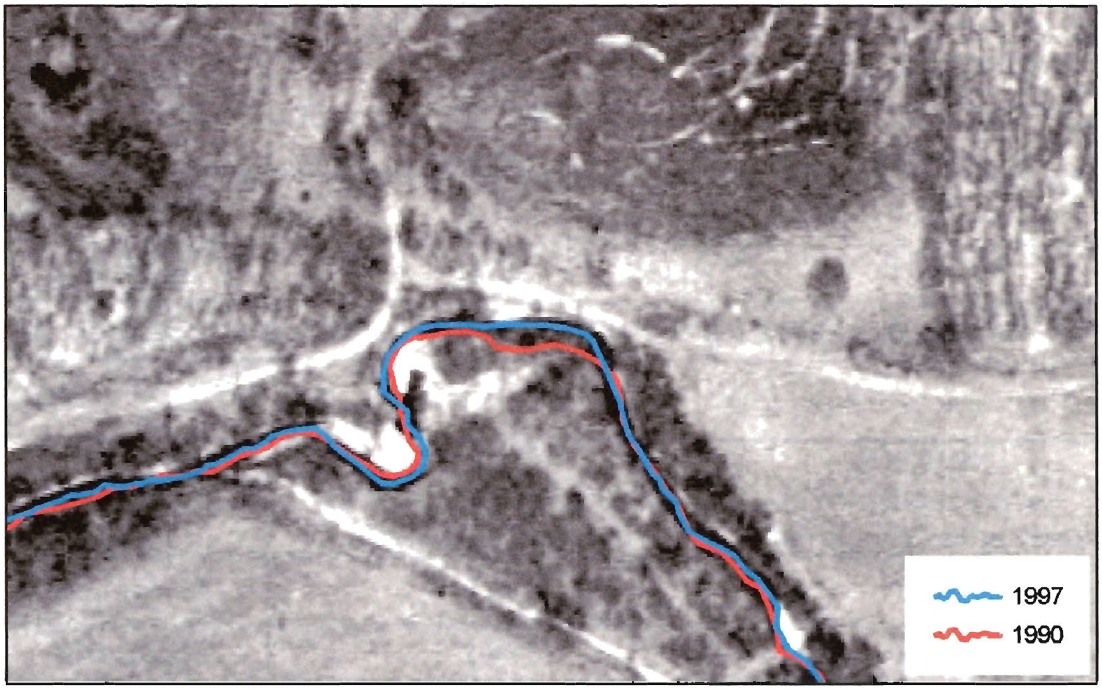


**Figure 6.2** Top photo is an example of a "channelized" reach and bottom photo is an example of "disturbance" reach.

**Table 6.2** Chat Creek's segments in each category and total stream length in each category from 1990-1997.

| Category | Number of Segments | Total Stream Length (m) | Percent of Study Area Length |
|---|---|---|---|
| ***Possibly No Movement** | 204 | 4,080 | 82 |
| **Channelized (N/A)** | 24 | 480 | 8 |
| **Disturbed (>8.6 m. total)** | 13 | 260 | 5 |
| **Typical (<8.6 m. total)** | 238 | 4,760 | 87 |
| **Total** | 275 | 5,500 | 100 |

* Segments within all categories that occur within the determined error limit. These segments were also excluded from the computation of the budget filtered for measured error.

**Table 6.3** Chat Creek's segment migration totals for 1990-1997.

| Category (Migration in Meters) | 1990-1997 (Raw Ave. Total Migration in meters) | 1990-1997 (Raw Ave. Migration/Yr in meters) |
|---|---|---|
| **Channelized** | 2.32 | 0.33 |
| **Disturbed** | 10.24 | 1.46 |
| **Typical** | 1.99 | 0.28 |

| Category (Migration in Meters) | 1990-1997 (Error-filtered Ave. Total Migration in meters) | 1990-1997 (Error-filtered Ave. Migration/Yr in meters) |
|---|---|---|
| **Channelized** | 0.61 | 0.09 |
| **Disturbed** | 2.92 | 0.42 |
| **Typical** | 0.61 | 0.09 |

total lateral migration from 1990 – 1997 were categorized as "disturbed" (Figure 6.2). Thirteen total segments were categorized as "disturbed", constituting only 5% of the 5.5 km study area (Table 6.2). "Disturbed" segments averaged 1.46 meters of migration annually using raw data and 0.42 meters/yr using the error-filtered data for the seven-year study period (Table 6.3). The remaining 238 segments were categorized as "typical" segments (Table 6.2). While the threshold for this category is a maximum of 8.6 meters of total migration from 1990-1997, the mean total raw migration for these segments is much lower at 1.99 meters with the raw data and 0.61 meters for the error-filtered data (Table 6.3). The resulting average migration for "typical" segments is 28 cm/yr for the seven-year study period (Table 6.3).

## Contemporary Migration Patterns

Twenty-meter segment migration rates measured for the study area are extremely variable and range from 0 – 1.8 meters/yr for the raw data and 0 – 1.4 m/yr for error-filtered data (Figure 6.3). In order to examine the general downstream trend in rates, a five point moving average line was fit to the data (Figure 6.3). This was done for visualization only; the actual migration rates for the data not filtered for error and the data filtered for error are used in the floodplain budget. Raw migration rates generally increase downstream with higher minimum and maximum rates nearer the confluence with the Spring River (Figure 6.3A). There are seven spikes in migration rates when evaluating the data that has been filtered for error (Figure 6.3B). These spikes increase in magnitude with distance downstream. Spikes in migration rates occur downstream of tributary junctions (Figure 6.3B and Figure. 6.4). These major spikes also occur in areas that are dominated by pastureland and where riparian buffers are at a minimum. This

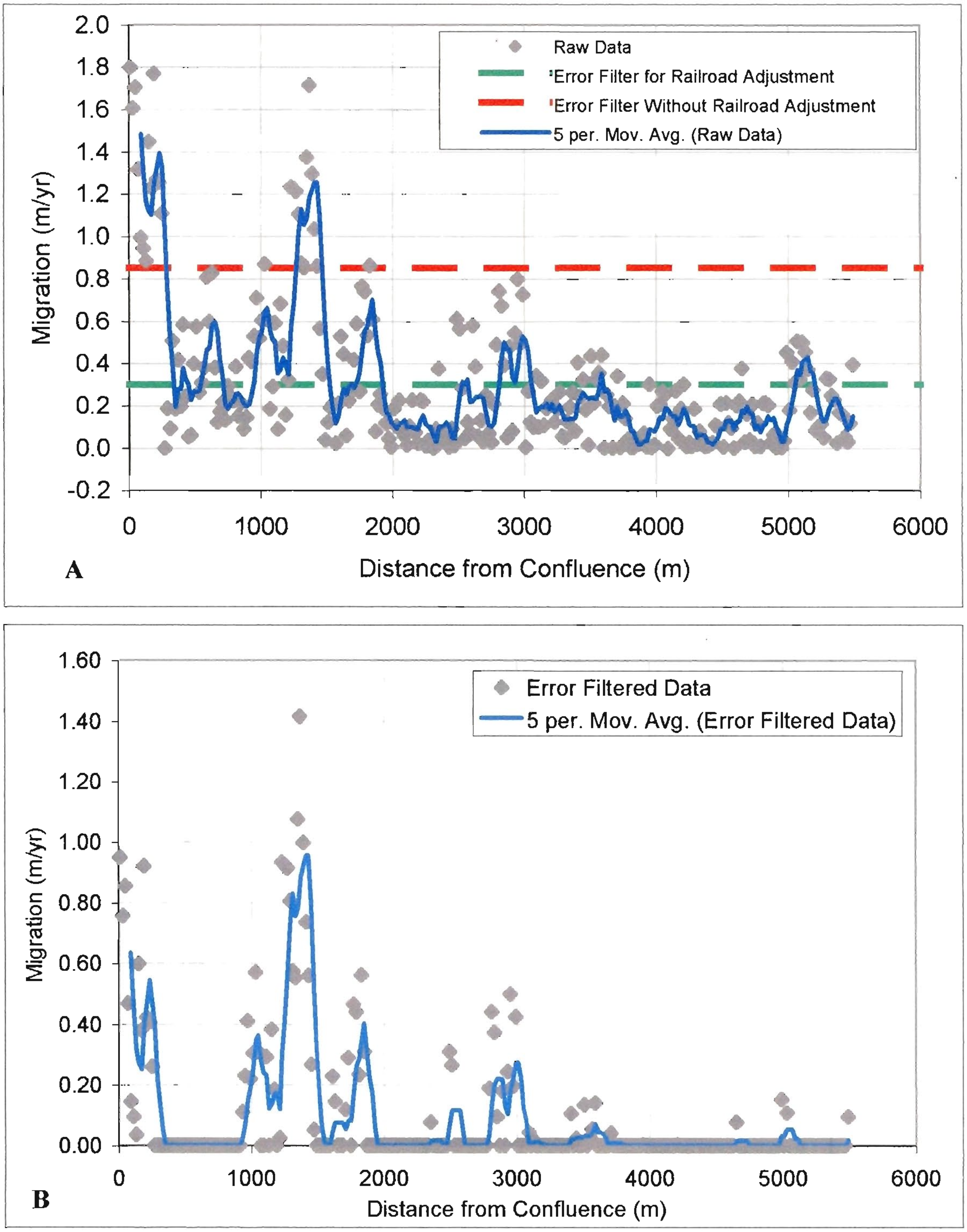
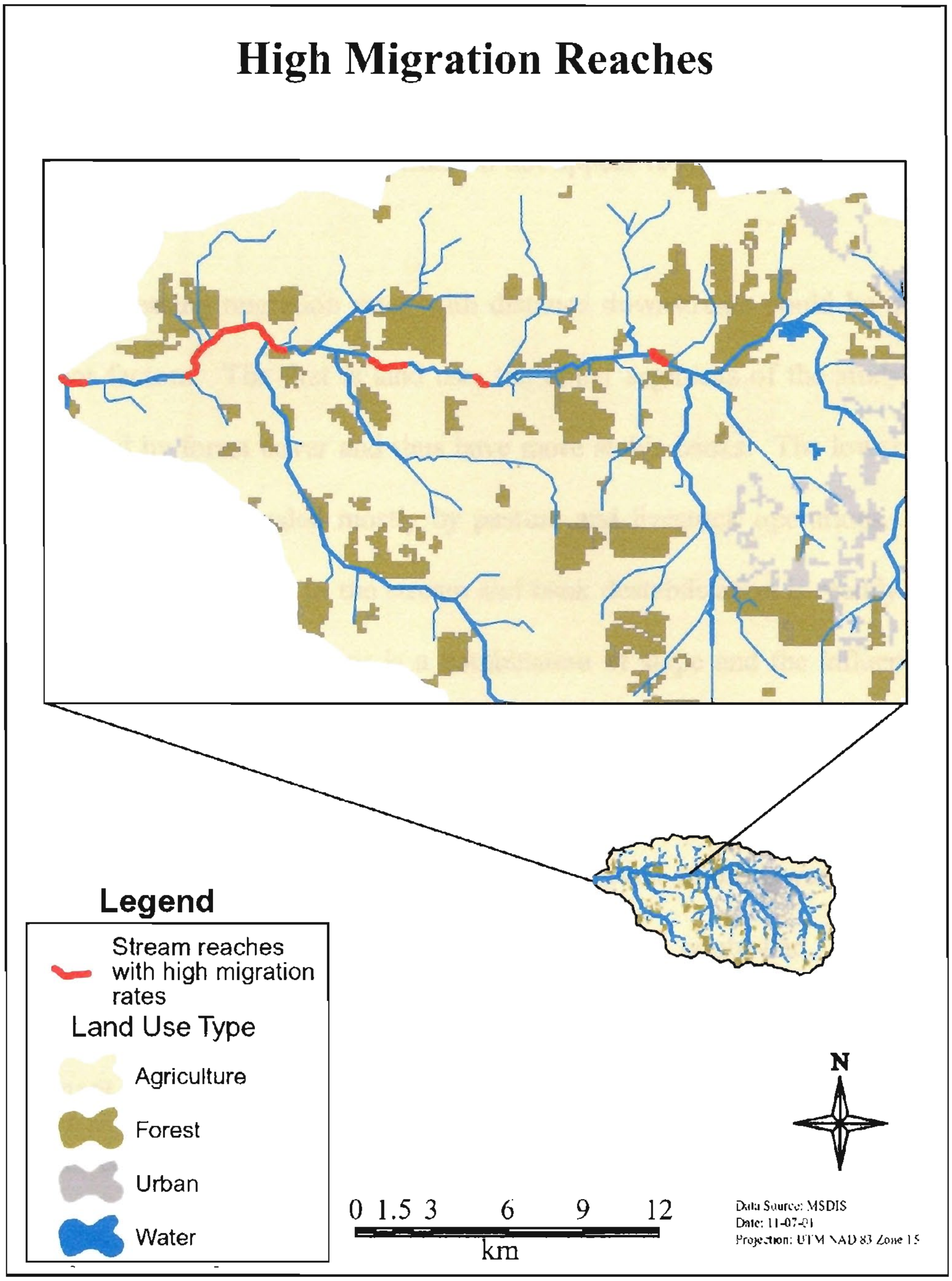


**Figure 6.3** Relationship between distance from Spring River and Migration rates. (A) Downstream trend of 20-meter migration with raw migration data. Error thresholds for segments adjusted with railroad displacement and for segments not adjusted with railroad displacement. (B) Downstream trend of migration rates with error filtered out of data.



Data Source: MSDIS
Date: 11-07-01
Projection: UTM NAD 83 Zone 15

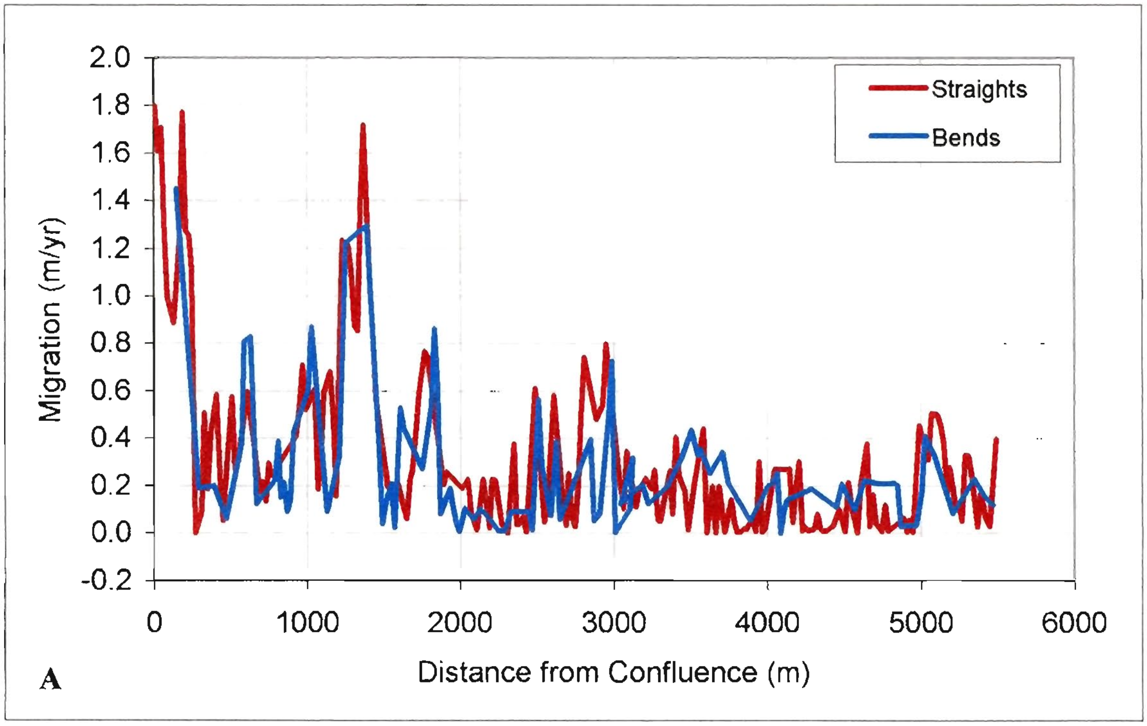
**Figure 6.4** Areas of high migration in relation to tributary junctions and land use types.

same trend is evident when analyzing the migration trends of the 96 bends and 180 straights separately (Figure 6.5). The low migration rates between approximately 1,000 and approximately 500 meters from the confluence are in channelized sections of the stream. These straightened segments do not appear to migrate laterally at very high rates (Figure 6.5).

Increasing migration rates with distance downstream could be attributed to four different factors. The first is land use; the upper segments of the study area are mostly surrounded by forest cover and thus have more stable banks. The lower segments of the study area are surrounded mostly by pasture and livestock operations. In many places cattle have direct access to the stream and bank destabilization is readily observed on the landscape. The second factor is a combination of slope and the influence of the Spring River. As Chat Creek flattens near the Spring River, high flow events tend to back up Chat Creek increasing bank saturation increasing the likelihood of failure and collapse. The third factor contributing to higher migration rates in the lower segments of the study area is the fact that this area is largely bedrock- controlled. Hydraulic energy is dissipated by lateral migration and bank erosion rather than downcutting. The last important factor is tributary junctions that increase drainage area and change local flow regimes causing instability in the mainstem of Chat Creek.

### Chapter Summary

Propagation of error is an important consideration when utilizing digital spatial data. Methods were used in order to quantify and minimize error in the current study. The rectification accuracy was statistically tested through criteria set forth by the federal



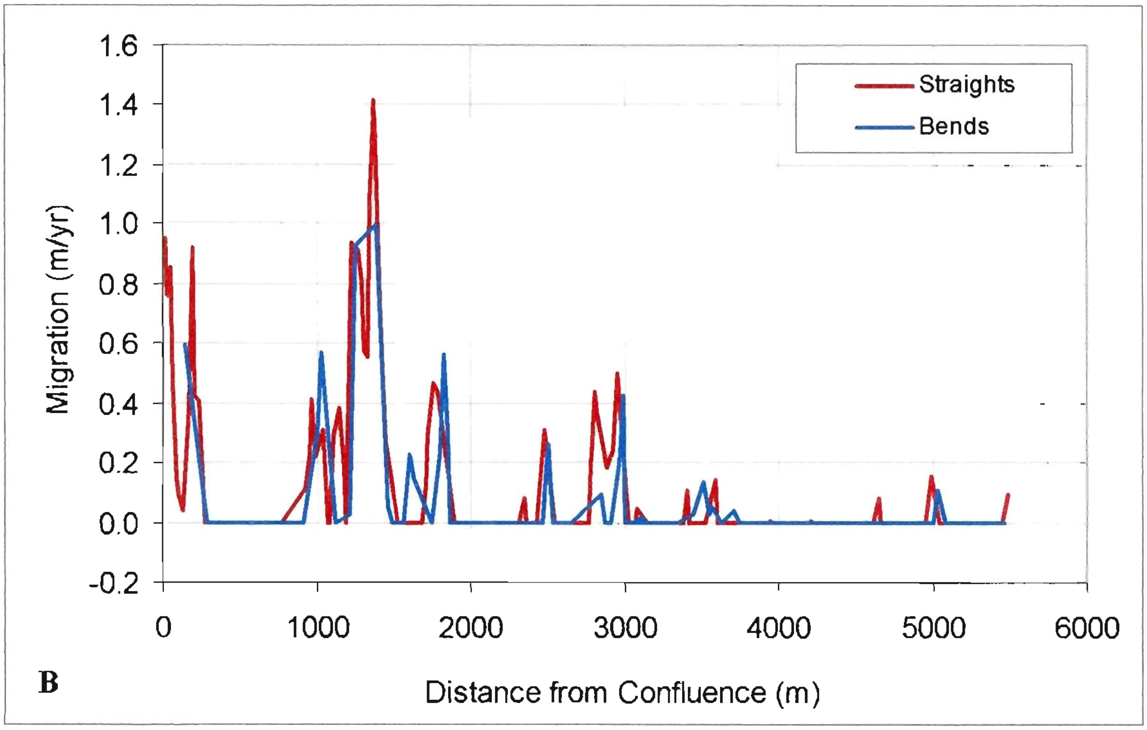


**Figure 6.5** Migration trends for straight and bend reaches for 1990-1997. (A) Trends for raw data. (B) Trends with error filtered data.

geographic data committee. The offset created in the rectification process was minimized in 214 segments by correcting with the railroad adjustment. Error was also created during placement of digitized channel centerlines. A 95% confidence interval for the mean of this error was computed. Migration rates were filtered using the total error that was calculated. Segments adjusted with railroad offset were filtered with 0.30 m/yr and segments not adjusted with railroad offset were filtered with 0.85 m/yr.

The rate of migration for each 20-meter stream segment is an important variable for determining the volume of deposition and erosion. Migration patterns within the 5.5 km study area are highly variable, ranging from 0 – 1.8 m/yr for raw data and 0 – 1.4 m/yr for error-filtered data. There is generally a pattern of increasing migration rates with increasing distance downstream.

# CHAPTER 7

# FLOODPLAIN SEDIMENT, LEAD, AND ZINC BUDGET

Several variables (metal concentrations, bank heights, erosion rates, fine-grain composition, bulk density, and point bar heights) must be determined in order to calculate a sediment, lead, and zinc budget for floodplain erosion. Computing the budget for each 20-meter segment in the 5.5 km study area requires modeling most of the variables from a few sampled reaches. One variable, migration rate, was measured directly for each 20-meter segment and was discussed in the previous chapter. This chapter discusses the modeling results for the remaining variables. Secondly, a discussion of sediment-metal release rates for the study area is presented. These results will be most applicable for watershed managers developing TMDLs for Chat Creek. Next, given the two assumptions of constant channel geometry and negligible overbank deposition, the sediment-metal budget due to floodplain erosion is presented. Lastly, the implications of these findings on sediment-metal release rates to watershed management efforts are discussed.

## Construction of Floodplain Erosion Budget

The computation of a floodplain erosion budget for each 20-meter segment requires computation of two major parameters that are dependent on modeled variables. The two parameters are: (1) Mass of erosion/release (sediment, lead, and zinc) from cut banks within each segment; and (2) Mass of deposition (sediment, lead, and zinc) on point bar features within each segment (Figure 4.5). The following discussion will focus on the modeling results for five variables in Figure 4.5. Bank height values for bend and straight reaches as well as point bar heights for bend reaches is discussed. The model results for fine-grain composition for both active channel and floodplain deposits are given. Model results for floodplain metal concentrations used to determined metal release is discussed.

### *Channel Geomorphology*

Bank Height. A cross-section survey at each study reach for both "bends" and "straights" are used to determine bank height. A complete description of channel parameters at each cross section is presented in Appendix I. The bank heights at the study reach for both "bend" and "straight" reaches were plotted against distance from the confluence and the relationship examined (Figure 7.1). For "bend" segments the relationship between bank heights at the ten study reaches is nearly linear with a slight dip in heights in the middle portion of the study area (Figure 7.1). This dip was not ignored in modeling the remaining segment bank heights. The dip occurs in an area along the stream where numerous cattle operations exist. The lower cut bank heights could be the result of cattle access to the stream and disturbance to the bank. It was decided to connect each adjacent study reach with a straight line and use the slope of that line to interpolate cut bank heights for the segments between the two study reaches (Figure 7.1). The last study reach (#10) is 820 m from the confluence with the Spring River. The slope of the line between study reach #9 and study reach #10 was extended in order to extrapolate cut bank heights for the balance of the channel length (Figure 7.1).

The relationship of "straight" segment bank heights for the study reaches is more complicated than for "bend" segments (Figure 7.1). The trend is not as linear with a more pronounced dip in height in the middle of the study area. However, the model for "straight" segments was computed the same as for "bend" segments.

