Summer 2018

Spatial and Temporal Trends of Mining-Related Lead-Zinc Sediment Contamination, Galena River Watershed, SW Wisconsin-NW Illinois

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Recommended Citation

King, Dylan Alexander, "Spatial and Temporal Trends of Mining-Related Lead-Zinc Sediment Contamination, Galena River Watershed, SW Wisconsin-NW Illinois" (2018). *MSU Graduate Theses*. 3302.
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SPATIAL AND TEMPORAL TRENDS OF MINING-RELATED LEAD-ZINC SEDIMENT CONTAMINATION, GALENA RIVER WATERSHED, SW WISCONSIN-NW ILLINOIS

A Masters Thesis
Presented to
The Graduate College of
Missouri State University

In Partial Fulfillment
Of the Requirements for the Degree
Master of Science, Geospatial Science

By
Dylan Alexander King
August 2018

SPATIAL AND TEMPORAL TRENDS OF MINING-RELATED LEAD-ZINC SEDIMENT CONTAMINATION, GALENA RIVER WATERSHED, SW WISCONSIN-NW ILLINOIS

Geography, Geology, and Planning

Missouri State University, August 2018

Master of Science

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ABSTRACT

Alluvial sediments within the Galena River Watershed were severely contaminated with heavy metals by historical zinc (Zn) and lead (Pb) mining operations during the early 1800s until 1979. Since the mines closed, there have been efforts to remediate on-site mine waste. However, the effectiveness of these efforts to reduce metal concentrations in stream sediments is unknown. This study compares present-day (2017) contamination trends in the Galena River Watershed to trends reported 25 years ago. A total of 415 sediment/soil samples were collected and analyzed using X-ray florescence spectrometry to determine sediment metal concentrations. The highest concentrations of zinc measured were 23,577 ppm in the channel bed, 19,825 ppm in the channel banks, and 51,273 ppm in tailings. Zinc concentrations averaged 198 ppm within the unmined Madden Branch (n=10), 2,057 ppm within the main branch of the Galena (n=31), 9,569 ppm within the heavily mined Diggings Branch (n=11), and 26,158 ppm in tailings (n=16). Present day contamination trends show little difference compared to 25 years ago. However, stream sediments collected downstream of some large-scale remediation projects have shown significant decreases in Zn concentrations. Nevertheless, even with continued efforts to remediate contaminated sediments in the Galena River, high concentrations will probably persist far into the future.

KEYWORDS: sediment contamination, lead, zinc, mining, remediation, Galena River

This abstract is approved as to form and content

Robert T. Pavlowsky, PhD
Chairperson, Advisory Committee
Missouri State University

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ACKNOWLEDGEMENTS

I would like to thank several people for the support and guidance I have received throughout this thesis process. First I would like to thank my thesis advisor and committee chair Dr. Bob Pavlowsky for his mentoring and support throughout this entire thesis project. In addition, I would also like to thank my committee members Drs. Xiaomin Qiu and Toby J. Dogwiler for their support.

I would also like to thank the entire July 2017 field crew that collected samples in Wisconsin and Illinois. Thanks goes out to Drs. Bob Pavlowsky, Doug Faulkner, Scott Lecce, Mark Bowen, Joan Bunbury, and Colin Belby and including the following members of OEWRI: Hannah Adams, Sara LeTarte, Heather Moule, Joe Nash, and Kelly Rose. Also a thanks to Ken Braunling, Elliot Smith, and Dakota Tollakson from UW Eau Claire.

A special thanks goes out to OEWRI and Missouri State University Graduate College for the funding and support received to accomplish this thesis. I would also like to thank Marc Owen from OEWRI for assistants and advise along the way. Lastly, a huge thanks to my parents and family for their continued support and motivation that got me to where I am today.

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CHAPTER 1 – INTRODUCTION

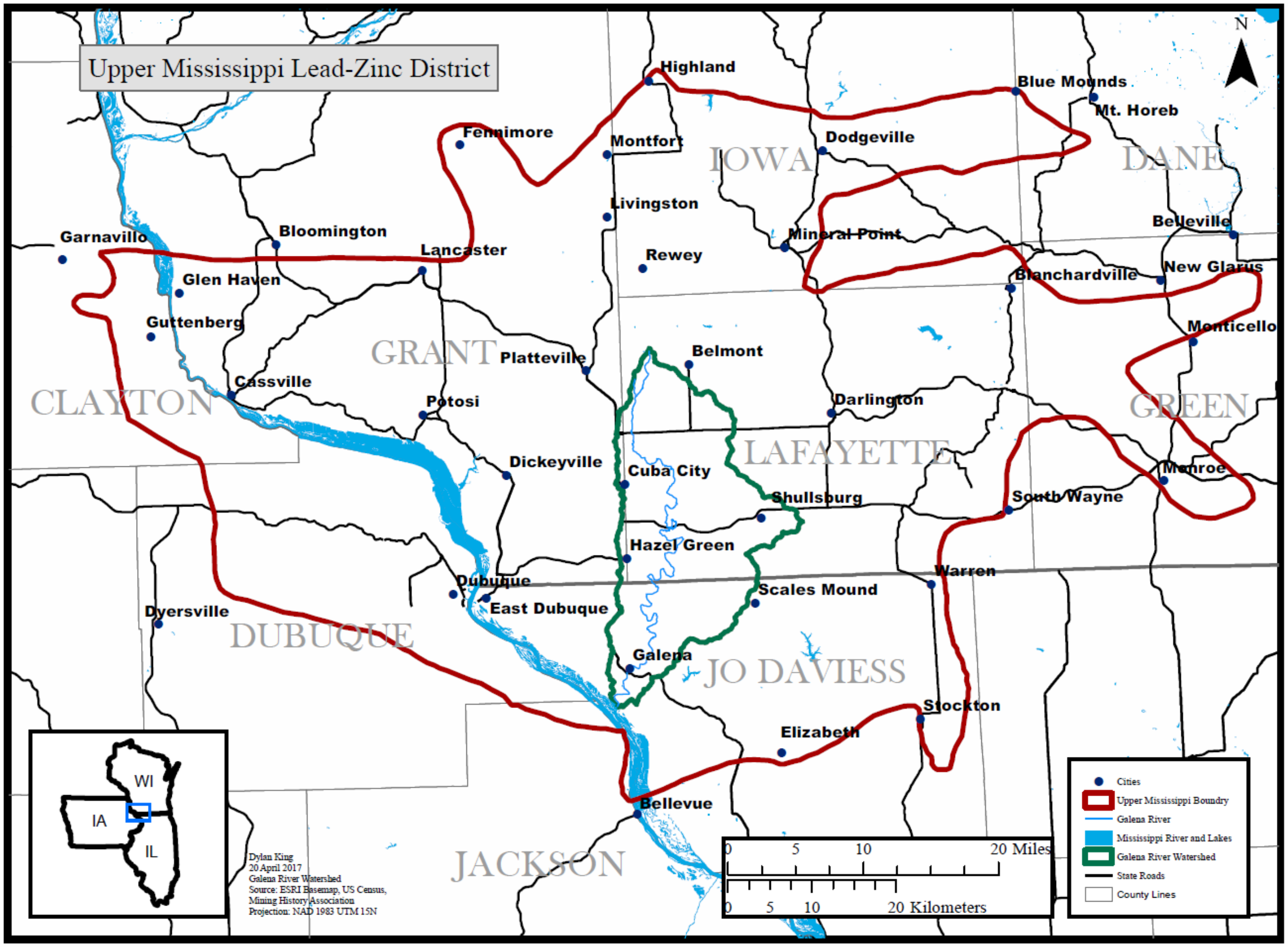
Base metal mining for metallic ores has been occurring for millennia, but it was not until after the 1960s that widespread concern began to develop for protecting the environment from its adverse effects (Brown et al., 2009). Base metals include non-precious metals such as zinc (Zn), lead (Pb), nickel (Ni), and copper (Cu) (Leblanc et al., 2000). Base metal ores may also contain trace amounts of other metals such as cadmium (Cd) and arsenic (As). Over the past two centuries, mining operations began to grow in size and production creating contamination problems worldwide (Amezaga et al., 2011). Early base metal mining and ore milling was inefficient and produced large quantities of metal pollution (Pavlowsky, 1996). Regulations in the United States were not created at the federal level until the mid-1970s, which required proper and thorough remediation after mine closure (Brown et al., 2009). Even with an increase in regulations, most mines today are large in order to compete within the market, resulting in a greater potential for pollution. Further, many small operations in Latin America, Asia, and Africa are unregulated or illegal and cause large amounts of contamination (Amezaga et al., 2011).

Many mining sites across the world were abandoned prior to regulatory closure procedures leaving large areas of land covered in mine-related waste (Brown et al., 2009). Mine waste, usually in the form of tailing piles, can be mobilized by erosion and weathering causing heavy metal contamination of nearby soils, water, and alluvial sediments (Knox, 1987). These contaminated sediments may become part of a stream's sediment load eventually being dispersed downstream within channel and floodplain deposits during periods of high discharge. These contaminated deposits of sediments become secondary sources of pollution that can be eroded, reworked, and transported further downstream over time (Lecce and Pavlowsky, 1997). Due to the effects of sediment mixing, dilution, and sedimentation downstream, the highest concentrations of metals are typically found close to the mine source (Pavlowsky, 1996).

Many studies have examined the spatial trends of metal contamination within entire watersheds (Adams, 1944; Swennen et al., 1994; Pavlowsky, 1996; Miller et al., 1999; Sutherland, 2000; Lecce and Pavlowsky, 2001; Coulthard and Macklin, 2003; Nieto et al., 2007; Vandeberg and Martin, 2011; Lecce and Pavlowsky, 2014). However, what is lacking in the literature are studies of the temporal trends of mining contamination in river systems. This thesis will address a gap in knowledge to evaluate remediation effectiveness and associated sediment transport processes to reduce metal contamination levels through time and better understand how fluvial systems recover from the effects of mining.

Mining in the Upper Mississippi Valley Lead-Zinc District

This study focuses on Pb and Zn contamination in river sediments caused by mining in the Upper Mississippi Valley Lead-Zinc District (UMVD) which started as early as the mid-1600s and became widespread by the mid-1800s (Fig. 1) (Heyl et al., 1959; Knox, 1987). The district is well known for rich Pb and Zn deposits found in northwest Illinois, northeast Iowa, and southwest Wisconsin (Knox, 1987). Mines targeted sulfide ore minerals such as galena (PbS) and sphalerite (ZnS) contained in carbonate host rock (Heyl et al., 1959). Lead mining peaked in 1845 several years prior to the start of Zn mining (Fig. 2). Zinc smelting technology was not available until later



Dylan King
20 April 2017
Galena River Watershed
Source: ESRI Basemap, US Census, Mining History Association
Projection: NAD 1983 UTM 15N

Fig. 1. Map of the UMVD and the Galena River Watershed.

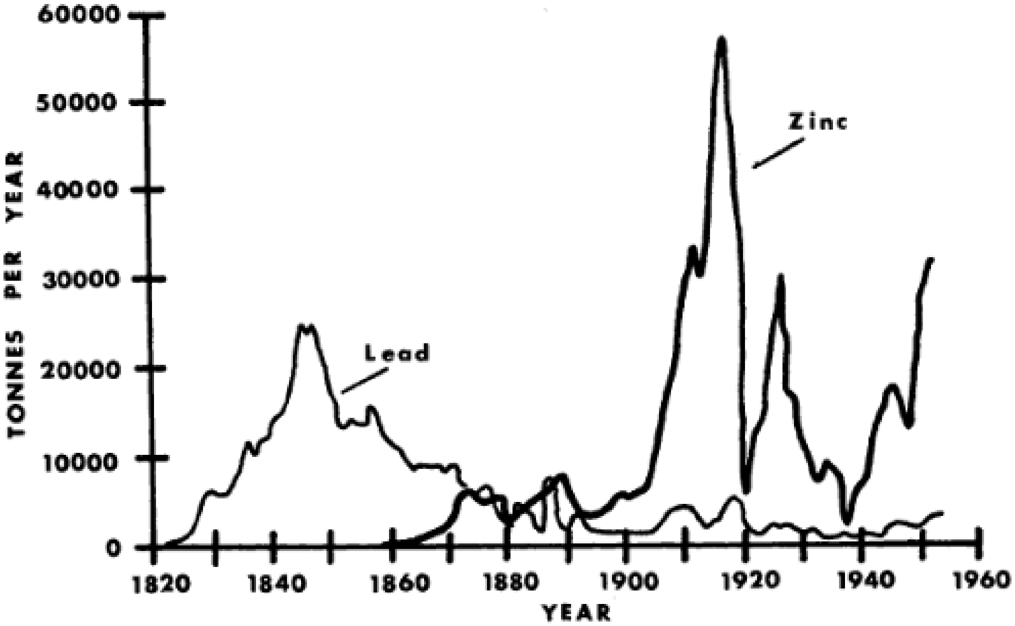


Fig. 2. Production of Pb and Zn ore in the UMVD (Heyl et al., 1959).

years. After the 1850s, Pb mining declined as Zn mining began to boom in the district. Zinc mining peaked in 1917 with nearly 60,000 Mg of ore being produced a year (Heyl et al., 1959). After the Zn boom, the economy crashed in the late 1920s with a sharp decrease in ore production. There was a short revival during the Second World War, but only large producing mines were able to stay in business until the last mine closed in 1979 (Heyl et al., 1959, Knox, 1987). With a low price for Zn at the market as well as growing concerns about the lowering of the local water table, river pollution, and air contamination from diesel mining equipment and blowing dust, all mining activity ceased as of 1979 in the Galena River Watershed (Brown et al., 2009). By the mid-1900s, most operations were relatively large and few in number (Heyl et al., 1959). The last mining operation to close was Shullsburg (Eagle Picher) Mine just south of the City of Shullsburg.

In the UMVD, mining operations remained almost entirely unregulated and decentralized under the General Mining Act of 1872 that promoted quick expansion of mining activities rather than a sustainable economy with environmental protections (Amezaga et al., 2011). It was not until the late 1900s that the act was amended to include regulations on post-closure procedures (Brown et al., 2009). The Federal Land Policy and Management Act of 1976 prevented unnecessary degradation to public lands and required remediation of the land post-closure. Due to the difficult nature of locating former owners and companies of abandoned mines, mines closed prior to 1976 (1974 in Wisconsin) were "grandfathered" into the act and not required to clean up mine waste (Brown et al., 2009).

This lack of regulation resulted in large quantities of tailing piles to accumulate and remain at most abandoned mine locations throughout the watershed (Heyl et al., 1959). Tailing piles are the after product of the milling process where mined rock is sent to a mill to be crushed and separated (Figs. 3 and 4) (Johnson, 2018). Lead and Zn concentrates are removed and sent to a smelter whereas the remaining waste is placed in tailing piles. Early milling involved hand operated jigging which was extremely wasteful and often resulted in tailing piles with grain sizes <2 mm in size with very high concentrations of Pb and Zn (Taggart, 1945). Most tailing piles in the Galena Watershed contained >1,000 ppm Pb and Zn (Pavlowsky, 1995). To reduce the waste of early milling processes, steam powered gravity mills were introduced at the start of the 20th century (Heyl et al., 1959). With this process, steam power operated machinery crushed and separated the ores from waste rock more efficiently. The ore would be obtained by separating crushed rock by specific gravity on shaker tables (Richards, 1909). Even at

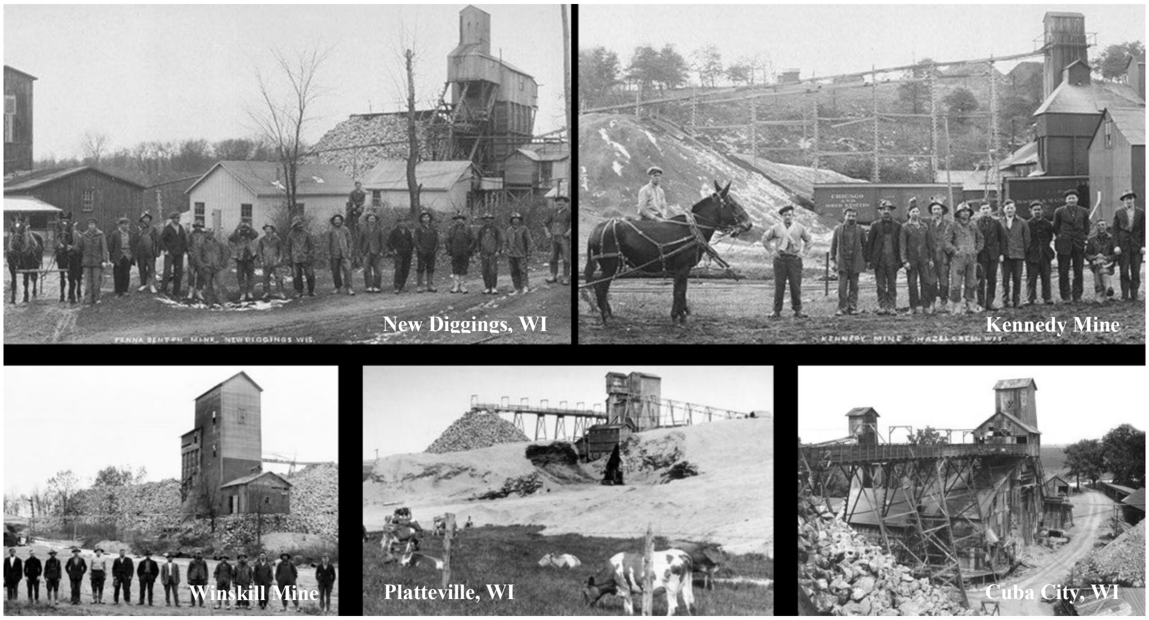


Fig. 3. Historical photos of mining operations during the 1800s and early 1900s in the UMVD (Johnson, 2018).

Fig. 4. Examples of tailing piles today within the Galena River Watershed, July 2017.

some mine locations, previous tailing piles would be re-processed through these new more efficient mills (Heyl et al., 1959).

In 1929, the first flotation mill in the UMVD was built in Linden, WI (Heyl et al., 1959). Later in 1938, the first flotation mill in the Galena River Watershed was built in Cuba City. This process eliminated excessive ore waste, eliminated the need to magnetically separate iron (Fe) impurities, and finally allowed the mill to remove barite from Pb and Zn ores (Heyl, et al., 1959). In addition to crushing rock, the mill would also grind the material until it was very fine. They would then separate and concentrate the ore depending on specific gravity and chemical makeup using different oils (Richards, 1909). This process produced very fine tailings which would be released into slime pounds or nearby streams.

Source and Effect of Mining Contamination

The release of tailing material from mills into tailing piles is the primary source of Pb and Zn contamination within the watershed (Appendices A1, A2 A3, and A4) (Pavlowsky, 1996). Earlier tailing piles prior to flotation methods were mostly sand and fine gravels which were loosely held together and heavily contaminated. The highest tailing pile concentration measured by Pavlowsky (1995) from Galena River Watershed in the early 1990s was 89,092 ppm Zn from Kennedy Mine. These tailings are prone to increased erosion and mass wasting causing runoff to nearby streams.

Lead and Zn concentrations now within the stream network will be stored in channel and bank deposits directly downstream of their source material (Lecce and Pavlowsky, 1997). Metals stored within the stream channel can become remobilized seasonally by floods and are considered the most recent sediments given their short storage time. However, metals stored in bank material and floodplains may remained stored for years to millennia if rarely reworked by lateral channel migration and bank erosion (Lecce and Pavlowsky, 1997). If these deposits are remobilize they become a secondary source of contamination where the river effectively contaminates itself. The input of sediment contamination from secondary sources is commonly ignored in most studies and remediation projects (CDM Smith, 2018). A Total Maximum Daily Load (TMDL) report for the Galena Watershed has recognized dissolved metals and abandoned mine sites as contamination sources in the Galena Watershed (CDM Smith, 2018). However, the TMDL has overlooked the potential for metals and mine wastes stored in floodplain deposits to be important sources of metals to stream sediments (Coulthard and Macklin, 2003).

An additional source of contamination can be the result of the chemical breakdown (known as leaching) of tailing piles resulting in a dissolved loads of Pb and Zn (Adams, 1944; Leblanc et al., 2000; Kemper and Sommer, 2002; Nieto et al., 2007). The chemical breakdown of a sulfuric mineral can cause acid mine drainage where sulfuric acids greatly lower the pH of a stream making it very acidic. While there is continued potential for leaching and dissolved metals in the Galena River Watershed, acid mine drainage is rare due to the primary host rock of the ore being dolomite, a carbonate (Adams, 1944; Heyl et al., 1959; Brown et al., 2009). The high pH of dolomite will commonly neutralize the low pH of sulfuric acid (Adams, 1944). The remaining dissolved Pb and Zn tends to bond to fine sediments including clay particles and organic matter (OM) (Horowitz, 1991). Moreover, contaminated fine-grained sediment can be easily dispersed downstream by high flows and floods (Pavlowsky, 1995).

Tailing piles are also a source for several other metals that contaminate the Galena River Watershed. Since most tailing piles are dolomitic, fine gravels and sand particles in channel sediments near mine areas typically contain high calcium (Ca) concentrations (Adams, 1944). Other metals such as Fe and manganese (Mn) are byproducts of Pb and Zn mining and tend to have high concentrations within some tailing piles where pyrite (FeS) and other sulfuric minerals were present in measurable amounts (Heyl et al., 1959). Lastly, some metals such as As and Cd are released to streams as a result of Pb and Zn mining and have the potential to accumulate in high concentrations in some parts of the watershed (Leblanc et al., 2000).

Ultimately, all sources of metal contaminants within the watershed are at their highest concentrations near their mining source (Lecce and Pavlowsky, 1997). The further Pb and Zn are dispersed downstream, the more the metals will mix with uncontaminated sediments in the stream bed or from tributaries (Marcus, 1987). This level of dilution can be estimated by dividing the production mass of ore or metal by drainage area at the sample point in the stream network. For this reason, contaminant ion levels will be the highest in small watersheds with high production. The greater the area and spacing between mines and the sampling point, the greater the rate of mining sediment dilution (Pavlowsky, 1996).

Streams segments that are in close proximity to mines have received large tonnages of tailing inputs that may result in harm to aquatic life in the Galena River watershed (CDM Smith, 2018). The most recent TMDL of the Galena River states the entire length of the river below the East Fork is impaired as a result of mining and dissolved Zn load which is extremely high in concentration. According to a study conducted by MacDonald et al. (2000), high concentrations of Pb (>128 ppm) and Zn (>459 ppm) can be toxic to sediment-dwelling organisms. This study shows that focus on dissolved metal concentrations may only indicate part of the toxic risk in mined watersheds. Furthermore, nearly in all stream segments, excluding mostly unmined branches, Pb and Zn concentrations frequently exceed these thresholds in the Galena River Watershed according to the results of Pavlowsky (1995).

Purpose and Objective

The purpose of this study is to evaluate present day contamination trends within the Galena River Watershed and compare them to contamination trends found in the early 1990s reported by Pavlowsky (1995). In addition, the study plans to determine where Pb and Zn concentrations have decreased on average within the watershed and if remediation resulted in decreased contamination over the past 25 years. The objectives of this study are to (i) resample sites from the Pavlowsky (1995) study and add several new sampling sites to the lower Galena River below Galena, IL; (ii) create a GIS database of government documented remediation sites and assess all present day mine locations and change over the past 25 years; (iii) determine the trends of present day sediment contamination and their correlation with other variables such as Fe, Mn, Ca, and OM; and (iv) assess the influence of sediment transport, sediment-metal storage, and remediation in the watershed on contamination trends over the past 25 years. Many studies that focus on mining-related metal contamination tend not to revisit the study area to assess change over time with few exceptions, usually over shorter periods of time (Axtmann and Luoma, 1991). Given the lack of current literature, it is relatively unknown what effect remediation will have on the watershed and to what magnitude and extent. Revisiting the Pavlowsky (1995) study sites of the early 1990s will give insight into the potential for geochemical recovery of the Galena River as a result of nearly 40 years of mining inactivity, reworking and sediment dilution, and ongoing remediation efforts over the past 25 years.

CHAPTER 2 – STUDY AREA

The Galena River Watershed (525 km^2) is located in southwest Wisconsin and northwest Illinois (Fig. 1). The highest elevation is in the north part of the watershed at 380 m above sea level and the lowest elevation is at the confluence with the Mississippi at 177 m above sea level (CDM Smith, 2018). The northern portion of the watershed is located within Lafayette County and partially within Grant County of Wisconsin. The southern portion of the watershed is located completely in Jo Daviess County in Illinois. The headwaters of the Galena River originate just east of Platteville, Wisconsin and its mouth on the Mississippi River is 16 kilometers downstream of Galena, Illinois at Harris Slough (WVI, 2015b). Galena, Illinois (42.4167°N - 90.4290°W) is the largest city in the watershed (USCB, 2017). Other significant villages and towns include Shullsburg, Hazel Green, New Diggings, Belmont, and Cuba City in Wisconsin.

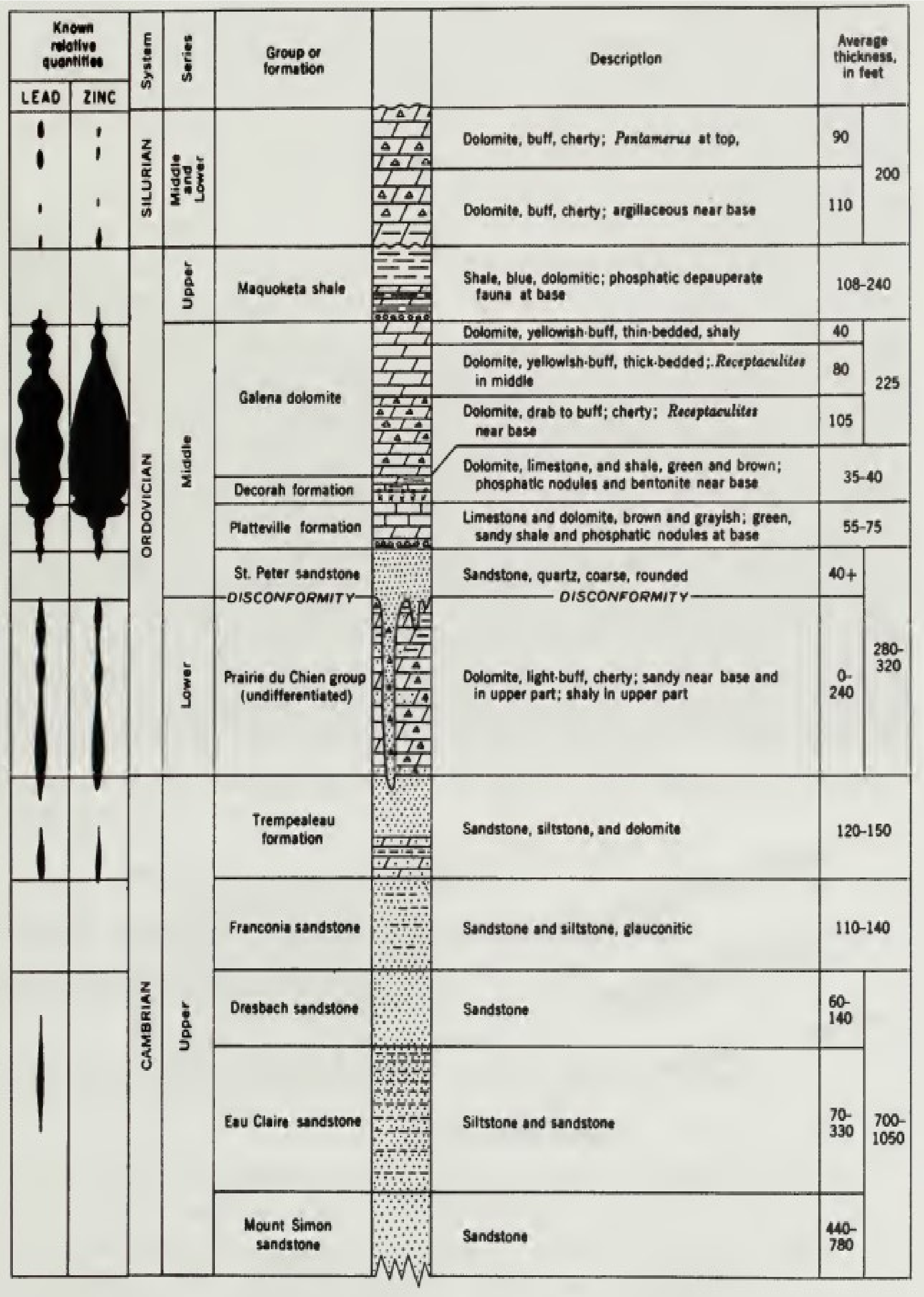
Geology

The Galena River Watershed is entirely within the physiographic region known as the Driftless Area (Knox, 2006). During the Wisconsin Glaciation the Driftless Area (which covers parts of Wisconsin, Illinois, Minnesota, and Iowa) was unglaciated resulting in a unique and river dissected landscape much greater in relief in comparison to surrounding regions (Knox, 2006). The upland regions of the Driftless area are abundant with loess deposits composed of fine grained sediments (Magilligan, 1985). Loess is the result of wind-blown sediment from glacial outwash deposits in neighboring regions that created up to four meter deposits in some areas (Magilligan, 1985).