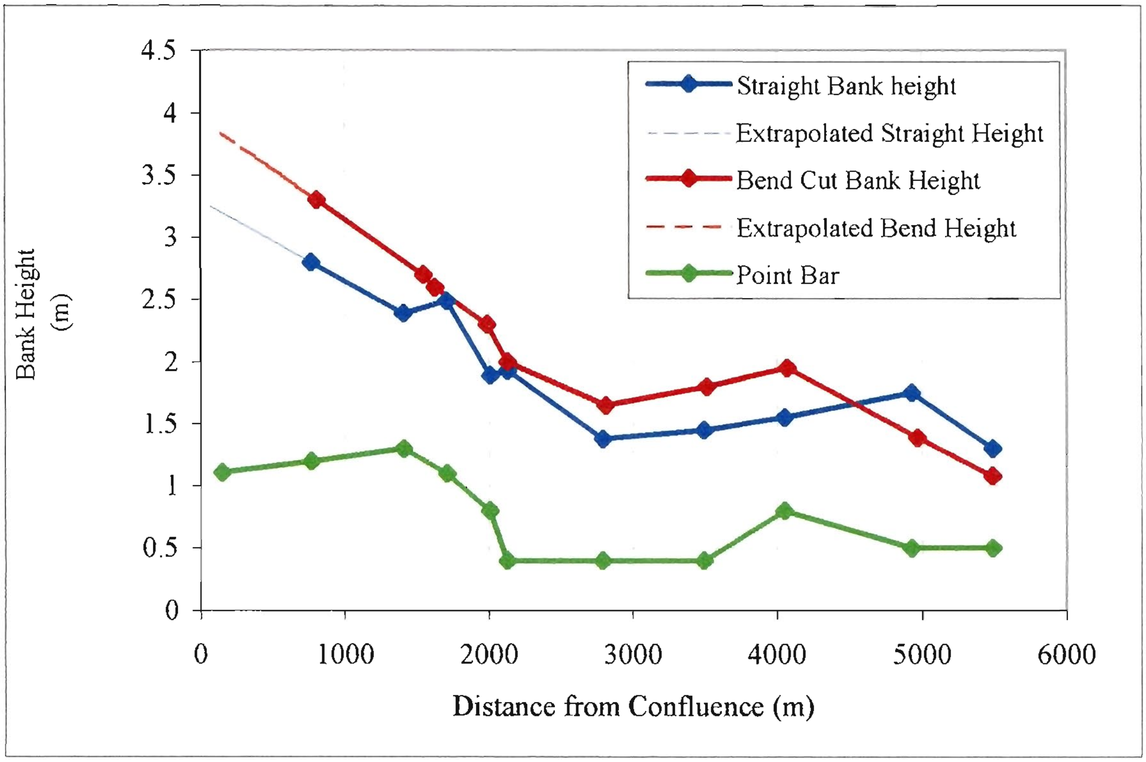


**Figure 7.1** Modeled bank height for "Bend" and "Straight" segments and modeled point bar heights for bend reaches.

The next important geomorphological variable is used to determine volume of deposition in "bend" segments. This variable, maximum point bar height was determined as a percentage of the total cut bank height for each study reach (Table 7.1). Multiplying the "volume of erosion" by the point bar percentage yields the volume of deposition for bend segments (Figure 4.5). This method was only conducted for "bend" segments; the "volume of deposition" for straight segments was determined to be equivalent to the "volume of erosion" for these segments (Figure 4.5). The downstream trend of point bar maximum height to total cut bank height is similar to the pattern for cut bank heights (Figure. 7.1). The maximum point bar height percentage of the total cut bank height increases downstream with a dip in heights in the middle of the study area (Figure 7.1).

**Table 7.1** Maximum point bar height shown as a percentage of total cut bank height.

| Study Reach # | Straight Reach Bank Height (m) | Total Cut Bank Height (m) | Maximum Point Bar Height (m) | Percent of Total Height |
|---|---|---|---|---|
| **1** | 1.3 | 1.08 | 0.5 | 46 |
| **2** | 1.75 | 1.39 | 0.5 | 36 |
| **3** | 1.55 | 1.95 | 0.8 | 41 |
| **4** | 1.45 | 1.8 | 0.4 | 22 |
| **5** | 1.38 | 1.65 | 0.4 | 24 |
| **6** | 1.93 | 2.0 | 0.4 | 20 |
| **7** | 1.89 | 2.3 | 0.8 | 35 |
| **8** | 2.49 | 2.6 | 1.1 | 42 |
| **9** | 2.39 | 2.7 | 1.3 | 48 |
| **10** | 2.8 | 3.3 | 1.2 | 36 |

Point bar heights also do not remain proportional to total cut bank height in the lower portion of the study area and actually decline in relation to total height (Figure 7.1).

Alluvial Sediment Texture. Three more physical variables that are important for the computation of a budget for sediment-metal release due to floodplain erosion are floodplain fine-grain percentage, in-channel fine-grain percentage, and soil bulk density (Figure 4.5). Fine-grain bulk density soil values are approximated, for floodplain soils in the area, to be 1.4 g/cm$^3$ (Hughes, 1982). This bulk density value was used for the density of the floodplain sediment as well as the density of the in-channel sediment. Bulk density was used in the calculation of the mass of eroded sediment and the mass of deposited sediment (Figure 4.5). The fine-grain sediment composition was estimated in the field for both floodplain deposits and in-channel point bar features at each of the ten study reaches. Values, for cut bank and in-channel fine-grain percentage, for the remaining segments were interpolated similarly to bank heights (Figure 7.2). The

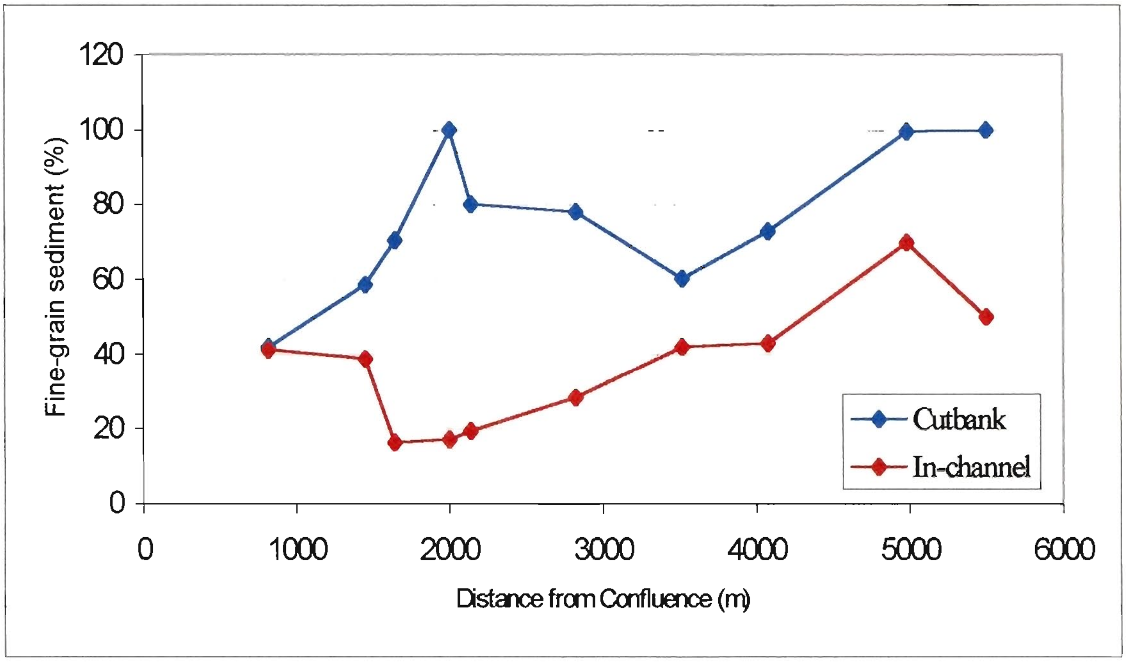


**Figure 7.2** Model for eroded and deposited fine-grain sediment percentage in study.

floodplain fine-grain percentage was used to determine mass of eroded sediment (Figure 4.5). The in-channel fine-grain percentage was used to determine mass of deposited sediment (Figure 4.5).

### *Floodplain Metal Content*

Lead and zinc concentrations in cut bank deposits are essential variables in determining the mass of metals released into Chat Creek due to floodplain erosion (Figure 4.5). Sediment was sampled from each stratigraphic unit in the cut bank deposit of each study reach to determine concentrations of several geochemical elements (Appendix E). The anthropogenic enrichment factor was also computed for each stratigraphic unit in each cut bank (Appendices G and H). Although not of major importance to the current study, the depth of contamination is easily determined for each cut bank by examining the AEF in Appendices G and H. Generally, cut bank profiles are contaminated throughout, however, some profiles indicate increasing or decreasing metal contamination trends with depth. Carlson (1999) found similar trends.

Lead and zinc concentrations in floodplain deposits decrease downstream away from the abandoned mining area (Tables 7.2 and 7.3 and Figures 7.3 and 7.4). This result is consistent with in-channel lead and zinc concentrations. This indicates that the sediment wave containing the metal contaminants is still in the upper reaches of Chat Creek near the mining operations. This wave is stored not only in the active channel but also in floodplain and terrace deposits. The highest weighted floodplain lead and zinc concentrations are at study reach #1 (Tables 7.2 and 7.3). The lowest weighted floodplain of both lead and zinc is at study reach #9 (Tables 7.2 and 7.3). These concentrations decrease since clean sediment dilutes the contaminated mining-derived sediment while contaminated sediment is also being deposited in bed and bar deposits. The weighted concentration for lead and zinc at each of the ten cut banks was used to model floodplain concentrations in the remaining segments. The model was calculated by plotting lead and zinc concentrations against distance from confluence and fitting a line through the data points (Figures 7.5 and 7.6). The best representation of the distribution in both cases was an exponential line fit through the data. Exponential relationships between distance and concentrations are commonly used in other studies and were thus used in the present research (Marcus, 1987; Goodyear *et al.*, 1996). These equations were used to model floodplain metal concentrations for all segments including the ten study reaches (Figures 7.5 and 7.6).

**Table 7.2** Weighted lead concentrations in floodplain deposits for Chat Creek.

| Study Reach # | $A_d$ ($km^2$) | Distance from Confluence (m) | Mean Weighted Pb (ppm) | Min (ppm) | Max (ppm) |
|---|---|---|---|---|---|
| 1 | 16.10 | 5,470 | 643 | 460 | 662 |
| 2 | 16.47 | 4,970 | 412 | 72 | 598 |
| 3 | 22.72 | 4,070 | 195 | 82 | 446 |
| 4 | 23.69 | 3,510 | 274 | 208 | 622 |
| 5 | 24.40 | 2,850 | 61 | 54 | 112 |
| 6 | 27.54 | 2,130 | 240 | 222 | 314 |
| 7 | 27.56 | 2,130 | 86 | 28 | 116 |
| 8 | 30.82 | 1,630 | 129 | 32 | 226 |
| 9 | 30.83 | 1,470 | 59 | 34 | 140 |
| 10 | 31.38 | 810 | 84 | 62 | 146 |

**Table 7.3** Weighted zinc concentrations in floodplain deposits for Chat Creek.

| Study Reach # | $A_d$ ($km^2$) | Distance from Confluence (m) | Mean Weighted Zn (ppm) | Min (ppm) | Max (ppm) |
|---|---|---|---|---|---|
| 1 | 16.10 | 5,470 | 5,377 | 3,490 | 5,570 |
| 2 | 16.47 | 4,970 | 3,133 | 264 | 4,730 |
| 3 | 22.72 | 4,070 | 1,277 | 284 | 3,600 |
| 4 | 23.69 | 3,510 | 1,092 | 448 | 4,150 |
| 5 | 24.40 | 2,850 | 195 | 142 | 578 |
| 6 | 27.54 | 2,130 | 896 | 648 | 1,890 |
| 7 | 27.56 | 2,130 | 193 | 54 | 286 |
| 8 | 30.82 | 1,630 | 728 | 134 | 1,770 |
| 9 | 30.83 | 1,470 | 191 | 90 | 946 |
| 10 | 31.38 | 810 | 321 | 156 | 1,160 |

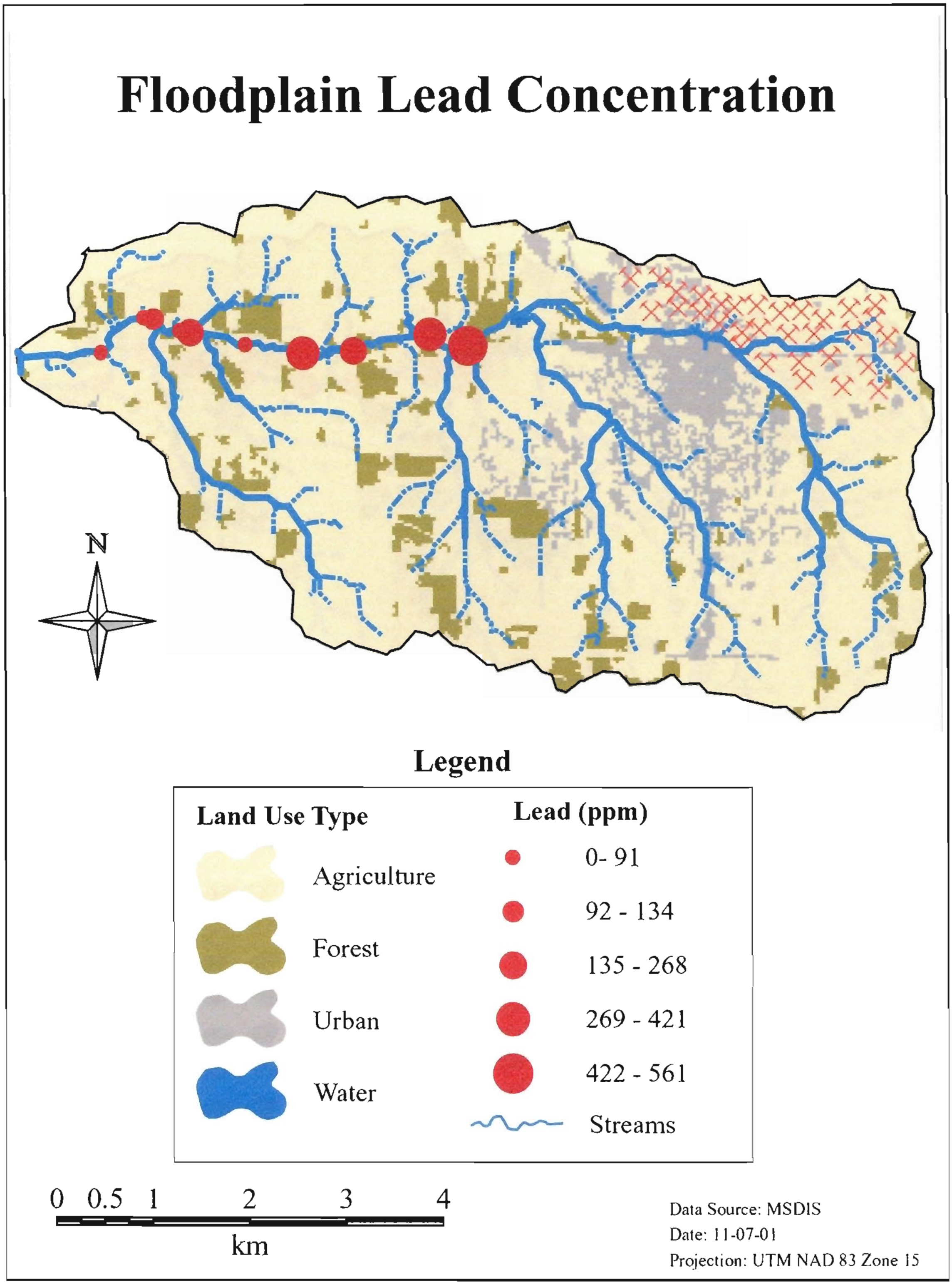


**Figure 7.3** Downstream distribution of weighted floodplain lead concentrations in Chat Creek.

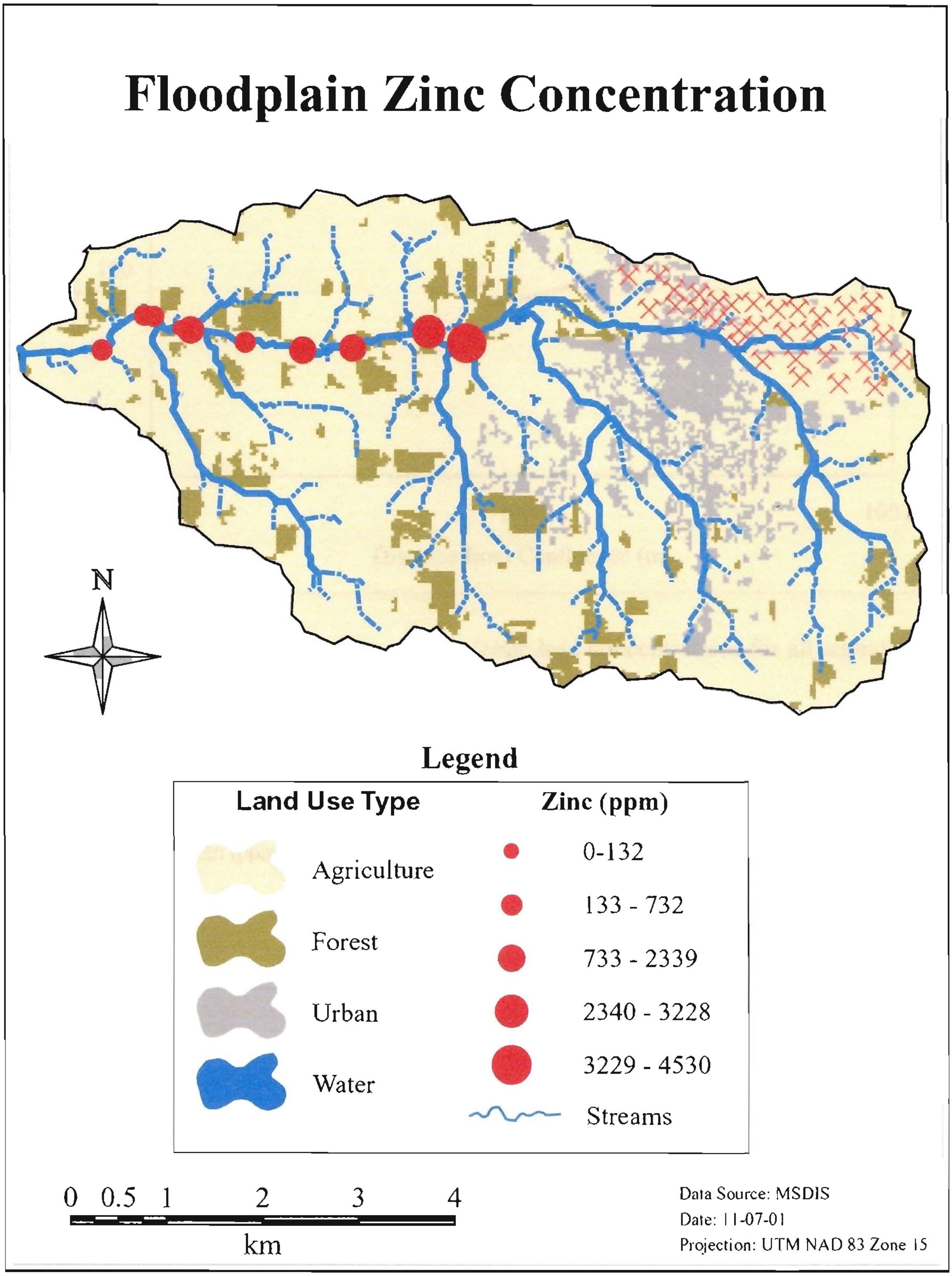


**Figure 7.4** Downstream distribution of weighted floodplain zinc concentration in Chat Creek.

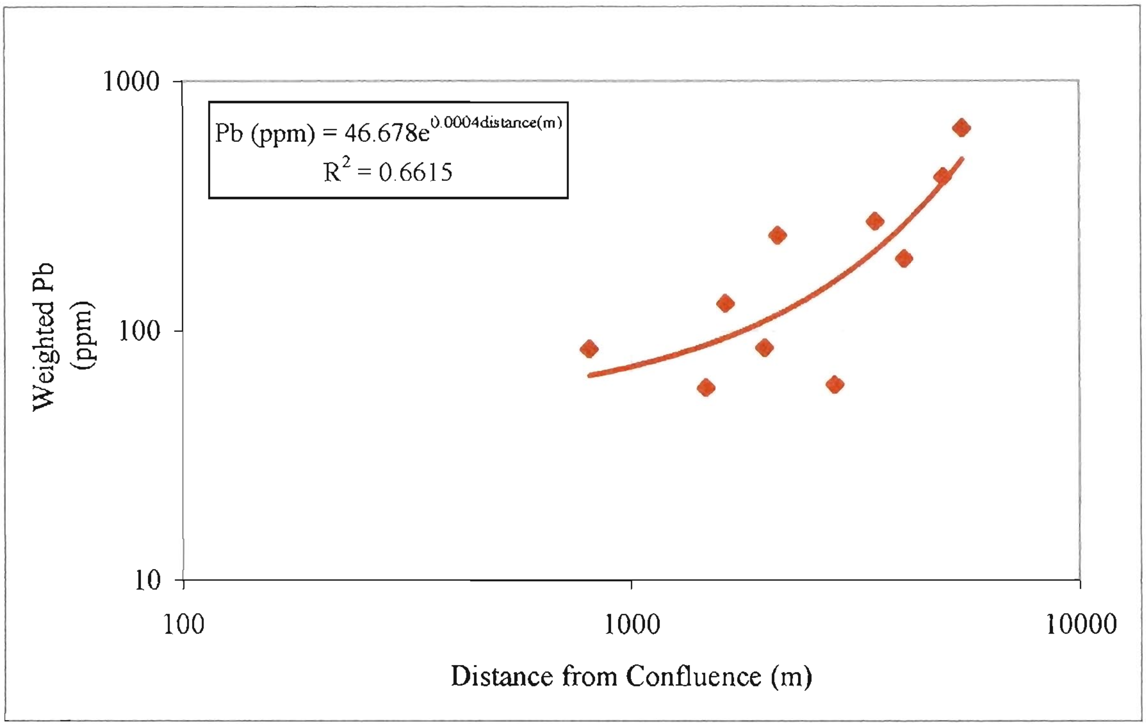


**Figure 7.5** Model used to determine floodplain lead concentrations for all segments.

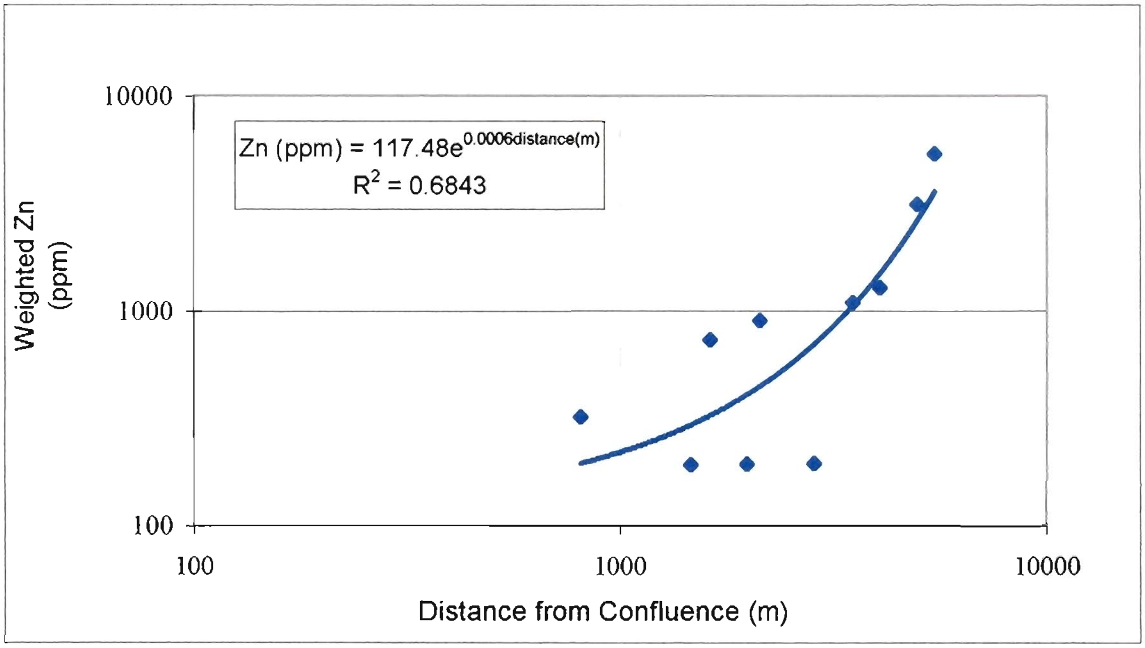


**Figure 7.6** Model used to determine floodplain zinc concentrations for all segments.

## Release of Sediment-Metals

The release of sediment and metals by to floodplain erosion is important information for examining potential sources of metals and sediment in the Chat Creek watershed, particularly since most tailings piles and distributed mining sites have been cleaned up or stabilized. A preliminary step in determining TMDL standards is identifying sources and loading rates of pollutants. This section will focus on floodplain erosion as a source of sediment, lead, and zinc into the stream. This discussion will focus on the results according to the migration data that has been filtered for error. However, results according to the raw data are presented for comparison. In most cases, the pattern of release remains constant among the datasets, the magnitude of release changes depending on the dataset used. The error-filtered data represents the minimum release values accounting for all error while the raw data indicates release values assuming minimal error effect. In actuality, the precise release amounts probably in between these two values.

The WRAS (2000) report for the Upper Spring River identifies sediment introduction into Chat Creek as a concern of local citizens. Floodplain erosion introduces 3,057 Mg (according to the raw data) and 929 Mg (according to error filtered data) of sediment into the active channel each year (Table 7.4). The release of sediment varies greatly with distance downstream (Figure 7.7). Spikes in the downstream trend occur where tall banks are combined with high floodplain fine-grain percentage, and high migration rates. Three spikes in release amounts also occur downstream of major tributary junctions (Figure 7.8). A majority of the sediment, 84% of error-filtered amounts, introduced into the stream is from the lower 2 k (Table 7.5 and Figure 7.7).