The surficial bedrock within the Galena River Watershed is middle Ordovician to Silurian in age (Heyl et al., 1959). From oldest to youngest the bedrock is part of the following formations: St. Peter sandstone, Platteville limestone, Decorah shale, Galena dolomite, Maquoketa shale, and Edgewood dolomite (Mullens, 1964). All formations are middle to late Ordovician while Edgewood dolomite is early Silurian (Fig. 5). Seen in the geological map below, the majority of exposed bedrock is dolomitic and Ordovician in age and mostly from the Platteville, Galena, and Maquoketa formations (Figs. 6 and 7) (ISGS, 1967; GNHS, 1995).

A total of around 832,000 Mg of Pb ore and a total of around 44 million Mg of Zn ore was mined between the early 1800s and the mid-1900s (Heyl et al., 1959). Most of these ore deposits range between a few hundred to nearly four million Mg. However, the majority of deposits produced less than 100,000 Mg (Heyl et al., 1959). The majority of minerals that were mined included galena (PbS), sphaleraite (ZnS), pyrite (FeS), and small quantities of smithsonite ($ZnCO_3$). Pyrite was primarily mined for the manufacturing of sulfuric acid (Heyl et al., 1959). Most of these ores are retrieved from dolomitic [$CaMg(CO_3)_2$] base rock which has a neutralizing effect in local ground and surface waters with primarily mined sulfuric minerals within the watershed (Adams, 1944; Heyl et al., 1959).

The most common soil in the Galena River Watershed is Tama Silt Loam (NRCS, 2017; CDM Smith, 2018). Tama Silt Loam is an upland soil with a moderate relief of 2-6%, is well drained, and its parent material is loess over cherty residuum (NRCS, 2017). Another common upland soil is Palsgrove Silt Loam also formed from loess. A common drainageway soil is Worthen Silt Loam with a common relief of 2-6%, well drained, and



System	Series	Group or formation	Description	Average thickness, in feet	
SILURIAN	Middle and Lower		Dolomite, buff, cherty; *Pentamerus* at top,	90	200
			Dolomite, buff, cherty; argillaceous near base	110	
ORDOVICIAN	Upper	Maquoketa shale	Shale, blue, dolomitic; phosphatic depauperate fauna at base	108-240	
	Middle	Galena dolomite	Dolomite, yellowish-buff, thin-bedded, shaly	40	225
			Dolomite, yellowish-buff, thick-bedded; *Receptaculites* in middle	80	
			Dolomite, drab to buff; cherty; *Receptaculites* near base	105	
		Decorah formation	Dolomite, limestone, and shale, green and brown; phosphatic nodules and bentonite near base	35-40	
		Platteville formation	Limestone and dolomite, brown and grayish; green, sandy shale and phosphatic nodules at base	55-75	
		St. Peter sandstone	Sandstone, quartz, coarse, rounded	40+	280-320
		DISCONFORMITY	DISCONFORMITY		
	Lower	Prairie du Chien group (undifferentiated)	Dolomite, light-buff, cherty; sandy near base and in upper part; shaly in upper part	0-240	
CAMBRIAN	Upper	Trempealeau formation	Sandstone, siltstone, and dolomite	120-150	
		Franconia sandstone	Sandstone and siltstone, glauconitic	110-140	
		Dresbach sandstone	Sandstone	60-140	700-1050
		Eau Claire sandstone	Siltstone and sandstone	70-330	
		Mount Simon sandstone	Sandstone	440-780	

Fig. 5. Geology of the Galena River Watershed (Brown et al., 2009).

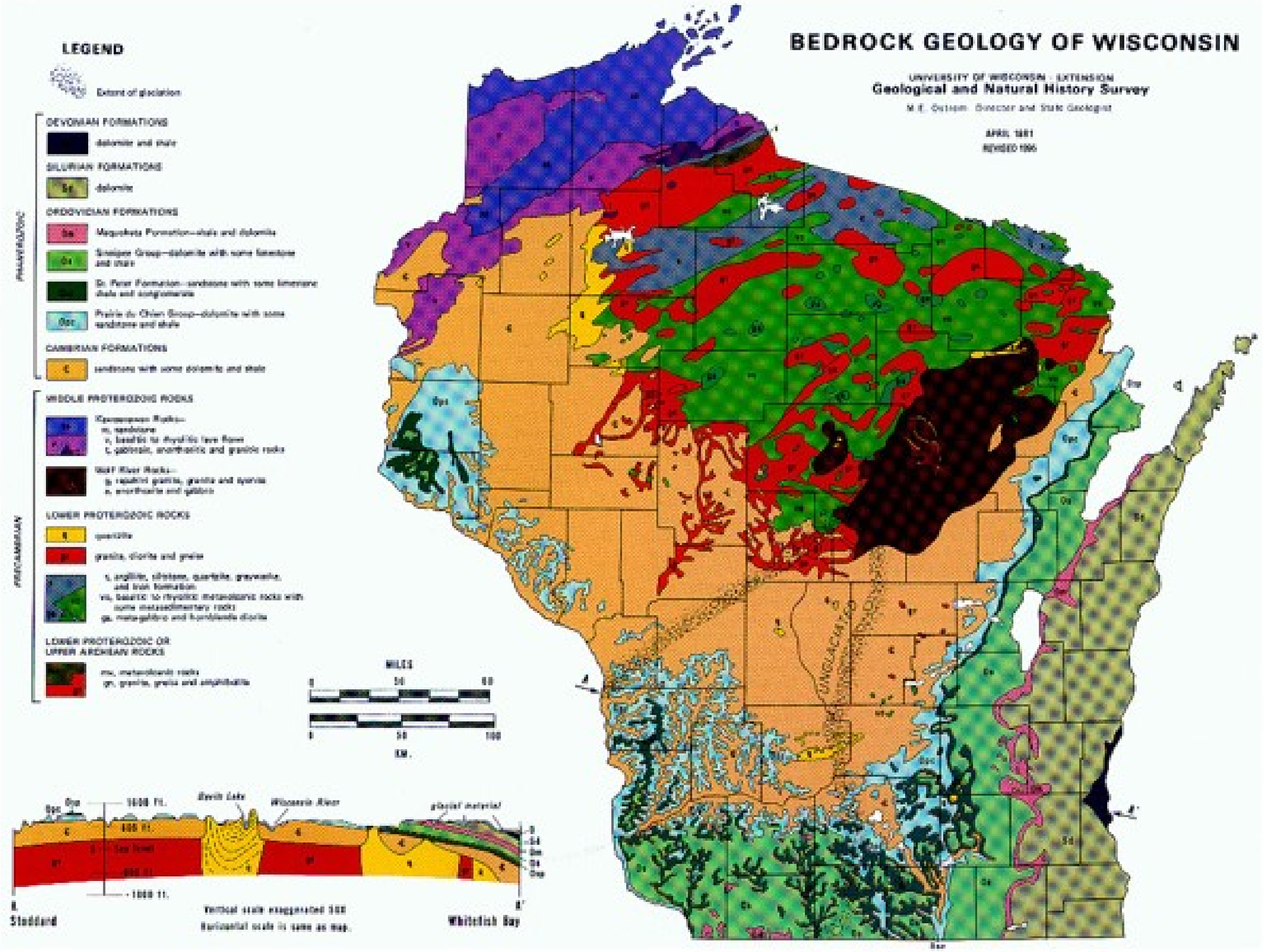


Fig. 6. Bedrock geology of the State of Wisconsin. Study area located in southwest most counties of state (Grant and Lafayette) (GNHS, 1995). The Sinnippe Group is composed of Platteville, Decorah, and Galena formations.

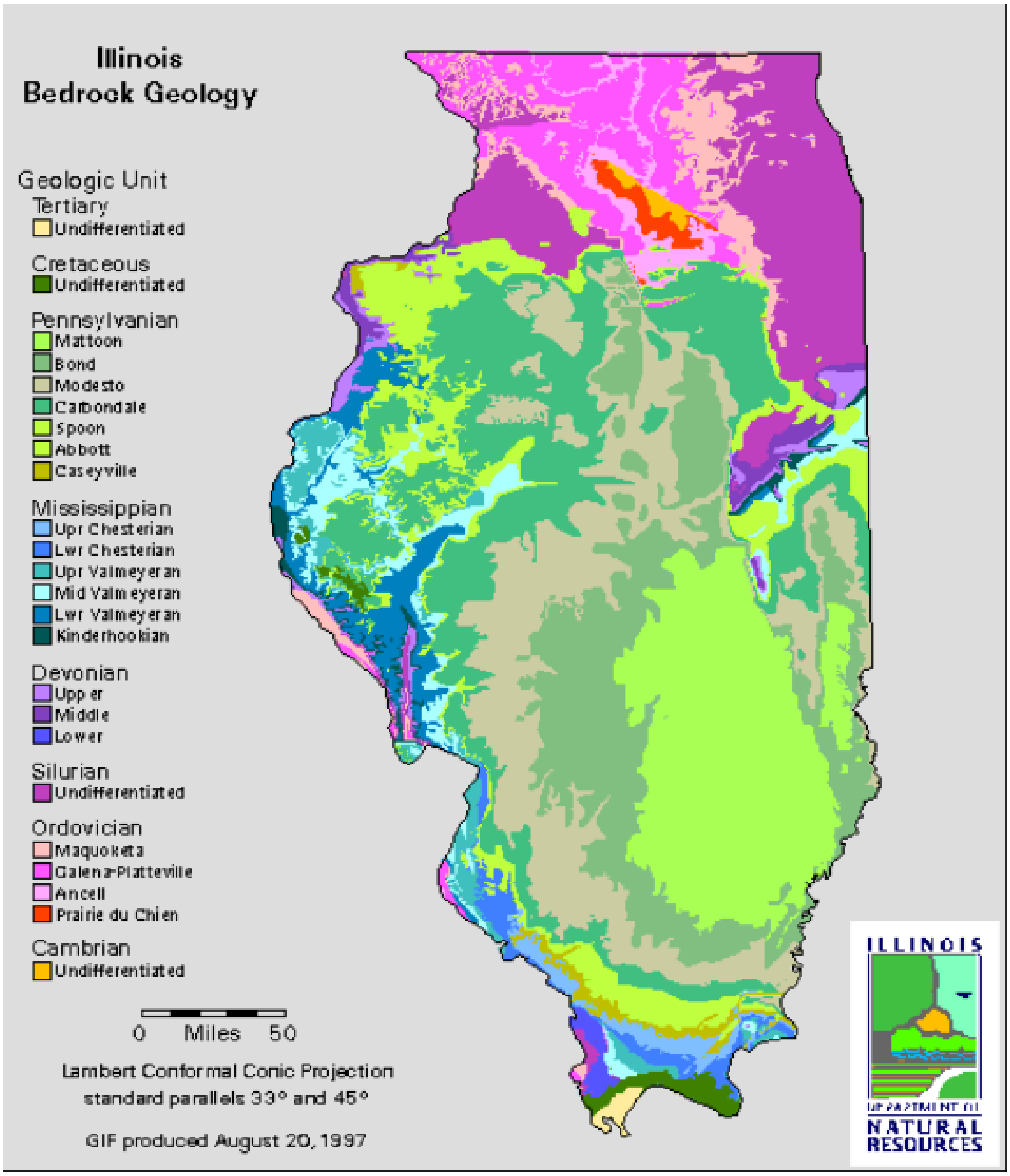


Fig. 7. Bedrock geology of the State of Illinois. Study area located in northwest most corner of state (ISGS, 1967).

parent material is silty alluvium. The most common floodplain soil is the Orion Silt Loam which has a common relief of 0-3%, somewhat poorly drained, and parent material is silty alluvium (NRCS, 2017). The most common soil order within both states and the Galena River Watershed is an Alfisol (Fig. 8 and 9) (NRCS, 2009; Hartemink et al., 2012).

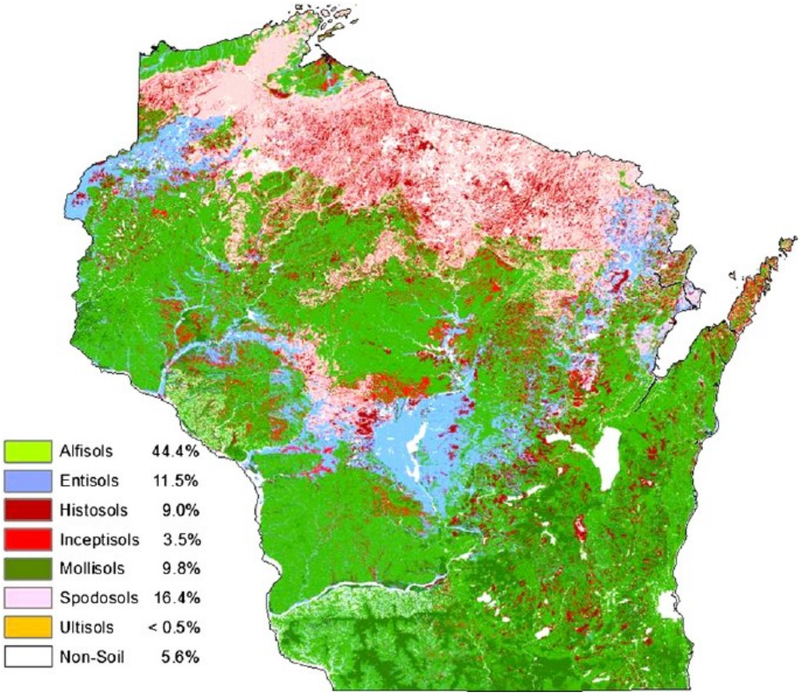


Fig. 8. Soils map of Wisconsin by soil order groups (Hartemink et al., 2012).

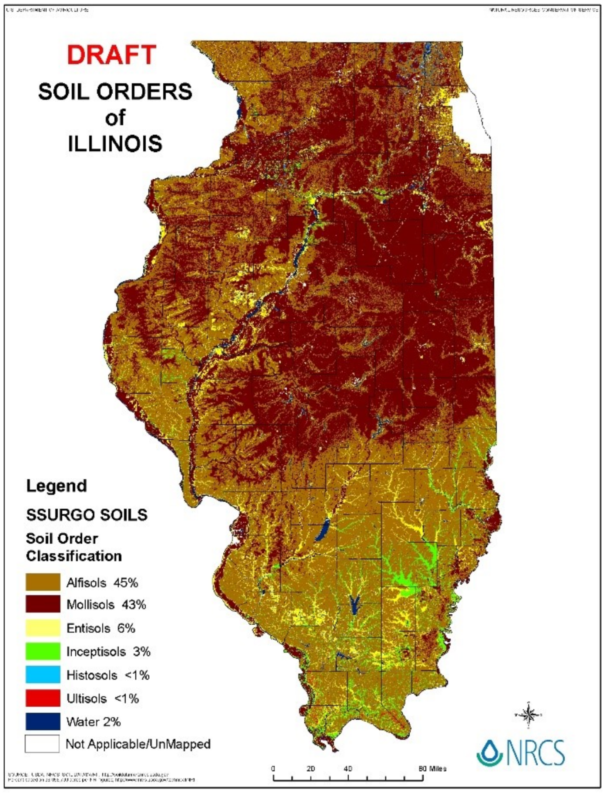


Fig. 9. Soils map of Illinois by soil order groups (NRCS, 2009).

Climate and Hydrology

The climate of the City of Galena, IL is seasonally hot in summer and cold in winter (CDM Smith, 2018). The table below lists average temperatures and precipitation rates in the Dubuque, IA area over the past 30 years (Table 1) (NOAA, 2018). Dubuque, IA is located about 26 kilometers northwest of Galena, IL. The average temperature for Dubuque is highest in the month of July (22.2°C) and lowest in the month of January (-7°C). Both June and July have the highest rate of precipitation annually at around 12.09 cm and 12.14 cm respectfully. The highest rate for snowfall on average takes place during December at 27.69 cm. Annually, Dubuque has an average temperature of 8.2°C, average precipitation of 91.97 cm, and an average snowfall of 106.17 cm. This data is typical of the Dubuque area and is similar to the available Galena, IL records (NOAA, 2018).

Table 1
Average monthly climate data for Dubuque, IA for past 30 years.

Month	Average Temperature (°C)	Average High Temperature (°C)	Average Low Temperature (°C)	Average Precipitation (cm)	Average Snowfall (cm)
JAN	-7.0	7.8	-24.4	3.10	24.64
FEB	-4.9	10.6	-20.6	3.63	25.40
MAR	1.9	20.6	-14.4	5.84	14.73
APR	8.7	26.1	-5.6	10.03	3.56
MAY	15.0	29.4	0.6	10.36	0.00
JUN	20.3	32.2	7.2	12.09	0.00
JUL	22.2	33.3	10.6	12.14	0.00
AUG	21.1	32.2	10.0	10.67	0.00
SEPT	16.8	30.6	2.8	7.62	0.00
OCT	10.0	26.7	-4.4	6.35	0.51
NOV	2.8	18.9	-11.7	5.64	7.37
DEC	-4.6	10.0	-21.1	4.57	27.69
ANNUAL	8.2	33.3	-26.7	91.97	106.17

For hydrologic data, there are a total of four inactive streamflow gages within the Galena River Watershed that were once operated by the USGS (CDM Smith, 2018). Two of these gages were along the Madden Branch, one on Pats Creek, and one on the Galena River. The gages located on Madden Branch and Pats Creek were only operated for a short two year period between 1980 and 1982. The gage (USGS Gage 05415000) on the Galena River at Buncombe, WI (drainage area of 324 km^2) was in operation from 1939 until it closed in 1992. Even though this gage has been closed for 25 years it offers the only overall discharge record of this area. The mean annual discharge for the gage is 79 m^3/s, the highest average monthly discharge from this gage is in March at 159 m^3/s, and the lowest average monthly discharge from this gage is in December at 54 m^3/s. The highest maximum flow recorded took place on June 29, 1969 at a peak of 3,400 m^3/s (USGS, 2018).

Settlement History and Land Use

The first known record of Pb mining in the UMVD was reported by French fur traders in 1658 in the Dubuque area (Heyl et al., 1959). Since then there were small scale mining operations by French, Native American, and American settlers until the beginning of large scale mining in the early 1800s. It was in 1819 that large permanent settlements started to appear throughout the UMVD (Heyl et al., 1959). A rapid increase in settlement took place in 1820s as a result of increased mining operations, farming, and logging (Knox, 1987). Many of these settlers came from the eastern states, southern Illinois (majority of which migrated from Peoria County), and parts of Europe (GHS, 2012).

This growth in population and increase in Pb and eventually Zn ore mining led to a golden era of steamboat traffic for Galena, IL making it one of the greatest shipping centers in the United States at the time (Heyl et al., 1959; GHS, 2012). The 1840s was the golden decade of Galena steamboat traffic with large quantities of cargo being shipped through the Mississippi River. By the end of the 1850s, steamboats were no longer a significant shipping center in Galena, IL as the railroad out of Chicago dominated the state's shipping industry (Heyl et al., 1959; GHS, 2012).

After Zn mining peaked in 1917 mining operations were in decline until the final mine closed in 1979. As mining operations decrease, logging and farming increased within the district (Knox, 1987). Increased agricultural lands led to an increased rate of sedimentation and flood magnitude within the watershed (Woltemade, 1994). Farm field runoff as well as contaminated sediments from abandoned tailing piles would disperse during high discharge events and settle along the banks of the Galena River. These legacy sediments can be seen throughout the watershed and are known as post settlement alluvium (PSA) or legacy deposits (Magilligan, 1985; James, 2013). A PSA deposit is characteristic of a light colored, sometimes contaminated sediment overlaying late Holocene floodplain deposits of a darker color (Appendices A5 and A6).

The Galena River Watershed is primarily pastoral and agricultural with very little industry and only small settlements the largest of which is Galena, IL (CDM Smith, 2018). As of 2014, the highest percent of land cover in the Galena River Watershed and the neighboring Sinsinawa River Watershed is pasture/hay around 36% of the area (CDM Smith, 2018). Other land uses are listed in the following table including the most populous crop being corn and the most populous forest cover being deciduous (Table 2).

Table 2
Land cover for the Galena River and Sinsinawa River Watersheds (CDM Smith, 2018).

USDA/NASS Land Use Cropland Category	Area (km^2)	Percentage
Pasture/Hay	306.24	35.95
Corn	248.08	29.12
Deciduous Forest	96.25	11.3
Soybeans	72.56	8.52
Alfalfa	37.09	4.35
Developed/Open Space	35.16	4.13
Open Water	18.13	2.13
Developed/Low Intensity	17.24	2.02
Woody Wetlands	7.68	0.9
Developed/Med Intensity	2.93	0.34
Grassland Herbaceous	2.68	0.31
Oats	2.44	0.29
Winter Wheat	1.25	0.15
Evergreen Forest	0.86	0.1
Herbaceous Wetlands	0.75	0.09
Shrubland	0.72	0.08
Developed/High Intensity	0.66	0.08
Barren	0.63	0.07
Other Hay/Non Alfalfa	0.39	0.05
Other	0.12	0.01
Total	851.87	100

Mining History

While some small operations existed likely as early as the mid-17th century, the majority of Pb and Zn mining in the UMVD took place from the 1820s until 1979 (Heyl et al., 1959). There were several well-known mining towns that formed during this period such as Mineral Point, Dodgeville, Platteville, and Dubuque; however, two-thirds of all the Pb and Zn ore coming out of the UMVD came out of Galena, IL and the Galena River Watershed (Heyl et al., 1959). At the peak of Pb mining in 1845 a quick decline began as easily found sources decreased and the gold rush in California drove many settlers away. After the start of the 20th century, Pb was primarily the byproduct of Zn mining operations. As Pb mining started to declined, the technology for Zn smelting became more readily available in the 1860s and Zn surpassed Pb production permanently in the late 19th century (Heyl et al., 1959; Knox, 1987). Zinc production remained high throughout the First World War but depletion of readily available ore and the Great Depression of the 1930s caused a steep decline in Zn mining from which the district would never recover. With only a short revival during the Second World War, all mining operations ceased in 1979 (Heyl et al., 1959; Knox, 1987; Brown et al., 2009).

Many of these abandoned mine locations were archived in the USGS report created by Heyl et al. (1959). The map and table below show 171 known abandoned mine locations in the Galena River Watershed and their estimated production. Production values were estimated from averages found in the USGS report (Fig. 10; Table 3). The majority of all mines (n=100) produced less than 100,000 Mg of ore overall; however, some of the largest mines produced greater than two million Mg. The tributaries with the largest number of historical mine locations is Shullsburg Branch at 44 mines (Heyl et al., 1959).

Mining Contamination of Channel and Floodplain Sediments (1992)

The following section will briefly discuss the contamination trends of Pb and Zn found in the Pavlowsky (1995) study (Appendix B). As expected, the highest concentrations of Pb and Zn were found in tailing piles throughout the watershed. Pavlowsky (1995) surveyed 15 different tailing piles of which the highest concentrations

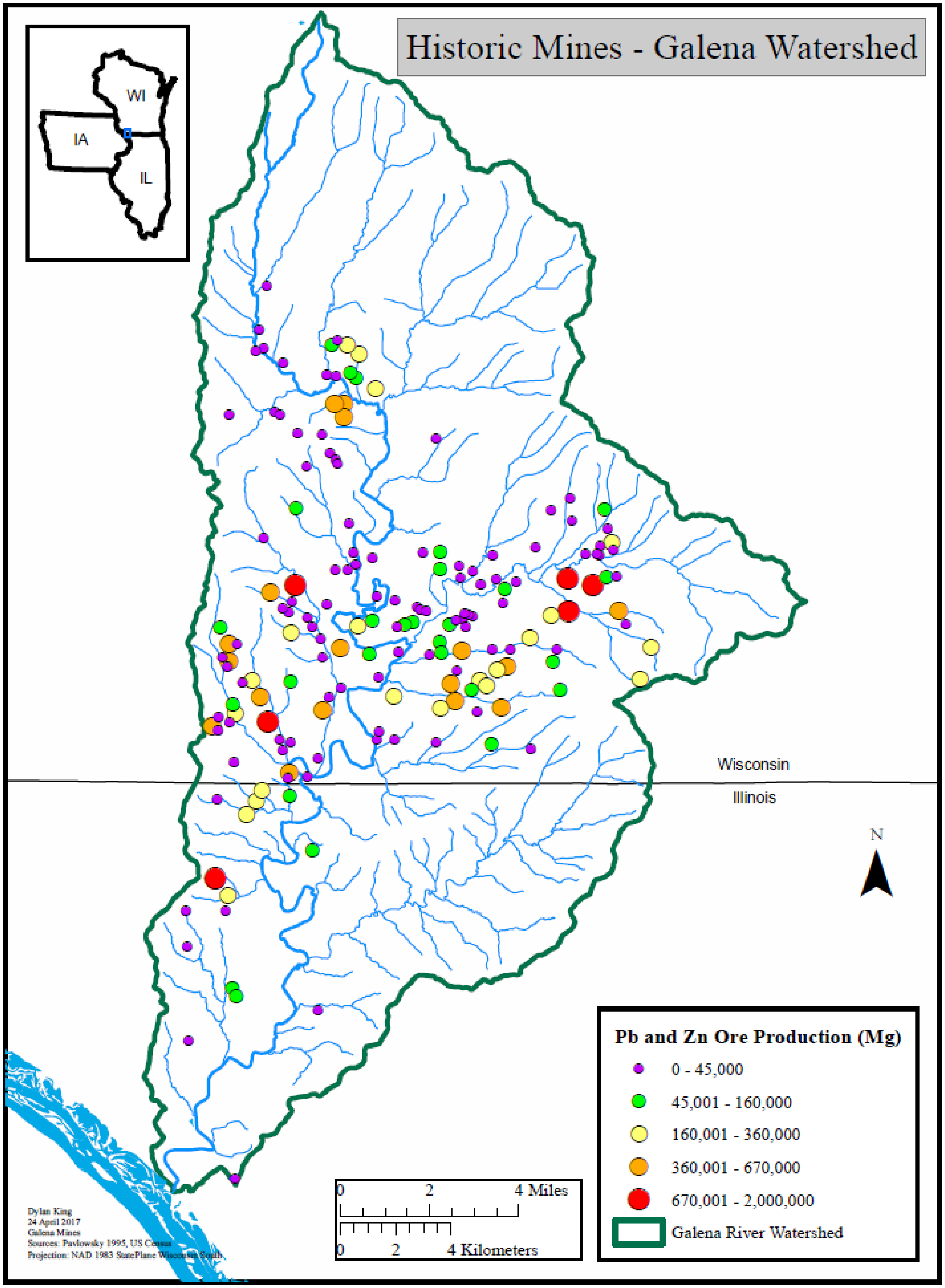


Fig. 10. Map of historic mine production in the Galena River Watershed.