**Table 7.4** Yearly release of sediment, lead, and zinc from Chat Creek

| Component | Total Release for Raw Data | Total Release for Error-Filtered Data |
|---|---|---|
| **Fine-Grain Sediment (Mg/yr)** | 3,057 | 929 |
| **Lead (kg/yr)** | 394 | 84 |
| **Zinc (kg/yr)** | 1,952 | 321 |

**Table 7.5** Fine-grain sediment releases for raw data and for error-filtered data for the study area

| Segments<br>Distance from Confluence (m) | Percent of Total Study Area | Sediment Release (Mg/yr) (Raw Data) | Percent of Total Release | Sediment Release (Mg/yr) (Error-filtered Data) | Percent of Total Release |
|---|---|---|---|---|---|
| **261 - 243<br>(5,330 – 4,970)** | 7 | 222 | 7 | 11 | 1 |
| **174 – 134<br>(3,590 – 2,790)** | 15 | 254 | 8 | 100 | 11 |
| **120 - 119<br>(2,510 – 2,490)** | <1 | 22 | 2 | -- | -- |
| **87 – 45<br>(1,850 – 930)** | 17 | 1,139 | 37 | 635 | 68 |
| **13 – 1<br>(250 – 0)** | 5 | 416 | 14 | 151 | 16 |
| **Totals** | 44 | 2,031 | 66 | 897 | 97 |

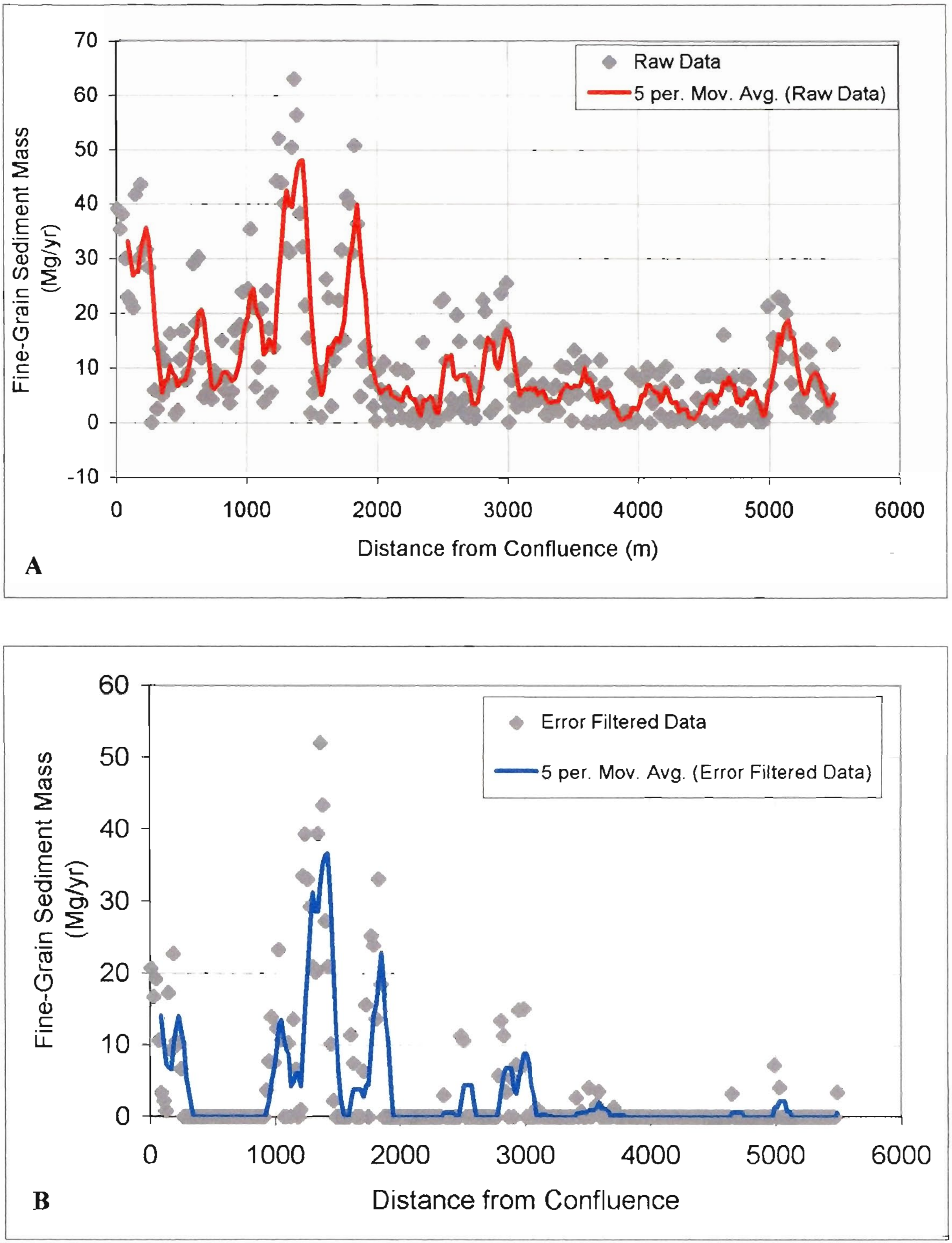


**Figure 7.7** Floodplain erosion contribution of fine-grain sediment in study area. (A) Release with raw migration data and (B) Release with error filtered data.

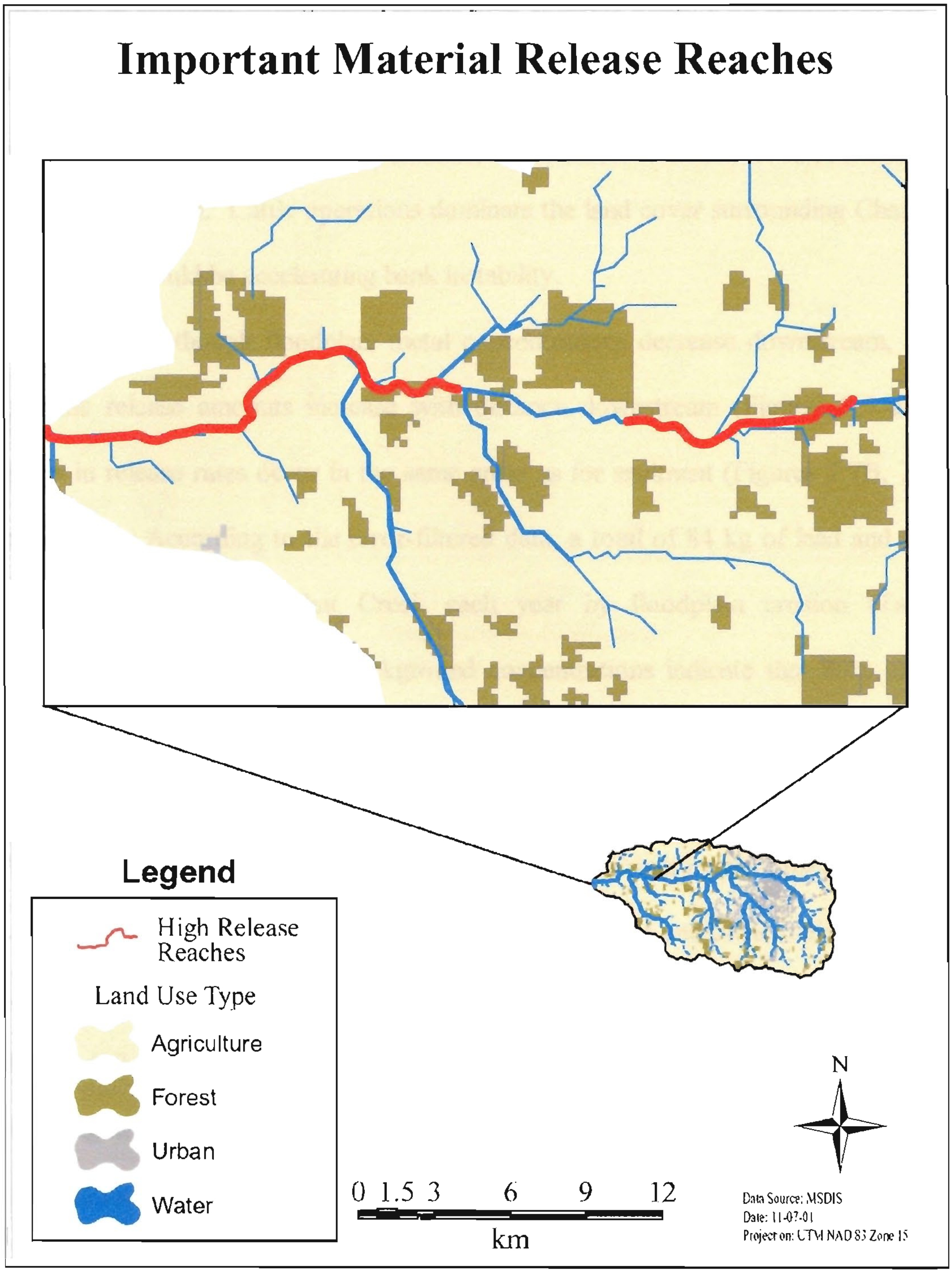


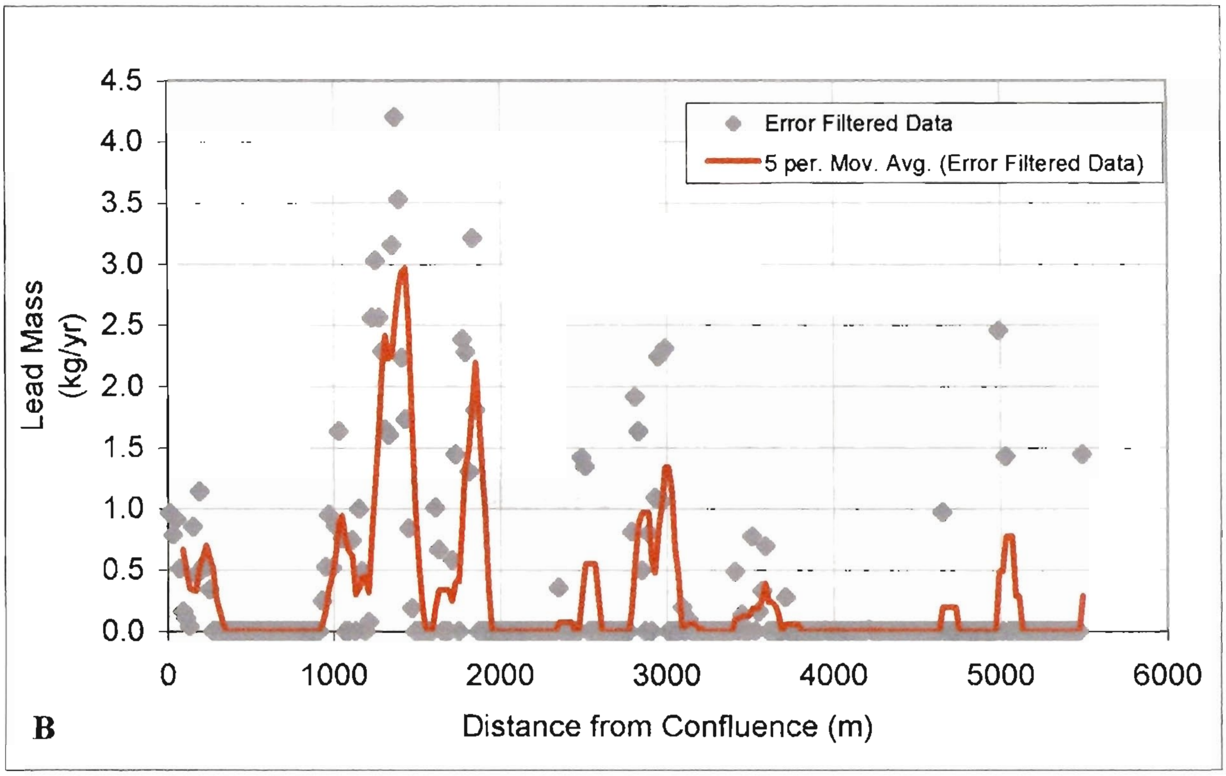
**Figure 7.8** Map of reaches of high release rates in relation to tributary junctions.

The dips in sediment introduction in this area coincide partly with reaches of the stream that have been straightened. These 2 kilometers of Chat Creek is composed of tall banks that are non-cohesive due to the high chert content. This portion of Chat Creek is largely bedrock-controlled. Cattle operations dominate the land cover surrounding Chat Creek in this area and could be accelerating bank instability.

Even though floodplain metal concentrations decrease downstream, both lead and zinc release amounts increase with distance downstream (Figures 7.9 and 7.10). Spikes in release rates occur in the same areas as for sediment (Figures 7.7B, 7.8, 7.9B, and 7.10B). According to the error-filtered data, a total of 84 kg of lead and 321 kg of zinc are released into Chat Creek each year by floodplain erosion (Table 7.4). Comparing these values with background concentrations indicate that 80% of the lead release originated from mining operations and 77% of the zinc is from mining activities and not natural sources. Four reaches totaling 62% of the total study area contribute nearly all lead and zinc (98%), introduced into Chat Creek by floodplain erosion (Table 7.6B). Similar to sediment, a large majority, 68% of lead and 58% of zinc, is introduced in the lower 2 km of Chat Creek (Table 7.6B). By far the single largest contributing area of lead (50 kg/yr or 60% of total) and zinc (168 kg/yr or 52% of total) is a reach extending from 1,850 – 930 meters from the confluence with the Spring River (Table 7.6B and Figure. 6.4).

## Sediment-Metal Budget

A complete sediment-metal budget for floodplain erosion for the current study can only be calculated under the assumptions of constant channel geometry as the stream



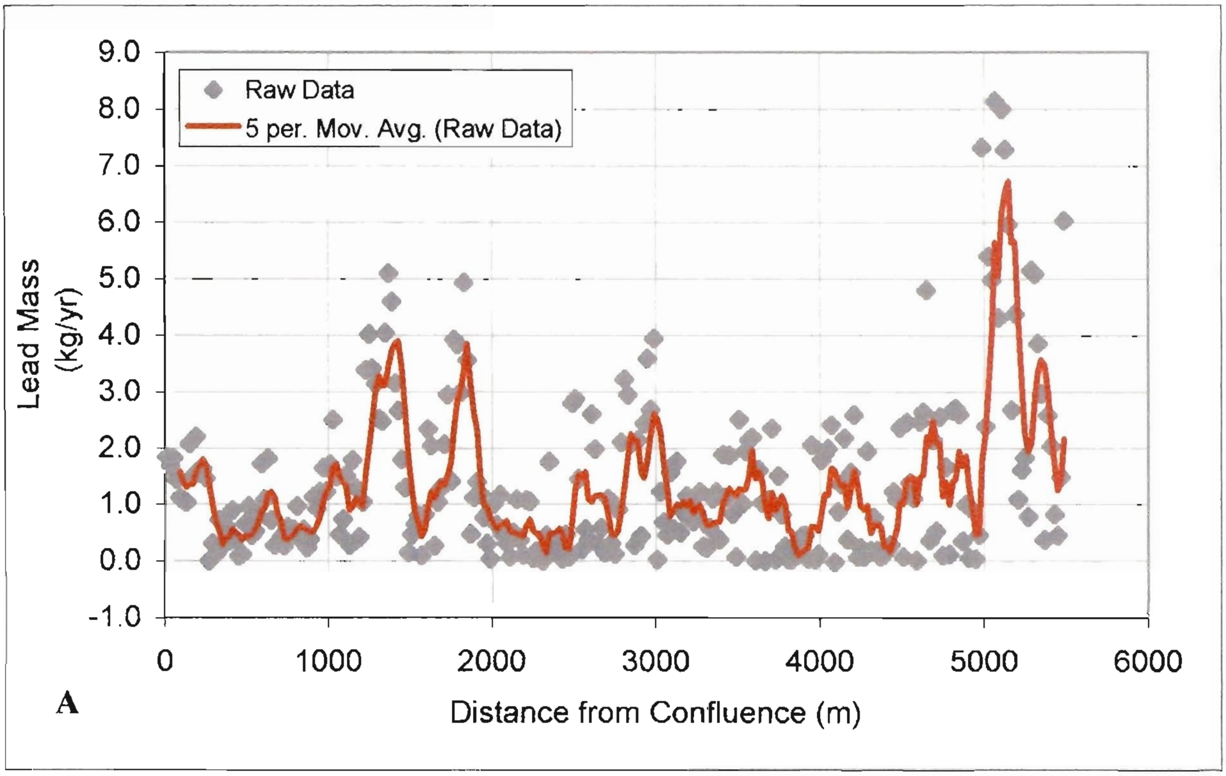
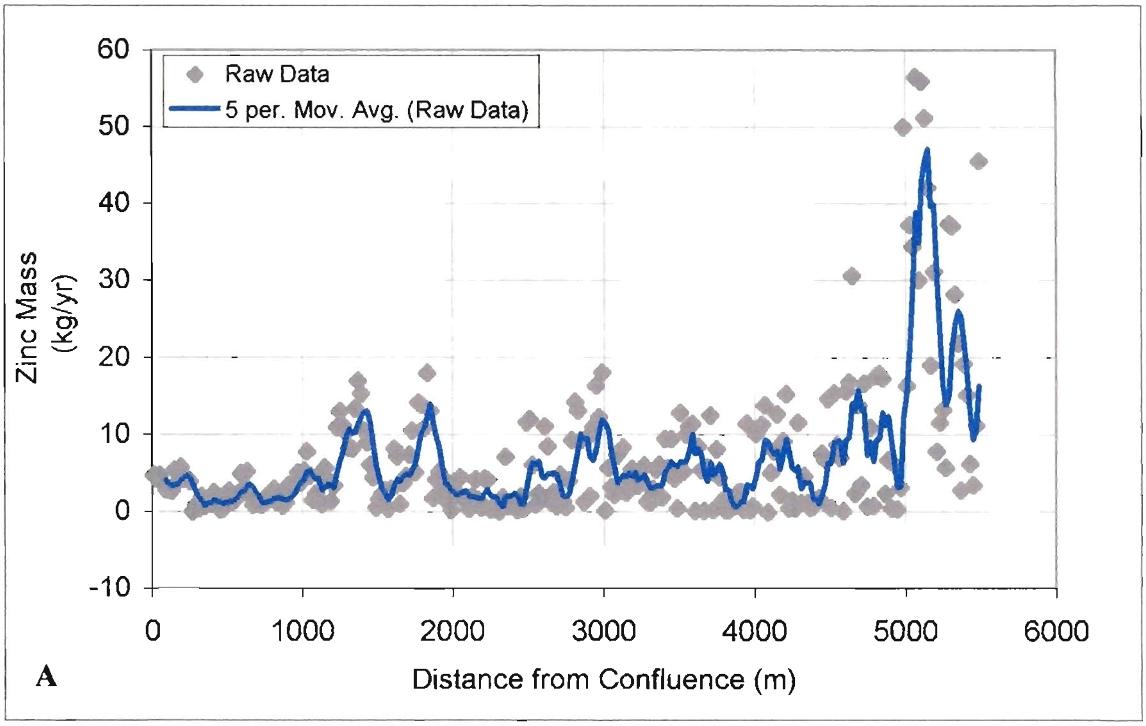


**Figure 7.9** Release of lead due to floodplain erosion in study area. (A) Lead release using raw migration data. (B) Lead release using error-filtered data.



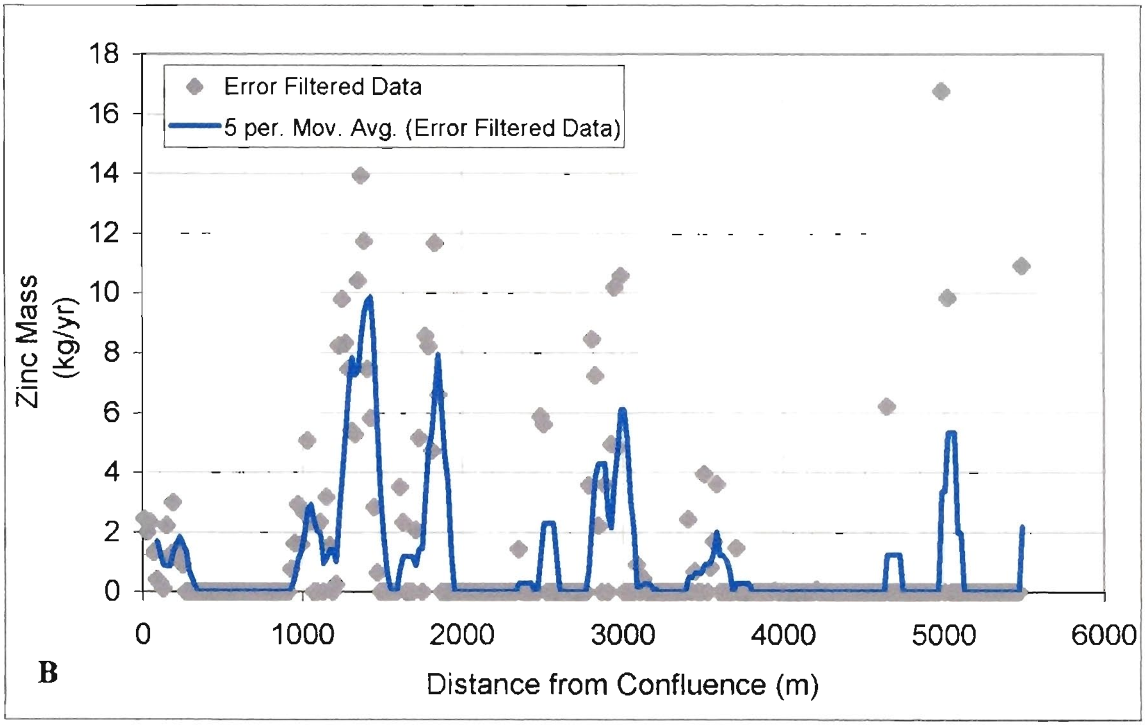


**Figure 7.10** Zinc release due to floodplain erosion in study area. (A) Zinc release with raw data and (B) zinc release with error filtered data.

**Table 7.6** Metal release due to floodplain erosion in the study area. (A) Release amounts for raw data and (B) release amounts for error-filtered data.

A

| Segment<br>Distance from Confluence (m) | Percent of Total Study Area | Lead Release (kg/r) | Percent of Total | Zinc Release (kg/yr) | Percent of Total |
|---|---|---|---|---|---|
| 261 – 197<br>(5,330 – 4,050) | 23 | 135 | 34 | 908 | 47 |
| 182 – 121<br>(3,750 – 2,530) | 22 | 76 | 19 | 358 | 18 |
| 92 – 45<br>(1,950 – 930) | 17 | 100 | 25 | 339 | 17 |
| Total | 62 | 311 | 78 | 1,605 | 82 |

B

| Segment<br>Distance from Confluence (m) | Percent of Total Study Area | Lead Release (kg/r) | Percent of Total | Zinc Release (kg/yr) | Percent of Total |
|---|---|---|---|---|---|
| 269 – 227<br>(5,490 – 4,650) | 15 | 6 | 7 | 44 | 14 |
| 180 – 112<br>(3,710 – 2,350) | 25 | 19 | 23 | 84 | 26 |
| 87 – 45<br>(1,850 – 930) | 17 | 50 | 60 | 168 | 52 |
| 13 – 1<br>(250 – 0) | 5 | 7 | 8 | 19 | 6 |
| Total | 62 | 82 | 98 | 315 | 98 |

migrates laterally and that negligible amounts of sediment-metal are being deposited in over-bank and other channel features. The results of the budget using these assumptions are briefly discussed. Major budget variables for each 20-segment is presented in Appendix (J). Discussion will again focus on results according to error-filtered data, however, raw data results will also be presented. As with release amounts, the actual budget results probably occur between these two values.

Table 7.7 shows the results for each major component of the sediment-metal budget for floodplain erosion within the 5.5 km study reach. These values do not reflect unknown inputs from sources upstream of the study area. According to this data, 319 Mg of fine-grain sediment introduced by floodplain erosion exits the Chat Creek drainage each year (Table 7.7B). Table 7.7B also shows that Chat Creek is a net sink for metals introduced by floodplain erosion.

Figure 7.11 illustrates the downstream trend in net release/storage of fine-grain sediment for all segments. A five-point moving average trend line has been fit to the raw data points to gain a general understanding of the downstream trend. The plot illustrates that according to the budget, the lower 250 meters of Chat Creek is a net sink for sediment (Figure 7.11B and Table 7.8B). Upstream of this segment to the upper end of the study area, Chat Creek is a net source of sediment. Not surprisingly, the model is highly dependent on fine-grain percentage in floodplain deposits as well as in the active channel and on bank height. Excluding the channelized sections, there are five reaches of Chat Creek that are net sources of sediment to downstream reaches (Figure 7.11B and Table 7.8B). These five reaches constitute approximately only 26% of the total study area, but contribute 93% of the sediment that is released upstream of the channelized section (Table 7.8B). Seventy – two percent of this amount is produced by a reach of Chat Creek that is 1,850 – 930 meters from the confluence with the Spring River (Table 7.8B and Figure 6.4).