Table 3
Number of mines based on estimated production of ore (Heyl et al., 1959).

Watershed	Total Mines	Estimated Production of Ore (Mg)							
		5,051	43,478	160,000	357,143	666,667	1,666,667	2,000,000	Total
Galena R.	50	17	17	6	5	4	0	1	8,237,376
Pats Cr.	3	1	1	1	0	0	0	0	208,529
Madden Br.	0	0	0	0	0	0	0	0	0
Blacks Cr.	3	1	1	1	0	0	0	0	208,529
Shullsburg Br.	44	15	14	7	4	1	0	3	9,899,696
Ellis Br.	12	2	3	3	2	2	0	0	2,668,156
Diggings Br.	10	0	1	2	4	3	0	0	3,792,051
Kelsey Br.	3	2	0	1	0	0	0	0	170,102
Coon Br.	17	7	5	0	1	3	1	0	4,276,558
Bull Br.	8	1	3	1	1	1	0	1	3,319,295
Scrabble Br.	13	4	3	2	1	3	0	0	2,827,782
Vinegar Hill	4	0	0	1	3	0	0	0	1,231,429
East Fork	0	0	0	0	0	0	0	0	0
Hughlett Br.	4	1	1	2	0	0	0	0	368,529

detected were found at Kennedy Mine at 85,913 ppm Zn and at DeRocher Mine at 3,220 ppm Pb. Kennedy Mine had one of the highest rates of production within the watershed at over 2,000,000 Mg overall (Heyl et al., 1959). The average of all tailing piles sampled for the Pavlowsky (1995) study is 21,378 ppm Zn and 1,036 ppm Pb.

The background level of Pb and Zn from unmined tributary channel sediments within the Galena River Watershed recorded for the Pavlowsky (1995) study was 146 ppm Zn and 40 ppm Pb. These concentrations represents the natural occurrence of Pb and Zn in the watershed (Church et al., 2000; Mast et al., 2000). The average concentrations for all recent channel sediments (mined or unmined) was 4,037 ppm Zn and 411 ppm Pb. The highest sediment Zn concentrations were from Vinegar Hill Tributary and the highest sediment Pb concentrations were from Ellis Branch (Table 4).

Floodplain samples from the Pavlowsky (1995) study were on average similar to those within channel sediments if not slightly higher. The average concentrations for floodplain samples was 5,839 ppm Zn and 811 ppm Pb. The highest soil Zn concentrations were from Scrabble Branch and the highest soil Pb concentrations were from Ellis Branch (Table 5).

Remediation

As of close in 1979, the Shullsburg (Eagle Picher) Mine, located just south of Shullsburg, WI, has been required to follow the 1974 Wisconsin metallic mining remediation regulations (Brown et al., 2009). Starting 1995, the remediation of the remaining land began by the operator Terra Industries. The remediation project is still active today.

Table 4
Average recent channel sediment concentrations (1992).

Reach	n	Fe	Mn	Zn	Pb	OM
Upper Galena R.	14	17,858	1,088	486	70	5.2
Mid Galena R.	12	19,255	1,049	3,223	184	3.3
Lower Galena R.	6	20,258	1,025	2,685	215	4.5
Pats Cr.	5	19,817	1,252	645	41	5.0
Madden Br.	11	17,848	1,208	194	38	5.8
Blacks Cr.	1	35,958	1,426	1,159	124	5.0
Shullsburg Br.	19	25,225	1,510	2,427	421	4.7
Ellis Br.	14	26,131	1,193	6,499	685	4.3
Diggings Br.	11	37,383	996	10,270	427	3.2
Kelsey Br.	4	13,935	948	427	83	5.2
Coon Br.	6	56,819	1,045	5,881	648	3.6
Bull Br.	6	26,342	1,507	4,657	250	4.2
Scrabble Br.	3	23,127	850	4,646	337	5.8
Vinegar Hill	6	25,515	1,282	18,205	292	3.7
East Fork	5	19,364	1,026	396	127	4.9
Hughlett Br.	4	13,910	984	689	158	3.8
Total	127	25,633	1,223	4,037	411	4.4

Table 5
Average surface overbank floodplain soil concentrations (1992).

Reach	n	Fe	Mn	Zn	Pb	OM
Upper Galena R.	6	14,953	783	579	46	4
Mid Galena R.	9	17,570	927	1,857	285	4
Lower Galena R.	2	21,053	1,008	2,530	228	3
Shullsburg Br.	5	22,225	840	2,148	714	4
Ellis Br.	2	33,355	1,017	10,693	1,293	4
Coon Br.	6	36,316	913	4,851	903	4
Bull Br.	2	32,050	1,175	2,810	1,425	3
Scrabble Br.	1	33,897	987	19,825	1,236	3
Total	33	23,748	912	3,392	574	4

Other recent remediation projects (last 25 years) reported in government documents include the consolidation project of Champion Mine (2007) on Diggings Branch, Vinegar Hill EPA Superfund site at Inspiration and nearby Little Giant, and a few other large operations such as Graham-Snyder, Graham-Ginte, Cuba City, and West Blackstone (Table 6) (Reinertsen, 1992; WDNR, 2001; WDNR, 2008; Brown et al., 2009; EPA, 2018a; EPA, 2018b). The following figures briefly show locations of remediated sites and reductions and removals of mine waste (Fig. 11) as well as remaining mine waste including examples within 100 m of a stream (Fig. 12). Given there have been several remediation efforts over the past 25 years it would be beneficial for local and federal government agencies to know the effects of remediation on the reduction of Pb and Zn within the watershed.

Table 6
List of government documented remediation projects in the past 25 years in the Galena River Watershed.

Mine Name	Affected Stream	Type of Remediation	Source
Champion	Diggings Br.	Consolidation	WDNR, 2008
Cuba City	Coon Br.	Removal	WDNR, 2001
Eagle Picher	Shullsburg Br.	Ongoing	Brown et al., 2009
Graham-Snyder	Galena R.	Removal	Reinertsen, 1992
Graham-Ginte	Galena R.	Removal	Reinertsen, 1992
Inspiration	Vinegar Hill	Ongoing	EPA, 2018a
Little Giant	Vinegar Hill	Ongoing	EPA, 2018b
West Blackstone	Shullsburg Br.	Removal	WDNR, 2001

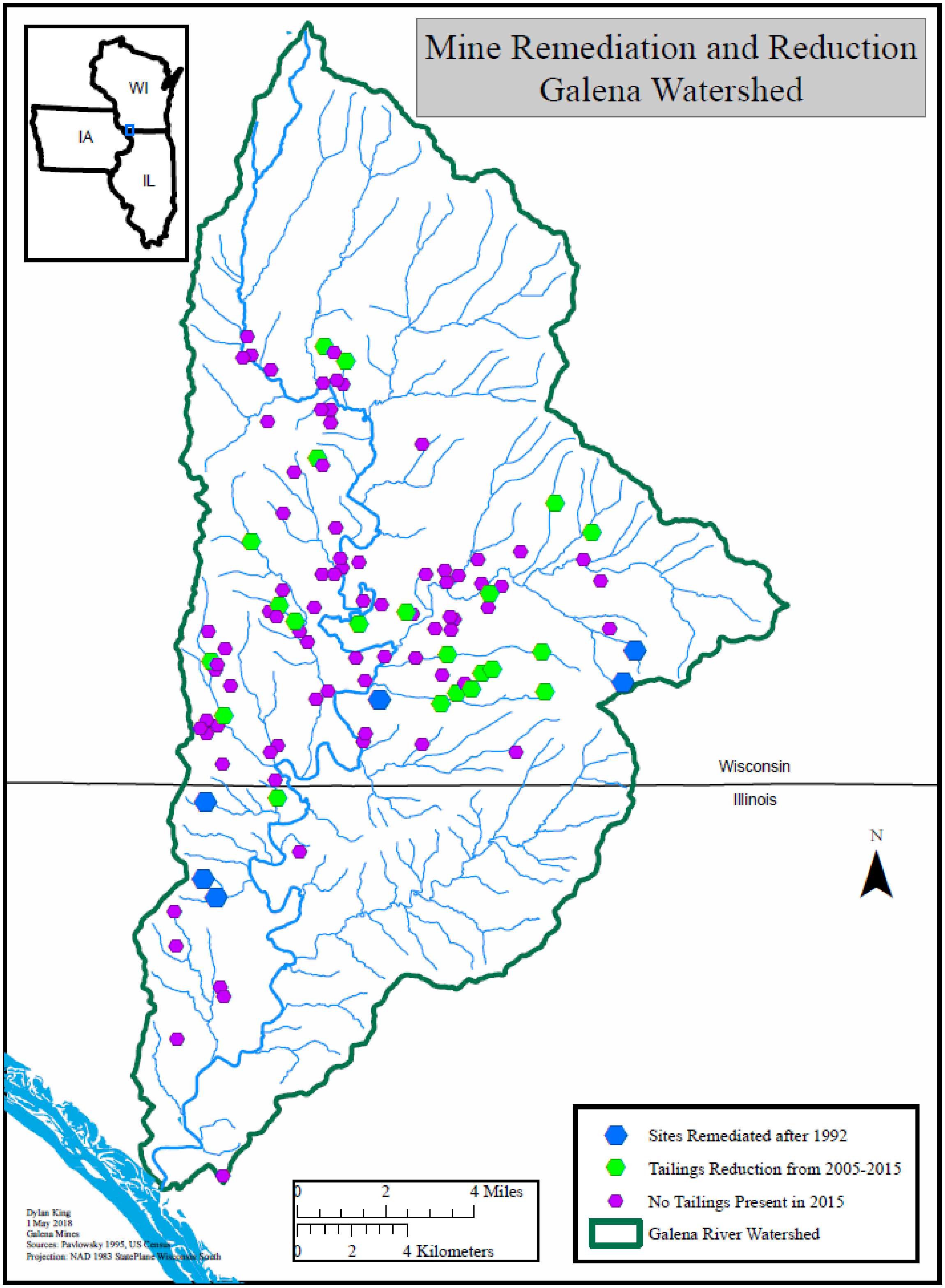


Fig. 11. Map of remediated mine sites, reductions, and removals (Heyl et al., 1959).

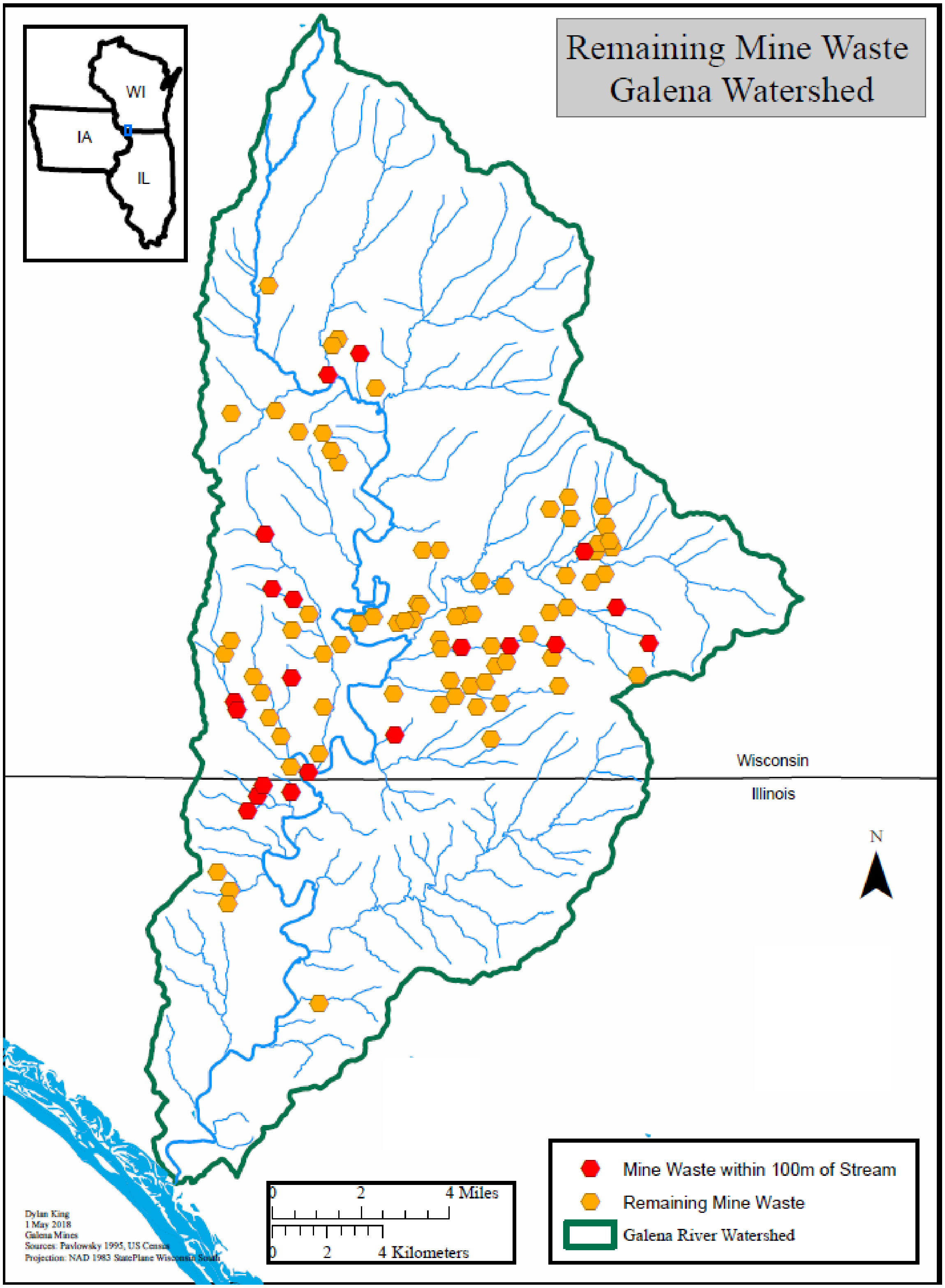


Fig. 12. Map of remaining mine waste. Red symbols indicate waste within 100 meters of stream (Heyl et al., 1959).

CHAPTER 3 – METHODS

The field and, to a lesser degree, laboratory methods used for this thesis project were based on those used by Pavlowsky (1995). Geospatial data were collected and analyzed to approximate modern day conditions and compare the location of 2017 samples to those from 1992. Based on sample sites from 1992, samples were collected in field and returned to the Ozarks Environmental and Water Resources Institute (OEWRI) laboratory (oewri.missouristate.edu) at Missouri State University for further analysis. These results were added to the new Galena River Watershed database and statistically analyzed for geochemical, spatial, and temporal relevance.

The Pavlowsky (1995) study dataset was used as a guide to locate locations for resampling as well as previous mine locations within the watershed. This dataset includes the sediment concentrations of Zn, Pb, Fe, and Mn as well as OM% for each sample and several tailing piles. Any data or information obtained about mine location and production recorded in the Pavlowsky (1995) study was originally obtained from a USGS report prepared by Heyl et al. (1959) discussing the geology of the UMVD. The concentrations and spatial data from 25 years ago was analyzed and compared to the newly obtained 2017 field data to determine trends and create several different maps and graphs displaying the findings of this research (Xiao and Ji, 2007).

Geospatial Data and Analysis

ESRI ArcGIS software was used to conduct remote sensing based analyses, compare heavy metal concentrations with area, distances, and spatial location, and map the final project to display the results. The first step was to geolocate hand-mapped sampling locations from 7½ quadrangle maps that were recorded in the early 1990s by Pavlowsky (1995). Using USGS quadrangle digital downloads, sample sites and mine locations were digitized into the new Galena River Watershed GIS database (USGS, 1952). Township and range coordinates tabulated in Pavlowsky (1995) were also used to locate the previous sampling sites. In addition, supporting information such as roads and state boundaries were obtained from the TIGER/Lines database on the United States Census Bureau website (USCB, 2017). This information helped with in field navigation during sampling and later digital display of the results. In addition, a digital elevation model (DEM) of the Galena River Watershed was obtained from the USGS EarthExplorer website and used to delineate the Galena River Watershed (NASA and METI, 2011).

Lastly, data was obtained to analyze mine location and changes to remaining waste over the past 25 years. SSURGO soil data obtained from the United States Department of Agriculture was used to reference soil types within the watershed and locate areas denoted as mine waste (NRCS, 2017). The original soil survey was published in Grant County in 1961, Lafayette County in 1966, and Jo Daviess in 1996. While the Illinois soil survey in Jo Daviess is more representative of the Pavlowsky (1995) study findings, the Wisconsin soil survey will represent soil features in the 1960s around 40 years prior to the Pavlowsky (1995) study. In the soil survey, mine wastes, tailings, and disturbed soil were mapped with the symbol, Mp (NRCS, 2017).

Aerial imagery was used to verify mine location and condition as a potential pollution source. Several image files were obtained from both Wisconsin View and the

Illinois State Geological Survey for both the year 2005 and the year 2015 (ISGS, 2015a; ISGS, 2015b; WVI, 2015a; WVI, 2015b). Tailing pile presence was noted for each year and change was recorded. Using both SSURGO and aerial imagery a general idea of mine waste cleanup from the 1960s to present can be analyzed and compared to the results of the sediment concentration analysis. In addition to the aerial image analysis, several different sources were contacted within the WDNR, IDNR, EPA, and local governments at county level to obtain any information about remediation within Grant, Lafayette, and Jo Daviess Counties.

Field Methods

Sampling was completed by four 2-4 person teams over three days in July 2017 to obtain samples from the original 153 sites from the Pavlowsky (1995) study (Fig. 13). Field maps were created to guide sampling teams to 1992 sample sites. Overall, 124 sites were revisited and both channel and floodplain samples were collected. There were five new sites sampled along several different tributaries. In addition, 12 new sites were sampled along the Lower Galena River and 14 tailings pile samples were collected.

At each site at least three samples were collected using a shovel at no more than five cm deep (Appendices A7, A8, and A9). Two sample duplicates were collected from within five m along the stream segment point bar. Samples from these locations represent recently active sediment temporarily stored and remobilized during seasonal flood events (124 sites sampled, total of 242 samples) (Pavlowsky, 1995). A third sample was collected from the bank-top of the bench or low floodplain deposits (114 samples obtained). Duplicates from recent channel sediments will be compared to the

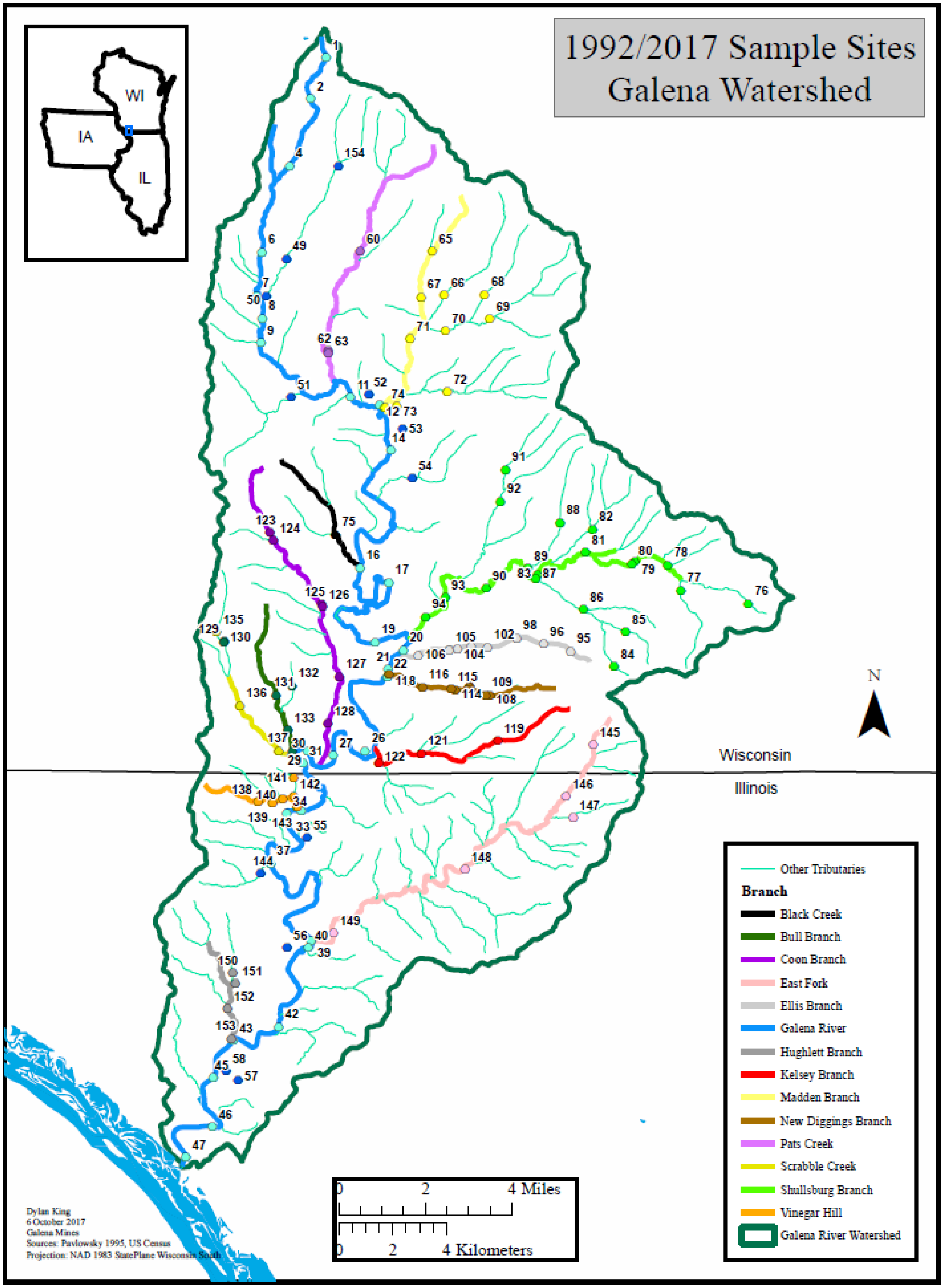


Fig. 13. Map of the sample sites from the Pavlowsky (1995) study collected from in 2017.

first to determine precision of sampling using relative percent difference (RPD) as well as the variation of concentrations located within the point bar sampled.

Samples collected from the Lower Galena River required a canoe and an Eckman-dredge type sampler to retrieve sediments from the bottom. Additional samples were also obtained from fine-grained deposits along the lower bank surfaces above the low waterline. All samples collected in the field were GPS located and placed into a quart sized Ziploc freezer bag and returned to the OEWRI laboratory in Springfield, MO.

Channel characteristics were recorded for future use to better understand the geomorphology of the channel (Appendices C1, C2, and C3). Channel depth, width, and bank height were all recorded to form a generalized cross-section of the sample site. The condition of the banks at each site were also recorded to determine the effects of erosion on the river's banks including tree debris that may be protecting a bank from erosion. Any visible PSA found within river banks was described.

Laboratory Methods

All samples were analyzed in the OEWRI laboratory located at Missouri State University (oewri.missouristate.edu). Each sample bag was opened and drained to let air dry overnight. The samples were dried in heating ovens at 60°C. Depending on the level of saturation, some samples remained in the oven for several days. Once dried, each sample was disaggregated with mortar and pestle and put through a 2-mm sieve to be used for further analysis (OEWRI, 2007b).

XRF Analysis. All samples from the original sample sites and the Lower Galena were analyzed using an x-ray florescence (XRF) analyzer (X-MET3000TXS+) that has been calibrated to determine Zn, Pb, Fe, Mn, and Ca concentrations within sediments and soils (OEWRI, 2007b). A total of 39 samples during this analysis fell below the level of Pb detection by the XRF. For these samples, they will be known as non-detect (ND) and assumed to have a concentration of 15 ppm Pb.

For XRF analysis each <2 mm sample was placed in a small metal-free bag, which was then placed in a Pb box and activated with x-ray radiation for 90 seconds to determine the concentrations of metals in the sediment. In order to stay consistent with testing, three standards with known concentrations were used before and after a set of samples including a blank to assure the instruments performance. Standards were used every ten samples. Every tenth sample was analyzed twice as a laboratory duplicate. Laboratory accuracy for all samples had very low coefficient of variation (Cv%) with almost all samples below 10% excluding Mn which had an average Cv% of 40%. The precision for all metals on average remained below 10 Cv% resulting in little variation between laboratory duplicates.

Aqua-Regia Analysis and Ratio Corrections. A subset of 33 samples was sent to the ALS Global Laboratory in Reno, NV to verify XRF results and expand the range of metals evaluated for this study. The samples were digested using an aqua-regia solution made of 3:1 nitric acid and hydrochloric acid and analyzed by inductively coupled plasma-atomic emission spectrometry (ALS, 2009). This method was similar to that used to determine sediment metal concentrations by Pavlowsky (1995). Therefore, converting XRF values to representative aqua-regia values should improve the accuracy of site comparisons between the 1992 and 2017 sediment studies.

Relationships between XRF and aqua-regia analyses were evaluated for each metal in two ways. First, correlating XRF values to other routine analyses is a standard procedure for validating XRF results (EPA, 1998). Following, aqua-regia over XRF concentration regression equations indicated strong linear trends for all metals with a power function (log-log regression) producing the best results with the following R^2 values: Pb, 0.966; Zn, 0.947; Fe, 0.929; Ca, 0.859; and Mn, 0.823. Log-Log regression generally explained 17% and 24% more variance compared to arithmetic/linear equations for Zn and Pb, respectively.

A second method was used in this study to correct XRF concentrations to predicted aqua-regia values based on regression equations between the XRF metal concentration and the ratio between the paired aqua-regia and XRF concentrations (not the aqua-regia concentration itself). This procedure can produce more accurate results for non-linear relationships that may develop over wide ranges of geochemical concentrations spanning several orders of magnitude as involved in this study. In addition, the original spatial variability of sediment geochemistry is maintained in the corrected data set, rather than reducing the natural variability of the sample to a single linear trend line (Pavlowsky et al., 2017).

Regression equations between XRF concentrations and aqua-regia: XRF ratios were developed for this study to convert sediment XRF results to aqua regia-based values (Table 7). The raw or original XRF concentration was multiplied by the ratio value predicted from the equation. In some cases, such as with Ca and Fe, a single “best-fit” ratio value was prescribed based on curve-fitting and error evaluation judgements. Comparisons of measured and predicted aqua-regia concentrations tend to plot close to a

Table 7
Aqua-regia/XRF ratio equations used for correction of XRF data.