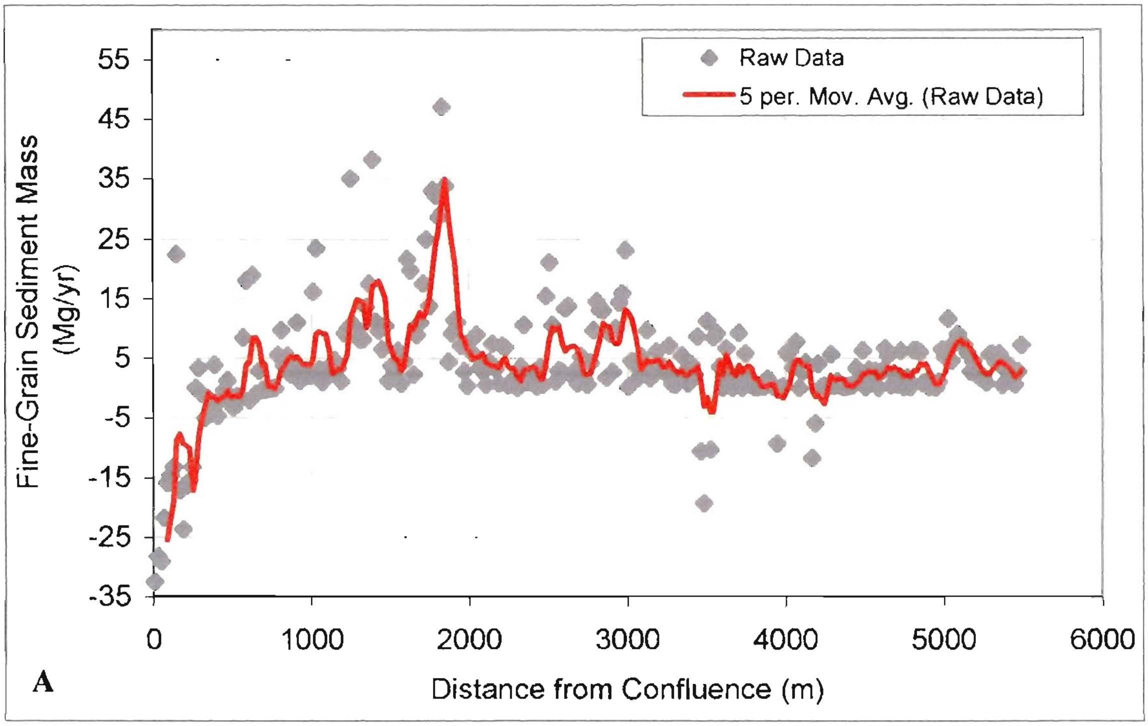
**Table 7.7** Totals for the mass balance budget for floodplain erosion in the study area. (A) Raw Data and (B) error-filtered data.

A

| Component | Total Release Mass | Total Deposition Mass | Net Mass Release into Spring River |
|---|---|---|---|
| Fine-Grain Sediment (Mg/yr) | 3,280 | 1,983 | 1,297 |
| Lead (kg/yr) | 439 | 412 | 27 |
| Zinc (kg/yr) | 2,197 | 2,086 | 111 |

B

| Component | Total Release Mass | Total Deposition Mass | Net Mass Release into Spring River |
|---|---|---|---|
| Fine-Grain Sediment (Mg/yr) | 929 | 610 | 319 |
| Lead (kg/yr) | 84 | 110 | -26 |
| Zinc (kg/yr) | 321 | 558 | -237 |



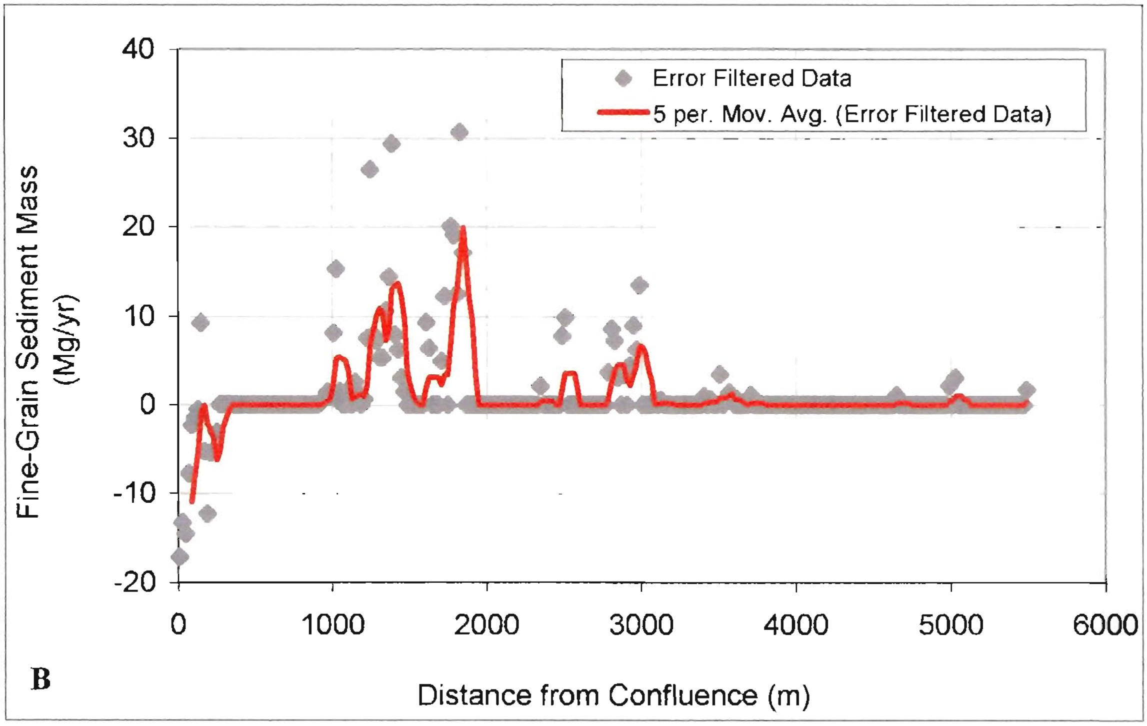


**Figure 7.11** The net release/storage of fine-grain sediment from 275 twenty-meter segments with (A) raw data and (B) error filtered data for the study area.

**Table 7.8** Sediment net release/storage for the study area. (A) Raw data and (B) Error-filtered data.

A

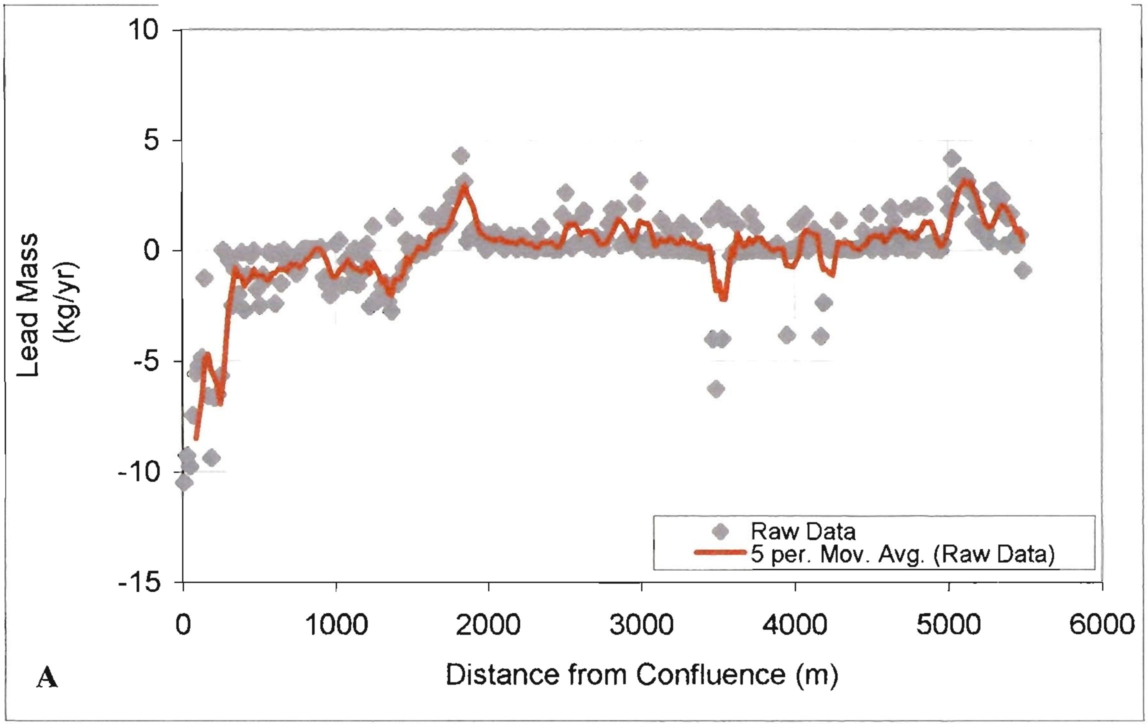
| **Segment**<br>**Distance from Confluence (m)** | **Percent Of Study Area** | **Net Release/Storage (Mg/yr)** | **Percent of Total Released from Non-Channelized Area** | **Percent of Total Net Release** |
|---|---|---|---|---|
| **262 – 226**<br>**(5,350 – 4,630)** | 13 | 145 | 6 | 13 |
| **182 – 118**<br>**(3,750 – 2,470)** | 23 | 322 | 14 | 30 |
| **92 – 40**<br>**(1,950 – 790)** | 21 | 664 | 28 | 61 |
| **28 – 1**<br>**(550 – 0)** | 10 | -237 | -- | -- |
| **Total** | 67 | 894 | -- | 82 |

B

| **Segment**<br>**Distance from Confluence (m)** | **Percent Of Study Area** | **Net Release/Storage (Mg/yr)** | **Percent of Total Released from Non-Channelized Area** | **Percent of Total Net Release** |
|---|---|---|---|---|
| **246 – 244**<br>**(5,030 – 4,990)** | <1 | 5 | 1 | 2 |
| **174 – 165**<br>**(3,410 – 3,590)** | 3 | 8 | 2 | <1 |
| **144 – 134**<br>**(2,990 – 2,790)** | 4 | 59 | 14 | 18 |
| **120 - 119**<br>**(2,510 – 2,490)** | <1 | 18 | 4 | 6 |
| **87 – 45**<br>**(1,850 – 930)** | 17 | 299 | 72 | 94 |
| **13 – 1**<br>**(250 – 0)** | 5 | -96 | -- | -- |
| **Total** | ~30 | 293 | -- | 120 |

The downstream trend in mass of release/storage metal in each segment is somewhat different from that of fine-grain sediment, especially in the lower sections of Chat Creek (Figures 7.11, 7.12, and 7.13). Much more of lower Chat Creek is a sink for metals than for sediment (Figures 7.11, 7.12, and 7.13). This is largely the result of the fact that in-channel metal concentrations are much higher than floodplain concentrations. These two reaches, 1,450 – 930 and 250 – 0 meters from the confluence are a net sink of 17 kg/yr and 32 kg/yr of lead, respectively (Table 7.9B and Figure 6.4). Likewise for zinc these reaches are a net sink of 150 kg and 179 kg, respectively (Table 7.9B and Figure 6.4). Still, a large majority, 86%, of the study area is either a net source or is balanced in terms of erosion and deposition of lead and zinc (Figures 7.12, 7.13 and Table 7.9B). Metal concentrations are also responsible for a larger portion of the lower study area being a net sink for lead and zinc. Still, a large majority of the study area is a net source of lead and zinc (Figures 7.12 and 7.13). Five reaches upstream of 1,450 meters from the confluence with the Spring River are net sources of lead and zinc (Table 7.9B). These five reaches contribute a total of 21 kg/yr lead and 86 kg/yr zinc to downstream reaches (Table 7.9B). A short reach between 1,850 and 1,710 meters from the confluence (3% of the total study area) contributes a large proportion of lead, 29%, and zinc, 33%, in the source areas (Table 7.9B).

Even though Chat Creek may be a net sink of metals introduced by floodplain erosion, it is contributing metals to the Spring River. Active channel sediment has a mean ($n = 3$) lead concentration of 21 ppm and mean zinc concentration of 113 ppm in the Spring River upstream of Chat Creek. Downstream of Chat Creek mean ($n = 3$)



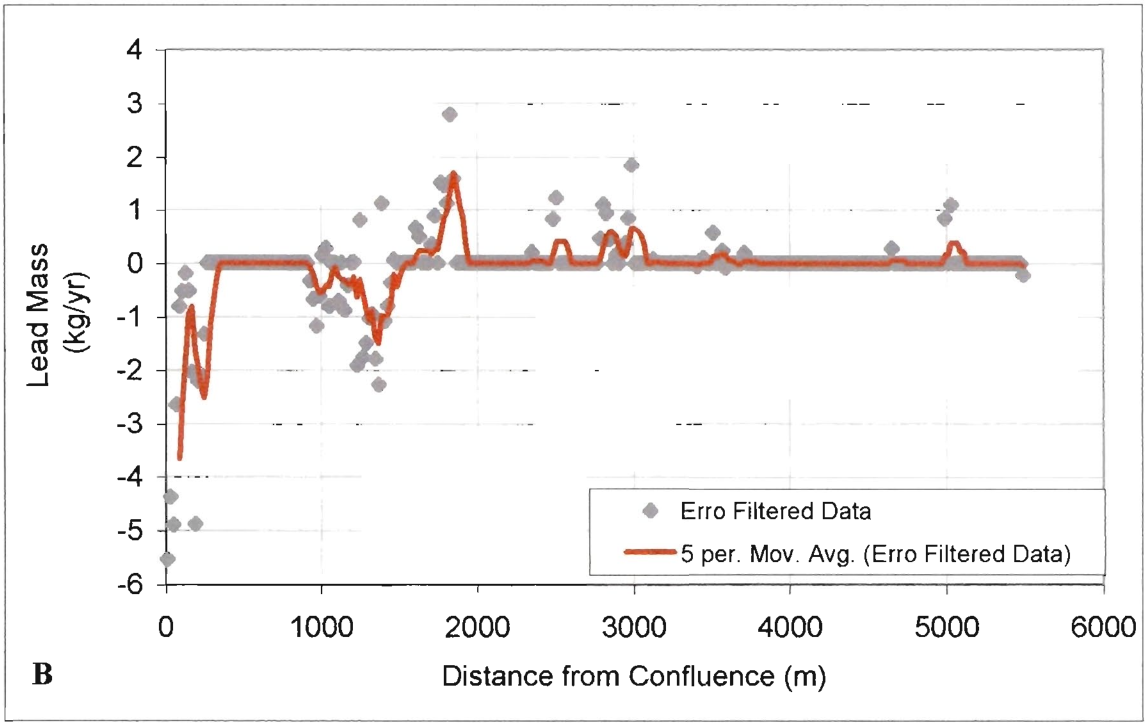
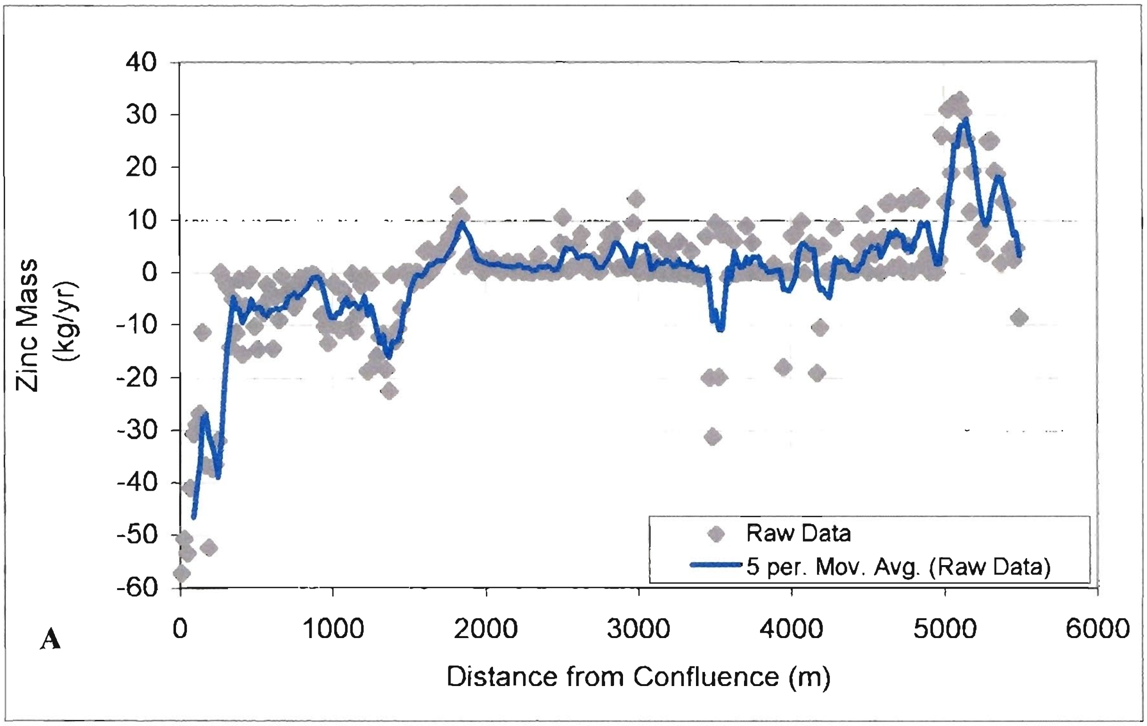


**Figure 7.12** Net release/storage of lead from 275 twenty-meter segments with (A) raw migration data and (B) error filtered migration data in the study area.



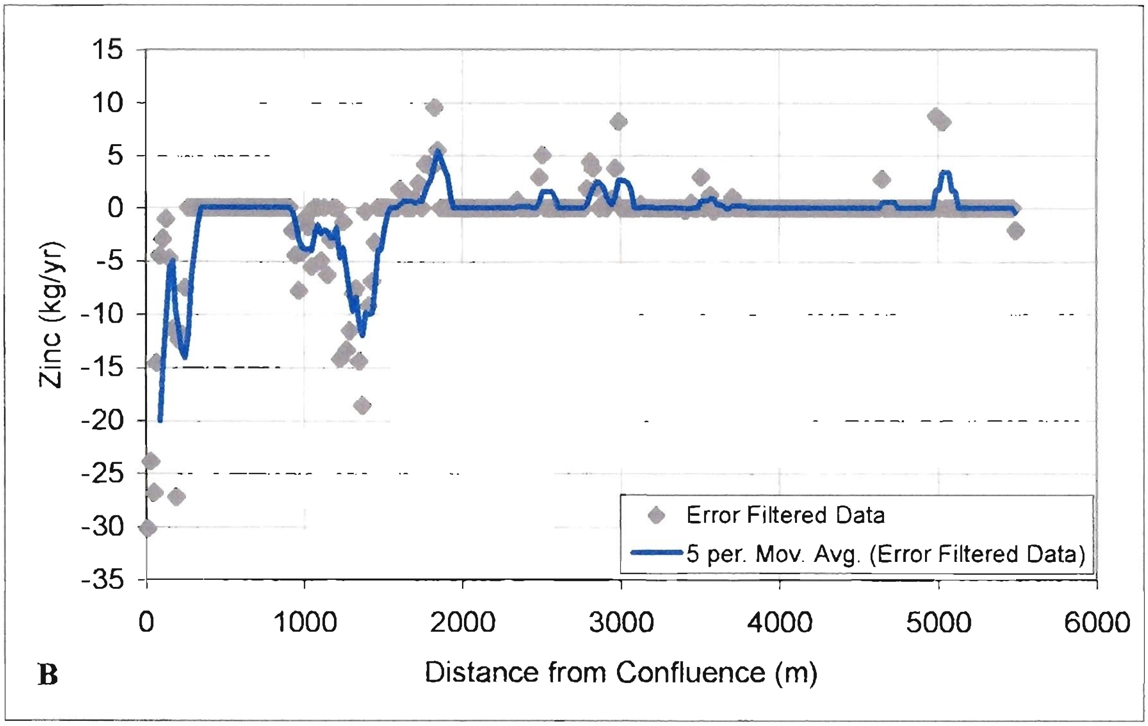


**Figure 7.13** Net release/storage of zinc from 275, twenty-meter segments with (A) raw migration data and (B) error filtered data in the study area.

**Table 7.9** Metal mass budget from floodplain erosion for the study area. (A) Budget totals by reach for raw data. (B) Budget totals by reach for error-filtered data.

A

| Segment Distance from Confluence (m) | Percent of Total Study Area | Lead Net Release/Storage (kg/yr) | Percent Of Total Released from Non-Sink Reaches | Zinc Net Release/Storage (kg/yr) | Percent Of Total Released from Non-Sink Reaches |
|---|---|---|---|---|---|
| 269 – 217<br>(5,500 – 4,450) | 19 | 2 | 2 | 562 | 103 |
| 147 – 117<br>(3,050 – 2,450) | 11 | 8 | 8 | 107 | 20 |
| 92 – 76<br>(1,950 – 1,630) | 6 | 26 | 26 | 81 | 15 |
| 74 – 44<br>(1,590 – 910) | 12 | -28 | -- | -252 | -- |
| 40 – 0<br>(790 – 0) | 14 | -114 | -- | -655 | -- |
| Totals | 62 | -106 | | -157 | 138 |

B

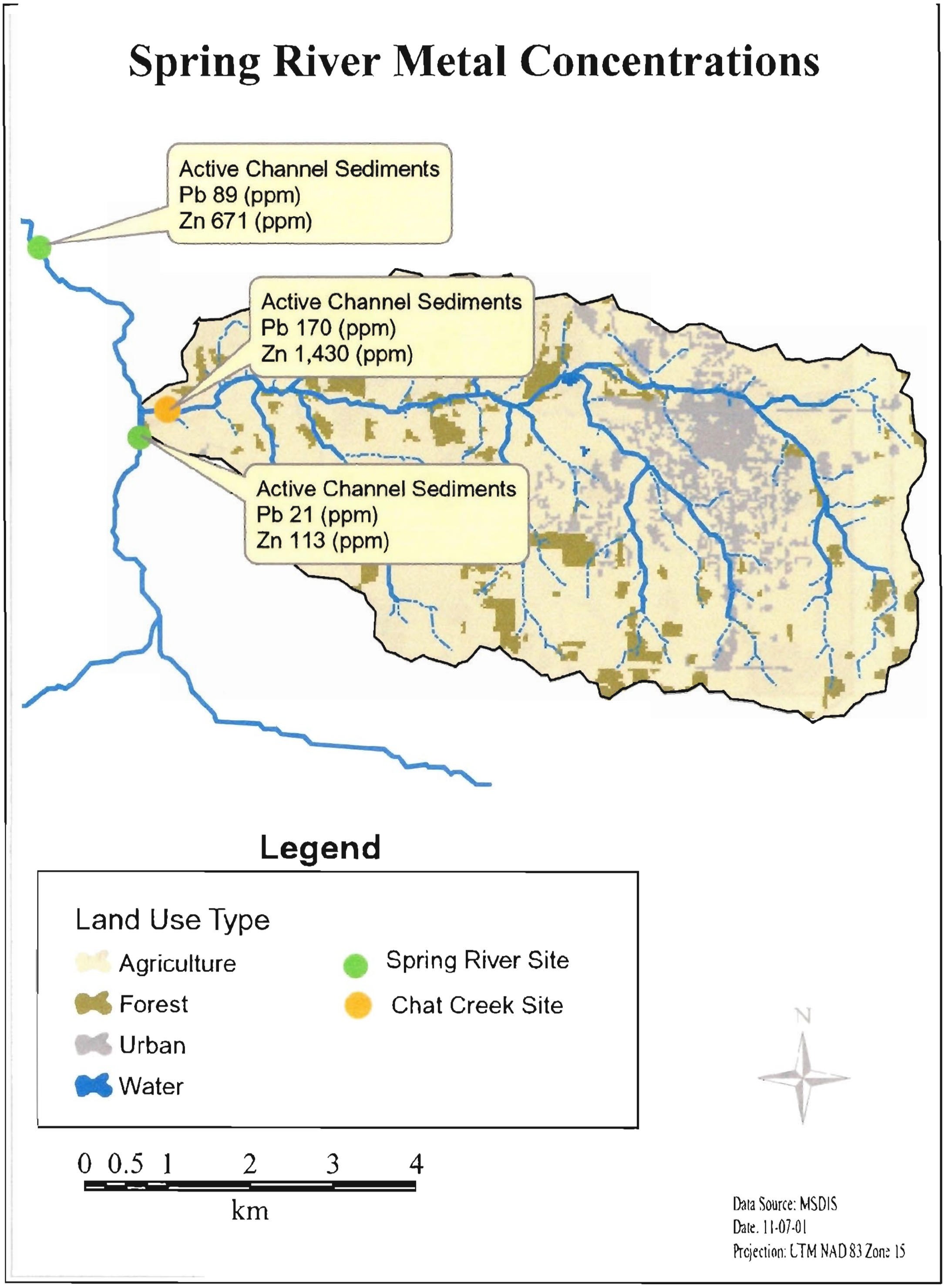
| Segment Distance from Confluence (m) | Percent of Total Study Area | Lead Net Release/Storage from these Reaches (kg/yr) | Percent Of Total Released from Non-Sink Reaches | Zinc Net Release/Storage from these Reaches (kg/yr) | Percent Of Total Released from Non-Sink Reaches |
|---|---|---|---|---|---|
| 246 – 244<br>(5,030 – 4,990) | <1 | 2 | 6 | 17 | 18 |
| 173 – 167<br>(3,570 – 3,450) | 2 | 1 | 3 | 5 | 5 |
| 144 – 134<br>(2,990 – 2,790) | 4 | 6 | 17 | 26 | 28 |
| 120 – 119<br>(2,510 – 2,490) | <1 | 2 | 6 | 8 | 9 |
| 87 – 80<br>(1,850 – 1,710) | 3 | 10 | 29 | 30 | 33 |
| 69 – 45<br>(1,450 – 930) | 9 | -17 | -- | -150 | -- |
| 13 – 1<br>(250 – 0) | 5 | -32 | -- | -179 | -- |
| Totals | ~25 | -28 | 61 | -243 | 93 |

concentrations in active channel sediments are 89 ppm lead and 671 ppm zinc (Figure 7.14). The budget calculated in this study represents a small proportion of the metals actively transported in the Chat Creek Watershed. Large amounts of metals are most likely still being introduced by the abandoned mining areas; this is evident when metal concentrations in the active channel sediment of upper Chat Creek are considered.

## Management Implications

This discussion focuses on how the masses of released material found in this study pertain to future management decisions and can serve to focus management efforts. Management efforts should focus on such measures as bank stabilization, riparian vegetation conservation/rehabilitation, and measures to limit livestock access to certain reaches of Chat Creek. Further monitoring and research in the watershed concerning tributary source areas, toxicity monitoring, metal load determination through baseflow and event sampling, and possible important future sources of metals would also be beneficial.

In terms of release of sediment and metals due to floodplain erosion in Chat Creek, management efforts should be focused on three specific reaches (Figure 7.15). The most important reach in terms of needed stabilization and monitoring for both sediment and metals extends from 1,850 to 930 meters from the confluence with the Spring River. Another reach, 250 meters from the confluence to the confluence, also releases much sediment into Chat Creek. Both of these reaches are pasture areas containing livestock and lacking significant riparian vegetation. Efforts to rehabilitate the riparian buffer zone and to limit livestock access to confined areas could help to slow



Spring River Metal Concentrations

Active Channel Sediments
Pb 89 (ppm)
Zn 671 (ppm)

Active Channel Sediments
Pb 170 (ppm)
Zn 1,430 (ppm)

Active Channel Sediments
Pb 21 (ppm)
Zn 113 (ppm)

Data Source: MSDIS
Date. 11-07-01
Projection: UTM NAD 83 Zone 15

**Figure 7.14** Metal concentrations in the Spring River upstream and downstream of the junction with Chat Creek.

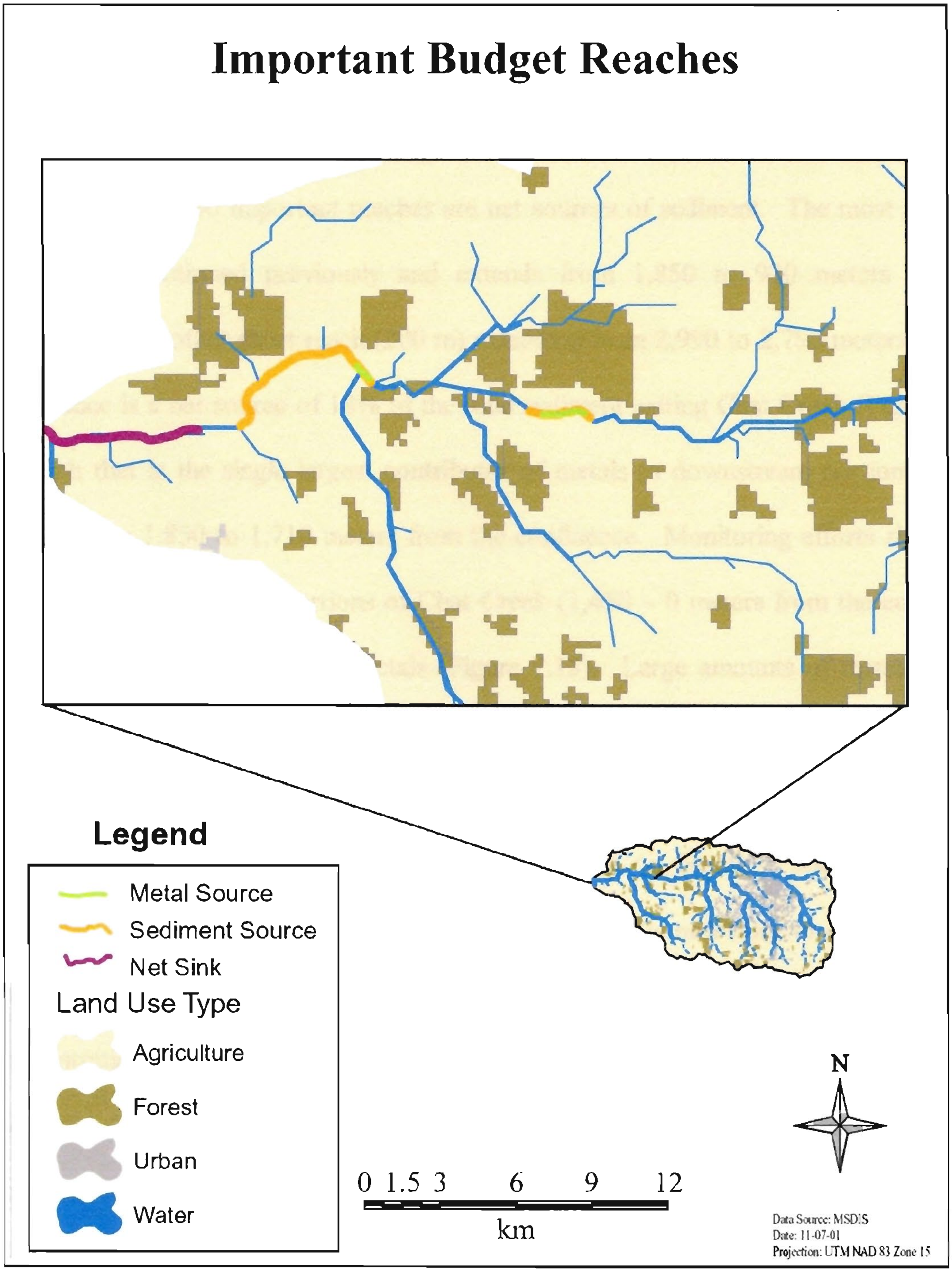


**Figure 7.15** Target reaches for monitoring and bank stabilization measures in study area.

material release rates. A reach further upstream, 3,710 – 2,350 meters from the confluence, also releases large amounts of metals into Chat Creek.

Important reaches of net release/storage of sediment and metals are more diffuse (Figure 7.15). Two important reaches are net sources of sediment. The most important reach was mentioned previously and extends from 1,850 to 930 meters from the confluence. Another short reach (200 m) extending from 2,990 to 2,790 meters from the confluence is a net source of 18% of the total sediment exiting Chat Creek (Figure 7.15). A reach that is the single largest contributor of metals to downstream portions of Chat Creek exists 1,850 to 1,710 meters from the confluence. Monitoring efforts should also be focused on the lower portions of Chat Creek (1,450 – 0 meters from the confluence) that are currently net sinks of metals (Figure 7.15). Large amounts of metals that are accumulating in the active stream sediments of this reach could be remobilized and flushed into the Spring River in a few major flow events.

Future management efforts should also focus on baseflow and bankfull event sampling. Water quality sampling during various events is necessary to establish loading rates that are important for TMDL determination. The excessive phosphorus concentrations should also be addressed through improvements to the wastewater treatment facility and nonpoint monitoring such as pasture and livestock areas. Extensive research is also needed concerning metal loadings from sources near the abandoned mining area. Even after mining operations have been inactive for over 80 years, the highest concentrations of metals in active stream sediments are still found in this area. Stabilization and remediation efforts in this area can act to limit downstream lead and zinc concentrations.

Several important limitations exist in this thesis research. Assumptions that were used may not provide the complete picture of metal transport processes in Chat Creek. It is highly possible and likely that the geometry of Chat Creek does not remain constant, especially in decadal time spans. Widening or narrowing of the stream channel would greatly affect erosion and deposition rates. In addition, lateral changes in floodplain metal concentrations will alter metal release amounts over time.

# CHAPTER 8

# CONCLUSION

Chat Creek Watershed (32 km$^2$) in southwestern Missouri that has been adversely affected by historical mining operations in the Tri-State Mining District. The Missouri State Department of Natural Resources recognizes Chat Creek on its 303d list of impaired watersheds due to high zinc concentrations attributed to the abandoned mining operations. Water quality degradation is a continuing concern even though mining ceased over 70 years ago. The goal of this thesis research is to gain an understanding of the distribution of mining-induced contamination and to assess fluvial processes that are secondarily introducing metals into the system.

The results of this study indicate lead and zinc levels in active stream sediment and floodplain deposits are extremely elevated downstream of the abandoned mining area. These concentrations decrease, but remain elevated above background, throughout the remaining length of the stream. Floodplain erosion is introducing large amounts of sediment, lead, and zinc into the active channel.

The final conclusions of this study are:

1. **Active stream sediments are contaminated downstream of the mining area. Contamination levels of lead and zinc generally decrease in a step-like trend with distance downstream.**

Lead concentrations rise from 80 ppm upstream of the mining area to 2,068 ppm downstream of the mining area. Lead levels remain high 7.8 km downstream near the confluence with the Spring River where the lead concentration is 170 ppm. Lead concentrations range from 3 – 124 times background levels. Zinc concentrations are 878 ppm upstream of the mining area and rise to 19,666 ppm just downstream of this area.

Near the confluence with the Spring River zinc levels are still high at 1,430 ppm. The level of contamination for zinc ranges from 3 to 279 times that of background levels. The step-like downstream trend for both metals is due to tributary inputs and added supply of uncontaminated sediment that dilutes pollutants.

2. **Concentrations of both lead and zinc are also extremely elevated in floodplain deposits of Chat Creek.**

Weighted floodplain concentration of lead is 643 ppm, 2,600 meters downstream of the mining area. Weighted zinc concentration at this same site is 5,377 ppm. Concentrations for both lead and zinc decrease downstream away for the mining area. The lowest floodplain concentration is 59 ppm approximately 6,700 meters from the mining area. The lowest floodplain zinc concentration is 191 ppm at this same site. Contamination levels according to cut bank profile depth vary downstream.

3. **Floodplain erosion is introducing large amounts of fine-grain sediment in the lower 2 km of Chat Creek.**

Floodplain erosion is introducing a total of 929 Mg of sediment into Chat Creek each year according to the minimum error-filtered values. Of this amount, 84% (780 Mg) is being released in the lower 2 km of the stream. Values assuming minimal error effects (raw data) are substantially higher. Floodplain erosion is introducing 3,057 Mg of sediment into Chat Creek according to the raw data. Fifty percent of this amount is introduced in the lower 2 km of Chat Creek.

4. **Floodplain erosion is contributing large masses of lead and zinc into the active channel of Chat Creek.**

According to error-filtered data, a total of 84 kg/yr. of lead are released into Chat Creek due to floodplain erosion. Sixty percent (50 kg) of this lead is being introduced between 1.8 and 0.9 km upstream of the confluence with the Spring River. The total zinc introduction per year due to floodplain erosion is 321 kg according to error-filtered data. Fifty-two percent (167 kg) of this is introduced into the stream by erosion between 1.8 and 0.9 km upstream of the confluence with the Spring River. Amounts of metal release according to the raw data are much higher for both lead and zinc. Three hundred and ninety-four kg of lead and 1,952 kg of zinc are released into Chat Creek annually due to floodplain erosion.

5. **The sediment wave containing most of the lead and zinc introduced by mining operations into Chat Creek remains in the upper reaches of the stream near the mining area.**

The highest concentrations of lead and zinc in both active channel sediment and floodplain sediment are just downstream of the mining area. Over seventy years after mining has ceased, the majority of the contamination remains within 4 km of the area. It will take at least another seventy years, most likely much longer, before this wave moves significantly downstream and sediment concentration trends are reversed.

6. **Reduction in lead and zinc should focus on bank stabilization of key reaches and the upper reaches of Chat Creek.**

There are two major floodplain erosion source reaches of metals in Chat Creek. The most important reach is a short area that extends from 1,850 meters from the confluence downstream to 1,710 meters from the confluence. Another important source area of metals extends from 2,990 meters from the confluence to 2,790 meters from the confluence. Also of importance in terms of metal transport are two reaches extending from 1,450 meters from the confluence to 930 meters from the confluence and 250 meters from the confluence to the confluence with the Spring River. These reaches are currently net sinks of metals but represent possible future sources of metals. The most important source area for sediment originating from floodplain erosion extends from

1,850 to 930 meters from the confluence. The reach from 250 meters from the confluence to the confluence is also a net sink of sediment. Management efforts should also focus on the upper reaches of Chat Creek near the abandoned mining area. According to metal concentrations in active channel sediment, this area is still a major contemporary source of metals to the stream system.

7. **Further monitoring and research is need on Chat Creek to improve degraded water quality.**

Five issues concerning water quality degradation require further monitoring and research. The first is concerned with lead and zinc loadings from possible important sources. Source loadings are a necessary component for TMDL determination. Source loadings can be determined through extensive baseflow and event sampling. The second issue concerning future monitoring requires geochemical and solution mobility studies on contaminated floodplain deposits. If metals are not actively being transported in solution and are not readily bioavailible then efforts should focus on erosion reduction. The third issue is local-scale variations in sediment-metal geochemistry, which can be used to determine causes of within-site variations in metal concentrations and potential environmental toxicity. Local-scale changes in sediment-metal geochemistry can indicate source characteristics and metal forms. The fourth important issue is to better understand sediment-metal depositional processes in Chat Creek. The budget calculated in this research provides information for release rates, but transport of metals can only be understood through a better knowledge of deposition. The last important issue is quantifying the importance of the abandoned mining areas as a contemporary source of metals. Remediation and monitoring efforts should focus to cleanup or stabilize remnant tailings piles and to stabilize stream banks storing contaminated sediment.

Degraded water quality due to excessive heavy metal accumulation in surface water is a concern for resource managers world wide. These contaminants not only affect aquatic flora and fauna but also are a concern for humans as the metals accumulate and move up the food chain. Environmental problems created by excessive heavy metals are a major concern in areas of historical mining operations. The Tri-State Mining District is one such area. Chat Creek, located on the eastern edge of the Tri-State District, is recognized by the Missouri Department of Natural Resources as having degraded water quality due to zinc contamination from abandoned mining operations. Little is understood about the distribution of mining-derived metals and possible contemporary sources. The results of this thesis research provide important information concerning areas to target for future monitoring and research aimed at improving water quality in the Chat Creek Watershed.

# LITERATURE CITED

Aslan, A. and W.J. Autin. 1998. "Holocene Flood-plain Soil Formation in the Southern Lower Mississippi Valley: Implications for Interpreting Alluvial Paleosols." *Geological Society of America Bulletin,* 110(4): 433-449.

Bannerman, R., 1991. "Pollutants in Wisconsin Stormwater." Unpublished report by the Wisconsin Department of Natural Resources, Madison, WI.

Barker, R. L. Dixon, J. Hooke. 1997. "Use of Terrestrial Photogrammetry for Monitoring and Measuring Bank Erosion." *Earth Surface Processes and Landforms,* 22:1217-1227.

Barks, J.H. 1977. "Effects of Abandoned Lead and Zinc Mines and Tailings Piles on Water Quality in the Joplin Area, Missouri." U.S. Geological Survey, Water Resources Investigations Report, 77-75.

Barry, J., S.E. Reutebuch, and T. Robison. 1996. "Use of Historical Aerial Photos to Evaluate Stream Channel Migration." In: Remote Sensing; People in Partnership with Technology; Proceedings of the Sixth Forest Service Remote Sensing Applications Conference; April 29-May 3, 1996, Denver, Colorado, J.D. Greer (ed.), ASPRS, Bethesda, Maryland.

Beeson, C.E. and P.F. Doyle. 1995. "Comparison of Bank Erosion at Vegetated and Non-Vegetated Channel Bends." *Water Resources Bulletin,* 31(6): 983-990.

Boulding, J.R. 1994. Description and Sampling of Contaminated Soils, A Field Guide, 2nd Edition. Boca Raton; Lewis Publishers.

Bradley, S.B. 1989. "Incorporation of Metalliferous Sediments from Historic Mining into River Floodplains." *GeoJournal,* 19.1: 5-14.

Bradley, S.B. and J.J. Cox. 1990. "The Significance of the Floodplain to the Cycling of Metals in the River Derwent Catchment, U.K." *The Science of the Total Environment,* 97/98: 441-454.

Burckhardt, J.C. and B.L. Todd. 1998. "Riparian Forest Effect on Lateral Stream Channel Migration in the Glacial Till Plains." *Journal of the American Water Resources Association,* 34(1): 179-184.

Campbell, J.B. 1996. Introduction to Remote Sensing, 2nd Edition. New York; The Guilford Press.

Carlson, J.L. 1999. Zinc Mining Contamination and Sedimentation Rates of Historical Overbank Deposits, Honey Creek Watershed, Southwest Missouri. Masters Thesis. Springfield, Missouri: Southwest Missouri State University

Carroll, S.A., P.A. O'Day, and M. Piechowski. 1998. "Rock-Water Interactions Controlling Zinc, Cadmium, and Lead Concentrations in Surface Water and Sediments, U.S. Tri-State Mining District. 2. Geochemical Interpretation." *Environmental Science and Technology,* 32:956-965.

Caruso, B.S. and R.C. Ward. 1998. "Assessment of Nonpoint Source Pollution from Inactive Mines Using a Watershed-Based Approach." *Environmental Management,* 22(2):225-243.

Combest, K.B. 1991. "Trace Metals in Sediment: Spatial Trends and Sorption Processes." *Water Resources Bulletin.* 27(1):19-28.

Dean, W.E. 1974. "Determination of carbonate and organic matter in calcareous sediments and sedimentary rocks by loss on ignition: comparison with other methods." *Journal of Sedimentary Petrology,* 44:242-248.

FGDC, 1998. Geospatial Positioning Accuracy Standards Part 3: National Standard for Spatial Data Accuracy, FGDC-STD-007.3-1998 *http://www.fgdc.gov/standards/ documents/standards/accuracy/chapter3.*

Forrester, D.J. 1950. Missouri, Its Resources, People, and Institutions. Columbia, Missouri: Curators of the University of Missouri.

Forstner, U. 1995."Land Contamination by Metals: Global Scope and Magnitude of Problem." In *Metal Speciation and Contamination of Soil,* eds. Herbert E. Allen, Chin P. Huang, George W. Bailey, Alan R. Bowers. Lewis Publishers.

Forstner, U. and Muller, G. 1981. "Concentrations of Heavy Metals and Polycyclic Aromatic Hydrocarbons in River Sediments: Geochemical Background, Man's Influence and Environmental Impact." *GeoJournal,* 5.5:417-432.

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

Fredrick, B., 2001. "Spatial Distribution of Phosphorus in Fluvial Sediments from the James River Basin, SW Missouri." Masters Thesis. Springfield, Missouri: Southwest Missouri State University.

Goodyear, K.L., M.H. Ramsey, I. Thornton, and M.S. Rosenbaum. 1996. "Heavy Metals in the Hydrological Cycle: Trends and Explanation." *Hydrological Processes,* 10:227-261.

Graf, W.L. 1996. "Transport and Deposition of Plutonium-Contaminated Sediments by Fluvial Processes, Los Alamos Canyon, New Mexico." *Geological Society of America Bulletin,* 108(10):1342-1355.

Grant, R.S. and G. Goddard. 1980. "Channel Erosion and Sediment Transport in Pheasant Branch Basin near Middleton, Wisconsin- A Preliminary Report." U.S. Geological Survey Water Resource Investigation- Open File Report 80-161.

Greenfeld, J. 2001. "Evaluating the Accuracy of Digital Orthophoto Quadrangles (DOQ) in the Context of Parcel-Based GIS." *Photogrammetric Engineering & Remote Sensing,* 67(2):199-205.

Hawes-Davis, D. 1993. "Mining The Ozark Highland: A Heavy Burden on the Future." *Focus,* 43(2):8-15.

Helgen, S.O. and J.N. Moore. 1996. "Natural Background Determination and Impact Quantification in Trace Metal-Contaminated River Sediments." *Environmental Sciences and Technologies,* 30:129-135.

Heritage, G.L., L.C. Fuller, M.E. Charlton, P.A. Brewer, and D.P. Passmore. 1998. "CDW Photogrammetry of Low Relief Fluvial Features: Accuracy and Implications for Reach-Scale Sediment Budgeting." *Earth Surface Processes and Landforms,* 23:1219-1233.

Holmgren, G.G.S., M.W. Meyer, R.L. Chaney, and R.B. Daniels. 1993. "Cadmium, Lead, Zinc, Copper, and Nickel in Agricultural Soils of the United States of America." *Journal of Environmental Quality,* 22:335-348.

Horowitz, A.J. 1991. Sediment-Trace Element Chemistry (Second Edition). Michigan: Lewis Publishers.

Hughes, E.H. 1982. Soil Survey of Greene and Lawrence Counties, Missouri. United States Department of Agriculture, Soil Conservation Service.

Jacobson, R.B. 1995 "Spatial Controls on Patterns of Land-Use Induced Stream Disturbance at the Drainage-Basin Scale—An Example from Gravel-bed Streams of the Ozark Plateaus, Missouri." In: Natural and Anthropogenic Influences in Fluvial Geomorphology Geophysical Monograph 89, published by the American Geophysical Union.

Jacobson, R.B. and K.B. Gran. 1999. "Gravel Sediment Routing from Widespread, Low-Intensity Landscape Disturbance, Current River Basin, Missouri." *Earth Surface Processes and Landforms,* 24:897-917.

Jacobson, R.B. and A.L. Pugh. 1995. "Riparian Vegetation Controls in the Spatial Pattern of Stream-Channel Instability, Little Piney Creek, Missouri." U.S. Geological Survey Water-Supply Paper 2494.

James, L.A. 1989. "Sustained Storage and Transport of Hydraulic Gold Mining Sediment in the Bear River, California." *Annals of the Association of American Geographers,* 79(4):570-592.

Kilsgaard, H.T. and C.W. Hayes. 1967. *Mineral and Water Resources of Missouri.* 2nd series, vol.43. U.S. Government Printing Office; Washington, D.C.

Kiner, L.K., C. Vitello, and K. Hash. 1997. Spring River Inventory and Management Plan. Jefferson City, Missouri: Missouri Department of Conservation.

Knox, J.C. 1977. "Human Impacts on Wisconsin Stream Channels." *Annals of the Association of American Geographers*, 67(3):323-342.

Knox, J.C. 1987. " Historical Valley Floor Sedimentation in the Upper Mississippi Valley." *Annals of the Association of American Geographers, 67*: 401-410.

Lecce, S.A. and R.T. Pavlowsky. 1997. "Storage of Mining- Related Zinc in Floodplain Sediments, Blue River, Wisconsin." *Physical Geography,* 18(5):424-439.

Lecce, S.A. and R.T. Pavlowsky. 2001. "Use of Mining-Contaminated Sediment Tracers to Investigate the Timing and Rates of Historical Flood Plain Sedimentation." *Geomorphology,* 38:85-108.

Leenaers, H. and C.J. Schouten. 1989. "Soil Erosion and Floodplain Soil Pollution: Related Problems in the Geographical Context of a River Basin." In: Sediments and the Environment (Proceedings from the Baltimore Symposium) IAHS Publication no.184.

Leenaers, H., C.J. Schouten, and M.C. Rang. 1988. "Variability of the Metal Content of Flood Deposits." *Environmental Geology and Water Sciences,* 11(1):95-106.

Leopold, Luna B., M.G. Wolman, and J.P. Miller. 1992. Fluvial Processes in Geomorphology. New York: Dover Publications Inc.

Lewin, J., B.E. Davies, and P.J. Wolfenden. 1977. "Interactions Between Channel Change Historic Mining Sediments." In: River Channel Changes, (ed.) Gregory, K.J., pp 353-367, John Wiley. Chichester.

Magilligan, F.J. and M.L. Stamp. 1997. "Historical Land-Cover Changes and Hydrogeomorphic Adjustment in a small Georgia Watershed." *Annals of the Association of American Geographers,* 87(4):614-635.