Metal	XRF Range	Aqua-Regia: XRF Ratio			Ratio value over XRF regression equations		
		n	mean	Cv%	n	equation	R^2
Pb	all	33	1.10	30	32	Ratio = 2.30 * RawXRF ^ -0.145	0.493
Zn	all	33	1.36	80	33	Ratio = 3.25 * RawXRF ^ -0.138	0.315
Fe	all	33	0.87	12		single ratio value of 0.87 used for all values	
Mn	all	33	1.03	16	32	Ratio = 1.27 - 0.0002 * RawXRF	0.412
Ca	<90,000 ppm	28	1.59	23		single ratio value of 1.59 used	
Ca	>90,000 ppm				4	Ratio = 2.20 - 0.000008 * RawXRF	0.807

1:1 trend with relatively low errors, typically in the range of ±20%. For Zn, the RPD values (i.e., predicted - measured/measured x 100) had a median of 9% ranging from a 25%-tile value of -6% to a 75%-tile value of 31% (Fig. 14). For Pb, the RPD values had a median of 5% ranging from a 25%-tile value of -10% to a 75%-tile value of 11% (Fig. 15).

LOI Test. Loss on ignition (LOI) is a laboratory test used to determine percent OM for each sample tested. Organic matter is strongly correlated with clay sized particle, both of which have high surface areas and tend to absorb free heavy metal ions during transportation (Lecce and Pavlowsky, 2004). Lead and Zn associated with OM may have a higher chance to be transported further downstream. LOI is a test that ignites the OM in a muffle furnace to determine CO_2 weight loss by ignition. The LOI method used here is based on Sparks (1996) and the OEWRI standard operating procedures manual in which five gram samples are ignited at 600°C for eight hours (OEWRI, 2007a).

Laboratory duplicates were taken for LOI testing during every burn (OEWRI, 2007a). Each burn could hold one rack which contained anywhere between 13-15 crucibles. On each rack there would be one duplicated sample to determine the precision of LOI testing. The average precision of all the duplicated samples is 1.3 Cv%. This means overall there was very little variation between all duplicated crucibles. There were a total of only four sets of duplicates yielding Cv% values between 10-20 Cv% while other 29 sets were all <10 Cv%.

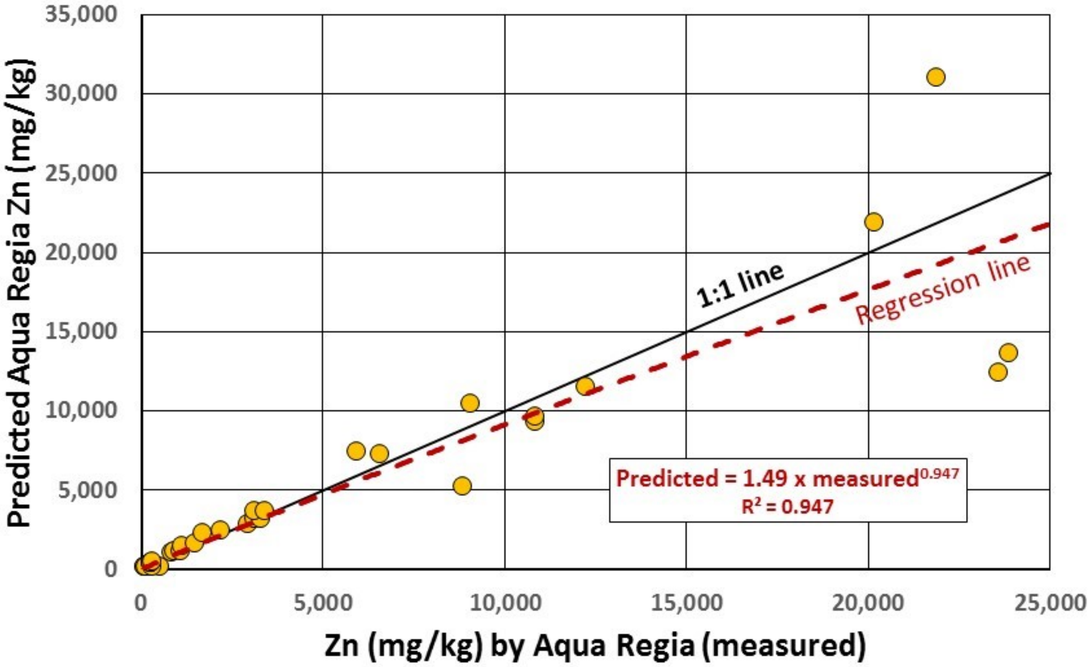


Fig. 14. Comparison of measured and predicted Zn concentrations using ratio correction method.

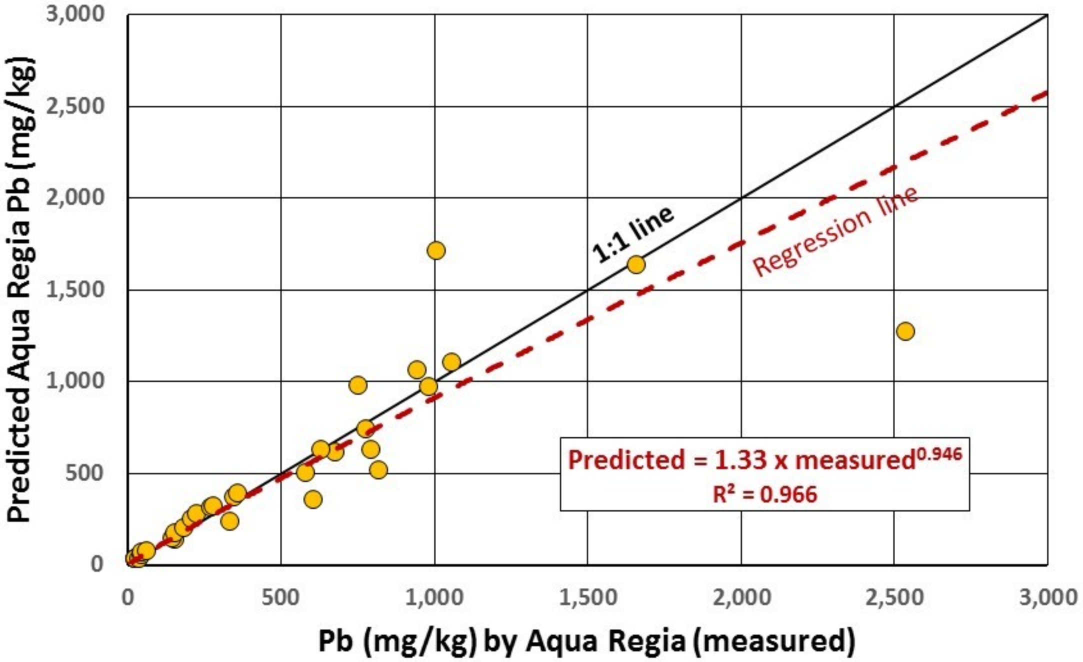


Fig. 15. Comparison of measured and predicted Pb concentrations using ratio correction method.

Statistical Analysis

Several different statistics were conducted on the results from the 2017 field and laboratory samples as well as the 1992 database. Pearson's correlation was used on the different variables of different segments of the watershed to determine strength and direction of the relationships between Pb, Zn, Fe, Mn, Ca, and OM (Carnahan et al., 2008; Navarro et al., 2008). In addition, regression models may also be normalized using other variables such as OM, Fe, and Mn to determine their effect on the overall concentrations and trends (Horowitz, 1991).

Finally, an overall paired t-test sample sets by tributaries will be conducted on both sample concentrations between 1992 and 2017 as well as locations below mine sites to determine the significance of remediation effects on sediment metal concentrations (Acosta et al., 2011; Mehrabi et al., 2015). The hypothesis for this test will be that there has been no change over the past 25 years. The test will either reject the null hypothesis that there has been a significant change to Pb and Zn concentrations over the past 25 years or it will fail to reject it meaning there is no significant evidence to say there is any difference between the two means. Each test will use the 95% confidence interval.

CHAPTER 4 – RESULTS AND DISCUSSION

During field work in July 2017, 415 sediment samples from stream channels (n=270), floodplains (n=121), and tailings piles (n=24) were collected and later analyzed at the OEWRI Laboratory at Missouri State University (oewri.missouristate.edu). Repeat samples occurred at 124 sites from Pavlowsky (1995) (Appendix B). Duplicates (n=135) were taken at channel sediment sites to evaluate the precision of field procedures and results. Further, 12 additional sites were collected from the Lower Galena River (below the East Fork) and 7 sites from the Harris Slough. The Harris Slough sample results are not discussed in great depth in this thesis.

Overall, the precision of channel geochemistry and OM analyses was good, typically below 20-30% RPD (Appendix D). Only Madden Branch, Kelsey Branch, East Fork, and Hughlett Branch were above 30% median RPD for Pb and Hughlett Branch for Zn. For Pb, 33% of branches were below 10% RPD median, 46% were between 10% and 30% RPD, and 15% were above 30% RPD. For Zn, only 7% of branches were below 10% RPD, 87% were between 10% and 30%, and 7% were above 30% RPD. For the rest of the metals analyzed only Mn for Scrabble Branch was above 30% RPD. For Mn, Ca, and OM almost all branches were between 10% and 30% with Ca completely between these two values. For Fe, 73% of branches were below 10% RPD.

There were typically three conditions that caused relatively high relative variability of Zn and Pb concentrations among the tributary segments. First, streams with low mean values will tend to have higher relative error (Madden Branch Pb = 94% RPD; East Fork Pb = 51% RPD). Second, low sample size will increase error since standard deviations will tend to be larger (Kelsey Branch Pb = 42% RPD). Finally, some stream segments have both heavily contaminated reaches and relatively less contaminated reaches reflecting the spatial variability of non-uniform sediment mixing from both mining and background sources (Hughlett Branch Zn = 51% RPD).

Metal Concentrations in Sediments and Tailing Samples (2017)

Tailing Materials and Background. The primary source of pollution to stream sediments within the Galena River Watershed is tailing materials created from the milling process of historical mining operations (Heyl et al., 1959; Knox, 1987; Pavlowsky, 1995). Concentrations within tailing piles of Pb (max=2,342 ppm), Zn (max=31,500 ppm), Fe (max=193,657 ppm), Mn (max=1,823 ppm), and Ca (max=151,523 ppm) are greatly elevated in comparison to channel and floodplain samples (Table 8; Appendix E). Generally Pb and Zn will be relatively concentrated in tailing piles as a result of Pb and Zn mining while high concentrations of byproducts such as Fe and Mn are also found within tailing piles. Calcium concentrations are also very high as a result of the primary tailing material being dolomite (21% Ca) with some calcite (40% Ca) (Adams, 1944).

The variability between tailing pile samples is high for both Pb and Zn samples (Table 9). When taking a sample from a tailing pile, the concentration can greatly change depending on location and depth. For this reason, samples from tailings cannot accurately represent trends downstream (Pavlowsky, 1995). However, tailing samples can still show examples of high concentrations representing a source material for contamination throughout the watershed mixing with background concentrations.

On the other hand, background levels are represented by unmined tributaries

Table 8
Tailing pile averages in 2017.

Mine Name	Pb	Zn	Fe	Mn	Ca	OM%
Blackstone	1,371	28,157	51,129	1,105	143,400	3.59
Century	922	5,163	62,292	1,143	67,659	5.89
Champion	463	12,081	68,653	1,592	144,406	4.74
Federal	959	22,292	62,422	1,190	151,523	4.86
Hoskins	499	10,448	40,754	1,206	136,589	2.88
Kennedy	552	12,183	73,488	1,823	75,474	3.69
Little Dad	1,243	19,994	45,366	1,023	151,070	4.73
Little Giant	2,037	20,972	62,680	1,270	121,519	5.68
Lucky Twelve (1)	316	9,651	42,955	1,271	146,436	3.75
Lucky Twelve (2)	1,141	17,315	193,657	980	112,951	4.79
Monroe-Longhorn-Little Joe	2,342	28,520	48,503	1,111	130,081	3.50
Old Ida Blende	705	31,500	162,742	1,445	77,403	6.57
Sally Waters	946	25,544	43,396	1,251	145,381	2.59
Vinegar Hill	1,474	27,866	84,137	1,217	146,403	6.76

Table 9
Variability of average tailing pile samples.

Metal/OM	25%	50%	75%	25%-75%	Mean	SD	Cv%
Pb	590	953	1,339	749	1,069	591.9	55.36
Zn	12,106	20,483	27,286	15,179	19,406	8,388.5	43.23
Fe	46,150	62,357	72,280	26,130	74,441	46,176.8	62.03
Mn	1,119	1,212	1,271	152	1,259	226.2	17.97
Ca	115,093	139,995	146,148	31,055	125,021	30,070.4	24.05
OM%	3.61	4.73	5.48	2	4.57	1.3	28.64

within the watershed. The only two tributaries that do not have records of historical mining operations are Madden Branch and East Fork. The average Pb concentrations for Madden Branch and East Fork are 33 ppm and 267 ppm respectively and for Zn concentrations are 244 ppm and 656 ppm respectively. Madden Branch better represents background levels while other external sources could be causing higher concentrations within the East Fork (i.e. roads and rails) (Adams, 1944).

Channel Sediments. Both Pb (max=1,622 ppm) and Zn (max=16,428 ppm) concentrations are extremely high within channel sediments from the Galena River Watershed (Figs. 16 and 17; Appendix F). For Pb concentrations, the highest average occurs in Coon Branch (731 ppm) and for Zn concentrations the highest average occurs in Diggings Branch (7,797 ppm). Metal concentrations within each tributary can also vary greatly depending on proximity to the nearest mine location as well as the density of mine locations and the watershed area (Marcus, 1987; Pavlowsky, 1995). For this reason, the Cv% of most large streams for Pb and Zn samples are high (i.e. Ellis, Diggings, Coon, Bull, Scrabble, Vinegar Hill).

Other concentrations analyzed such as Fe (max=116,036 ppm), Mn (max=1,990 ppm), and OM content (max=23.9%) have a much lower Cv% and have a more consistent spatial distribution throughout the watershed (Figs. 18, 19, and 20). The highest average concentrations for Fe was found in the Coon Branch (60,077 ppm), Mn in Bull Branch (1,382 ppm), and OM content in Vinegar Hill Tributary (9.0%). The Fe outlier in Coon Branch is a result of a historical roaster pile located near Cuba City and the headwaters of the Coon Branch causing acid mine drainage and the transport of rich Fe sediment from the processing plant to tailing piles and mill effluents that ultimately entered the stream system (Fig. 18) (WDNR, 2001). Even though this roaster pile is now removed, there are still high Fe concentrations today (Appendix A10). Another anomaly includes the high OM content in Vinegar Hill. For Fe, Mn, and OM content, Vinegar Hill has one of the highest Cv% while other tributaries are mostly below 30%. The maximum at Vinegar Hill is likely an outlier causing a high average or a sample taken in error that is resulting in a great Cv% for Fe, Mn, and OM content.

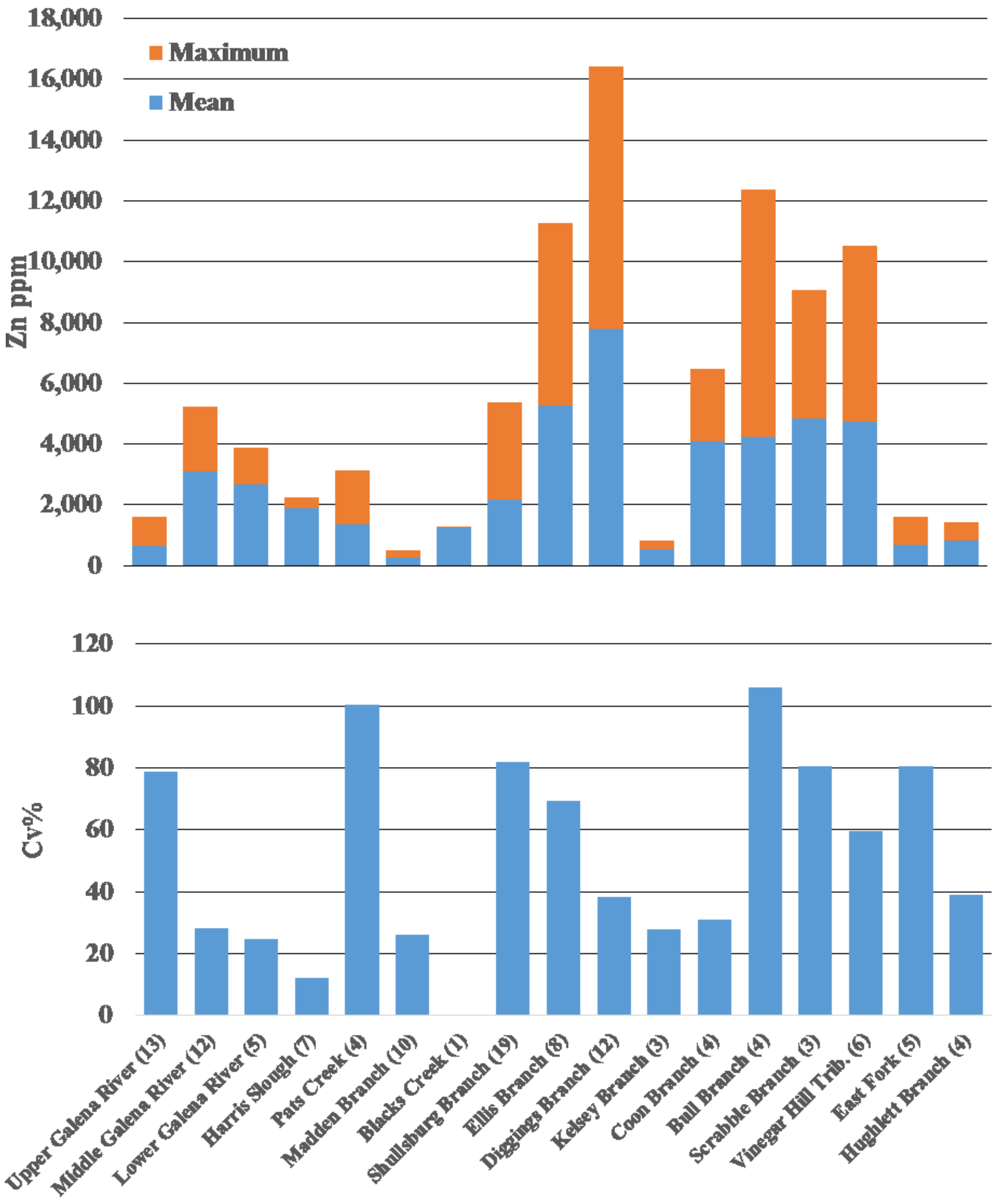


Fig. 16. Average concentrations of Zn by branch averages and Cv%.

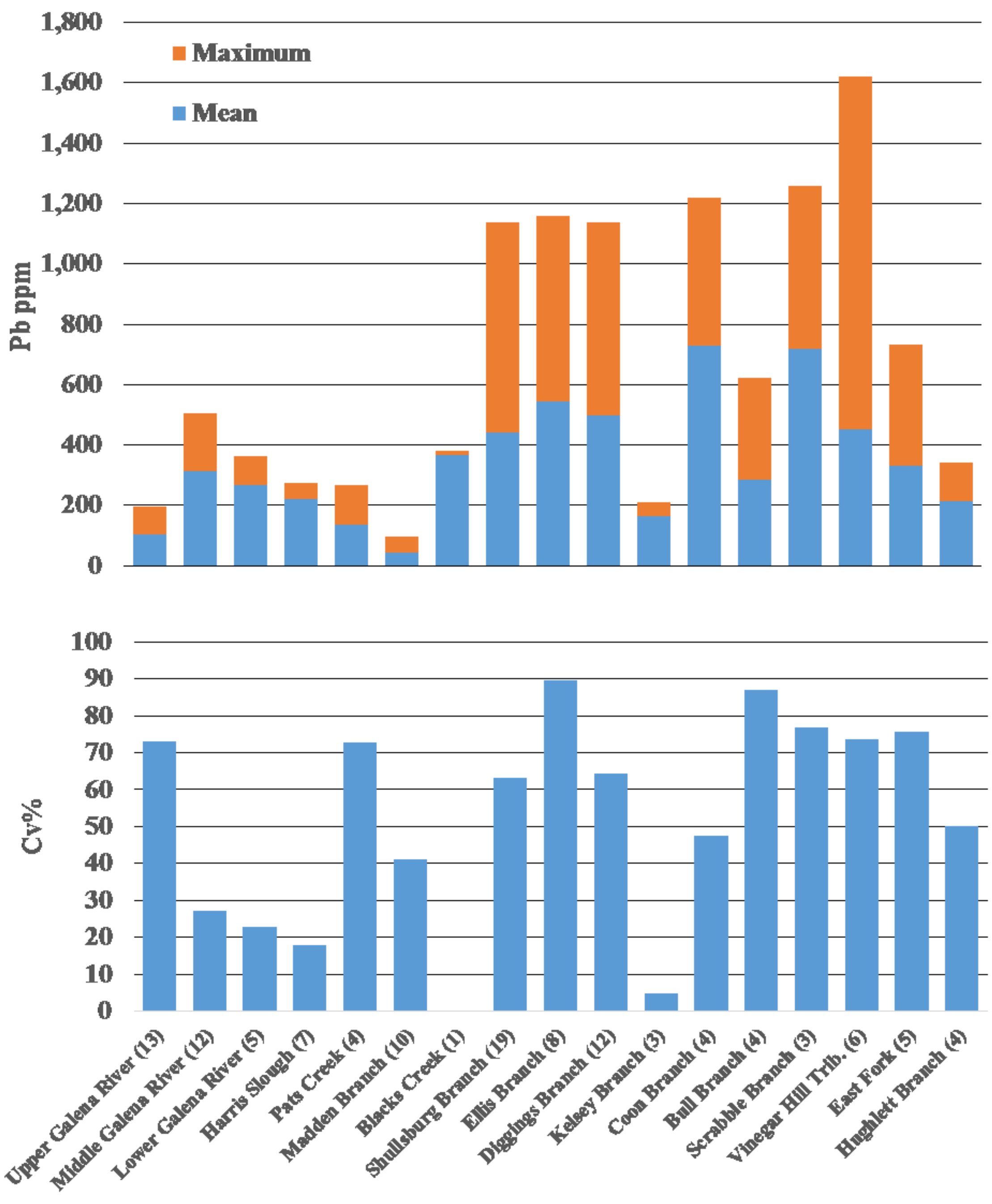


Fig. 17. Average concentrations of Pb by branch averages and Cv%.

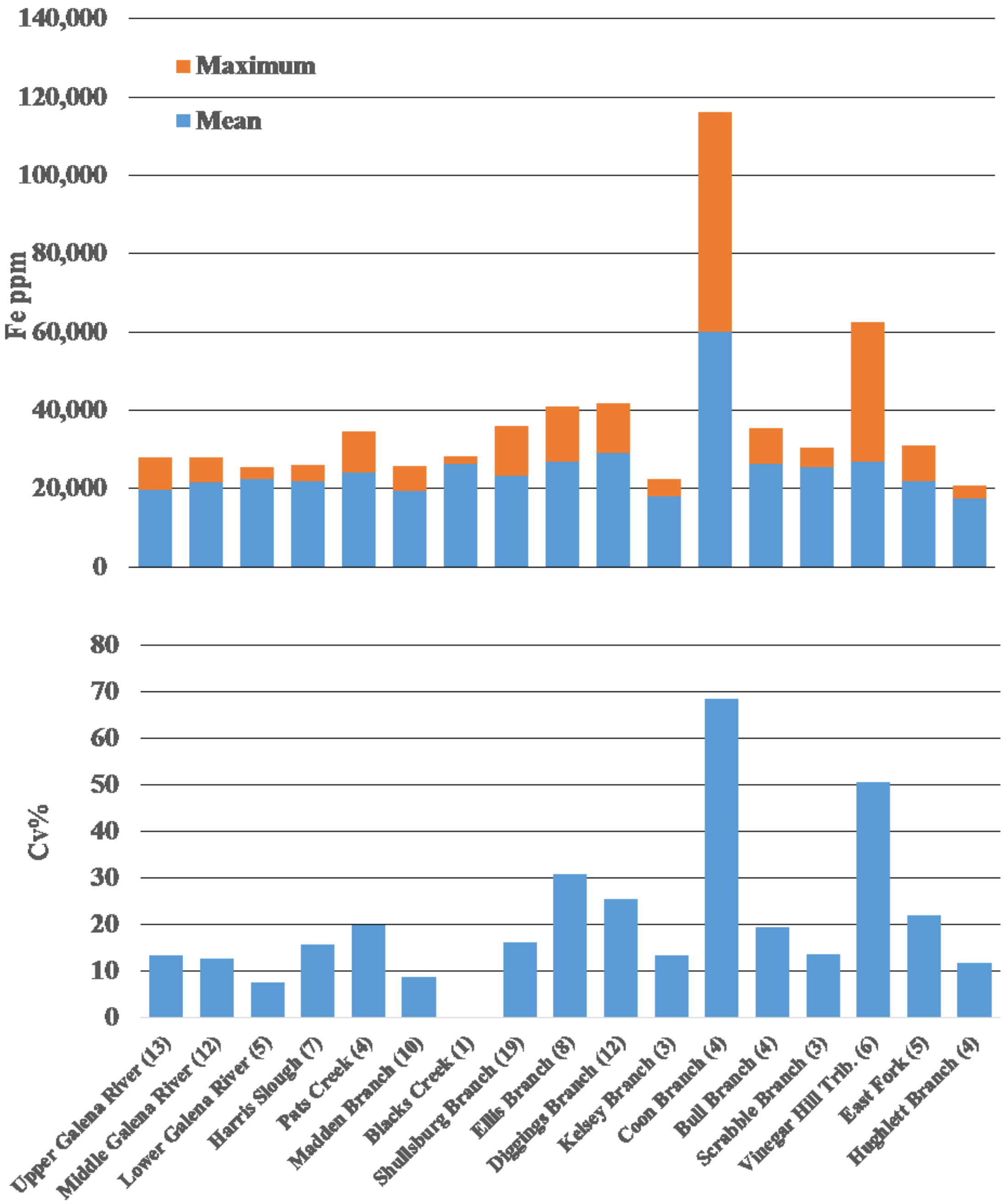


Fig. 18. Average concentrations for Fe by branch averages and Cv%.