Mantei, E.J. and E.J. Sappington. 1994. "Heavy Metal Concentrations in Sediments of Streams Affected by a Sanitary Landfill: A Comparison of Metal Enrichment in Two Size Sediment Fractions." *Environmental Geology,* 24:287-292.

Marcus, W.A. 1987. "Copper Dispersion in Ephemeral Stream Sediments." *Earth Surface Processes and Landforms,* 12:217-228.

Marcus, W.A. 1989. "Dilution Mixing Estimates of Trace Metal Concentrations in Suspended Sediments." *Environmental Geology and Water Science,* 14(3):213-219.

Marcus, W.A., G.A. Meyer, and R.N. DelWayne. 2001. "Geomorphic Control of Persistent Mine Impacts in a Yellowstone Park Stream and Implications for the Recovery of Fluvial Systems." *Geology,* 29(4):355-358.

Marsalek, J. 1986. "Toxic Contaminants in Urban Runoff" *In*: Urban Runoff Pollution (H. Torno, J. Marsalek, and M. Desbordes, eds.) pp 39-57, Springer Verlag, Berlin.

McKenney, R., R.B. Jacobson, and R.C. Wertmeimer. 1995. "Woody Vegetation and Channel Morphogenesis in Low-Gradient, Gravel-Bed Streams in the Ozark Plateaus, Missouri and Arkansas." *Geomorphology,* 13:175:198.

Meade, R.H. 1982. "Sources, Sinks, and Storage of River Sediments in the Atlantic Drainage of the United States." *The Journal of Geology,* 90:235-252.

Miller, J.R. 1997. "The Role of Fluvial Geomorphic Processes in the Dispersal of Heavy Metals from Mine Sites." *Journal of Geochemical Exploration,* 58:101-118.

Missouri Census Data Center. 2000. http://mcdc.missouri.edu.

Novak, K. 1992. "Rectification of Digital Imagery." *Photogrammetric Engineering and Remote Sensing,* 58(3):339-344.

Odemerho, F.O. 1992. "Limited Downstream Response of Stream Channel Size to Urbanization in a humid Tropical Basin." *Professional Geographer,* 44(3):332-339.

Pavlowsky, R.T. 1989. Trace Metal Yields and Sources in the Raritan Basin, New Jersey. Masters of Science Thesis, Department of Geography, Rutgers University, New Brunswick, New Jersey.

Pavlowsky, R.T. 1995. Spatial Variability of Mining-Related Zinc and Lead in Fluvial Sediments, Galena Watershed, Wisconsin-Illinois. Doctoral Dissertation, Department of Geography, University of Wisconsin, Madison.

Pavlowsky, R.T. 1996. "Fluvial Transport and Long-term Mobility of Mining Related Zinc." In: Tailings and Mine Waste. Rotterdam, Brookfield: A.A. Balkema 395-404.

Peterson, C.J., C.J. Adamski, W.R. Bell, V.J. Davis, R.S. Femmer, A.D. Freiwald, and L.J. Joseph. 1998. "Water Quality in the Ozarks Plateaus, Arkansas, Kansas, Missouri, and Oklahoma." U.S. Geological Survey Circular, 1158:1-33.

Pitt, R. and P. Barron. 1989. "Assessment of urban and industrial stormwater runoff toxicity and the evaluation/development of treatment for runoff toxicity abatement-Phase 1." A report for the U.S. Environmental Protection Agency, Storm and Combined Sewer Pollution Program, Edison, NJ.

Rafferty, M.D. 1983. Persistence Versus Change in Land Use and Landscape in the Springfield, Missouri Vicinity of the Ozarks. Ann Arbor, Michigan: University Microfilms International.

Rang, M.C. and C.J. Schouten. 1989. "Evidence of Historical Heavy Metal Pollution in Floodplain Soils: the Meuse." Historical Change of Large Alluvial Rivers: Western Europe. (ed.) Petts, G.E., John Wiley and Sons Ltd. 127-142.

Rowan, J.S., S.J.A. Barnes, S.L. Hetherington, B. Lambers, and F. Parsons. 1995. "Geomorphology and Pollution: the environmental; impacts of lead mining, Leadhills, Scotland." *Journal of Geochemical Exploration,* 52:57-65.

Ruhlman, M.B. and W.L. Nutter. 1999. "Channel Morphology Evolution and Overbank Flow in the Georgia Piedmont." *Journal of the American Water Resources Association,* 35(2): 277-290.

Salomons, W. 1995. "Environmental Impacts of Metals Derived from Mining Activities: Processes, Predictions, Prevention." *Journal of Geochemical Exploration,* 52: 5-23.

Schilling, K.E. and C.F. Wolter. 2000. "Application of GPS and GIS to Map Channel Features in Walnut Creek, Iowa." *Journal of the American Water Resources Association,* 36(6):1423-1434.

Sear, D. and S. Carver. 1996. "The Release and Dispersal of PB and ZN contaminated Sediments within an Arctic Braided River System." *Applied Geochemistry,* 11:187-195.

Smith, J. Dungan, John H. Lambing, David A. Nimick, Charles Parret, Michael Ramey, and William Schafer. 1998. "Geomorphology, Flood-Plain Tailings, and Metal Transport in the Upper Clark Fork Valley, Montana." *U.S. Geological Survey, Water-Resources Investigations Report, 98-4170*: 1-56.

Spruill, T.B. 1987. "Assessment of Water Resources in Lead-Zinc Mined Areas in Cherokee County, Kansas, and Adjacent Areas." *U.S. Geological Survey, Water-Supply Paper, 2268*: 1-68.

Steele, K.F. and G.H. Wagner. 1975. "Trace Metal Relationships in Bottom Sediments of a Fresh Water Stream-the Buffalo River, Arkansas." *Journal of Sedimentary Petrology,* 45(1): 310-319.

Swennen, R., I. Van Keer, and W. DeVos 1994. "Heavy Metal Contamination in Overbank Sediments of the Geul River (East Belgium): Its relation to former Pb-Zn mining activities." *Environmental Geology,* 24: 12-21.

Swennen, R. and J. Van der Sluys. 1998. "Zn, Pb, Cu, and As Distribution Patterns in Overbank and Medium-order Stream Sediment Samples: Their Use in Exploration and Environmental Geochemistry." *Journal of Geochemical Exploration,* 65:27-45.

Thorne, C.R. and N.K. Tovey. 1981. "Stability of Composite River Banks." *Earth Surface Processes and Landforms,* 6:469-484.

Trimble, S.W. 1983. "A Sediment Budget for Coon Creek Basin in the Driftless Area, Wisconsin, 1853-1977." *American Journal of Science,* 283:454-474.

Trimble, S.W. 1993. "The Distributed Sediment Budget Model and Watershed Management in the Paleozoic Plateau of the Upper Midwestern United States." *Physical Geography,* 14(no.3):285-303.

United States Environmental Protection Agency. 1995. Historic Hardrock Mining: The West's Toxic Legacy; the critical link between water quality and abandoned mine sites.

United States Environmental Protection Agency. 1998. "303d list for 1998" Internet Site: www.epa.gov/iwi/303d/11070207_303d.html.

United States Environmental Protection Agency. 1999. Protocol for Developing Sediment TMDLs. EPA 841-B-99-004. Office of Water (4503F), United States Environmental Protection Agency, Washington D.C.

Walling, D.E. 1983. "The Sediment Delivery Problem." *Journal of Hydrology,* 65:209-237.

Warren, L.J. 1982 "Contamination of Sediments by lead, zinc and cadmium: A Review." *Environmental Pollution,* (series B) 2:401-436.

White, J.W. 2001. Spatial Assessment of Nonpoint Phosphorous Sources Using Streambed Sediment Monitoring in the King's River Basin, NW, Arkansas. Masters Thesis. Springfield, Missouri: Southwest Missouri State University.

Winslow, Aurthor. 1894. Missouri Geological Survey. Jefferson City: Tribune Printing Company.

WRAS. 2000. WATERSHED RESTORATION ACTION STRATEGY; A Long Range Framework for Addressing Water Quality Concerns in the Upper Spring River Watershed, Lawrence County, Missouri. Natural Resource Conservation Service.

Xanthopolous, C. and H.H Hahn. 1993. "Anthropogenic wash-off from urban street surfaces" *In*: Proceedings of the Fifth International Conference on Urban Storm Drainage, Niagara Falls, Ontario, Canada. Pp.417-422. (Marsalek, J. and Torno, H.C. eds.). Seapoint Publishing, British Columbia.

# Appendix A

# In-Channel Sample Site Information

| Site # | Chemex Sample # | Lab # | Easting (UTM NAD 83, Zone 15s) | Northing (UTM NAD 83, Zone 15s) | $A_d$ | Distance from Confluence with Spring River (meters) |
|---|---|---|---|---|---|---|
| 401 | SR-1 | 401 | -- | -- | 3.91 | 9,765 |
| | SR-2 | 402 | -- | -- | 3.91 | 9,765 |
| | SR-3 | 403 | -- | -- | 3.91 | 9,765 |
| 101 | CC-SR 1A | 1011 | -- | -- | 4.66 | 9,276 |
| | CC-SR 1B | 1012 | -- | -- | 4.66 | 9,276 |
| | CC-SR 1C | 1013 | -- | -- | 4.66 | 9,276 |
| 103 | CC-SR 3A | 1031 | -- | -- | 6.73 | 8,373 |
| | CC-SR 3B | 1032 | -- | -- | 6.73 | 8,373 |
| | CC-SR 3C | 1033 | -- | -- | 6.73 | 8,373 |
| 104 | CC-SR 4A | 1041 | -- | -- | 6.93 | 8,130 |
| | CC-SR 4B | 1042 | -- | -- | 6.93 | 8,130 |
| | CC-SR 4C | 1043 | -- | -- | 6.93 | 8,130 |
| 105 | CC-SR 5A | 1051 | -- | -- | 7.15 | 7,724 |
| | CC-SR 5B | 1052 | -- | -- | 7.15 | 7,724 |
| | CC-SR 5C | 1053 | -- | -- | 7.15 | 7,724 |
| 404 | SR- 4 | 404 | -- | -- | 7.18 | 7,676 |
| | SR-5 | 405 | -- | -- | 7.18 | 7,676 |
| | SR-6 | 406 | -- | -- | 7.18 | 7,676 |
| 106 | CC-SR6A | 1061 | -- | -- | 8.83 | 6,483 |
| | CC-SR6B | 1062 | -- | -- | 8.83 | 6,483 |
| | CC-SR6C | 1063 | -- | -- | 8.83 | 6,483 |
| | CC-SR6D | 1064 | -- | -- | 8.83 | 6,483 |
| 119 | CHAT 119 | 119 | 433764.926 | 4092605.597 | 16.02 | 5,687 |
| 110 | CHAT1101 | 1101 | -- | -- | 16.07 | 5,583 |
| | CHAT1102 | 1102 | -- | -- | 16.07 | 5,583 |
| | CHAT1103 | 1103 | -- | -- | 16.07 | 5,583 |

| Site # | Chemex Sample # | Lab # | Easting (UTM NAD 83, Zone 15s) | Northing (UTM NAD 83, Zone 15s) | $A_d$ | Distance from Confluence with Spring River (meters) |
|---|---|---|---|---|---|---|
| 123 | CHAT 123 | 123 | 433589.398 | 4092507.582 | 16.09 | 5,504 |
| 118 | CHAT 1181 | 1181 | 433528.699 | 4092500.321 | 16.09 | 5,452 |
|  | CHAT 1182 | 1182 | 433528.699 | 4092500.321 | 16.09 | 5,452 |
|  | CHAT 1183 | 1183 | 433528.699 | 4092500.321 | 16.09 | 5,452 |
| 117 | CHAT 117 | 117 | 433257.635 | 4092580.414 | 16.47 | 5,117 |
| 124 | CHAT 1241 | 1241 | 433188.222 | 4092618.446 | 16.70 | 5,030 |
|  | CHAT 1242 | 1242 | 433188.222 | 4092618.446 | 16.70 | 5,030 |
|  | CHAT 1243 | 1243 | 433188.222 | 4092618.446 | 16.70 | 5,030 |
| 116 | CHAT 1161 | 1161 | 432425.262 | 4092447.150 | 22.71 | 4,149 |
|  | CHAT 1162 | 1162 | 432425.262 | 4092447.150 | 22.71 | 4,149 |
|  | CHAT 1163 | 1163 | 432425.262 | 4092447.150 | 22.71 | 4,149 |
| 115 | CHAT 115 | 115 | 431948.247 | 409388.475 | 22.8 | 3,645 |
| 125 | CHAT 125 | 125 | 431875.481 | 4092424.768 | 23.7 | 3,556 |
| 107 | CHAT 1071 | 1071 | -- | -- | 24.26 | 3,264 |
|  | CHAT 1072 | 1072 | -- | -- | 24.26 | 3,264 |
|  | CHAT 1073 | 1073 | -- | -- | 24.26 | 3,264 |
| 407 | SR-7 | 407 | -- | -- | 24.39 | 3,187 |
|  | SR-8 | 408 | -- | -- | 24.39 | 3,187 |
|  | SR-9 | 409 | -- | -- | 24.39 | 3,187 |
| 132 | CHAT 132 | 132 | 431287.479 | 4092518.190 | 24.40 | 2,870 |
| 122 | CHAT 122 | 122 | 430889.703 | 4092632.715 | 25.90 | 2,358 |
| 134 | CHAT 134 | 134 | 430822.970 | 4092646.948 | 27.40 | 2,287 |
| 120 | CHAT 120 | 120 | 430582.911 | 4092661.408 | 27.55 | 2,018 |
| 131 | CHAT 1311 | 1311 | 430337.798 | 4092758.047 | 30.57 | 1,704 |
|  | CHAT 1312 | 1312 | 430337.798 | 4092758.047 | 30.57 | 1,704 |
|  | CHAT 1313 | 1313 | 430337.798 | 4092758.047 | 30.57 | 1,704 |
| 128 | CHAT 128 | 128 | 430038.258 | 4092739.089 | 30.83 | 1,288 |
| 129 | CHAT 1291 | 1291 | 430146.151 | 4092794.738 | 30.83 | 1,407 |
|  | CHAT 1292 | 1292 | 430146.151 | 4092794.738 | 30.83 | 1,407 |
|  | CHAT 1293 | 1293 | 430146.151 | 4092794.738 | 30.83 | 1,407 |

| Site # | Chemex Sample # | Lab # | Easting (UTM NAD 83, Zone 15s) | Northing (UTM NAD 83, Zone 15s) | $A_d$ | Distance from Confluence with Spring River |
|---|---|---|---|---|---|---|
| 126 | CHAT 126 | 126 | 429792.268 | 4092440.573 | 31.33 | 850 |
| 127 | CHAT 127 | 127 | 429792.268 | 4092440.573 | 31.35 | 845 |
| 108 | CHAT 1081 | 1081 | -- | -- | 31.91 | 279 |
|  | CHAT 1082 | 1082 | -- | -- | 31.91 | 279 |
|  | CHAT 1083 | 1083 | -- | -- | 31.91 | 279 |
| 410 | SR–10 | 410 | -- | -- | 31.48 | 295 |
|  | SR-11 | 411 | -- | -- | 31.48 | 295 |
|  | SR-12 | 412 | -- | -- | 31.48 | 295 |

# Appendix B

## Floodplain Sample Information

| Study Reach # | Chemex Sample # | Lab # | Easting (UTM NAD 83, Zone 15s) | Northing (UTM NAD 83, Zone 15s) | $A_d$ | Distance from Confluence with Spring River (meters) |
|---|---|---|---|---|---|---|
| 1 | CHAT 2011 | 2011 | 433575.551 | 4092507.691 | 16.09 | 5,502 |
| | CHAT 2012 | 2012 | 433575.551 | 4092507.691 | 16.09 | 5,502 |
| 2 | CHAT 2021 | 2021 | 433182.511 | 4092620.880 | 16.47 | 4,985 |
| | CHAT 2022 | 2022 | 433182.511 | 4092620.880 | 16.47 | 4,985 |
| | CHAT 2023 | 2023 | 433182.511 | 4092620.880 | 16.47 | 4,985 |
| 3 | CHAT 2031 | 2031 | 432386.564 | 4092444.483 | 22.72 | 4,075 |
| | CHAT 2032 | 2032 | 432386.564 | 4092444.483 | 22.72 | 4,075 |
| | CHAT 2033 | 2033 | 432386.564 | 4092444.483 | 22.72 | 4,075 |
| | CHAT 2034 | 2034 | 432386.564 | 4092444.483 | 22.72 | 4,075 |
| 4 | CHAT 2041 | 2041 | 431867.885 | 4092430.186 | 23.69 | 3,517 |
| | CHAT 2042 | 2042 | 431867.885 | 4092430.186 | 23.69 | 3,517 |
| | CHAT 2043 | 2043 | 431867.885 | 4092430.186 | 23.69 | 3,517 |
| 5 | CHAT 2051 | 2051 | 431268.839 | 4092515.960 | 24.40 | 2,827 |
| | CHAT 2052 | 2052 | 431268.839 | 4092515.960 | 24.40 | 2,827 |
| 6 | CHAT 2061 | 2061 | 430700.220 | 4092642.594 | 27.54 | 2,140 |
| | CHAT 2062 | 2062 | 430700.220 | 4092642.594 | 27.54 | 2,140 |
| 7 | CHAT 2071 | 2071 | 430584.816 | 4092660.797 | 27.56 | 2,002 |
| | CHAT 2072 | 2072 | 430584.816 | 4092660.797 | 27.56 | 2,002 |
| | CHAT 2073 | 2073 | 430584.816 | 4092660.797 | 27.56 | 2,002 |
| | CHAT 2074 | 2074 | 430584.816 | 4092660.797 | 27.56 | 2,002 |
| 8 | CHAT 2081 | 2081 | 430314.608 | 4092783.234 | 30.83 | 1,644 |
| | CHAT 2082 | 2082 | 430314.608 | 4092783.234 | 30.83 | 1,644 |
| | CHAT 2083 | 2083 | 430314.608 | 4092783.234 | 30.83 | 1,644 |
| | CHAT 2084 | 2084 | 430314.608 | 4092783.234 | 30.83 | 1,644 |
| | CHAT 2085 | 2085 | 430314.608 | 4092783.234 | 30.83 | 1,644 |
| 9 | CHAT 2091 | 2091 | 430217.301 | 4092795.342 | 31 | 1,454 |
| | CHAT 2092 | 2092 | 430217.301 | 4092795.342 | 31 | 1,454 |
| | CHAT 2093 | 2093 | 430217.301 | 4092795.342 | 31 | 1,454 |
| | CHAT 2094 | 2094 | 430217.301 | 4092795.342 | 31 | 1,454 |
| 10 | CHAT 2101 | 2101 | 429774.065 | 4092433.582 | 31.38 | 820 |
| | CHAT 2102 | 2102 | 429774.065 | 4092433.582 | 31.38 | 820 |
| | CHAT 2103 | 2103 | 429774.065 | 4092433.582 | 31.38 | 820 |
| | CHAT 2104 | 2104 | 429774.065 | 4092433.582 | 31.38 | 820 |
| | CHAT 2105 | 2105 | 429774.065 | 4092433.582 | 31.38 | 820 |
| | CHAT 2106 | 2106 | 429774.065 | 4092433.582 | 31.38 | 820 |
| | CHAT 2107 | 2107 | 429774.065 | 4092433.582 | 31.38 | 820 |

# Appendix C

## Tributary Sample Site Information

| Site # | Chemex Sample # | Lab # | Easting (UTM NAD 83, Zone 15s) | Northing (UTM NAD 83, Zone 15s) | $A_d$ | Distance from Confluence with Spring River (meters) |
|---|---|---|---|---|---|---|
| 333 | CHAT 333 | 333 | 434674.14 | 4092058.157 | 5.74 | 5,890 |
| 311 | CC-SR 11A | 3111 | 433430.913 | 4092452.287 | 3.12 | 5,190 |
|  | CC-SR 11B | 3112 | 433430.913 | 4092452.287 | 3.12 | 5,190 |
|  | CC-SR 11C | 3113 | 433430.913 | 4092452.287 | 3.12 | 5,190 |
| 312 | CC-SR 12A | 3121 | 433427.065 | 4092448.746 | 0.51 | 5,190 |
|  | CC-SR 12B | 3122 | 433427.065 | 4092448.746 | 0.51 | 5,190 |
| 314 | CHAT 314 | 314 | 428125.970 | 4093845.630 | 0.86 | 3,450 |
| 321 | CHAT 321 | 321 | 430795.715 | 4092700.733 | 0.94 | 2,090 |
| 330 | CHAT 3301 | 3301 | 430242.741 | 4092753.472 | 2.90 | 1,370 |
|  | CHAT 3302 | 3302 | 430242.741 | 4092753.472 | 2.90 | 1,370 |
|  | CHAT 3303 | 3303 | 430242.741 | 4092753.472 | 2.90 | 1,370 |

# Appendix D

# In-Channel Sample Geochemical Data

| Lab # | Pb | Zn | P | Al | Ca | Fe | K | Mg | Mn | Ni | OM |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ppm | ppm | ppm | % | % | % | % | % | ppm | ppm | % LOI |
| 401 | 78 | 840 | 260 | 1.2 | 0.67 | 1.1 | 0.1 | 0.19 | 460 | 9 | -- |
| 402 | 72 | 716 | 270 | 1.22 | 0.63 | 1.1 | 0.1 | 0.18 | 470 | 9 | -- |
| 403 | 90 | 1,080 | 280 | 1.31 | 0.92 | 1.13 | 0.1 | 0.26 | 480 | 9 | -- |
| 1011 | 1,250 | 24,900 | 460 | 0.73 | 5.37 | 3.56 | 0.08 | 1.06 | 795 | 24 | 3.86 |
| 1012 | 656 | 12,600 | 550 | 1.22 | 4.73 | 1.4 | 0.15 | 1.06 | 300 | 21 | 6.26 |
| 1013 | 454 | 6,840 | 470 | 1.18 | 3.18 | 1.8 | 0.1 | 0.77 | 410 | 17 | 7.20 |
| 1031 | 954 | 7,020 | 280 | 2.4 | 1.33 | 2.14 | 0.21 | 0.29 | 3,980 | 16 | 7.66 |
| 1032 | 694 | 4,370 | 220 | 2.02 | 0.85 | 2.5 | 0.15 | 0.27 | 2,760 | 16 | 5.68 |
| 1033 | 1,295 | 8,300 | 430 | 2.24 | 1.24 | 2.07 | 0.23 | 0.3 | 5,920 | 17 | 9.15 |
| 1041 | 2,450 | 20,400 | 370 | 1.08 | 6.45 | 1.89 | 0.14 | 1.02 | 3,160 | 13 | 7.01 |
| 1042 | 1,820 | 16,500 | 490 | 1.48 | 7.1 | 2.12 | 0.16 | 0.65 | 4,550 | 16 | 7.14 |
| 1043 | 1,935 | 22,100 | 380 | 1.29 | 5.08 | 2.65 | 0.11 | 0.65 | 1,870 | 15 | 4.66 |
| 1051 | 720 | 6,270 | 430 | 1.33 | 8.49 | 2.57 | 0.13 | 1.98 | 2,210 | 20 | 5.12 |
| 1052 | 1,580 | 14,200 | 490 | 1.11 | 7.14 | 1.62 | 0.1 | 1.18 | 3,660 | 16 | 9.16 |
| 1053 | 342 | 3,370 | 310 | 0.61 | 14.2 | 1.07 | 0.09 | 4.9 | 1,335 | 12 | 4.56 |
| 404 | 1,040 | 8,560 | 480 | 0.95 | 8.93 | 1.37 | 0.08 | 2.18 | 2,780 | 14 | -- |
| 405 | 536 | 4,580 | 360 | 0.6 | 10.8 | 1.05 | 0.05 | 3.91 | 1,540 | 8 | -- |
| 406 | 772 | 6,560 | 410 | 0.77 | 10.4 | 1.23 | 0.07 | 3.16 | 2,210 | 10 | -- |
| 1061 | 1,190 | 7,810 | 710 | 1.42 | 5.51 | 2.15 | 0.13 | 0.97 | 1,130 | 17 | 8.03 |
| 1062 | 1,160 | 6,470 | 980 | 1.62 | 3.03 | 9.48 | 0.08 | 0.49 | 3,740 | 40 | 6.62 |
| 1063 | 840 | 8,410 | 810 | 1.3 | 6.79 | 1.62 | 0.12 | 1.24 | 1,305 | 17 | 11.28 |
| 1064 | 1,500 | 7,310 | 850 | 1.28 | 3.6 | 5.27 | 0.09 | 0.58 | 1,340 | 25 | 8.86 |

| OM |
|---|
| % LOI |
| 3.52 |
| 3.84 |
| 3.12 |
| 5.15 |
| 6.37 |
| 3.80 |
| 2.68 |
| 4.10 |
| 3.70 |
| 4.75 |
| 9.85 |
| 4.54 |
| 4.54 |
| 9.24 |
| 9.48 |
| 6.94 |
| -- |
| -- |
| -- |

| Lab # | Pb | Zn | P | Al | Ca | Fe | K | Mg | Mn | Ni | OM |
|---|---|---|---|---|---|---|---|---|---|---|---|
|  | ppm | ppm | ppm | % | % | % | % | % | ppm | ppm | % LOI |
| 119 | 1,365 | 7,030 | 1,370 | 1.62 | 0.81 | 1.97 | 0.17 | 0.21 | 870 | 15 | 4.94 |
| 1101 | 524 | 3,530 | 1,630 | 1.06 | 1.83 | 3.49 | 0.07 | 0.34 | 940 | 18 | 2.32 |
| 1102 | 786 | 5,230 | 2,460 | 1.55 | 2.44 | 2.18 | 0.17 | 0.43 | 870 | 17 | 9.83 |
| 1103 | 120 | 360 | 1,180 | 1.67 | 0.29 | 2.44 | 0.18 | 0.21 | 1,205 | 13 | 2.84 |
| 123 | 1,065 | 6,910 | 3,080 | 1.27 | 2 | 3.17 | 0.11 | 0.34 | 1,210 | 20 | 6.50 |
| 1181 | 822 | 5,560 | 2,350 | 1.29 | 1.85 | 2.21 | 0.14 | 0.33 | 1,415 | 17 | 8.81 |
| 1182 | 788 | 5,220 | 2,380 | 1.31 | 2.23 | 1.95 | 0.14 | 0.35 | 1,295 | 15 | 10.38 |
| 1183 | 774 | 5,360 | 2,230 | 1.31 | 2.12 | 1.91 | 0.14 | 0.35 | 1,275 | 15 | 10.48 |
| 117 | 206 | 916 | 1,510 | 1.98 | 0.5 | 3.63 | 0.19 | 0.25 | 1,460 | 19 | 3.67 |
| 1241 | 246 | 1,035 | 1,430 | 1.51 | 0.54 | 3.6 | 0.15 | 0.17 | 1,985 | 18 | 3.68 |
| 1242 | 384 | 2,440 | 1,900 | 1.57 | 1.55 | 2.8 | 0.18 | 0.24 | 1,695 | 16 | 8.20 |
| 1243 | 312 | 1,820 | 1,680 | 1.49 | 1.06 | 2.75 | 0.17 | 0.2 | 1,685 | 16 | 6.79 |
| 1161 | 550 | 2,980 | 2,090 | 1.45 | 1.3 | 3.1 | 0.15 | 0.29 | 2,250 | 24 | 10.68 |
| 1162 | 324 | 2,470 | 1,850 | 1.46 | 1.27 | 2.33 | 0.17 | 0.24 | 1,335 | 15 | 12.02 |
| 1163 | 246 | 1,780 | 1,300 | 1.63 | 1.2 | 1.88 | 0.17 | 0.21 | 1,230 | 15 | 9.91 |
| 115 | 300 | 1,570 | 1,770 | 1.11 | 0.66 | 3.71 | 0.09 | 0.14 | 1,545 | 20 | 5.53 |
| 125 | 310 | 1,590 | 2,050 | 1.23 | 0.81 | 3.82 | 0.1 | 0.16 | 1,915 | 24 | 7.91 |
| 1071 | 410 | 2,480 | 1,530 | 1.48 | 1.26 | 2.61 | 0.13 | 0.24 | 1,220 | 18 | 6.62 |
| 1072 | 344 | 1,870 | 1,490 | 1.35 | 1.22 | 3.4 | 0.11 | 0.2 | 1,140 | 18 | 6.42 |
| 1073 | 348 | 2,020 | 1,550 | 1.28 | 1.17 | 2.58 | 0.12 | 0.22 | 1,065 | 16 | 7.18 |
| 407 | 402 | 1,950 | 1,650 | 1.14 | 1.16 | 5.18 | 0.06 | 0.19 | 2,230 | 28 | -- |
| 408 | 358 | 1,630 | 1,630 | 1.19 | 1.16 | 4.79 | 0.07 | 0.19 | 1,860 | 26 | – |
| 409 | 348 | 1,355 | 1,640 | 1.06 | 0.98 | 5.55 | 0.04 | 0.14 | 1,860 | 26 | -- |

| Lab # | Pb | Zn | P | Al | Ca | Fe | K | Mg | Mn | Ni |
|---|---|---|---|---|---|---|---|---|---|---|
|  | ppm | ppm | ppm | % | % | % | % | % | ppm | ppm |
| 132 | 384 | 1,305 | 2,080 | 1.21 | 0.7 | 5.65 | 0.08 | 0.13 | 1,920 | 31 |
| 122 | 60 | 286 | 760 | 1.62 | 0.26 | 1.98 | 0.17 | 0.16 | 1,705 | 13 |
| 134 | 256 | 994 | 1,300 | 1.22 | 0.45 | 3.8 | 0.1 | 0.11 | 2,150 | 26 |
| 120 | 160 | 1,095 | 950 | 1.58 | 0.41 | 2.11 | 0.17 | 0.17 | 1,455 | 18 |
| 1311 | 180 | 1,140 | 1,180 | 1.79 | 0.55 | 2.61 | 0.18 | 0.2 | 1,595 | 19 |
| 1312 | 194 | 784 | 1,200 | 1.47 | 0.3 | 3.89 | 0.12 | 0.11 | 2,280 | 27 |
| 1313 | 396 | 730 | 1,590 | 1.19 | 0.21 | 7.56 | 0.05 | 0.06 | 4,310 | 56 |
| 128 | 194 | 538 | 1,010 | 1.64 | 0.25 | 5.56 | 0.13 | 0.11 | 2,960 | 43 |
| 1291 | 246 | 786 | 1,270 | 1.3 | 0.26 | 6.61 | 0.08 | 0.07 | 3,660 | 52 |
| 1292 | 192 | 454 | 1,110 | 3.02 | 0.38 | 6.11 | 0.24 | 0.24 | 3,820 | 77 |
| 1293 | 198 | 1,100 | 1,320 | 1.65 | 0.81 | 4.04 | 0.14 | 0.17 | 2,840 | 37 |
| 126 | 214 | 1,270 | 1,080 | 1.54 | 0.36 | 4.9 | 0.12 | 0.11 | 3,040 | 50 |
| 127 | 148 | 940 | 1,050 | 1.64 | 0.38 | 3.5 | 0.16 | 0.12 | 2,350 | 38 |
| 1081 | 148 | 1,025 | 1,140 | 2.14 | 0.92 | 2.42 | 0.2 | 0.19 | 1,520 | 25 |
| 1082 | 156 | 1,230 | 1,200 | 2.03 | 0.81 | 2.08 | 0.17 | 0.22 | 1,380 | 19 |
| 1083 | 172 | 1,230 | 970 | 2.03 | 0.83 | 2 | 0.22 | 0.24 | 1,270 | 22 |
| 410 | 170 | 1,430 | 1,350 | 1.67 | 1.58 | 2.03 | 0.16 | 0.22 | 1,740 | 17 |
| 411 | 166 | 1,380 | 1,240 | 1.54 | 1.32 | 1.96 | 0.14 | 0.21 | 1,735 | 17 |
| 412 | 174 | 1,480 | 1,330 | 1.94 | 1.26 | 2.12 | 0.18 | 0.24 | 1,730 | 18 |

# Appendix E

# Floodplain Samples Geochemical Results

| Study Reach | Lab | Depth | Fine-Grain Sediment | Pb | Zn | P | Al | Ca | Cu | Fe | K | Mg | Mn | Ni | OM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | # | cm | % | ppm | ppm | ppm | % | % | ppm | % | % | % | ppm | ppm | % LOI |
| 1 | 2011 | 0-10 | 100 | 460 | 3,490 | 550 | 1.27 | 0.55 | 25 | 1.63 | 0.16 | 0.15 | 1,000 | 14 | 6.18 |
| | 2012 | 10-108 | 100 | 662 | 5,570 | 470 | 1.53 | 0.38 | 24 | 1.74 | 0.15 | 0.13 | 735 | 17 | 5.93 |
| 2 | 2021 | 0-10 | 100 | 594 | 4,730 | 790 | 1.45 | 0.59 | 39 | 1.73 | 0.16 | 0.17 | 1050 | 15 | 7.16 |
| | 2022 | 10-90 | 100 | 598 | 4,690 | 460 | 1.66 | 0.3 | 23 | 1.75 | 0.17 | 0.13 | 865 | 15 | 4.33 |
| | 2023 | 90-139 | 99 | 72 | 264 | 150 | 1.11 | 0.12 | 9 | 1.22 | 0.12 | 0.1 | 240 | 8 | 1.88 |
| 3 | 2031 | 0-10 | 100 | 394 | 3,120 | 620 | 1.49 | 0.39 | 20 | 1.85 | 0.21 | 0.12 | 1120 | 14 | 7.78 |
| | 2032 | 10-45 | 100 | 446 | 3,600 | 590 | 1.45 | 0.33 | 20 | 1.93 | 0.19 | 0.12 | 1160 | 15 | 5.52 |
| | 2033 | 45-100 | 90 | 82 | 284 | 260 | 1.79 | 0.19 | 10 | 1.87 | 0.16 | 0.12 | 475 | 13 | 3.46 |
| | 2034 | 100-195 | 50 | 146 | 802 | 370 | 1.86 | 0.28 | 13 | 2.6 | 0.2 | 0.15 | 1050 | 15 | 3.90 |
| 4 | 2041 | 0-10 | 100 | 622 | 4,150 | 1,380 | 3.44 | 0.84 | 43 | 4.54 | 0.36 | 0.28 | 2590 | 34 | 6.09 |
| | 2042 | 10-50 | 100 | 400 | 2,420 | 450 | 1.57 | 0.34 | 18 | 1.73 | 0.16 | 0.12 | 1215 | 14 | 5.07 |
| | 2043 | 50-180 | 45 | 208 | 448 | 560 | 1.88 | 0.3 | 17 | 3.99 | 0.16 | 0.13 | 1365 | 22 | 5.15 |
| 5 | 2051 | 0-20 | 100 | 112 | 578 | 380 | 1.59 | 0.28 | 13 | 1.64 | 0.18 | 0.12 | 1010 | 13 | 4.72 |
| | 2052 | 20-165 | 75 | 54 | 142 | 230 | 1.82 | 0.14 | 11 | 2.03 | 0.17 | 0.14 | 715 | 15 | 3.28 |
| 6 | 2061 | 0-40 | 100 | 314 | 1,890 | 420 | 1.5 | 0.28 | 16 | 1.51 | 0.17 | 0.12 | 1095 | 13 | 4.28 |
| | 2062 | 40-200 | 75 | 222 | 648 | 690 | 1.84 | 0.23 | 14 | 3.98 | 0.16 | 0.12 | 2240 | 24 | 4.04 |

| Study Reach | Lab | Depth | Fine-Grain Sediment | Pb | Zn | P | Al | Ca | Cu | Fe | K | Mg | Mn | Ni | OM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | # | cm | % | ppm | ppm | ppm | % | % | ppm | % | % | % | ppm | ppm | % LOI |
| 7 | 2071 | 0-25 | 50 | 64 | 126 | 320 | 1.96 | 0.11 | 12 | 2.53 | 0.2 | 0.13 | 1,095 | 15 | 3.26 |
|  | 2072 | 25-70 | 85 | 28 | 62 | 250 | 1.72 | 0.04 | 9 | 1.76 | 0.17 | 0.12 | 675 | 10 | 2.52 |
|  | 2073 | 70-160 | 90 | 30 | 54 | 160 | 1.46 | 0.1 | 9 | 1.84 | 0.16 | 0.14 | 1,285 | 12 | 2.16 |
|  | 2074 | 160-230 | 40 | 116 | 286 | 550 | 1.71 | 0.18 | 15 | 3.54 | 0.18 | 0.15 | 3,290 | 24 | 3.02 |
| 8 | 2081 | 0-10 | 100 | 204 | 1,135 | 730 | 1.46 | 0.28 | 15 | 2.64 | 0.18 | 0.12 | 1,425 | 19 | 4.96 |
|  | 2082 | 10-85 | 100 | 226 | 1,770 | 400 | 1.42 | 0.22 | 15 | 1.59 | 0.16 | 0.11 | 1,225 | 13 | 3.80 |
|  | 2083 | 85-170 | 50 | 80 | 250 | 410 | 1.87 | 0.25 | 13 | 2.43 | 0.18 | 0.14 | 1,130 | 16 | 4.36 |
|  | 2084 | 170-210 | 95 | 32 | 134 | 160 | 2 | 0.21 | 11 | 2.06 | 0.2 | 0.23 | 1,095 | 14 | 2.90 |
|  | 2085 | 210-260 | 35 | 128 | 370 | 450 | 1.8 | 0.21 | 13 | 3.95 | 0.18 | 0.16 | 3,100 | 26 | 3.70 |
| 9 | 2091 | 0-10 | 100 | 140 | 946 | 320 | 1.2 | 0.18 | 11 | 1.33 | 0.14 | 0.1 | 1,070 | 11 | 4 |
|  | 2092 | 10-40 | 100 | 42 | 118 | 280 | 1.7 | 0.13 | 10 | 1.87 | 0.17 | 0.13 | 1,315 | 14 | 3.54 |
|  | 2093 | 40-120 | 95 | 34 | 90 | 190 | 1.87 | 0.13 | 17 | 1.86 | 0.22 | 0.15 | 1,285 | 15 | 2.56 |
|  | 2094 | 120-240 | 35 | 88 | 262 | 340 | 1.53 | 0.16 | 13 | 2.54 | 0.16 | 0.15 | 1,850 | 29 | 3.02 |

| Study Reach | Lab | Depth | Fine-Grain Sediment | Pb | Zn | P | Al | Ca | Cu | Fe | K | Mg | Mn | Ni | OM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | # | cm | % | ppm | ppm | ppm | % | % | ppm | % | % | % | ppm | ppm | % LOI |
| 10 | 2101 | 0-10 | 100 | 146 | 1,160 | 400 | 1.04 | 0.17 | 12 | 1.39 | 0.13 | 0.08 | 1,205 | 12 | 4 |
|  | 2102 | 10-50 | 95 | 88 | 394 | 510 | 1.52 | 0.26 | 12 | 2.16 | 0.15 | 0.11 | 1,615 | 17 | 4.38 |
|  | 2103 | 50-110 | 80 | 62 | 192 | 480 | 1.55 | 0.25 | 12 | 1.98 | 0.16 | 0.11 | 1,525 | 16 | 4.56 |
|  | 2104 | 110-150 | 60 | 66 | 156 | 360 | 1.49 | 0.15 | 12 | 2.87 | 0.13 | 0.09 | 1,375 | 19 | 2.82 |
|  | 2105 | 150-180 | 30 | 70 | 160 | 390 | 1.77 | 0.14 | 14 | 3.47 | 0.13 | 0.1 | 1,365 | 26 | 2.62 |
|  | 2106 | 180-240 | 10 | 126 | 598 | 550 | 2.23 | 0.22 | 21 | 4.31 | 0.18 | 0.14 | 1,810 | 41 | 3.91 |
|  | 2107 | 240-330 | 5 | 76 | 222 | 450 | 4.21 | 0.4 | 24 | 5.23 | 0.27 | 0.17 | 1,610 | 61 | 7.42 |

# Appendix F

## Tributary Sample Geochemical Data

| Lab # | Pb | Zn | P | Al | Ca | Cu | Fe | K | Mg | Mn | Ni | OM |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
|  | ppm | ppm | ppm | % | % | ppm | % | % | % | ppm | ppm | % LOI |
| 333 | 208 | 1,260 | 400 | 1.23 | 0.73 | 12 | 2.5 | 0.14 | 0.15 | 1,740 | 16 | 3.92 |
| 3111 | 62 | 500 | 350 | 0.98 | 0.26 | 11 | 1.22 | 0.13 | 0.1 | 685 | 9 | 5.88 |
| 3112 | 62 | 468 | 560 | 1.2 | 0.3 | 17 | 1.63 | 0.16 | 0.11 | 795 | 13 | 6.07 |
| 3113 | 64 | 276 | 340 | 1.78 | 0.25 | 11 | 2.2 | 0.22 | 0.13 | 1,245 | 13 | 3.96 |
| 3121 | 28 | 130 | 230 | 1.84 | 0.27 | 11 | 1.92 | 0.24 | 0.18 | 735 | 11 | 2.76 |
| 3122 | 50 | 298 | 300 | 2.11 | 0.32 | 8 | 2.5 | 0.23 | 0.2 | 940 | 14 | 3.38 |
| 314 | 232 | 844 | 930 | 1.37 | 0.48 | 15 | 4.56 | 0.16 | 0.09 | 2,610 | 23 | 8.69 |
| 321 | 78 | 540 | 780 | 1.01 | 0.4 | 13 | 1.23 | 0.14 | 0.08 | 1,070 | 10 | 11.28 |
| 3301 | 42 | 120 | 330 | 1.87 | 0.24 | 11 | 2.17 | 0.21 | 0.18 | 930 | 17 | 5.56 |
| 3302 | 32 | 116 | 360 | 1.78 | 0.23 | 11 | 1.97 | 0.21 | 0.19 | 940 | 15 | 3.94 |
| 3303 | 84 | 162 | 480 | 1.48 | 0.28 | 12 | 2.98 | 0.18 | 0.13 | 2,730 | 23 | 5.03 |

# Appendix G

# Floodplain Lead AEF

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|
| **Study Reach #** | **$A_d$ (km$^2$)** | **Distance from Confluence (meters)** | **Sample #** | **Depth (cm)** | **Fine-Grain Sediment (%)** | **Al (%)** | **Pb (ppm)** | **SamplePb/ Sample Al (8)/(7)** | **Pb AEF (9)/13** |
| **1** | 16.1 | 5,502 | Chat 2011 | 0-10 | 100 | 1.27 | 460 | 362 | 28 |
| | | | Chat 2012 | 10-108 | 100 | 1.53 | 662 | 433 | 33 |
| **2** | 16.47 | 4,985 | Chat 2021 | 0-10 | 100 | 1.45 | 594 | 410 | 32 |
| | | | Chat 2022 | 10-90 | 100 | 1.66 | 598 | 360 | 28 |
| | | | Chat 2023 | 90-139 | 95 | 1.11 | 72 | 65 | 5 |
| **3** | 22.72 | 4,075 | Chat 2031 | 0-10 | 100 | 1.49 | 394 | 264 | 20 |
| | | | Chat 2032 | 10-45 | 100 | 1.45 | 446 | 308 | 24 |
| | | | Chat 2033 | 45-100 | 90 | 1.79 | 82 | 46 | 4 |
| | | | Chat 2034 | 100-195 | 50 | 1.86 | 146 | 78 | 6 |
| **4** | 23.69 | 3,517 | Chat 2041 | 0-10 | 100 | 3.44 | 622 | 181 | 14 |
| | | | Chat 2042 | 10-50 | 100 | 1.57 | 400 | 255 | 20 |
| | | | Chat 2043 | 50-180 | 45 | 1.88 | 208 | 111 | 9 |
| **5** | 24.00 | 2,827 | Chat 2051 | 0-20 | 100 | 1.59 | 112 | 70 | 5 |
| | | | Chat 2052 | 20-165 | 75 | 1.82 | 54 | 30 | 2 |
| **6** | 27.54 | 2,140 | Chat 2061 | 0-40 | 100 | 1.5 | 314 | 209 | 16 |
| | | | Chat 2062 | 40-200 | 75 | 1.84 | 222 | 121 | 9 |
| **7** | 27.56 | 2,002 | Chat 2071 | 0-25 | 50 | 1.96 | 64 | 33 | 3 |
| | | | Chat 2072 | 25-70 | 85 | 1.72 | 28 | 16 | 1 |
| | | | Chat 2073 | 70-160 | 90 | 1.46 | 30 | 21 | 2 |
| | | | Chat 2074 | 160-230 | 40 | 1.71 | 116 | 68 | 5 |
| **8** | 30.83 | 1,644 | Chat 2081 | 0-10 | 100 | 1.46 | 204 | 140 | 11 |
| | | | Chat 2082 | 10-85 | 100 | 1.42 | 226 | 159 | 12 |
| | | | Chat 2083 | 85-170 | 50 | 1.87 | 80 | 43 | 3 |
| | | | Chat 2084 | 170-210 | 95 | 2 | 32 | 16 | 1 |
| | | | Chat 2085 | 210-260 | 35 | 1.8 | 128 | 71 | 5 |
| **9** | 30.83 | 1,454 | Chat 2091 | 0-10 | 100 | 1.2 | 140 | 117 | 9 |
| | | | Chat 2092 | 10-40 | 100 | 1.7 | 42 | 25 | 2 |
| | | | Chat 2093 | 40-120 | 95 | 1.87 | 34 | 18 | 1 |
| | | | Chat 2094 | 120-240 | 35 | 1.53 | 88 | 58 | 4 |
| **10** | 31.38 | 820 | Chat 2101 | 0-10 | 100 | 1.04 | 146 | 140 | 11 |
| | | | Chat 2102 | 10-50 | 95 | 1.52 | 88 | 58 | 4 |
| | | | Chat 2103 | 50-110 | 80 | 1.55 | 62 | 40 | 3 |
| | | | Chat 2104 | 110-150 | 60 | 1.49 | 66 | 44 | 3 |
| | | | Chat 2105 | 150-180 | 30 | 1.77 | 70 | 40 | 3 |
| | | | Chat 2106 | 180-240 | 10 | 2.23 | 126 | 57 | 4 |
| | | | Chat 2107 | 240-330 | 5 | 4.21 | 76 | 18 | 1 |

# Appendix H

# Floodplain Zinc AEF

| (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
|---|---|---|---|---|---|---|---|---|---|
| **Study Reach #** | **$A_d$ ($km^2$)** | **Distance from Confluence (meters)** | **Sample #** | **Depth (cm)** | **Fine-Grain Sediment (%)** | **Al (%)** | **Zn (ppm)** | **SampleZn/ Sample Al (8)/(7)** | **Zn AEF (9)/55** |
| **1** | 16.1 | 5,502 | Chat 2011 | 0-10 | 100 | 1.27 | 3,490 | 2,748 | 50 |
| | | | Chat 2012 | 10-108 | 100 | 1.53 | 5,570 | 3,641 | 66 |
| **2** | 16.47 | 4,985 | Chat 2021 | 0-10 | 100 | 1.45 | 4,730 | 3,262 | 59 |
| | | | Chat 2022 | 10-90 | 100 | 1.66 | 4,690 | 2,825 | 51 |
| | | | Chat 2023 | 90-139 | 95 | 1.11 | 264 | 238 | 4 |
| **3** | 22.72 | 4,075 | Chat 2031 | 0-10 | 100 | 1.49 | 3,120 | 2,094 | 38 |
| | | | Chat 2032 | 10-45 | 100 | 1.45 | 3,600 | 2,483 | 45 |
| | | | Chat 2033 | 45-100 | 90 | 1.79 | 284 | 159 | 3 |
| | | | Chat 2034 | 100-195 | 50 | 1.86 | 802 | 431 | 8 |
| **4** | 23.69 | 3,517 | Chat 2041 | 0-10 | 100 | 3.44 | 4,150 | 1,206 | 22 |
| | | | Chat 2042 | 10-50 | 100 | 1.57 | 2,420 | 1,541 | 28 |
| | | | Chat 2043 | 50-180 | 45 | 1.88 | 448 | 238 | 4 |
| **5** | 24.00 | 2,827 | Chat 2051 | 0-20 | 100 | 1.59 | 578 | 364 | 7 |
| | | | Chat 2052 | 20-165 | 75 | 1.82 | 142 | 78 | 1 |
| **6** | 27.54 | 2,140 | Chat 2061 | 0-40 | 100 | 1.5 | 1,890 | 1,260 | 23 |
| | | | Chat 2062 | 40-200 | 75 | 1.84 | 648 | 352 | 6 |
| **7** | 27.56 | 2,002 | Chat 2071 | 0-25 | 50 | 1.96 | 126 | 64 | 1 |
| | | | Chat 2072 | 25-70 | 85 | 1.72 | 62 | 36 | 1 |
| | | | Chat 2073 | 70-160 | 90 | 1.46 | 54 | 37 | 1 |
| | | | Chat 2074 | 160-230 | 40 | 1.71 | 286 | 167 | 3 |
| **8** | 30.83 | 1,644 | Chat 2081 | 0-10 | 100 | 1.46 | 1,135 | 777 | 14 |
| | | | Chat 2082 | 10-85 | 100 | 1.42 | 1,770 | 1,246 | 23 |
| | | | Chat 2083 | 85-170 | 50 | 1.87 | 250 | 134 | 2 |
| | | | Chat 2084 | 170-210 | 95 | 2 | 134 | 67 | 1 |
| | | | Chat 2085 | 210-260 | 35 | 1.8 | 370 | 206 | 4 |
| **9** | 30.83 | 1,454 | Chat 2091 | 0-10 | 100 | 1.2 | 946 | 788 | 14 |
| | | | Chat 2092 | 10-40 | 100 | 1.7 | 118 | 69 | 1 |
| | | | Chat 2093 | 40-120 | 95 | 1.87 | 90 | 48 | 1 |
| | | | Chat 2094 | 120-240 | 35 | 1.53 | 262 | 171 | 3 |
| **10** | 31.38 | 820 | Chat 2101 | 0-10 | 100 | 1.04 | 1,160 | 1,115 | 20 |
| | | | Chat 2102 | 10-50 | 95 | 1.52 | 394 | 259 | 5 |
| | | | Chat 2103 | 50-110 | 80 | 1.55 | 192 | 124 | 2 |
| | | | Chat 2104 | 110-150 | 60 | 1.49 | 156 | 105 | 2 |
| | | | Chat 2105 | 150-180 | 30 | 1.77 | 160 | 90 | 2 |
| | | | Chat 2106 | 180-240 | 10 | 2.23 | 598 | 268 | 5 |
| | | | Chat 2107 | 240-330 | 5 | 4.21 | 222 | 53 | 1 |