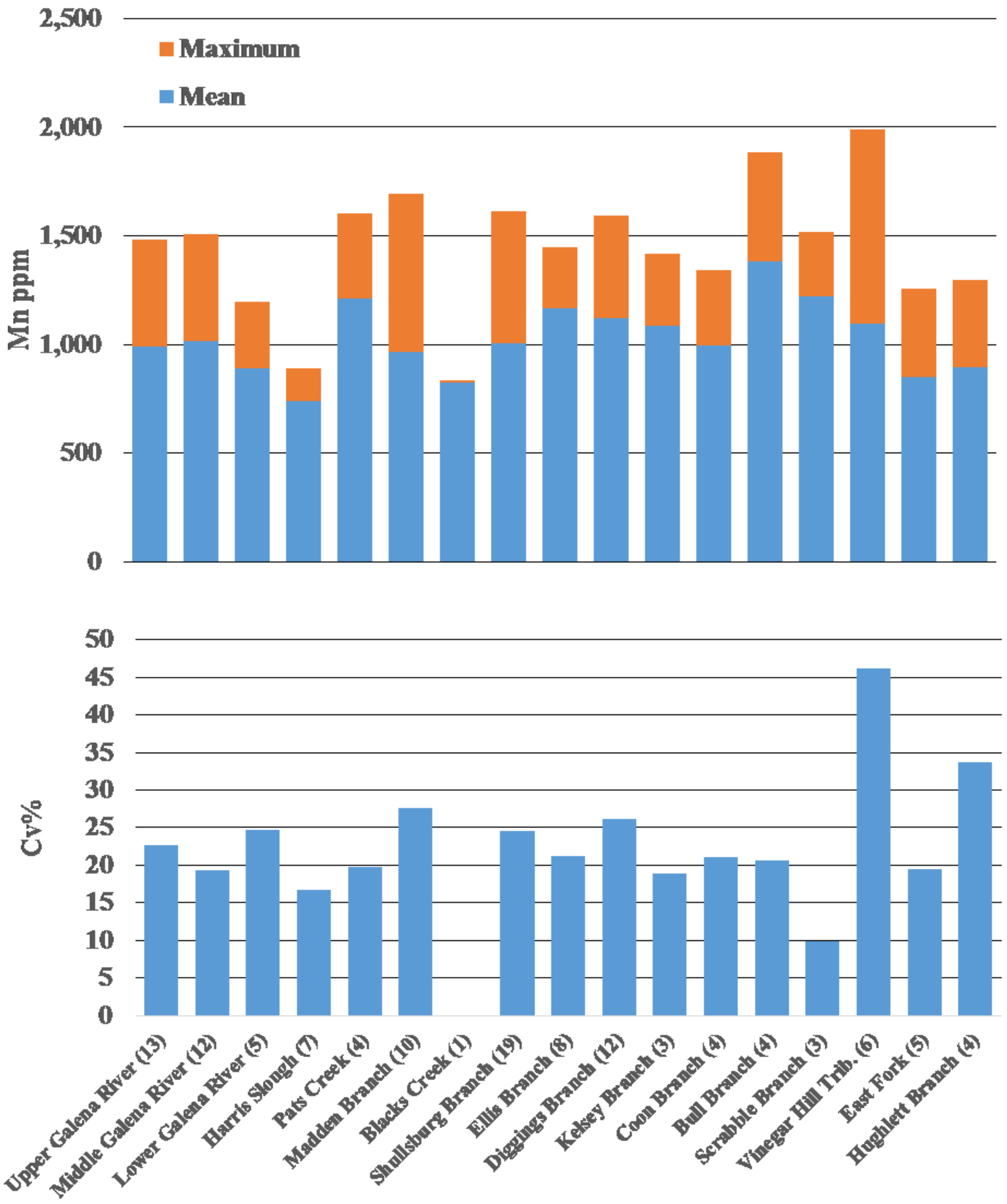


Fig. 19. Average concentrations for Mn by branch averages and Cv%.

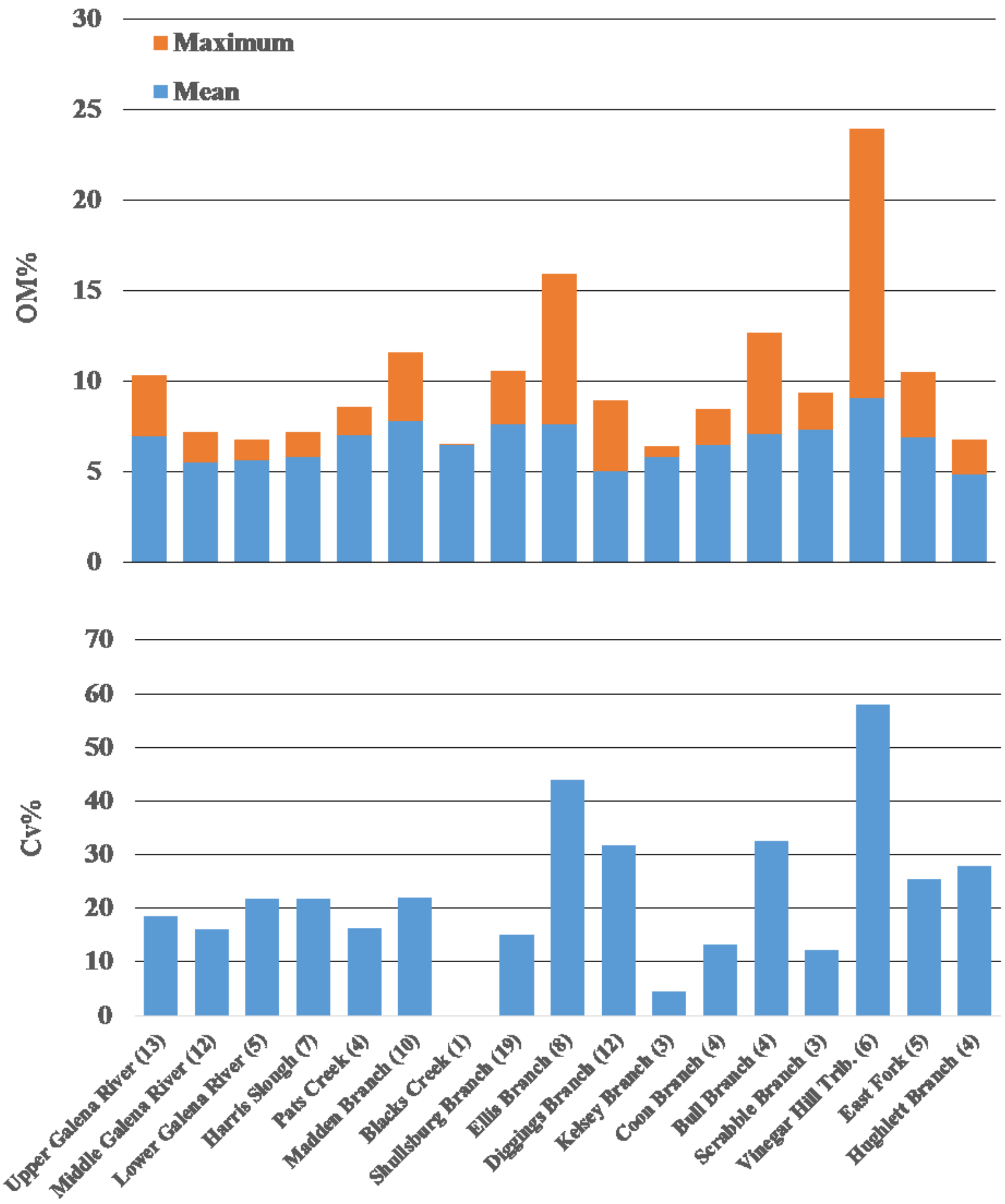


Fig. 20. Average OM% by branch averages and Cv%.

Calcium concentrations (max=150,669 ppm) are similar in trends to those of Pb and Zn (Fig. 21). The highest average for Ca was found in the Ellis Branch (102,908 ppm). The highest concentrations of Ca are found near tailing piles due to the high Ca content of dolomitic bedrock within the tailings (Adams, 1944). For this reason, the source of Pb and Zn is strongly associated with Ca concentrations (Pavlowsky, 1995). Similar to Pb and Zn, Ca also has a wide variation in Cv% throughout the watershed.

In addition, seven sites were sampled in the Harris Slough of the Mississippi River near the confluence of the Galena River as a pilot project with the University of Wisconsin – LaCrosse (Appendix G). Averages for Pb (221 ppm), Zn (1,906 ppm), Fe (22,019 ppm), Mn (738 ppm), Ca (32,016 ppm), and OM content (5.8%) were calculated for the slough. For all metals, the Harris Slough average is slightly lower than the Lower Galena average yet remains well above background levels (Appendix H). As a result, contaminated sediments from the Galena River Watershed may be responsible for recent contamination as well as historical contamination of the Mississippi River's backwaters, sloughs, and wetlands.

Channel versus Floodplain Bank Samples. The floodplain samples collected from nearby banks are very similar in concentrations to those samples retrieved from the channel bed (Appendices F, I, J, and K). Floodplain and channel samples collected at the same site are strongly correlated with each other using a logarithmic regression line (Table 10; Figs. 22 and 23). For Pb, the logarithmic formula is $y=0.632x^{1.071}$ with R^2 value of 0.899 and for Zn the logarithmic formula is $y=1.047x^{0.9771}$ with a R^2 value of 0.918 (y = floodplain Pb or Zn; x = channel Pb or Zn). This trend indicates almost a

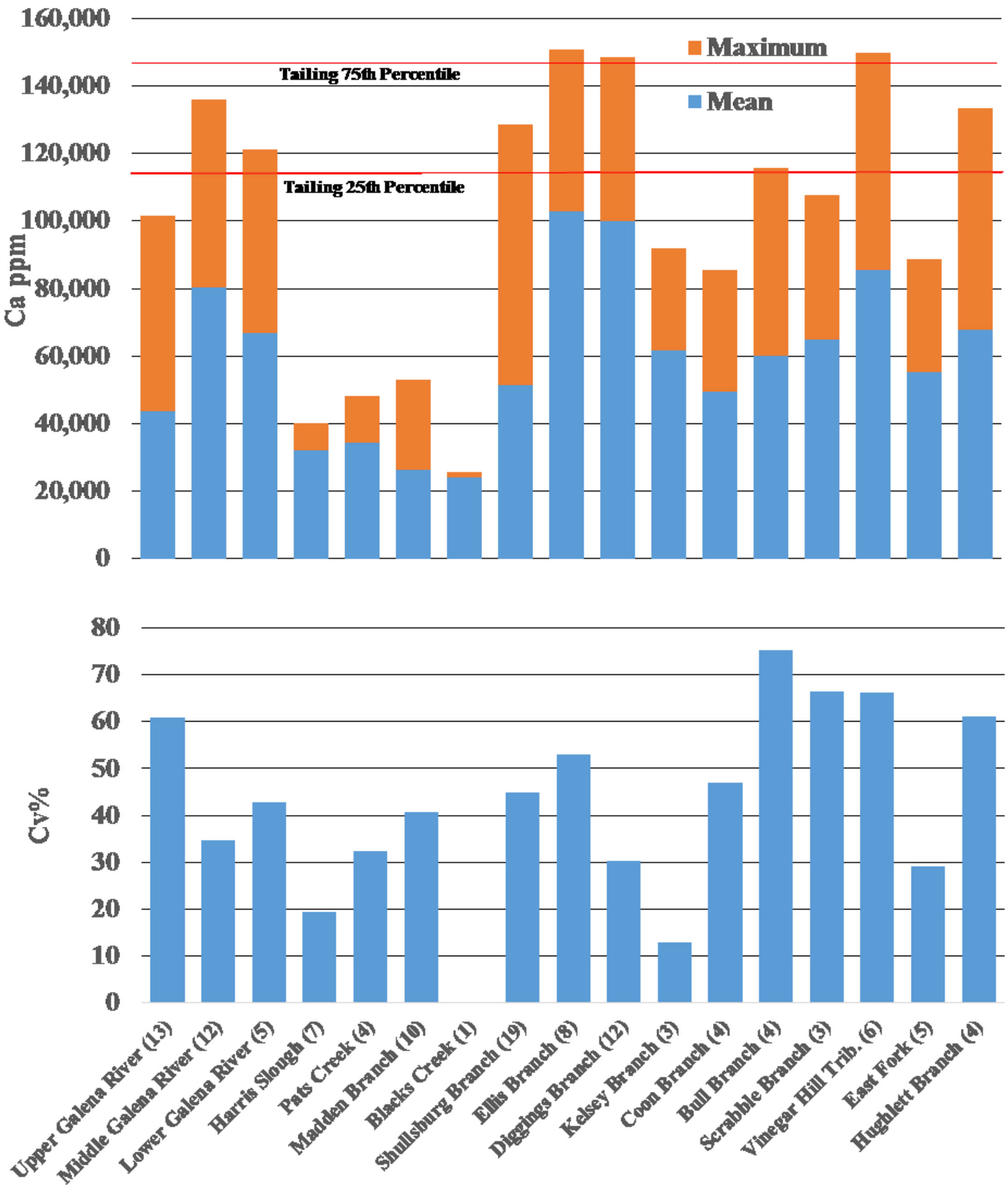


Fig. 21. Average concentrations of Ca by branch averages and Cv%.

Table 10
Correlation matrix between floodplain and channel sediment concentrations.

Sample Type	n	Pb	Zn	Fe	Mn	Ca	OM
Tributaries	77	0.906 [a]	0.898 [a]	0.898 [a]	0.473 [a]	0.770 [a]	0.323 [a]
Main Channel	29	0.786 [a]	0.712 [a]	0.524 [a]	0.287	0.568 [a]	0.196
All Samples	106	0.886 [a]	0.862 [a]	0.881 [a]	0.436 [a]	0.729 [a]	0.342 [a]

a. Correlations that are significant at the 0.01 level

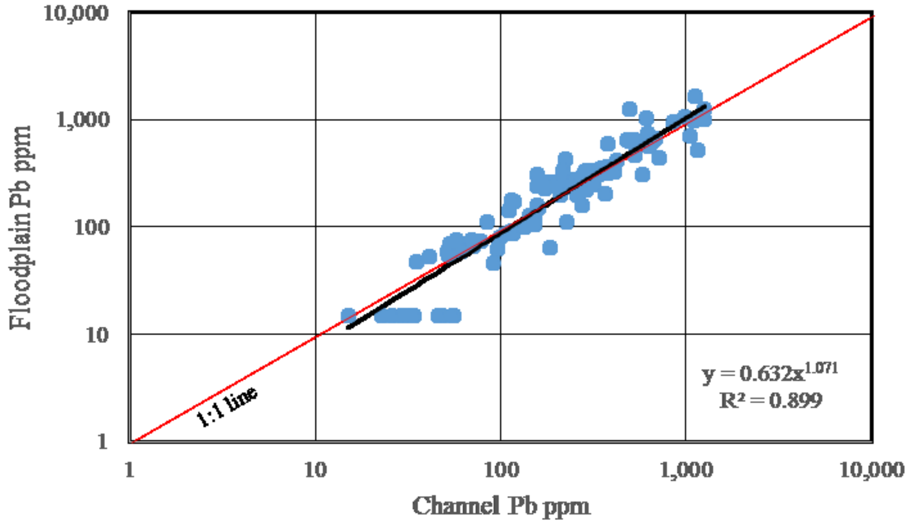


Fig. 22. Relationship between Channel Pb and Floodplain Pb concentrations.

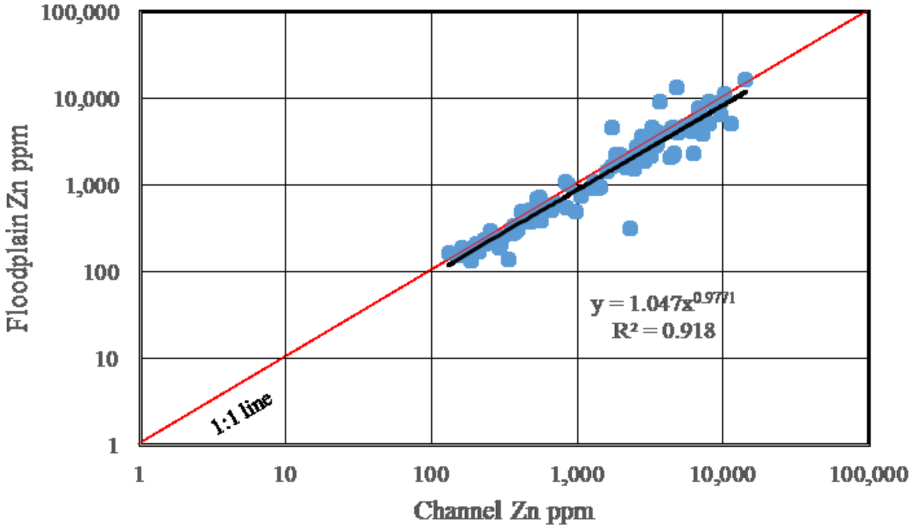


Fig. 23. Relationship between Channel Zn and Floodplain Zn concentrations.

perfect 1:1 relationship suggesting that bed and bank sediment are similar in source and transport pathway.

In addition, the correlation analysis shows that nearly all channel metals and OM content have a strong positive correlation with their floodplain counterparts (Table 10). The strongest relationships between floodplain and channel sediments are seen in Pb, Zn, and Fe concentrations with only Mn and OM content showing significant yet lesser relationships. Tributaries show a greater positive relationship over the main branch of the Galena and the strongest relationship is between channel and floodplain concentrations for Pb in tributaries. Ultimately, this strong relationship suggests that mining-metals are still being moved into long-term storage in alluvial floodplain deposits by channel sediment transport. These metals are then released back to the channel by bank erosion overtime (Knox, 1987).

Ecological Toxicity. The ecological thresholds of threshold effect concentration (TEC) and probable effect concentration (PEC) are commonly surpassed in the Galena River Watershed in most tributaries (MacDonald et al., 2000). From this analysis, only a few samples fell below the TEC threshold (<121 ppm Zn and <35.8 ppm Pb) while the majority of all samples exceeded the PEC (>459 ppm Zn and >128 ppm Pb) (Tables 9 and 10). A few samples from the Upper Galena River (31%), Madden Branch (60%), Shullsburg Branch (5%), and East Fork (20%) were the only samples to fall below the Pb TEC threshold. There were no samples that fell below the Zn TEC threshold. These results show that samples from the Upper Galena, Madden Branch, and East Fork are the least contaminated in the watershed. However, even these streams contain elevated Zn and Pb concentrations (Tables 11 and 12). It is possible that high concentrations of Pb

Table 11
Percent of samples above the PEC and below the TEC thresholds (Pb).

Stream	n	Percent of Sites (Pb)		
		<TEC	TEC-PEC	>PEC
Upper Galena River	13	31	46	23
Middle Galena River	12	0	0	100
Lower Galena River	6	0	0	100
Pats Creek	4	0	50	50
Madden Branch	10	60	40	0
Blacks Creek	1	0	0	100
Shullsburg Branch	19	5	11	84
Ellis Branch	8	0	25	75
Diggings Branch	11	0	0	100
Kelsey Branch	3	0	0	100
Coon Branch	4	0	0	100
Bull Branch	4	0	50	50
Scrabble Branch	3	0	0	100
Vinegar Hill	6	0	17	83
East Fork	5	20	20	60
Hughlett Branch	4	0	25	75

Table 12
Percent of samples above the PEC and below the TEC thresholds (Zn).

Stream	n	Percent of Sites (Zn)		
		<TEC	TEC-PEC	>PEC
Upper Galena River	13	0	46	54
Middle Galena River	12	0	0	100
Lower Galena River	6	0	0	100
Pats Creek	4	0	50	50
Madden Branch	10	0	100	0
Blacks Creek	1	0	0	100
Shullsburg Branch	19	0	16	84
Ellis Branch	8	0	0	100
Diggings Branch	11	0	0	100
Kelsey Branch	3	0	33	67
Coon Branch	4	0	0	100
Bull Branch	4	0	25	75
Scrabble Branch	3	0	0	100
Vinegar Hill	6	0	17	83
East Fork	5	0	40	60
Hughlett Branch	4	0	25	75

and Zn in unmined streams are a result of historical use and runoff of tailings being used for roads and rails (Adams, 1944).

On the other hand, all samples from branches including Middle Galena, Lower Galena, Blacks, Diggings, Coon, and Scrabble are above the PEC threshold (Tables 11 and 12) (MacDonald et al., 2000). Only the unmined Madden Branch remains entirely below the PEC threshold. A total of 67% of Pb samples and 76% of Zn samples within the entire watershed exceed the PEC causing great potential for harm to sediment dwelling organisms. These concentrations stay elevated from continued input of contaminated sediments released from tailing piles and floodplain storage (Knox, 1987). In addition, other metals from the aqua-regia analysis (Appendix L) show that As (8%) and Cd (46%) also exceed the PEC threshold (ALS, 2009). Both As and Cd are potential trace elements of Pb and Zn mining and can also cause ecological harm (Leblanc et al., 2000). According to MacDonald et al. (2000), the current concentrations of contamination within the Galena River Watershed would be dangerous for sediment dwelling organisms.

Sediment and Mining Source Effects

Pearson's correlation analysis indicates strong relationships among geochemical components for most sediment types (Table 13). The strongest positive relationship is between Pb and Zn concentrations with all categories having a relationship above 0.5. The strongest positive relationship between Pb and Zn is found in the main branch of the Galena River from floodplain samples (0.959). This relationship is also very strong in the main branch of the Galena River from channel samples (0.892). Other metals have a

Table 13
Correlation matrices for metals and OM.

Metal	Tailings	Background	Channel		Floodplain	
			Trib.	Main	Trib.	Main
n	24	15	82	31	82	31
Pb-Zn	0.573 [a]	0.605 [a]	0.556 [a]	0.892 [a]	0.736 [a]	0.959 [a]
Pb-Fe	0.033	0.435 [b]	0.623 [a]	0.615 [a]	0.732 [a]	0.876 [a]
Pb-Mn	-0.169	-0.218	0.009	0.395 [a]	-0.105	0.592 [a]
Pb-Ca	0.177	0.404 [b]	0.371 [a]	0.467 [a]	0.441 [a]	0.566 [a]
Pb-OM	0.194	-0.109	-0.006	-0.368 [a]	0.079	0.080
Zn-Fe	0.176	0.755 [a]	0.419 [a]	0.438 [a]	0.6 [a]	0.867 [a]
Zn-Mn	-0.075	-0.230	0.245 [a]	0.356 [a]	0.093	0.606 [a]
Zn-Ca	0.246	0.366	0.634 [a]	0.648 [a]	0.56 [a]	0.624 [a]
Zn-OM	0.251	0.079	-0.030	-0.448 [a]	0.213	0.127
Fe-Mn	0.285	0.266	0.121	0.482 [a]	-0.137	0.622 [a]
Fe-Ca	-0.44 [b]	0.347	0.124	0.111	0.264 [b]	0.339 [b]
Fe-OM	0.579 [a]	0.094	0.136	0.023	-0.020	0.058
Mn-Ca	-0.080	0.075	0.218 [a]	0.461 [a]	0.296 [a]	0.596 [a]
Mn-OM	0.199	-0.396 [b]	-0.177 [b]	-0.131	0.046	-0.018
Ca-OM	-0.165	-0.099	-0.288 [b]	-0.414 [a]	0.047	0.178

a. Correlations that are significant at the 0.01 level
b. Correlations that are significant at the 0.05 level

weaker relationship with Pb and Zn as they represent more of a byproduct of historical mining in the Galena River Watershed (Heyl et al., 1959). For example, Fe also has a strong positive relationship with both Pb and Zn with the strongest relationship in the main branch of the Galena River floodplain samples. To a much lesser degree, Mn has a positive relationship with Pb and Zn in most channel and floodplain samples. This relationship indicates that variations in Fe and Mn are associated with tailing inputs as byproducts of Pb and Zn mining. Furthermore, Ca concentrations also have a strong positive relationship with Pb and Zn concentrations due to high concentrations of Ca in the ore host rock (Adams, 1944). Overall, all metal concentrations tend to be connected due to source contaminates from tailings input.

On the other hand, most metals have a negative or weak relationship with OM content within the watershed. Naturally, this relationship would be expected stronger as OM will transport metals by sorption (Horowitz, 1991; Pavlowsky, 1995). Organic matter relationships are strongest within floodplain samples of both the tributaries and the main branch suggesting OM may be binding Pb and Zn within floodplain soils at a greater rate than within the channel. Fine-sediment particles containing OM with Pb and Zn may be deposited during overbank floods on floodplains more than in higher energy channel environments. Additionally, background and tailing samples also have much lower relationships between all metals and OM content. The reasons for these may be due to the variability of tailing pile samples in general as well as lower metal concentrations in background streams overall that would not show strong relationships to OM given detection limit errors and mixed sediment sources.

Zn and Pb change trends between 1992 and 2017

Temporal changes in sediment contamination for repeated sampling sites were evaluated in two ways. First, average metal concentrations were calculated for all sites within a tributary and compared at the segment-scale (Figs. 24 and 25). Second, metal concentrations from each site were compared by regression analysis between the values from the two sampling years (Figs. 26 and 27). Lead and Zn concentrations in stream sediments in 2017 have changed very little since 1992. Accordingly, Pb and Zn concentrations continue to remain very high within the watershed.

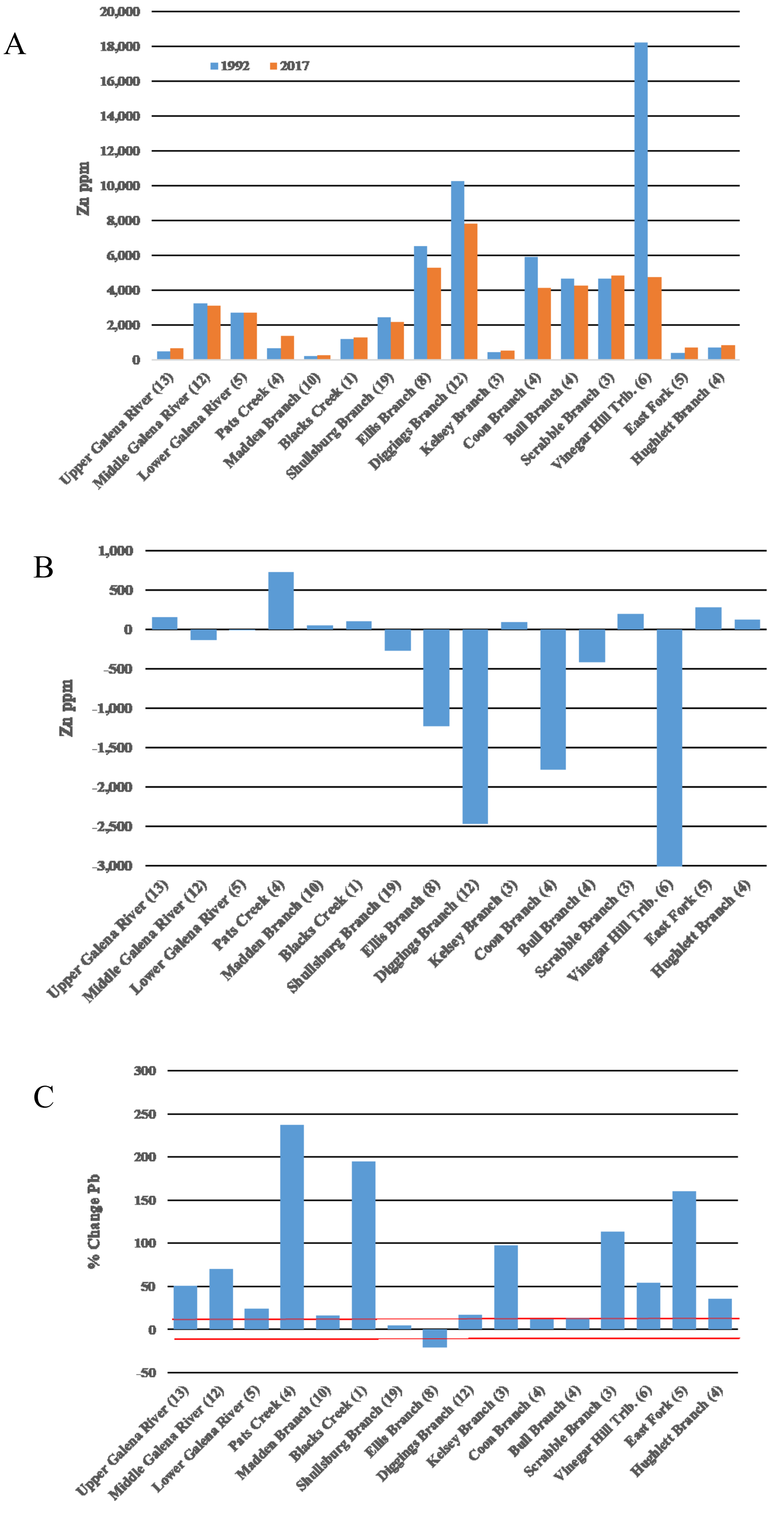


Fig. 24. (A) Zn concentration comparison between 1992 and 2017 (n). (B) Zn concentration difference (n). Note: Vinegar Hill value is -13,470 ppm. (C) Zn concentration percent difference. Between red lines represents no change. Values >30% change are significant.