# Appendix I

## Cross Section Data

| Study Reach # | Cross-Section Type | Bankfull Width (meters) | Maximum Depth (meters) | Mean Depth (meters) | Cross-Section Area (meters$^2$) |
|---|---|---|---|---|---|
| 1 | Bend | 8.20 | 1.10 | 0.71 | 5.84 |
|  | Straight | 8.75 | 1.30 | 1.06 | 9.25 |
| 2 | Bend | 9.30 | 1.60 | 1.14 | 10.59 |
|  | Straight | 7.30 | 1.75 | 1.60 | 11.70 |
| 3 | Bend | 10.75 | 2.05 | 1.51 | 16.28 |
|  | Straight | 2.80 | 1.75 | 1.26 | 3.54 |
| 4 | Bend | 11.3 | 1.85 | 1.35 | 15.23 |
|  | Straight | 9.30 | 1.45 | 1.18 | 10.95 |
| 5 | Bend | 6.50 | 1.30 | 0.78 | 5.05 |
|  | Straight | 10.50 | 1.38 | 1.03 | 10.80 |
| 6 | Bend | 11.40 | 1.95 | 1.39 | 15.88 |
|  | Straight | 12.00 | 1.93 | 1.31 | 15.72 |
| 7 | Bend | 14.90 | 1.90 | 1.15 | 17.15 |
|  | Straight | 13.75 | 1.89 | 1.19 | 16.37 |
| 8 | Bend | 9.20 | 1.40 | 0.94 | 8.65 |
|  | Straight | 10.75 | 2.49 | 1.82 | 19.59 |
| 9 | Bend | 17.45 | 2.10 | 1.16 | 20.31 |
|  | Straight | 12.80 | 2.49 | 1.93 | 24.76 |
| 10 | Bend | 12.60 | 4.20 | 2.30 | 28.98 |
|  | Straight | 11.50 | 2.80 | 2.02 | 23.18 |

# Appendix J

## Floodplain Erosion Budget

| Segment | Distance From Confluence (m) | Segment Type | Segment Category | Migration Rate (m) | Migration Rate For Error-Filtered Data (m) |
|---|---|---|---|---|---|
| *1 | 10 | Straight | Disturbed | 1.80 | 0.95 |
| *2 | 30 | Straight | Disturbed | 1.61 | 0.76 |
| *3 | 50 | Straight | Disturbed | 1.71 | 0.86 |
| *4 | 70 | Straight | Disturbed | 1.32 | 0.47 |
| *5 | 90 | Straight | Typical | 0.99 | 0.14 |
| *6 | 110 | Straight | Typical | 0.94 | 0.09 |
| *7 | 130 | Straight | Typical | 0.88 | 0.03 |
| *8 | 150 | Bend | Disturbed | 1.45 | 0.60 |
| *9 | 170 | Straight | Disturbed | 1.23 | 0.38 |
| *10 | 190 | Straight | Disturbed | 1.77 | 0.92 |
| *11 | 210 | Straight | Disturbed | 1.27 | 0.42 |
| *12 | 230 | Straight | Disturbed | 1.26 | 0.41 |
| *13 | 250 | Straight | Typical | 1.11 | 0.26 |
| *14 | 270 | Straight | Typical | 0.00 | 0.00 |
| *15 | 290 | Bend | Channelized | 0.19 | 0.00 |
| *16 | 310 | Straight | Typical | 0.09 | 0.00 |
| *17 | 330 | Straight | Typical | 0.51 | 0.00 |
| *18 | 350 | Straight | Channelized | 0.19 | 0.00 |
| *19 | 370 | Straight | Channelized | 0.42 | 0.00 |
| *20 | 390 | Bend | Channelized | 0.20 | 0.00 |
| *21 | 410 | Straight | Channelized | 0.58 | 0.00 |
| *22 | 430 | Straight | Channelized | 0.25 | 0.00 |
| *23 | 450 | Straight | Channelized | 0.05 | 0.00 |
| *24 | 470 | Bend | Channelized | 0.06 | 0.00 |
| *25 | 490 | Straight | Channelized | 0.40 | 0.00 |
| *26 | 510 | Straight | Channelized | 0.57 | 0.00 |
| *27 | 530 | Straight | Channelized | 0.26 | 0.00 |
| *28 | 550 | Straight | Typical | 0.31 | 0.00 |
| *29 | 570 | Bend | Typical | 0.38 | 0.00 |
| *30 | 590 | Bend | Typical | 0.81 | 0.00 |
| *31 | 610 | Straight | Channelized | 0.60 | 0.00 |
| *32 | 630 | Bend | Channelized | 0.83 | 0.00 |
| *33 | 650 | Straight | Channelized | 0.38 | 0.00 |
| *34 | 670 | Bend | Channelized | 0.12 | 0.00 |
| *35 | 690 | Straight | Channelized | 0.17 | 0.00 |
| *36 | 710 | Straight | Typical | 0.22 | 0.00 |
| *37 | 730 | Straight | Channelized | 0.13 | 0.00 |
| *38 | 750 | Straight | Channelized | 0.29 | 0.00 |
| *39 | 770 | Straight | Channelized | 0.24 | 0.00 |
| *40 | 790 | Bend | Channelized | 0.22 | 0.00 |
| *41 | 810 | Bend | Typical | 0.39 | 0.00 |
| *42 | 830 | Bend | Typical | 0.15 | 0.00 |
| *42 S | 850 | Bend | Typical | 0.21 | 0.00 |

| Segment | Distance From Confluence (m) | Segment Type | Segment Category | Migration Rate (m) | Migration Rate For Error-Filtered Data (m) |
|---|---|---|---|---|---|
| *43 | 870 | Bend | Typical | 0.09 | 0.00 |
| *43S | 890 | Bend | Typical | 0.15 | 0.00 |
| *44 | 910 | Bend | Typical | 0.43 | 0.00 |
| 45 | 930 | Straight | Typical | 0.41 | 0.11 |
| 46 | 950 | Straight | Typical | 0.53 | 0.23 |
| 47 | 970 | Straight | Typical | 0.71 | 0.41 |
| 48 | 990 | Straight | Typical | 0.52 | 0.22 |
| 49 | 1010 | Bend | Typical | 0.60 | 0.30 |
| 50 | 1030 | Bend | Channelized | 0.87 | 0.57 |
| 51 | 1050 | Straight | Channelized | 0.61 | 0.31 |
| 52 | 1070 | Straight | Typical | 0.19 | 0.00 |
| 53 | 1090 | Straight | Typical | 0.29 | 0.00 |
| 54 | 1110 | Straight | Typical | 0.59 | 0.29 |
| 55 | 1130 | Bend | Typical | 0.09 | 0.00 |
| 56 | 1150 | Straight | Typical | 0.68 | 0.38 |
| 57 | 1170 | Straight | Typical | 0.49 | 0.19 |
| 58 | 1190 | Straight | Typical | 0.16 | 0.00 |
| 322 | 1210 | Bend | Typical | 0.32 | 0.02 |
| 59 | 1230 | Straight | Disturbed | 1.23 | 0.93 |
| 60 | 1250 | Bend | Typical | 1.22 | 0.92 |
| 61 | 1270 | Straight | Typical | 1.21 | 0.91 |
| 321 | 1290 | Straight | Typical | 1.11 | 0.81 |
| 62 | 1310 | Straight | Typical | 0.87 | 0.57 |
| 63 | 1330 | Straight | Typical | 0.85 | 0.55 |
| 64 | 1350 | Straight | Disturbed | 1.37 | 1.07 |
| 65 | 1370 | Straight | Disturbed | 1.72 | 1.42 |
| 66 | 1390 | Bend | Disturbed | 1.30 | 1.00 |
| 67 | 1410 | Straight | Typical | 1.04 | 0.74 |
| 68 | 1430 | Straight | Typical | 0.86 | 0.56 |
| 69 | 1450 | Straight | Typical | 0.57 | 0.27 |
| 320 | 1470 | Bend | Typical | 0.35 | 0.05 |
| 70 | 1490 | Bend | Typical | 0.04 | 0.00 |
| 71 | 1510 | Bend | Typical | 0.12 | 0.00 |
| *319 | 1530 | Straight | Typical | 0.19 | 0.00 |
| *72 | 1550 | Bend | Typical | 0.21 | 0.00 |
| 73 | 1570 | Bend | Typical | 0.02 | 0.00 |
| 74 | 1590 | Straight | Typical | 0.21 | 0.00 |
| 75 | 1610 | Bend | Typical | 0.53 | 0.23 |
| 76 | 1630 | Bend | Typical | 0.44 | 0.14 |
| 77 | 1650 | Straight | Typical | 0.06 | 0.00 |
| 78 | 1670 | Straight | Typical | 0.23 | 0.00 |
| 79 | 1690 | Straight | Typical | 0.27 | 0.00 |
| 80 | 1710 | Straight | Typical | 0.42 | 0.12 |
| 81 | 1730 | Straight | Typical | 0.59 | 0.29 |

| Segment | Distance From Confluence (m) | Segment Type | Segment Category | Migration Rate (m) | Migration Rate For Error-Filtered Data (m) |
|---|---|---|---|---|---|
| 82 | 1750 | Bend | Typical | 0.27 | 0.00 |
| 83 | 1770 | Straight | Typical | 0.77 | 0.47 |
| 84 | 1790 | Straight | Typical | 0.74 | 0.44 |
| 85 | 1810 | Bend | Typical | 0.53 | 0.23 |
| 86 | 1830 | Bend | Typical | 0.86 | 0.56 |
| 87 | 1850 | Bend | Typical | 0.61 | 0.31 |
| 88 | 1870 | Bend | Typical | 0.08 | 0.00 |
| 89 | 1890 | Straight | Typical | 0.21 | 0.00 |
| 90 | 1910 | Straight | Typical | 0.26 | 0.00 |
| 91 | 1930 | Bend | Typical | 0.19 | 0.00 |
| 92 | 1950 | Bend | Typical | 0.12 | 0.00 |
| 93 | 1970 | Bend | Typical | 0.05 | 0.00 |
| 94 | 1990 | Bend | Typical | 0.01 | 0.00 |
| 95 | 2010 | Straight | Typical | 0.19 | 0.00 |
| 96 | 2030 | Bend | Typical | 0.10 | 0.00 |
| 97 | 2050 | Straight | Typical | 0.23 | 0.00 |
| 98 | 2070 | Straight | Typical | 0.09 | 0.00 |
| 99 | 2090 | Bend | Typical | 0.06 | 0.00 |
| 100 | 2110 | Straight | Typical | 0.01 | 0.00 |
| 101 | 2130 | Bend | Typical | 0.10 | 0.00 |
| 102 | 2150 | Straight | Typical | 0.23 | 0.00 |
| 103 | 2170 | Bend | Typical | 0.08 | 0.00 |
| 104 | 2190 | Straight | Typical | 0.02 | 0.00 |
| 105 | 2210 | Straight | Typical | 0.23 | 0.00 |
| 106 | 2230 | Straight | Typical | 0.22 | 0.00 |
| 107 | 2250 | Bend | Typical | 0.01 | 0.00 |
| 108 | 2270 | Straight | Typical | 0.04 | 0.00 |
| 109 | 2290 | Bend | Typical | 0.01 | 0.00 |
| 110 | 2310 | Straight | Typical | 0.00 | 0.00 |
| 111 | 2330 | Bend | Typical | 0.09 | 0.00 |
| 112 | 2350 | Straight | Typical | 0.38 | 0.00 |
| 113 | 2370 | Straight | Typical | 0.04 | 0.08 |
| 114 | 2390 | Straight | Typical | 0.04 | 0.00 |
| 115 | 2410 | Straight | Typical | 0.07 | 0.00 |
| 116 | 2430 | Straight | Typical | 0.01 | 0.00 |
| 117 | 2450 | Bend | Typical | 0.09 | 0.00 |
| 118 | 2470 | Bend | Typical | 0.01 | 0.00 |
| 119 | 2490 | Straight | Typical | 0.61 | 0.00 |
| 120 | 2510 | Bend | Typical | 0.57 | 0.31 |
| 121 | 2530 | Bend | Typical | 0.28 | 0.27 |
| 122 | 2550 | Straight | Typical | 0.05 | 0.00 |
| 123 | 2570 | Straight | Typical | 0.12 | 0.00 |

| Segment | Distance From Confluence (m) | Segment Type | Segment Category | Migration Rate (m) | Migration Rate For Error-Filtered Data (m) |
|---|---|---|---|---|---|
| 124 | 2590 | Bend | Typical | 0.08 | 0.00 |
| *125 | 2610 | Straight | Typical | 0.58 | 0.00 |
| *126 | 2630 | Bend | Typical | 0.39 | 0.00 |
| 127 | 2650 | Bend | Typical | 0.06 | 0.00 |
| 128 | 2670 | Straight | Typical | 0.13 | 0.00 |
| 129 | 2690 | Straight | Typical | 0.03 | 0.00 |
| 130 | 2710 | Straight | Typical | 0.25 | 0.00 |
| 131 | 2730 | Straight | Typical | 0.07 | 0.00 |
| 132 | 2750 | Straight | Typical | 0.03 | 0.00 |
| 133 | 2770 | Straight | Typical | 0.21 | 0.00 |
| 134 | 2790 | Straight | Typical | 0.49 | 0.00 |
| 135 | 2810 | Straight | Typical | 0.74 | 0.19 |
| 136 | 2830 | Straight | Typical | 0.67 | 0.44 |
| 137 | 2850 | Bend | Typical | 0.39 | 0.37 |
| 138 | 2870 | Bend | Typical | 0.05 | 0.09 |
| 139 | 2890 | Straight | Typical | 0.48 | 0.00 |
| 140 | 2910 | Bend | Typical | 0.08 | 0.18 |
| 141 | 2930 | Straight | Typical | 0.54 | 0.00 |
| 142 | 2950 | Straight | Typical | 0.80 | 0.24 |
| 143 | 2970 | Bend | Typical | 0.50 | 0.50 |
| 144 | 2990 | Bend | Typical | 0.73 | 0.20 |
| 145 | 3010 | Bend | Typical | 0.00 | 0.43 |
| *146 | 3030 | Straight | Typical | 0.27 | 0.00 |
| 147 | 3050 | Bend | Typical | 0.12 | 0.00 |
| 148 | 3070 | Straight | Typical | 0.10 | 0.00 |
| 149 | 3090 | Straight | Typical | 0.34 | 0.04 |
| 150 | 3110 | Bend | Typical | 0.10 | 0.00 |
| 151 | 3130 | Bend | Typical | 0.32 | 0.02 |
| 152 | 3150 | Straight | Channelized | 0.11 | 0.00 |
| 153 | 3170 | Straight | Channelized | 0.19 | 0.00 |
| 154 | 3190 | Bend | Typical | 0.21 | 0.00 |
| 155 | 3210 | Straight | Typical | 0.23 | 0.00 |
| 156 | 3230 | Bend | Typical | 0.12 | 0.00 |
| 157 | 3250 | Straight | Typical | 0.19 | 0.00 |
| 158 | 3270 | Straight | Typical | 0.26 | 0.00 |
| 159 | 3290 | Straight | Typical | 0.06 | 0.00 |
| 160 | 3310 | Straight | Typical | 0.05 | 0.00 |
| 161 | 3330 | Straight | Typical | 0.13 | 0.00 |
| 162 | 3350 | Bend | Typical | 0.19 | 0.00 |
| 163 | 3370 | Straight | Typical | 0.26 | 0.00 |
| 164 | 3390 | Straight | Typical | 0.08 | 0.00 |
| 165 | 3410 | Straight | Typical | 0.40 | 0.00 |
| 166 | 3430 | Straight | Typical | 0.24 | 0.10 |
| 167 | 3450 | Bend | Typical | 0.32 | 0.00 |

| Segment | Distance From Confluence (m) | Segment Type | Segment Category | Migration Rate (m) | Migration Rate For Error-Filtered Data (m) |
|---|---|---|---|---|---|
| 168 | 3470 | Straight | Typical | 0.18 | 0.00 |
| 169 | 3490 | Straight | Typical | 0.01 | 0.00 |
| 170 | 3510 | Bend | Typical | 0.43 | 0.13 |
| 171 | 3530 | Straight | Typical | 0.21 | 0.00 |
| 172 | 3550 | Bend | Typical | 0.33 | 0.03 |
| 173 | 3570 | Bend | Typical | 0.35 | 0.05 |
| 174 | 3590 | Straight | Typical | 0.44 | 0.14 |
| 175 | 3610 | Straight | Typical | 0.00 | 0.00 |
| 176 | 3630 | Bend | Typical | 0.25 | 0.00 |
| 177 | 3650 | Straight | Typical | 0.20 | 0.00 |
| 178 | 3670 | Straight | Typical | 0.00 | 0.00 |
| 179 | 3690 | Straight | Typical | 0.20 | 0.00 |
| 180 | 3710 | Bend | Typical | 0.34 | 0.04 |
| 181 | 3730 | Straight | Typical | 0.00 | 0.00 |
| 182 | 3750 | Bend | Typical | 0.21 | 0.00 |
| 183 | 3790 | Straight | Typical | 0.14 | 0.00 |
| 184 | 3810 | Straight | Typical | 0.04 | 0.00 |
| 185 | 3830 | Straight | Typical | 0.00 | 0.00 |
| 186 | 3850 | Straight | Typical | 0.00 | 0.00 |
| 187 | 3870 | Straight | Typical | 0.02 | 0.00 |
| 188 | 3890 | Straight | Typical | 0.02 | 0.00 |
| 189 | 3910 | Bend | Typical | 0.05 | 0.00 |
| 190 | 3930 | Straight | Typical | 0.07 | 0.00 |
| 191 | 3950 | Straight | Typical | 0.01 | 0.00 |
| 192 | 3970 | Straight | Typical | 0.30 | 0.00 |
| 193 | 3990 | Straight | Typical | 0.00 | 0.00 |
| 194 | 4010 | Straight | Typical | 0.02 | 0.00 |
| 195 | 4030 | Bend | Typical | 0.20 | 0.00 |
| 196 | 4050 | Bend | Typical | 0.21 | 0.00 |
| 197 | 4070 | Straight | Typical | 0.27 | 0.00 |
| 198 | 4090 | Bend | Typical | 0.25 | 0.00 |
| 199 | 4110 | Bend | Typical | 0.00 | 0.00 |
| 200 | 4130 | Bend | Typical | 0.09 | 0.00 |
| 201 | 4150 | Bend | Typical | 0.14 | 0.00 |
| 202 | 4170 | Straight | Typical | 0.27 | 0.00 |
| 203 | 4190 | Straight | Typical | 0.05 | 0.00 |
| 204 | 4210 | Straight | Typical | 0.19 | 0.00 |
| 205 | 4230 | Straight | Typical | 0.30 | 0.00 |
| 206 | 4250 | Straight | Typical | 0.01 | 0.00 |
| 207 | 4270 | Straight | Typical | 0.03 | 0.00 |
| 208 | 4290 | Straight | Typical | 0.01 | 0.00 |
| 209 | 4310 | Bend | Typical | 0.19 | 0.00 |
| 210 | 4330 | Straight | Typical | 0.02 | 0.00 |

| Segment | Distance From Confluence (m) | Segment Type | Segment Category | Migration Rate (m) | Migration Rate For Error-Filtered Data (m) |
|---|---|---|---|---|---|
| 211 | 4350 | Straight | Typical | 0.08 | 0.00 |
| 212 | 4370 | Straight | Typical | 0.02 | 0.00 |
| 213 | 4390 | Straight | Typical | 0.01 | 0.00 |
| 214 | 4410 | Straight | Typical | 0.01 | 0.00 |
| 215 | 4430 | Straight | Typical | 0.02 | 0.00 |
| 216 | 4450 | Straight | Typical | 0.03 | 0.00 |
| 217 | 4470 | Bend | Typical | 0.11 | 0.00 |
| 218 | 4490 | Straight | Typical | 0.10 | 0.00 |
| 219 | 4510 | Bend | Typical | 0.21 | 0.00 |
| 220 | 4530 | Straight | Typical | 0.01 | 0.00 |
| 221 | 4550 | Straight | Typical | 0.21 | 0.00 |
| 222 | 4570 | Straight | Typical | 0.12 | 0.00 |
| 223 | 4590 | Bend | Typical | 0.09 | 0.00 |
| 224 | 4610 | Straight | Typical | 0.00 | 0.00 |
| 225 | 4630 | Straight | Typical | 0.20 | 0.00 |
| 226 | 4650 | Bend | Typical | 0.22 | 0.00 |
| 227 | 4670 | Straight | Typical | 0.38 | 0.08 |
| 228 | 4690 | Straight | Typical | 0.03 | 0.00 |
| 229 | 4710 | Straight | Typical | 0.16 | 0.00 |
| 230 | 4730 | Straight | Typical | 0.04 | 0.00 |
| 231 | 4750 | Bend | Typical | 0.21 | 0.00 |
| 232 | 4770 | Straight | Typical | 0.01 | 0.00 |
| 233 | 4790 | Straight | Typical | 0.12 | 0.00 |
| 234 | 4810 | Straight | Typical | 0.01 | 0.00 |
| 235 | 4830 | Bend | Typical | 0.21 | 0.00 |
| 236 | 4850 | Bend | Typical | 0.21 | 0.00 |
| 237 | 4870 | Bend | Typical | 0.20 | 0.00 |
| 238 | 4890 | Bend | Typical | 0.03 | 0.00 |
| 239 | 4910 | Straight | Typical | 0.06 | 0.00 |
| 240 | 4930 | Straight | Typical | 0.00 | 0.00 |
| 241 | 4950 | Straight | Typical | 0.06 | 0.00 |
| 242 | 4970 | Straight | Typical | 0.00 | 0.00 |
| 243 | 4990 | Bend | Typical | 0.03 | 0.00 |
| 244 | 5010 | Straight | Typical | 0.45 | 0.15 |
| 245 | 5030 | Bend | Typical | 0.18 | 0.00 |
| 246 | 5050 | Bend | Typical | 0.41 | 0.11 |
| *247 | 5070 | Straight | Typical | 0.31 | 0.00 |
| *248 | 5090 | Straight | Typical | 0.51 | 0.00 |
| *249 | 5110 | Bend | Typical | 0.33 | 0.00 |
| *250 | 5130 | Straight | Typical | 0.50 | 0.00 |
| *251 | 5150 | Straight | Typical | 0.46 | 0.00 |
| *252 | 5170 | Straight | Typical | 0.37 | 0.00 |

| Segment | Distance From Confluence (m) | Segment Type | Segment Category | Migration Rate (m) | Migration Rate For Error-Filtered Data (m) |
|---|---|---|---|---|---|
| *253 | 5190 | Straight | Typical | 0.17 | 0.00 |
| *254 | 5210 | Straight | Typical | 0.28 | 0.00 |
| 255 | 5230 | Bend | Typical | 0.08 | 0.00 |
| 256 | 5250 | Straight | Typical | 0.10 | 0.00 |
| 257 | 5270 | Straight | Typical | 0.12 | 0.00 |
| 258 | 5290 | Straight | Typical | 0.05 | 0.00 |
| *259 | 5310 | Straight | Typical | 0.33 | 0.00 |
| *260 | 5330 | Straight | Typical | 0.33 | 0.00 |
| 261 | 5350 | Straight | Typical | 0.25 | 0.00 |
| 262 | 5370 | Bend | Typical | 0.23 | 0.00 |
| 263 | 5390 | Straight | Typical | 0.02 | 0.00 |
| 264 | 5410 | Straight | Typical | 0.17 | 0.00 |
| 265 | 5430 | Bend | Typical | 0.16 | 0.00 |
| 266 | 5450 | Straight | Typical | 0.05 | 0.00 |
| 267 | 5470 | Bend | Typical | 0.03 | 0.00 |
| 268 | 5490 | Straight | Typical | 0.12 | 0.00 |
| 269 | 5510 | Straight | Typical | 0.39 | 0.09 |

***Indicates segments not adjusted with railroad offset.**