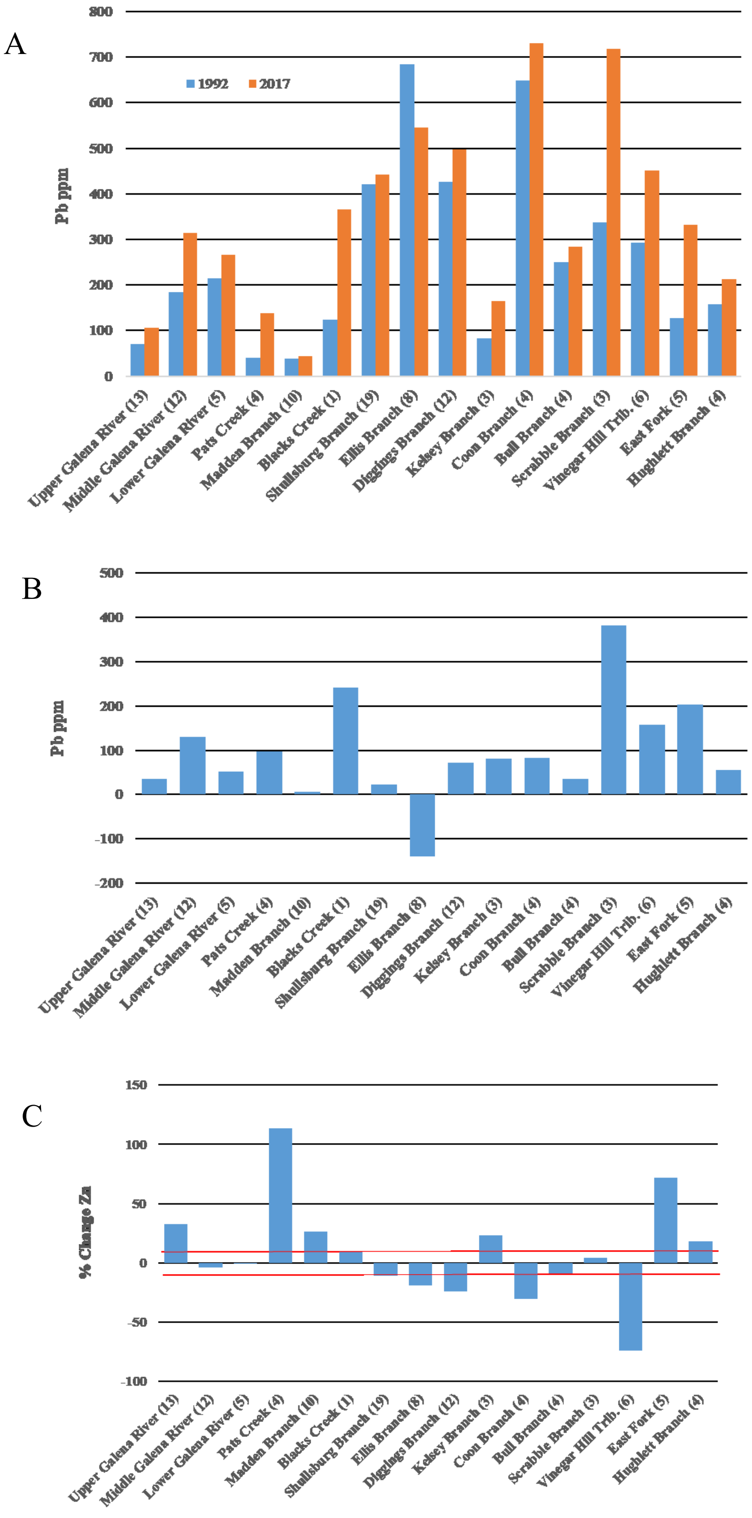


Fig. 25. (A) Pb concentration comparison between 1992 and 2017 (n). (B) Pb concentration difference (n). (C) Pb concertation percent difference. Between red lines represents no change. Values >30% change are significant.

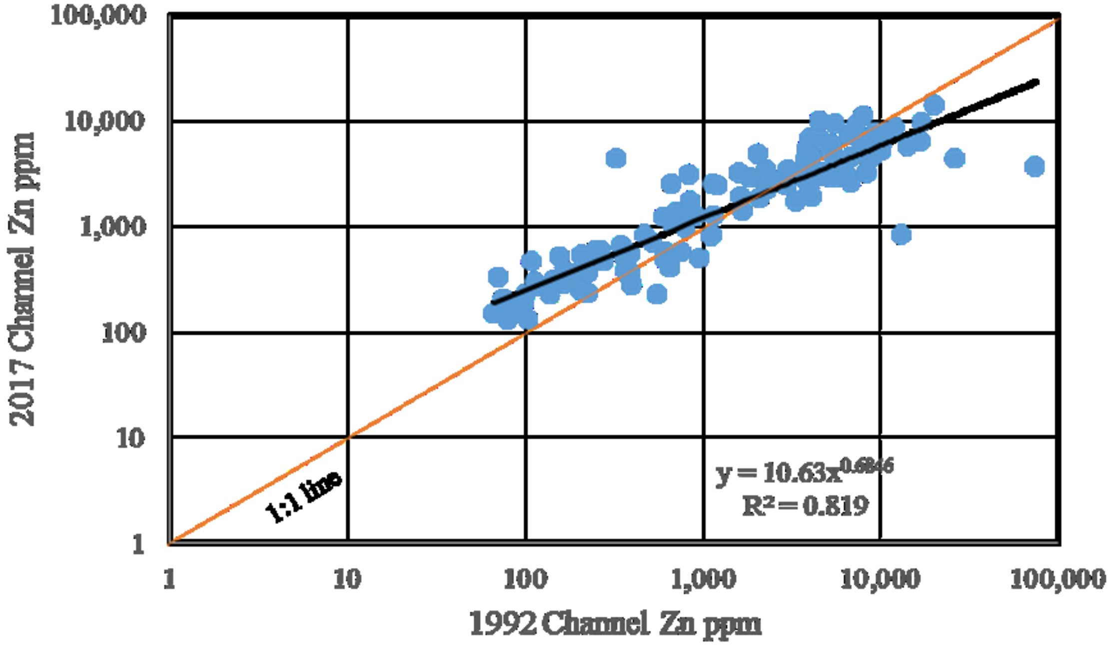


Fig. 26. Relationship between 1992-2017 Channel Zn.

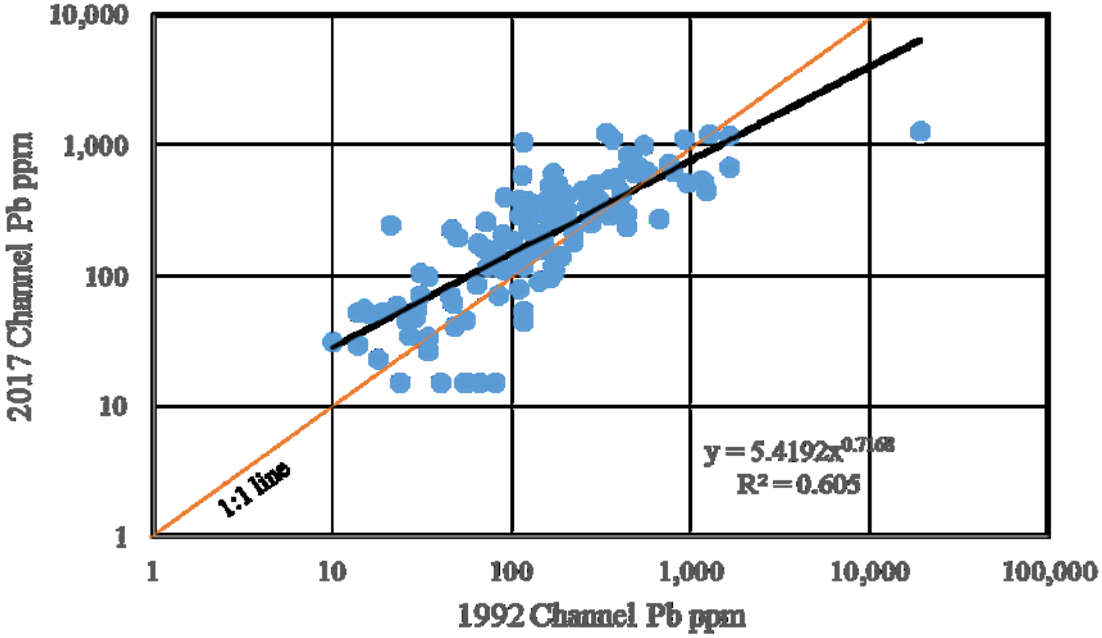


Fig. 27. Relationship between 1992-2017 Channel Pb.

Segment-Scale Averages. For Zn concentrations, the Middle Galena, Lower Galena, Shullsburg, Ellis, Diggings, Coon, Bull, and Vinegar Hill all exhibited an average decrease over the past 25 years (Figs. 22 and 23). Only Ellis Branch had a decrease for Pb concentrations (-20%). Segments with an increase or decrease greater than 30% are higher than the average range of duplicate error showing some level of significance while values below 10% will show statistically no change. For Zn concentrations most segments did not see much change (Table 14). Only the Upper Galena and Pats Creek saw a >30% increase while Coon Branch and Vinegar Hill saw a >30% decrease. Several sites for Pb had a >30% increase including Upper Galena, Middle Galena, Pats Creek, Blacks Creek, Kelsey Branch, Scrabble Branch, Vinegar Hill

Table 14
Average Zn percent change by stream branch.

Stream Segment	Decrease[a]		No Change[a]	Increase[a]	
	>30%	10%-30%	±10%	10%-30%	>30%
Upper Galena[b]					XX
Middle Galena			XX		
Lower Galena			XX		
Pats[b]					XX
Madden				X	
Blacks			XX		
Shullsburg		XX			
Ellis		XX			
Diggings		XX			
Kelsey				X	
Coon[b]	XX				
Bull			XX		
Scrabble			XX		
Vinegar Hill[b]	XX				
East Fork					X
Hughlett				XX	
Watershed		XX			

a. X = less than PEC but above TEC and XX = above PEC (MacDonald et al., 2000)
b. Significant Change

Branch, East Fork, and Hughlett Branch (Table 15). However, only a portion of these sites are above the PEC threshold making their change far more significant. There were no >30% Pb decreases.

The magnitude of the percent change in metal concentrations can be influenced by the level of contamination in the segment. Segments with low contamination will have a smaller absolute change, but potentially a higher relative percent change such as Upper Galena, Madden Branch, and East Fork. For this reason, branches with the greatest absolute change would be the decrease at Vinegar Hill for Zn concentrations and the increase at Scrabble Branch for Pb concentrations. However, the large decrease at Vinegar Hill Branch may be due to the fact that the 1992 average for the tributary is

Table 15
Average Pb percent change by stream branch.

	Decrease[a]		No Change[a]	Increase[a]	
Stream Segment	>30%	10%-30%	±10%	10%-30%	>30%
Upper Galena					X
Middle Galena[b]					XX
Lower Galena				XX	
Pats					X
Madden				X	
Blacks					X
Shullsburg			XX		
Ellis		XX			
Diggings				XX	
Kelsey					X
Coon				XX	
Bull				XX	
Scrabble[b]					XX
Vinegar Hill[b]					XX
East Fork					X
Hughlett[b]					XX
Watershed[b]					XX

a. X = less than PEC but above TEC and XX = above PEC (MacDonald et al., 2000)
b. Significant Change

extremely high compared to other branch averages. While it is possible that a sample was collected in very close proximity to a tailing pile input in the early 1990s, Pb concentrations were rather low, possibly because Pb production had much declined in the early 1900s when the mine was most active in producing Zn ore (Heyl et al., 1959; Knox 1987). Additionally, the decrease of Zn contamination may be the result of a continued EPA Superfund site at Little Giant and Inspiration on Vinegar Hill Branch (EPA, 2018a; EPA, 2018b).

Site-level Regression Trends. Compared to differences between segment metals trends, comparisons of changes in metal concentrations by site over the past 25 years indicate to a further degree the relatively small differences overall between the two study periods (Figs. 26 and 27). Almost half of all the recent channel sediment sample sites (42%) indicated a decrease in Zn concentrations over the past 25 years while Pb samples indicated a smaller average site decrease (31%) over the past 25 years. Both Pb and Zn concentrations have a high R^2 value and fit the regression model well. Comparison to the 1:1 line shows that samples between 1992 and 2017 have not changed much over the past 25 years. Furthermore, the regression model shows a slight increasing trend for less contaminated sites and a slight decreasing trend for the most contaminated sites. The decrease in high concentrations is likely due to a more direct response of sediment metal contamination to mine inactivity. The slight increase in less contaminated streams possibly reflect the use of tailings for fill and road pavements that may have subtly added metals to local streams.

Factors affecting the reduction or increase of sediment contamination within tributaries in the Galena Watershed over the past 25 years may include the: (1) Rate mine production and waste inputs into the stream system (Heyl et al. 1959), (2) degree of contaminated sediment stored and released by erosion from channel and floodplain deposits (Knox, 1987; Pavlowsky, 1996), (3) dilution rate of contaminated sediment being dispersed downstream (Marcus, 1987; Pavlowsky, 1996), (4) variable geomorphic and sediment transport process that influence sediment and channel conditions overall (Knox, 1989; Coulthard and Macklin, 2003), (5) type and distribution of mining land remediation, and (6) systematic effects of sampling and analytical errors on metal concentration values. In summary, Pb and Zn concentrations have changed very little since 1992 if the effects of sampling variability and differences in analytical procedures on geochemical results are considered (Table 14 and 15).

Paired T-Test. To more objectively test the changes in sediment geochemistry over the past 25 years a paired t-test using SPSS was used to evaluate differences between the two sampling periods at a 0.05 significance level (Tables 16 and 17) (Simmons, 2008; IBM, 2016). On average there has been very little significant change over the past 25 years with nearly all samples showing insignificant results. While changes in metal concentrations greater than and less than ±10% occurred, relatively low sample sizes and high sediment variability reduced the number of significant differences. For Pb, the Middle Galena, Kelsey Branch, and East Fork indicated a small significant increase over the past 25 years. For Zn, no stream indicated significant change. However, all samples together show a weak significant decrease overall within the watershed for Zn samples. Overall, neither Pb nor Zn concentrations within any branch showed significant decrease over the past 25 years. It is possible that due to a large-scale remediation project that the Vinegar Hill Tributary has made a surprisingly large

Table 16
Paired T-test for Pb by channel average (significance level=.05).

Reach	n	t	df	Sig (2-tailed)	Sig. Difference
Upper Galena River	13	-0.3	12	0.77	No
Middle Galena River	12	-4.056	11	0.002	Yes
Lower Galena River	6	-0.806	5	0.457	No
Pats Creek	4	-1.85	3	0.161	No
Madden Branch	10	0.493	9	0.634	No
Shullsburg Branch	19	0.164	18	0.871	No
Ellis Branch	8	-0.028	7	0.978	No
Diggings Branch	11	-0.387	10	0.707	No
Kelsey Branch	3	-9.743	2	0.01	Yes
Coon Branch	4	-2.002	3	0.139	No
Bull Branch	4	0.748	3	0.509	No
Scrabble Branch	3	-1.26	2	0.335	No
Vinegar Hill	6	-0.889	5	0.415	No
East Fork	5	-2.823	4	0.048	Yes
Hughlett Branch	4	-1.971	3	0.143	No
Watershed Total	124	0.624	123	0.534	No

Table 17
Paired T-test for Zn by channel average (significance level=.05).

Reach	n	t	df	Sig (2-tailed)	Sig. Difference
Upper Galena River	13	-1.933	12	0.077	No
Middle Galena River	12	0.315	11	0.759	No
Lower Galena River	6	-0.038	5	0.971	No
Pats Creek	4	-1.147	3	0.335	No
Madden Branch	10	-0.884	9	0.4	No
Shullsburg Branch	19	0.868	18	0.397	No
Ellis Branch	8	-1.153	7	0.287	No
Diggings Branch	11	1.725	10	0.115	No
Kelsey Branch	3	-3.954	2	0.058	No
Coon Branch	4	0.61	3	0.585	No
Bull Branch	4	1.507	3	0.229	No
Scrabble Branch	3	-0.001	2	0.999	No
Vinegar Hill	6	1.184	5	0.289	No
East Fork	5	-1.733	4	0.158	No
Hughlett Branch	4	-0.813	3	0.476	No
Watershed Total	123	1.99	123	0.049	Yes

recovery for Zn concentrations. However, excluding the high outlier from the Pavlowsky (1995) study, the change is less.

Remediation Influence on Stream Contamination

The analysis of mine pit and waste locations from SSURGO soil maps and disturbed mine lands and tailing piles on aerial imagery showed an overall decrease in mine waste area over time (Appendix M) (Heyl et al., 1959). Mine wastes were not observed (2015) at 47% of original mine sites documented by Heyl et al. (1959) (Fig. 28; Table 18). However, the majority of mine locations that have been removed were of the lowest production rate (about 5,000 Mg). In fact, all abandoned mines classified as having the highest production in the District (about 2,000,000 Mg) still have relatively large areas of tailings and other wastes potentially available for transport to local streams. As a result, the remaining mines within the watershed represent the largest historical and contemporary sources of tailing materials, seepage, and eroded contaminated sediment to the stream system. Moreover, many of the smaller mines may not have initially produced waste or released contaminated sediment due to lack of production and/or potential for significant land disturbance (Heyl et al., 1959). Therefore, the supply of mine waste inputs to streams may not have reduced greatly since the last mine closed. Following, more effort needs to be placed on remediation of the largest mines and tailing disposal sites in the watershed to reduce the risk on ongoing contamination from abandoned mining areas.

Remediated Segments. In the stream segments where mine site remediation occurred, sediment-Pb concentrations increased and Zn concentrations generally

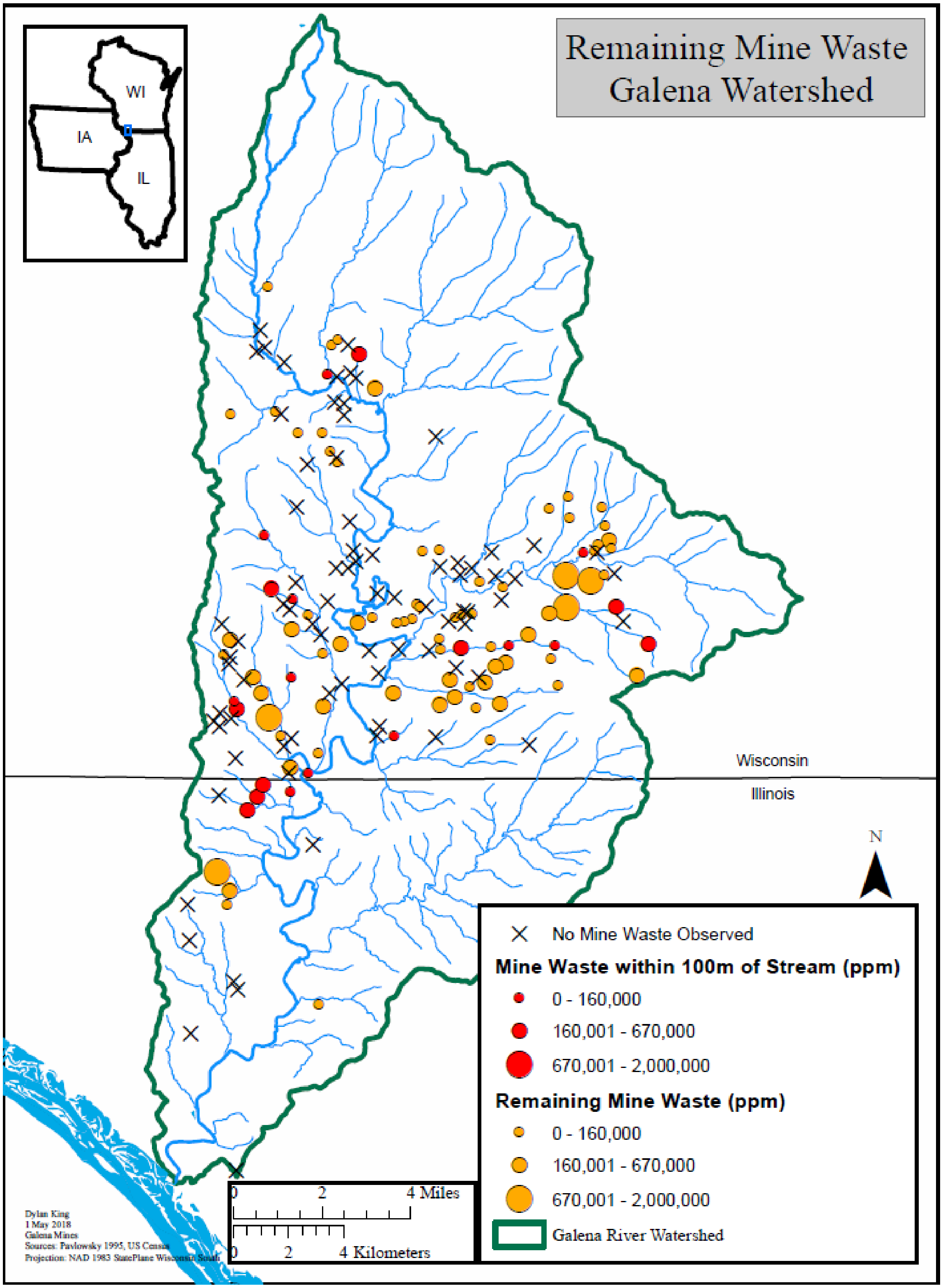


Fig. 28. Galena River Watershed Mines with Remaining Waste in 2015. Production values according to Heyl et al. (1959).

Table 18
Percent of remaining historical mines by production.

Segment	Total Mines[a]	% of remaining historical mines by Production (Mg)[a]		
		<100,000	100,000-400,000	>400,000
Galena	50	32	45	40
Pats	3	100	100	-
Madden	0	-	-	-
Blacks	3	50	0	-
Shullsburg	44	45	73	100
Ellis	12	60	100	100
Diggings	10	0	83	100
Kelsey	3	100	0	-
Coon	17	42	0	75
Bull	8	50	100	100
Scrabble	13	14	67	33
Vinegar Hill	4	-	100	-
East Fork	0	-	-	-
Hughlett	4	0	0	-
Total	171	20	57	59

a. production values and mines obtained from Heyl et al., 1959.

decreased between 1992 and 2017 (Table 19 and 20). Of the five stream segments with remediated mines, Vinegar Hill Branch had the highest decrease of sediment-Zn (-74% change) and a small Galena Tributary with Graham-Snyder and Graham-Ginte Mines had the highest sediment-Pb increase (92% change) (Table 19). Stream segments with the fewest mine sites remaining from the Heyl et al. (1959) inventory did not show consistent decreases in metal contamination since 1992. However, it is not clear when the mines were cleaned up or if they ever were associated with tailings inputs. Nevertheless, Hughlett, Blacks, Kelsey, and Scrabble Branches indicated very little change in sediment-Zn concentrations and slight increases for Pb concentrations over the past 25 years (Figs. 24 and 25; Table 18). Ultimately, even with nearly half of the historical mines and

Table 19

Metal Trends in Segments with Remediated Mines

Name	Operation Years	Stream	Stream Pb (ppm)		Stream Zn (ppm)		% Change[a]	
			1992	2017	1992	2017	Pb	Zn
Champion	1913-1946	Diggings	427	498	10,270	7,797	17	-24
Cuba City (Tailings)	?	Coon	648	731	5,881	4,096	13	-30
Eagle Picher	1949-1979	Shullsburg	421	443	2,427	2,163	5	-11
West Blackstone	?	Shullsburg						
Graham-Snyder, Ginte	1947-1953, 1955-1957	Galena Trib.	124	238	3,983	2,183	92	-45
Inspiration/Little Giant	1839-1947 (periodically)	Vinegar Hill	292	450	18,205	4,735	54	-74

a. change is represented by (+) for increase and (-) for decrease

Table 20

Metal Trends at Sites Downstream of Remediated Mines

Name	Operation Years	Site	Site Pb (ppm)		Site Zn (ppm)		% Change[a]	
			1992	2017	1992	2017	Pb	Zn
Champion	1913-1946	118	447	851	10,697	8,043	90	-25
Cuba City (Tailings)	?	123	1,278	1,215	5,387	5,955	-5	11
Eagle Picher	1949-1979	84	114	583	324	4,370	412	1,249
West Blackstone	?	85	92	403	369	386	338	5
Graham-Snyder, Ginte	1947-1953, 1955-1957	144	124	238	3,983	2,183	92	-45
Inspiration/Little Giant	1839-1947 (periodically)	138	116	1,055	74,601	675	809	-99

a. change is represented by (+) for increase and (-) for decrease tailings piles now gone today, there are still very high concentrations of Zn and Pb in stream sediments with historical mine sites.

Remediated Sites. Of the six remediated mine sites, only about half produced decreases in metal concentrations at sampling sites directly downstream of the site location (Table 20) (Brown et al., 2009). The largest decrease decreases to sediment-Zn was downstream of Inspiration/Little Giant Mines in Vinegar Hill Branch (-95% change) and the largest increase was below the Eagle Picher mine in Shullsburg Branch (1,249% increase). The only decrease to sediment-Pb was below Cuba City (-5% change) and the largest increase was below the Inspiration/Little Giant Mines (809% change). The recent and ongoing remediation work at Eagle Picher Mine may be causing increased erosion rates as material is disturbed while being removed. For this reason, ongoing remediation projects may not see expected decreases in Pb and Zn concentrations until after construction with time for recovery.

Even through sediment-Zn concentration decreased below some mine sites over the past 25 years, there are many other mines that have had equal if not greater decreases that were not considered remediated. This result suggests that even though there is a decrease in sediment-Zn concentrations downstream of some remediated mines, it is just as possible that these decreases are caused by random sediment processes, overall mining inactivity, and movement of wastes into alluvial storage independent of remediation activities (Knox, 1987). On the other hand, the effects of remediation of a mine source may not be apparent until the effects of dilution and transport by uncontaminated sediment lowers channel sediment metal concentrations. Nevertheless, removal and stabilization of historical tailing piles is important to long-term improvement in sediment quality and more monitoring is needed to accurately evaluate effectiveness.

Present-Day Contamination Problems

Even with past and on-going remediation efforts and nearly half the mines cleaned-up, the concentrations of Pb and Zn within the Galena River Watershed have remained relatively high over the past 25 years with very little change. Therefore, these metals are probably being maintained by other sources within the watershed including other abandoned tailing piles, remobilization of contaminated channel bar and bed deposits, and secondary storage within the floodplain and banks as have been previously recognized in the Galena Watershed and other streams in the district (Knox, 1987; Pavlowsky, 1996; Lecce and Pavlowsky, 1997).

Present day concentrations in floodplain deposits are similar to channel sediments showing that present day floods are storing metals within the banks of the river for future remobilization. To better understand the long-term environmental risk due to the release of metals from floodplain storage back to the stream, a study of the spatial patterns of bank erosion rates and associated sediment inputs and contaminant loads for the Galena River and its heavily mined tributaries should be completed. Historically, sediment yield to the Galena River and its tributaries has been decreasing every few decades due to modern conservation practices (Knox, 1987; Trimble, 1999). However, the role of bank erosion in maintaining high metal concentrations in channel sediments has not been evaluated.

To date, the influence of remediation efforts at abandoned mine sites on the reduction of channel sediment contamination has been limited and long-term effects are unknown. This study may have identified local improvements in sediment quality below remediated sites. However, the sampling design for the present study was focused on the repeat sampling of 1992 sites and not assessing the specific effects of remediation projects. In addition, channel disturbance and reworking of tailing piles as part of ongoing remediation projects may itself be a source of contaminated sediment to nearby streams. Therefore, additional channel contamination assessments of remediated reaches and the long-term monitoring of contaminated streams is needed. More focused and short-interval sampling from above to below remediation sites with a pre-treatment control assessment would be beneficial to address our lack of knowledge regarding the role that site clean-up may have on improvements in water and sediment quality in the Galena watershed.

Sediment contamination by historical mine sites and ongoing remobilization from tailing piles and alluvial sediments still pose a risk to aquatic life including sediment dwelling organisms in the Galena River and its tributaries (MacDonald et al., 2000). The recently USEPA-approved TMDL for the Lower Galena River in Illinois did not address mining sediment contamination directly, but focused on dissolved Zn impairments (CDM Smith, 2018). In addition, TMDL recommendations included mine site treatments and broader-aimed nonpoint sediment control practices to reduce future mine water discharges, tailing inputs, and channel sediment contamination. However, stored contaminated sediment in floodplains within the watershed is probably an important secondary source of pollution that has not been addressed in long-term watershed management plans for the Galena River. The results of this thesis and previous studies have shown that Galena River Watershed sediments, both recent and stored, are heavily contaminated with Pb and Zn more so than surrounding watersheds such as Blue River (Lecce and Pavlowsky, 2004). For this reason alone, the Galena River Watershed should continue to be monitored and to better support remediation efforts of mine-waste in the future. More focus on contaminated sediment as a long-term metal source to the Galena River Watershed is needed.

CHAPTER 5 – CONCLUSION

Even after more than 40 years of mining inactivity, the Galena River and its tributaries remain heavily contaminated with metals from historical Pb and Zn mining. In 2017, a total of 415 samples were collected from the Galena River Watershed for this study. Results showed that all tributaries including the main branch of the Galena River and some unmined areas contain environmentally toxic concentrations of sediment Pb and Zn as well as Cd, and to a lesser degree As (MacDonald et al., 2000). Since the Pavlowsky (1995) study sediments were sampled in 1991-92 there have been several remediation projects and clean-up efforts. However, these projects appeared to have only local effect on current overall Pb and Zn concentrations. The key findings of this study are as follows:

1. **Concentrations of sediment Pb and Zn are high in 2017.** Concentrations of 2017 channel sediments range from <30 to 1,261 ppm Pb and 130 to 14,223 ppm Zn while concentrations for floodplain sediments range from <30 to 1,626 ppm Pb and 136 to 16,441 ppm Zn. The concentrations of Pb (67% of sites) and Zn (76% of sites) are on average well above the PEC threshold for toxic effect on sediment dwelling organisms (MacDonald et al., 2000). Additional metal concentrations from the aqua-regia analysis show that Cd (46%) and As (8%) concentrations are also above PEC threshold. In addition, relatively high concentrations extend from the Galena River mouth out into the Harris Slough of the Mississippi River system averaging 221 ppm Pb and 1,906 ppm Zn. The average channel background concentrations not affected by documented mining operations for the Madden Branch were 33 ppm Pb (Cv=74%) and 243 ppm Zn (Cv=34%).

2. **There are strong associations among elements in sediments reflecting the strong control of tailing wastes and their mineralogy and sediment geochemistry.** Channel sediment metals have strong positive relationships with other metals such as Pb, Zn, Fe, and Ca. The greatest relationship in any location is a strong positive correlation between Pb and Zn concentrations. Lead and Zn also share a positive relationship at most sites with Fe and Ca. To a lesser degree, Mn has a strong positive correlation with Pb and Zn concentrations only in the main channel of the Galena. Typically, mining metals are associated with OM as

a result of binding of dissolved metals downstream. However, most metals appear to have weak relationships with OM suggesting that contamination is related more to tailings and fine-sediment particles to a significant degree (Pavlowsky, 1995).

3. **There is a strong positive relationship between 1992 and 2017 samples.** On average, there were very few significant decreases in Pb and Zn concentrations by branch averages over the past 25 years. For Pb concentrations, every branch increased except the Ellis Branch (20% decrease). For Zn concentrations there were several overall slight decreases in 8 different branches and several overall slight increases in 8 different branches. Of these decreases, three were below 10%, three were between 10%-30%, and the last two were above 30% decrease. Overall, Zn concentrations as a whole indicated a weak significant decrease over the past 25 years. This can be further explained by the strong positive relationship between 1992 and 2017 Pb and Zn channel concentrations. This suggests that even though there has been some clean-up and 40 years of mining inactivity, recovery to background levels is slow and can take centuries.

4. **There has been little effect from mine waste remediation.** The majority of mine sites cleaned-up prior to the Pavlowsky (1995) study were mostly low producing mines that created very little waste (Heyl et al., 1959). Most high-producing historical mines continue to have large tailing piles effecting local streams. Even in tributaries with the most mine clean-up activities, Pb and Zn concentrations have barely changed and in some cases have increased. The majority of documented remediation projects in the past 25 years have seen a slight decrease in Zn concentrations in sediment within 3 km of the mine site with the highest decrease in Vinegar Hill for Zn at Inspiration and Little Giant. With only Eagle Picher mine showing a large increase, remediation appears to have some effect on the reduction of downstream contamination locally. However, similar changes also occurred at some mine sites that have not been remediated. It is possible that the small decreases and lack of an overall trend may be due to lack of time for recovery of remediated mine sites. More monitoring is needed to evaluate effectiveness of remediation on stream sediment metal concentrations.

5. **Continued high Pb and Zn concentrations are likely due to remaining tailing piles and contaminated floodplains and banks.** Even though mining ceased in 1979, many tailing piles still remain throughout the watershed with 21% of all remaining tailing piles located within 100 m of a stream (Pavlowsky, 1996). These tailing piles have extremely high Pb and Zn concentrations and will continue to be a source of metals to the watershed. Additionally, contaminated banks and floodplain deposits will continue to be a secondary source to the channel during floods, erosion, and reworking (Knox, 1987; Lecce and Pavlowsky, 1997). It is likely that Pb and Zn concentrations will remain high well into the future even with continued remediation projects.

In conclusion, the Galena River Watershed channel and floodplain samples are heavily contaminated with Pb and Zn and there has been little to no decrease over the past 25 years in most branches of the watershed. To date, remediation efforts appear to have little or unknown effects on channel sediment concentrations with the largest decrease being at an EPA Superfund site. The results of this analysis show that TMDL reports that only focus on dissolved Zn concentrations are severely underestimating the scale of metal contamination in Galena River sediments (CDM Smith, 2018). Watershed management goals to improve water quality should include sediment as a risk as well as a potential future source of pollution released from storage in channel deposits and floodplain soils.

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APPENDICES

Appendix A. Photo Log (July 2017)

Appendix A-1. Remaining tailings at Kennedy Mine, Wisconsin

Appendix A-2. Tailings and waste rock at Federal Mine, Wisconsin

Appendix A-3. Tailing pile at Lucky Twelve Mine, Wisconsin

Appendix A-4. Tailing pile at Vinegar Hill Mine, Illinois

Appendix A-5. Example of PSA in the Shullsburg Branch, Wisconsin

Appendix A-6. Example of PSA in the Shullsburg Branch

Appendix A-7. Example of sample site on bank/floodplain on the Middle Galena River, Wisconsin

Appendix A-8. Geomorphological survey example, Shullsburg Branch, Wisconsin

Appendix A-9. Sediment sampling in the Lower Galena River, below Galena, IL

Appendix A-10. Example of acid mine drainage near previous roaster pile site

Appendix B. Channel sediment site location and concentration averages (1992)

Site	Reach	Latitude	Longitude	OM%	1992 Metal Concentrations (ppm)			
					Pb	Zn	Fe	Mn
1	Upper Galena	42.7478	-90.3829	8.61	57	104	18,334	993
2	Upper Galena	42.7339	-90.3899	5.02	82	80	21,656	1,474
4	Upper Galena	42.7115	-90.3993	5.35	67	80	17,004	1,067
6	Upper Galena	42.6824	-90.4118	5.58	14	137	18,677	1,225
7	Upper Galena	42.6677	-90.4141	7.43	19	144	17,116	987
8	Upper Galena	42.6602	-90.4113	4.5	116	648	16,833	1,026
9	Upper Galena	42.6519	-90.4119	5.23	31	393	18,141	1,119
11	Upper Galena	42.6338	-90.371	4.56	110	854	18,444	1,017
12	Upper Galena	42.6311	-90.3579	6.21	50	711	18,233	911
14	Upper Galena	42.6158	-90.3526	4.22	85	263	18,436	1,153
16	Upper Galena	42.5764	-90.3664	2.22	34	616	14,890	1,291
17	Upper Galena	42.5716	-90.3532	3.16	83	518	17,077	1,045
19	Upper Galena	42.5514	-90.3593	3.64	191	1,666	15,943	933
20	Middle Galena	42.549	-90.3465	2.45	351	2,925	22,940	1,038
21	Middle Galena	42.5425	-90.3533	3.48	205	2,279	18,490	1,044
22	Middle Galena	42.54	-90.3537	2.03	203	4,934	21,929	823
26	Middle Galena	42.5149	-90.3637	5.12	133	1,204	19,322	1,015
27	Middle Galena	42.5135	-90.3784	3.46	152	1,648	16,092	987
29	Middle Galena	42.515	-90.3899	2.49	155	5,269	19,230	1,201
30	Middle Galena	42.5133	-90.3972	3.08	164	4,396	19,190	941
31	Middle Galena	42.5106	-90.3919	2.15	114	5,756	17,445	1,177
33	Middle Galena	42.4945	-90.3925	4.88	180	2,028	20,076	997
34	Middle Galena	42.4936	-90.3992	3.25	279	4,065	21,536	1,282
37	Middle Galena	42.4769	-90.4064	5.17	111	1,141	20,831	1,012

Appendix B continued. Channel sediment site location and concentration averages (1992)

Site	Reach	Latitude	Longitude	OM%	1992 Metal Concentrations (ppm)			
					Pb	Zn	Fe	Mn
39	Middle Galena	42.4508	-90.388	1.82	161	3,034	13,976	1,062
40	Lower Galena	42.4485	-90.3892	2.81	268	3,977	21,552	1,483
42	Lower Galena	42.4221	-90.4022	3.95	123	1,862	15,270	879
43	Lower Galena	42.4171	-90.423	8.14	175	2,681	17,209	883
45	Lower Galena	42.4043	-90.4326	4.11	123	1,588	17,887	778
46	Lower Galena	42.3884	-90.4323	4.22	158	2,066	22,338	968
47	Lower Galena	42.378	-90.4442	3.96	440	3,934	27,290	1,161
49	Upper Galena Trib.	42.6803	-90.4005	6.23	16	99	20,136	831
50	Upper Galena Trib.	42.6678	-90.4096	5.93	23	214	20,527	1,153
51	Upper Galena Trib.	42.6338	-90.3981	4.16	31	3,739	25,413	2,206
52	Upper Galena Trib.	42.6347	-90.3626	2.82	19,117	26,503	178,304	545
53	Upper Galena Trib.	42.6234	-90.3473	1.96	14	116	15,298	1,605
54	Upper Galena Trib.	42.6067	-90.3429	3.66	45	212	23,171	2,982
55	Middle Galena Trib.	42.4856	-90.3899	5.11	131	13,224	25,700	1,536
56	Lower Galena Trib.	42.4484	-90.3987	3.06	166	959	56,738	5,359
57	Lower Galena Trib.	42.4041	-90.4206	2.79	64	615	15,698	796
58	Lower Galena Trib.	42.407	-90.4263	2.68	91	357	12,640	713
60	Pats	42.6828	-90.367	5.11	29	66	18,051	1,018
61	Pats	42.6536	-90.3841	5.36	30	83	17,478	1,011
62	Pats	42.6493	-90.3812	2.76	102	2,290	24,516	1,628
63	Pats	42.6487	-90.3812	3.78	21	662	21,284	1,457
65	Madden	42.6829	-90.3342	5.65	54	98	14,702	1,025
66	Madden	42.6683	-90.3285	5.58	10	75	20,188	1,046
67	Madden	42.6676	-90.3392	8.43	48	202	17,917	1,214

Appendix B continued. Channel sediment site location and concentration averages (1992)

Site	Reach	Latitude	Longitude	OM%	1992 Metal Concentrations (ppm)			
					Pb	Zn	Fe	Mn
68	Madden	42.6685	-90.3102	6.08	15	70	15,684	879
69	Madden	42.6604	-90.3078	6.13	18	91	19,181	1,600
70	Madden	42.6563	-90.3279	6.18	34	555	20,076	1,606
71	Madden	42.6535	-90.344	4.99	24	76	14,475	1,078
72	Madden	42.6359	-90.3271	4.78	26	184	20,648	1,717
73	Madden	42.6309	-90.35	5.51	117	401	14,368	481
74	Madden	42.6305	-90.3555	2.79	34	224	19,811	1,680
75	Blacks	42.5877	-90.3777	5.02	124	1,159	35,958	1,426
76	Shullsburg	42.5649	-90.19	4.49	40	81	14,212	1,159
77	Shullsburg	42.5693	-90.2206	7.51	920	113	16,898	889
78	Shullsburg	42.5778	-90.2265	5	65	108	14,535	594
79	Shullsburg	42.5788	-90.2414	4.34	755	274	18,613	1,289
80	Shullsburg	42.5781	-90.2428	4.25	1,125	1,125	22,127	1,497
81	Shullsburg	42.5818	-90.2641	3.97	958	6,887	40,593	1,915
82	Shullsburg	42.5897	-90.2606	4.86	1,216	3,786	27,219	1,011
83	Shullsburg	42.5743	-90.2857	4.75	383	3,752	30,568	1,745
84	Shullsburg	42.5435	-90.2508	7.14	114	324	34,686	1,946
85	Shullsburg	42.5553	-90.2456	5.34	92	369	23,304	849
86	Shullsburg	42.5626	-90.2648	4.5	204	4,134	25,811	1,040
87	Shullsburg	42.5732	-90.2864	5.18	252	5,254	25,530	1,627
88	Shullsburg	42.5919	-90.2756	5.61	46	843	16,662	843
89	Shullsburg	42.5764	-90.2901	3.89	148	600	22,240	1,901
90	Shullsburg	42.5697	-90.3091	3.05	801	9,097	28,316	1,250
91	Shullsburg	42.6097	-90.3004	4.87	111	208	17,463	873

Appendix B continued. Channel sediment site location and concentration averages (1992)

Site	Reach	Latitude	Longitude	OM%	1992 Metal Concentrations (ppm)			
					Pb	Zn	Fe	Mn
92	Shullsburg	42.599	-90.3026	4.25	176	247	43,924	5,122
93	Shullsburg	42.5665	-90.3276	2.78	304	4,099	28,855	1,525
94	Shullsburg	42.56	-90.3366	2.75	297	4,810	27,727	1,619
95	Ellis	42.5487	-90.2706	6.98	56	472	24,776	962
96	Ellis	42.5511	-90.2828	4.06	148	827	15,826	215
98	Ellis	42.5531	-90.2951	4.8	171	3,361	15,214	723
102	Ellis	42.55	-90.3082	3.21	312	6,618	24,621	1,454
103	Ellis	42.5503	-90.3157	3.34	223	5,675	24,797	1,503
104	Ellis	42.5494	-90.3219	2.01	1,646	8,061	36,554	1,433
105	Ellis	42.549	-90.3257	5.99	545	4,023	25,555	1,056
106	Ellis	42.5471	-90.3398	5.4	577	4,640	26,016	1,163
108	Diggings	42.5338	-90.3072	1.48	129	6,366	18,612	898
109	Diggings	42.5338	-90.3091	2.77	124	16,605	19,605	933
110	Diggings	42.5355	-90.3161	4.22	143	10,239	18,755	998
111	Diggings	42.5368	-90.3163	2.78	197	7,194	34,279	1,219
112	Diggings	42.5362	-90.3166	0.9	171	20,259	34,313	1,141
113	Diggings	42.5356	-90.317	1.33	155	14,368	33,510	1,148
114	Diggings	42.5356	-90.3229	3.43	127	7,903	24,651	1,360
115	Diggings	42.5357	-90.3247	2.7	365	4,548	25,218	1,145
116	Diggings	42.5364	-90.3378	5.17	1,187	9,289	29,058	973
117	Diggings	42.5389	-90.3467	6.71	1,647	5,505	125,642	47
118	Diggings	42.5407	-90.353	3.54	447	10,697	47,565	1,094
119	Kelsey	42.5185	-90.3036	5.37	83	348	13,419	1,093
121	Kelsey	42.5142	-90.3382	4.89	67	380	15,761	1,059

Appendix B continued. Channel sediment site location and concentration averages (1992)

Site	Reach	Latitude	Longitude	OM%	1992 Metal Concentrations (ppm)			
					Pb	Zn	Fe	Mn
122	Kelsey	42.5109	-90.3576	5.66	71	224	13,512	943
123	Coon	42.5883	-90.4076	5.92	1,278	5,387	134,644	336
124	Coon	42.5856	-90.4059	1.39	511	2,263	52,280	800
127	Coon	42.54	-90.3755	3.1	163	3,776	35,024	1,236
128	Coon	42.524	-90.3806	2.03	294	8,414	31,582	1,623
131	Bull	42.5334	-90.4043	3.7	117	918	18,033	1,243
132	Bull	42.5366	-90.3971	5.04	142	394	24,538	2,508
133	Bull	42.5217	-90.3988	3.23	668	8,570	36,290	1,567
134	Bull	42.5146	-90.3966	2.02	487	17,069	39,601	1,583
135	Scrabble	42.5547	-90.4315	9	221	745	26,929	777
136	Scrabble	42.5299	-90.4208	5.74	339	3,812	22,773	766
137	Scrabble	42.5149	-90.403	2.54	451	9,382	19,679	1,007
138	Vinegar Hill	42.4975	-90.4122	3.65	116	74,601	17,723	657
139	Vinegar Hill	42.4975	-90.4057	3.62	279	9,970	20,671	741
140	Vinegar Hill	42.4986	-90.401	4.33	414	5,313	19,628	871
141	Vinegar Hill	42.5058	-90.396	4.8	111	382	16,516	1,989
142	Vinegar Hill	42.4996	-90.396	2.73	397	12,153	51,646	2,138
143	Vinegar Hill	42.4959	-90.3945	3.3	436	6,811	26,907	1,296
144	Middle Galena Trib.	42.4735	-90.4109	4.7	124	3,983	24,398	1,547
145	East Fork	42.5172	-90.2601	6.26	111	841	22,154	1,023
146	East Fork	42.4999	-90.2723	5.74	353	652	26,331	781
147	East Fork	42.4928	-90.2691	4.92	27	165	15,698	854
148	East Fork	42.4752	-90.3182	3.5	72	157	19,290	1,665
149	East Fork	42.4535	-90.3777	4.01	74	164	13,349	809

Appendix B continued. Channel sediment site location and concentration averages (1992)

Site	Reach	Latitude	Longitude	OM%	1992 Metal Concentrations (ppm)			
					Pb	Zn	Fe	Mn
150	Hughlett	42.4401	-90.4233	4.95	47	189	14,363	1,129
151	Hughlett	42.4365	-90.4221	2.95	205	1,112	14,447	1,401
152	Hughlett	42.4279	-90.4256	3.81	288	792	12,845	741
153	Hughlett	42.418	-90.4239	3.38	90	661	13,986	665

Appendix C. Channel Characteristics

Appendix C-1. Channel Characteristics (m)

Site	Bed Width	Bankfull width	Water Depth	Bankfull depth	Bar Height	Bench Height	Bank Height	
							Left	Right
2	1.5	3.3	0.3	0.7			0.6	0.5
4	1.9	3	0.3	1			1	0.7
6	3.1	6.1	0.25	0.75			0.25	0.7
7	2.7	6	0.25	0.6				1.75
8	5.5	8.8	0.28	1.4			0.25	1.3
9	5.5	8.6	0.4	0.7			0.3	1.8
11	6.8	10.5	0.45	1.9			2.2	0.6
12	12.6	16	0.76	3	1.56	1.3	3	
14	7.9	14	0.85	2.8	0.1	1.85	2.8	2.6
16	13.5	21	0.62	2.3		0.7		
17	12	21	0.6	1	0.7	1.4		
19	14.6	16.6	0.75	1.8			1.15	1.3
20	20.4	22.7	0.48	1.7			1.9	1.3
21	12.8	15.8	0.6	1.84				0.35
22	14.7	18.1	0.8	1.5			2.75	0.5
26	15	25	0.9	3			1.2	1.2
27	20	31	0.6	3.5			1	2
29	17.5	30	0.9	4.2			1.7	1.6
30	13	28	0.5	2				
31	11.3	23.7	1.3	3.3			1.6	1.9
33	1.7	3.3	0.11	0.8	0.2		0.8	0.8
34	12.8	21.3	1	2			2	2
37								
39	17	23	0.71	3.2				
40	23.5	32.5	0.5	2.7				
42				4.2				2.7
43				2.5			2.5	
46			2.3					
47			4.3					
49	5	7.6	0.2	0.5			0.3	0.3
50	2.5	4.4	0.3	0.5			1.4	0.4
51	3.1	4.7	0.3	0.4			0.3	0.3
52	4	6	0.25	1.2			0.75	0.55
53	0.6	1.6	0.005	1.6	0.1		1.2	
54	2	7.5	0.22	1.2	0.4		1.2	1.2

Appendix C-1 continued. Channel Characteristics (m)

Site	Bed Width	Bankfull width	Water Depth	Bankfull depth	Bar Height	Bench Height	Bank Height	
							Left	Right
55	1.3	1.9	0.12	0.7				
56	5.5	6	0	1				
57	2.2	5	0.35	1				
58	2.7	3.6	0.4	1			0.75	1
60	3.3	4.2	0.4	0.75			0.7	0.6
61	4.8	11.2	0.5	1.3			0.8	0.6
62	0.8	3.6	0.15	1.2			1.2	1.35
63	7.7	9.5	0.31	1.7			1.9	1.7
65	1.3	2.5	0.6	1.1			1.1	1.3
66	4.47	5.1	0.18	0.6			1.15	0.4
67	4.1	5.8	0.45	0.9			0.8	0.9
68	1.95	2.2	0.43	0.55			0.55	0.55
69	2.5	6	0.45	0.65			2	0.75
70	6.1	10.5	0.45	0.65			0.6	0.55
71	2.8	8.5	0.28	0.9			0.35	0.4
72	4.5	8.2	0.22	1.1			1.1	0.6
74	5.4	9.3	0.38	2	1	1	2	1.38
75	2.1	8	0.3	1.6	0.3	0.5		
76	1.1	6	0.19	1.1			0.8	0.7
77	1.7	2	0.28	1.3			0.7	1.1
78	6.1	14.1	0.64	1.8			1.2	2
79	2.3	14.3	0.43	1.4			1.2	1.4
80	3.2	10.5	0.33	1.5				
81	9.2	10	0.25	1.1	0.4	1.1		
82	2.2	8	0.3	0.6	0.6	0.4		
83	4.3	9.1	0.2	2	0.3	1.5		
84	1	1	0.05	0.5			0.3	0.3
85	1.55	3.7	0	1.6			0.85	0.7
86	3.15	9	0.24	0.5	0.3	0.9		
87	4.1	7.1	0.29	2	0.3	1		
88	1.65	2.9	0.32	0.7	0.4	0.7		
89	1.5	9.4	0.08	0.4	0.1			
90	14.7	14.7	0.5	1.5	0.6	1.5		
91	1.4	5.3	0.24	0.7	0.4	0.8		
92	1.2	7.5	0.2	0.6	0.3	1		

Appendix C-1 continued. Channel Characteristics (m)

Site	Bed Width	Bankfull width	Water Depth	Bankfull depth	Bar Height	Bench Height	Bank Height	
							Left	Right
93	5.5	16.2	0.27					
94	6.2	19	0.45	1.2	0.7	1.2		
95		1						
96	1	1.5	0.2	0.4				
98	1.7	3	0.4	0.8				
102	2.6	4	0.2	0.7				
103	1.3	2.7	0.2	0.95			0.2	0.5
104	1.25	2.7	0.2	0.75			0.4	0.35
105	1.15	5	0.35	1.15			1.15	1.15
106	1.4	4.4	0.18	1			0.6	1
108	0.8	2	0.2	0.65				
109	2.3	2.7	0.23	0.7			0.7	0.6
110	2	4	0.21	1.6	0.8		0.9	1.6
111	1	1	0.1	0.8	0.1			
112		0.5	0					
113	3	3.8	0.28	1.8			1.8	0.8
114	2.2	5.3	0.14	1.1	0.14		1.1	1.1
115	2.7	4.8	0.23	1.2	0.23		1.2	1.2
116	3	7	0.28	1	0.28		1	1
117	2.5	4	0.3	1.2	0.4		1.2	1.2
118	2.5	5	0.35	1.2	0.4		1	1.2
119	2.3	7.7	0.15	1.3			1.7	0.7
121	4							
122	6.5	12	0.2	2			0.6	1.4
123	1.5	35	0.21	1.4	0.5			
124	2.4	5	0.38	1.85	0.45			
127	5	5.5						0.7
128	2	6	0.2	2.6			2	2.5
131	3.8	5	0.22	0.6				
132	0.5	1.5	0.15	1				
133	2.9	3.1	0.22	1.1				
134	4.6	8.3	0.2	1.2				
135	0.5							
136	2.1	2.7	0.16	0.7	0.5			
137	3	5.5	0.21	1.2	0.4			

Appendix C-1 continued. Channel Characteristics (m)

Site	Bed Width	Bankfull width	Water Depth	Bankfull depth	Bar Height	Bench Height	Bank Height	
							Left	Right
138	2.4	6	0.2	1	0.3		1	0.8
139	3.6	7.5	0.25	1.6	0.35		1	1.6
140	2.9	6	0.42	2.5	0.5		2.5	1.5
142		1	0	0.3				
143	15.3	22.3	0.65	1.8	1		1.8	1.8
144	2.6	7	0.31	0.5	0.5			
145	1.35	7.35	0.13	1			0.3	0.4
146	3.4	7.4	0.41	1.7			1.2	1.4
147	2.8	13.8	0.3	1.6			0.6	0.4
148	7.5	150	0.61	1.8			1	1.4
149	9.2	18	0.71	2				
150	2.4	3.7	0.1	0.4				
151	1.4	2	0.18	0.3			0.25	0.25
152	3	5.25	0.25	1.25			0.6	0.6
153	5.8	9.9	0.6	2.4			1.6	1.6

Appendix C-2. Bank Stability

Site	Left (%)				Right (%)			
	Stable	Steep	Raw	Artificial	Stable	Steep	Raw	Artificial
2	80	15	5	0	100	0	0	0
4	100	0	0	0	100	0	0	0
6	100	0	0	0	0	100	15	0
7	100	0	0	0	0	90	15	0
8	100	0	5	0	50	50	5	0
9	100	0	0	0	100	0	80	0
11	100	0	0	0	100	0	0	0
12	5	95	20	0	95	5	5	0
14	5	95	80	0	100	0	0	0
16	100	0	0	10	30	70	50	10
17	95	5	0	0	100	0	0	0
19	5	95	0	0	50	50	0	0
20	100	0	0	0	40	60	10	0
21	85	15	15	0	66	33	20	0

Appendix C-2 continued. Bank Stability

Site	Left (%)				Right (%)			
	Stable	Steep	Raw	Artificial	Stable	Steep	Raw	Artificial
22	100	0	100	0	100	0	0	0
26	100	0	0	0	100	0	0	0
27	20	0	80	0	0	0	100	0
29	90	0	10	0	0	100	0	0
30	95	0	5	0	100	0	0	0
31	75	20	5	0	100	0	0	0
33	70	30	10	0	70	30	10	0
34	2	98	5	0	0	100	30	0
37	100	0	0	0	70	0	30	0
39	90	0	10	0	100	0	0	0
40	0	50	50	0	80	20	0	0
42	100	0	100	30	100	0	100	30
43	100	0	100	10	100	0	100	10
49	100	0	0	0	100	0	0	0
50	0	100	20	0	100	0	0	0
51	100	0	0	0	100	0	0	0
52	40	30	30	0	25	25	50	0
53	10	90	10	0	50	50	0	0
54	100	0	10	0	100	0	5	0
55	0	50	50	0	0	0	100	0
56	0	80	20	0	0	80	20	0
57	100	0	0	100	100	0	0	0
58	100	0	15	0	50	50	10	0
60	100	0	0	0	100	0	0	0
61	100	0	0	0	0	100	0	0
62	0	34	66	0	0	0	100	0
63	0	90	10	0	0	70	30	0
65	80	20	0	0	0	95	5	0
66	0	95	5	0	95	0	5	0
67	90	0	10	0	90	0	10	0
68	25	0	75	0	20	0	75	0
69	0	100	0	0	100	0	0	0
70	100	0	0	0	100	0	0	0
71	100	0	0	0	0	90	10	0
72	0	0	100	0	100	0	0	0

Appendix C-2 continued. Bank Stability

Site	Left (%)				Right (%)			
	Stable	Steep	Raw	Artificial	Stable	Steep	Raw	Artificial
74	20	80	60	0	0	100	0	0
75	10	80	10	0	100	0	0	0
76	80	0	20	0	80	0	20	0
77	80	0	20	0	70	0	30	0
78	0	0	100	0	0	80	20	0
79	90	0	10	0	80	0	20	0
80	0	0	100	0	0	0	100	0
81	80	0	10	10	85	0	10	5
82	0	90	10	0	100	0	0	0
83	0	80	0	20	100	0	0	0
84	100	0	0	0	100	0	0	0
85	0	0	100	0	0	0	100	0
86	25	0	75	0	95	0	5	0
87	80	0	10	10	0	90	0	10
88	0	10	90	0	100	0	0	0
89	80	0	20	0	95	0	0	5
90	0	0	100	0	0	10	90	0
91	100	0	0	0	100	0	0	0
92	78	0	20	2	50	0	50	0
93	90	10	0	0	10	80	0	10
94	55	15	30	0	90	10	0	0
96	0	90	0	10	0	100	0	0
98	10	80	10	0	0	100	0	0
102	0	90	10	0	100	0	0	0
103	100	0	10	0	100	0	0	0
105	50	50	0	0	100	0	0	0
106	10	90	10	0	100	0	15	0
108	100	0	0	0	80	20	0	0
109	90	10	60	0	90	10	70	0
110	100	0	2	0	95	5	2	0
111	90	10	10	0	100	0	0	0
113	50	50	10	0	100	0	0	0
114	100	0	3	1	100	0	2	1
115	100	0	0	0	80	20	30	0
116	100	0	0	0	100	0	0	0

Appendix C-2 continued. Bank Stability

Site	Left (%)				Right (%)			
	Stable	Steep	Raw	Artificial	Stable	Steep	Raw	Artificial
118	90	10	0	0	10	90	50	0
119	0	0	100	0	0	0	100	0
122	100	0	0	0	100	0	0	0
123	90	10	0	0	100	0	0	0
124	80	20	2	0	90	10	2	0
127	33	66	30	0	0	100	0	30
128	100	0	0	0	0	0	100	0
131	95	0	5	0	80	0	20	0
132	10	80	10	0	0	95	5	0
133	20	30	50	0	5	15	80	0
134	80	0	20	0	0	0	100	0
135	100	0	0	0	100	0	0	0
136	10	80	10	0	100	0	0	0
137	100	0	0	0	0	95	5	0
138	100	0	0	0	80	20	5	0
139	100	0	0	5	60	40	20	5
140	20	80	70	0	90	10	10	0
142	100	0	0	0	100	0	0	0
143	70	30	20	0	80	20	10	0
144	100	0	0	0	100	0	0	0
145	100	0	0	0	100	0	0	0
146	0	0	100	0	0	0	100	0
147	100	0	0	0	100	0	0	0
148	40	0	60	0	60	0	40	0
149	80	0	20	0	0	95	5	0
150	0	50	50	0	90	0	10	0
151	0	0	0	10	0	0	0	10
152	20	80	0	0	20	80	5	0
153	100	0	10	30	100	0	100	30

Appendix C-3. Bank Condition (0=not present, 1=present, 2=common)

Site	Left				Right			
	Tree Roots	Fallen Tree	Slumps	Toe Erosion	Tree Roots	Fallen Tree	Slumps	Toe Erosion
1	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	1	1
8	0	0	0	0	0	0	1	0
9	0	0	0	0	0	0	1	1
11	0	0	0	0	0	0	0	0
12	2	0	1	1	0	0	1	1
14	0	0	2	2	0	0	1	0
16	0	0	0	0	0	0	2	1
17	0	0	2	0	0	0	0	0
19	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0
21	0	0	0	0	1	0	0	0
22	0	0	0	1	0	0	0	0
26	0	0	0	0	0	0	0	0
27	0	0	0	0	2	0	0	0
29	0	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0
33	0	0	2	2	0	0	2	1
34	0	0	1	1	0	0	1	1
37	0	0	0	0	0	1	0	0
39	1	0	0	0	0	0	0	0
40	0	1	1	1	0	1	0	0
42	1	0	0	0	1	0	0	0
43	1	0	0	0	1	0	0	0
46	0	0	0	0	0	0	0	0
47	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0
50	0	0	1	1	0	0	0	0
51	0	0	0	0	0	0	0	0
52	2	2	2	0	2	2	2	0
53	0	0	2	1	0	0	1	1

Appendix C-3 continued. Bank Condition (0=not present, 1=present, 2=common)

Site	Left				Right			
	Tree Roots	Fallen Tree	Slumps	Toe Erosion	Tree Roots	Fallen Tree	Slumps	Toe Erosion
54	0	0	0	1	0	0	0	0
55	1	0	1	0	1	0	0	0
56	1	1	0	0	0	0	0	0
57	0		0	0	0		0	0
58	1	0	0	0	1	0	0	1
60	0	0	0	0	0	0	0	0
61	0	0	1	0	0	0	1	0
62	0	1	0	0	1	1	0	0
63	1	1	0	0	1	1	0	0
65	0	0	0	0	0	0	0	0
66	1	1	1	0	2	2	0	0
67	0	0	1	0	0	0	1	0
68	0	0	0	0	0	0	0	0
69	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0
71	0	1	1	0	0	0	0	0
72	0	1	0	0	1	1	0	0
73	0	0	0	0	0	0	0	0
74	1	0	2	2	0	0	1	0
75	0	0	2	1	0	0	0	0
76	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0
78	0	0	0	0	1	1	0	0
79	0	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0	0
81	0	0	0	1	0	0	0	0
82	0	0	0	1	0	0	0	0
83	0	0	0	0	0	0	0	0
84	0		0	0	0	0	0	0
85	1	1	0	0	1	1	0	0
86	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0
88	0	0	1	1	0	0	0	0
89	0	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0	0

Appendix C-3 continued. Bank Condition (0=not present, 1=present, 2=common

Site	Left				Right			
	Tree Roots	Fallen Tree	Slumps	Toe Erosion	Tree Roots	Fallen Tree	Slumps	Toe Erosion
91	0	0	0	0	0	0	0	0
92	0	0	0	1	0	0	1	0
93	0	0	0	0	0	0	0	0
94	0	0	1	1	0	0	0	0
95	0	0	0	0	0	0	0	0
96	0	0	0	0	0	0	0	0
98	0	0	0	1	0	0	0	0
102	0	0	0	0	0	0	0	0
103	0	0	0	1	0	0	0	0
104	0	0	0	0	0	0	0	0
105	0	0	0	0	0	0	0	0
106	0	0	1	0	0	0	0	0
108	0	0	0	0	0	0	0	0
109	0	0	2	2	0	0	0	1
110	0	0	0	0	0	0	1	0
111	0	0	0	1	0	0	0	1
112	0	0	0	0	0	0	0	0
113	2	0	2	1	0	0	0	1
114	0	0	2	1	0	1	0	1
115	0	0	2	0	0	0	2	1
116	0	0	1	0	0	0	2	0
117	0	0	2	0	0	0	2	0
118	0	0	1	0	0	0	1	2
119	1	2	1	0	1	2	0	0
121	0	0	0	0	0	0	0	0
122	0	0	0	0	0	0	0	0
123	0	0	1	1	0	0	0	0
124	0	0	2	1	0	0	1	1
127	0	0	0	0	0	0	0	0
128	0	0	0	0	0	0	2	0
131	0	0	1	0	0	0	1	0
132	1	1	0	1	0	1	0	1
133	0	0	1	2	1	0	1	1
134	0	1	1	0	1	1	0	1
135	0	0	0	0	0	0	0	0

Appendix C-3 continued. Bank Condition (0=not present, 1=present, 2=common)

Site	Left				Right			
	Tree Roots	Fallen Tree	Slumps	Toe Erosion	Tree Roots	Fallen Tree	Slumps	Toe Erosion
136	0	0	0	0	0	0	0	0
137	0	0	0	0	1	0	1	0
138	0	0	2	0	0	0	2	0
139	0	0	0	1	0	0	1	2
140	0	0	2	1	0	0	2	1
141	0	0	0	0	0	0	0	0
142	0	0	0	0	0	0	0	0
143	2	2	2	1	1	1	1	1
144	0	0	0	0	0	0	0	0
145	0	0	0	0	0	0	0	0
146	0	0	0	0	2	1	0	0
147	0	0	0	0	0	0	0	0
148	0	0	0	0	0	0	0	0
149	1	0	1	0	0	0	0	1
150	0	1	0	1	0	0	0	1
151	0	0	0	1	0	0	0	1
152	1	0	0	0	0	1	0	0
153	1	0	0	2	1	0	0	0

Appendix D. RPD% and Cv% of samples

Reach	Pb		Zn		Fe		Mn		Ca		OM	
	Median RPD%	Cv%	Median RPD%	Cv%	Median RPD%	Cv%	Median RPD%	Cv%	Median RPD%	Cv%	Median RPD%	Cv%
Upper Galena River	5.2	73.1	13.4	78.7	9.4	13.6	20.8	22.6	19.5	60.9	13.9	18.5
Middle Galena River	12.3	27.3	20.9	28.2	7.8	12.7	8.6	19.3	28.1	34.7	10.5	13.6
Lower Galena River	6.7	45.8	13.3	81.6	6.3	14.9	12.6	23.8	29.4	55.5	13.9	23.2
Pats Creek	15.7	72.7	23.2	100.5	9.4	19.9	16.9	19.7	21.5	32.2	9.9	14.5
Madden Branch	94.0	41.0	9.5	26.1	6.0	8.7	20.7	27.6	26.3	40.8	20.6	20.6
Shullsburg Branch	7.0	63.2	11.9	82.1	6.5	16.1	13.8	24.6	32.5	44.8	8.1	16.0
Ellis Branch	15.8	89.7	19.7	69.4	8.7	30.9	6.5	21.3	38.0	52.9	17.0	42.3
Diggings Branch	8.8	64.3	23.9	38.5	7.1	25.5	17.9	26.2	23.6	30.2	21.9	31.5
Kelsey Branch	42.2	4.8	26.2	28.0	22.2	13.5	23.1	18.9	22.2	12.7	11.6	5.9
Coon Branch	15.9	47.6	17.5	30.9	6.3	68.5	13.2	21.0	12.5	46.9	5.5	17.5
Bull Branch	18.9	87.1	19.6	105.8	15.6	19.4	15.7	20.7	27.7	75.2	28.8	36.7
Scrabble Branch	7.2	76.8	19.9	80.4	7.8	13.7	30.7	9.8	10.1	66.4	20.3	15.0
Vinegar Hill	27.5	73.6	19.3	59.5	9.7	50.6	11.1	46.2	14.0	66.2	10.8	68.7
East Fork	50.5	75.8	14.4	80.6	13.8	22.1	22.6	19.4	16.4	29.2	16.9	31.8
Hughlett Branch	37.2	50.1	51.4	39.1	10.8	11.9	15.2	33.7	16.4	61.1	11.4	21.7
Average	24.3	59.5	20.3	62.0	9.8	22.8	16.6	23.7	22.5	47.3	14.7	25.2

Appendix E. Tailing Pile sediment site location and concentration averages (2017)

Site	Mine	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
T135	Blackstone	42.5318	-90.33	3.59	1,371	28,157	51,129	1,105	143,400
125	Century	42.5655	-90.3799	5.89	922	5,163	62,292	1,143	67,659
T137	Champion	42.5353	-90.3507	4.74	463	12,081	68,653	1,592	144,406
T158	Federal	42.5109	-90.3961	4.86	959	22,292	62,422	1,190	151,523
104	Hoskins	42.5522	-90.3201	2.88	499	10,448	40,754	1,206	136,589
136	Kennedy	42.5272	-90.4057	3.69	552	12,183	73,488	1,823	75,474
133	Little Dad	42.5212	-90.4004	4.73	1,243	19,994	45,366	1,023	151,070
81	Little Giant	42.4659	-90.4238	5.68	2,037	20,972	62,680	1,270	121,519
108	Lucky Twelve (1)	42.5377	-90.3163	3.75	316	9,651	42,955	1,271	146,436
T108	Lucky Twelve (2)	42.5377	-90.3163	4.79	1,141	17,315	193,657	980	112,951
T162	Monroe	42.5342	-90.3235	3.50	2,342	28,520	48,503	1,111	130,081
T142	Old Ida Blende	42.5583	-90.3665	6.57	705	31,500	162,742	1,445	77,403
105	Sally Waters	42.5499	-90.3296	2.59	946	25,544	43,396	1,251	145,381
T144	Vinegar Hill	42.4968	-90.415	6.76	1,474	27,866	84,137	1,217	146,403

Appendix F. Channel sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
1	Upper Galena	42.7478	-90.3829	8.61	15	130	18,423	869	5,515
2	Upper Galena	42.7339	-90.3899	6.77	15	130	16,436	634	36,254
4	Upper Galena	42.7115	-90.3993	6.57	15	160	17,180	849	32,883
6	Upper Galena	42.6824	-90.4118	7.84	29	231	19,261	840	26,679
7	Upper Galena	42.6677	-90.4141	8.11	52	307	20,300	984	46,612
8	Upper Galena	42.6602	-90.4113	8.18	53	410	18,130	848	37,583
9	Upper Galena	42.6519	-90.4119	5.99	71	557	19,806	943	35,629
11	Upper Galena	42.6338	-90.371	7.24	134	1,378	20,787	1,081	46,235
12	Upper Galena	42.6311	-90.3579	7.52	194	1,392	26,218	1,244	76,910
14	Upper Galena	42.6158	-90.3526	5.50	70	604	18,048	872	26,101
16	Upper Galena	42.5764	-90.3664	6.60	100	581	20,140	838	18,283
17	Upper Galena	42.5716	-90.3532	3.86	115	715	18,641	1,385	86,838
19	Upper Galena	42.5514	-90.3593	7.32	142	1,440	23,841	1,333	94,618
20	Middle Galena	42.549	-90.3465	6.99	288	2,435	22,841	895	52,471
21	Middle Galena	42.5425	-90.3533	5.44	312	2,482	23,110	1,049	76,453
22	Middle Galena	42.54	-90.3537	5.25	412	2,992	22,469	1,248	80,736
26	Middle Galena	42.5149	-90.3637	5.29	212	2,499	18,161	710	112,420
27	Middle Galena	42.5135	-90.3784	4.47	190	1,954	17,491	951	92,681
29	Middle Galena	42.515	-90.3899	5.78	317	2,906	22,691	828	65,294
30	Middle Galena	42.5133	-90.3972	5.83	376	2,995	21,383	971	46,417
31	Middle Galena	42.5106	-90.3919	6.27	318	3,219	21,326	1,066	116,498
33	Middle Galena	42.4945	-90.3925	4.80	498	4,848	26,829	1,443	69,867

Appendix F continued. Channel sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
34	Middle Galena	42.4936	-90.3992	3.73	250	4,584	17,251	936	126,170
37	Middle Galena	42.4769	-90.4064	6.34	286	2,537	22,623	889	40,343
39	Middle Galena	42.4508	-90.388	5.49	282	3,429	21,847	1,074	80,173
40	Lower Galena	42.4485	-90.3892	5.78	338	3,549	22,521	1,157	98,494
42	Lower Galena	42.4221	-90.4022	5.56	273	2,883	20,883	710	77,193
43	Lower Galena	42.4171	-90.423	6.47	275	2,743	24,902	1,040	75,355
45	Lower Galena	42.4043	-90.4326	5.60	261	3,198	23,012	1,039	121,304
46	Lower Galena	42.3884	-90.4323	3.13	158	1,845	20,880	787	53,969
47	Lower Galena	42.378	-90.4442	6.18	240	2,005	24,538	605	28,859
49	Upper Galena Trib.	42.6803	-90.4005	8.83	51	230	21,723	949	29,350
50	Upper Galena Trib.	42.6678	-90.4096	7.16	58	465	21,439	889	27,573
51	Upper Galena Trib.	42.6338	-90.3981	5.50	105	2,926	22,870	1,245	55,539
52	Upper Galena Trib.	42.6347	-90.3626	12.08	1,261	4,430	93,192	369	27,474
53	Upper Galena Trib.	42.6234	-90.3473	4.22	52	275	20,981	1,408	29,381
54	Upper Galena Trib.	42.6067	-90.3429	6.52	72	417	18,524	816	16,425
55	Middle Galena Trib.	42.4856	-90.3899	5.06	152	846	23,995	1,516	82,124
56	Lower Galena Trib.	42.4484	-90.3987	4.93	96	502	18,494	1,245	110,771
57	Lower Galena Trib.	42.4041	-90.4206	5.68	85	479	18,323	736	117,082
58	Lower Galena Trib.	42.407	-90.4263	6.17	111	525	17,212	662	66,107
60	Pats	42.6828	-90.367	8.45	49	152	19,410	941	17,830
61	Pats	42.6536	-90.3841	7.17	55	187	21,591	1,066	41,092
62	Pats	42.6493	-90.3812	6.46	184	2,298	24,497	1,319	39,612
63	Pats	42.6487	-90.3812	5.81	244	2,509	30,397	1,460	39,172
65	Madden	42.6829	-90.3342	10.26	15	185	18,570	775	13,295

Appendix F continued. Channel sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
67	Madden	42.6676	-90.3392	8.14	41	251	16,945	628	19,652
68	Madden	42.6685	-90.3102	8.73	55	339	19,724	732	41,164
69	Madden	42.6604	-90.3078	8.72	23	152	17,950	1,019	44,917
70	Madden	42.6563	-90.3279	6.02	26	229	18,053	733	16,072
71	Madden	42.6535	-90.344	6.95	15	204	19,727	1,085	25,575
72	Madden	42.6359	-90.3271	5.91	46	351	22,957	1,505	26,364
73	Madden	42.6309	-90.35	6.55	44	279	18,519	885	15,772
74	Madden	42.6305	-90.3555	6.27	34	241	19,900	1,178	32,640
75	Blacks	42.5877	-90.3777	6.45	365	1,265	26,357	825	23,972
76	Shullsburg	42.5649	-90.19	10.08	15	182	19,173	815	10,957
77	Shullsburg	42.5693	-90.2206	6.82	1,106	300	19,671	849	48,214
78	Shullsburg	42.5778	-90.2265	7.57	175	474	20,873	990	35,052
79	Shullsburg	42.5788	-90.2414	8.71	717	469	20,733	1,154	58,646
80	Shullsburg	42.5781	-90.2428	8.92	528	858	21,738	591	104,595
81	Shullsburg	42.5818	-90.2641	8.24	519	2,661	20,773	787	49,455
82	Shullsburg	42.5897	-90.2606	6.60	444	2,779	21,591	889	78,767
83	Shullsburg	42.5743	-90.2857	6.75	551	4,230	30,170	1,297	49,155
84	Shullsburg	42.5435	-90.2508	6.69	583	4,370	33,739	432	73,784
85	Shullsburg	42.5553	-90.2456	7.53	403	386	23,945	1,030	65,889
86	Shullsburg	42.5626	-90.2648	9.22	307	1,929	24,578	941	56,579
87	Shullsburg	42.5732	-90.2864	6.43	451	5,181	25,551	1,436	64,728
88	Shullsburg	42.5919	-90.2756	7.54	223	1,718	21,982	1,006	58,797
89	Shullsburg	42.5764	-90.2901	8.46	204	1,249	20,022	978	15,173
90	Shullsburg	42.5697	-90.3091	5.96	628	4,637	26,592	1,229	54,171

Appendix F continued. Channel sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
91	Shullsburg	42.6097	-90.3004	8.05	78	549	20,738	1,046	25,772
92	Shullsburg	42.599	-90.3026	7.22	108	603	21,459	1,024	19,222
93	Shullsburg	42.5665	-90.3276	5.89	376	3,227	24,864	1,319	52,879
94	Shullsburg	42.56	-90.3366	7.52	373	3,255	23,708	1,059	54,434
95	Ellis	42.5487	-90.2706	9.61	46	836	19,709	713	10,486
96	Ellis	42.5511	-90.2828	14.70	209	3,081	18,611	1,083	65,789
98	Ellis	42.5531	-90.2951	6.95	118	1,730	20,733	1,057	98,992
102	Ellis	42.55	-90.3082	5.68	350	7,267	26,410	1,381	108,176
103	Ellis	42.5503	-90.3157	6.48	220	2,876	21,399	946	47,679
104	Ellis	42.5494	-90.3219	4.53	1,157	11,278	41,051	1,341	150,669
105	Ellis	42.549	-90.3257	4.73	982	6,942	35,792	1,412	143,249
106	Ellis	42.5471	-90.3398	8.06	616	6,771	30,214	1,276	89,188
108	Diggings	42.5338	-90.3072	5.09	153	3,080	19,486	810	46,407
109	Diggings	42.5338	-90.3091	3.23	227	6,360	23,339	1,176	88,856
110	Diggings	42.5355	-90.3161	3.73	157	6,282	18,004	1,095	96,571
111	Diggings	42.5368	-90.3163	3.83	401	9,122	41,281	1,422	128,576
112	Diggings	42.5362	-90.3166	6.35	613	14,223	33,702	1,045	111,703
113	Diggings	42.5356	-90.317	3.78	372	5,844	31,776	882	73,175
114	Diggings	42.5356	-90.3229	3.57	218	6,078	23,405	1,419	124,869
115	Diggings	42.5357	-90.3247	6.95	1,117	10,190	34,104	758	110,208
116	Diggings	42.5364	-90.3378	7.91	525	6,113	25,329	686	49,456
117	Diggings	42.5389	-90.3467	4.66	682	9,546	34,742	1,358	117,641
118	Diggings	42.5407	-90.353	6.20	851	8,043	33,438	1,460	120,210
119	Kelsey	42.5185	-90.3036	5.52	157	660	17,742	1,093	55,737

Appendix F continued. Channel sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
121	Kelsey	42.5142	-90.3382	5.81	173	546	20,731	1,277	70,729
122	Kelsey	42.5109	-90.3576	6.03	161	369	15,870	870	59,088
123	Coon	42.5883	-90.4076	7.67	1,215	5,955	113,097	1,244	61,092
124	Coon	42.5856	-90.4059	5.80	698	3,501	72,244	899	76,935
127	Coon	42.54	-90.3755	6.07	480	3,575	27,720	758	29,894
128	Coon	42.524	-90.3806	6.16	493	3,267	27,245	1,039	30,609
131	Bull	42.5334	-90.4043	10.25	115	1,293	21,743	1,149	34,694
132	Bull	42.5366	-90.3971	5.36	91	375	22,346	1,764	9,569
133	Bull	42.5217	-90.3988	7.22	276	4,552	28,892	1,213	102,905
134	Bull	42.5146	-90.3966	5.40	605	9,684	32,221	1,283	93,676
135	Scrabble	42.5547	-90.4315	8.29	182	577	22,119	1,226	17,254
136	Scrabble	42.5299	-90.4208	6.91	1,245	5,441	29,078	1,330	76,250
137	Scrabble	42.5149	-90.403	6.64	655	7,923	25,099	1,091	101,263
138	Vinegar Hill	42.4975	-90.4122	5.50	1,055	3,712	23,369	517	64,748
139	Vinegar Hill	42.4975	-90.4057	5.31	356	5,290	20,911	749	120,097
140	Vinegar Hill	42.4986	-90.401	10.90	424	4,947	23,608	727	118,834
141	Vinegar Hill	42.5058	-90.396	9.48	120	351	18,297	1,118	9,418
142	Vinegar Hill	42.4996	-90.396	18.38	362	8,853	54,200	1,837	32,710
143	Vinegar Hill	42.4959	-90.3945	4.61	298	4,492	20,445	1,200	143,293
144	Middle Galena Trib.	42.4735	-90.4109	8.01	238	2,183	26,819	1,266	56,739
145	East Fork	42.5172	-90.2601	8.91	383	1,587	29,048	709	56,905
146	East Fork	42.4999	-90.2723	6.79	538	485	21,711	778	48,103
147	East Fork	42.4928	-90.2691	8.24	35	388	23,510	1,104	57,795
148	East Fork	42.4752	-90.3182	4.54	259	530	17,003	726	34,703

Appendix F continued. Channel sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
149	East Fork	42.4535	-90.3777	5.94	117	290	17,980	901	78,824
150	Hughlett	42.4401	-90.4233	6.71	62	358	18,208	1,229	77,358
151	Hughlett	42.4365	-90.4221	3.68	274	824	17,584	982	42,525
152	Hughlett	42.4279	-90.4256	4.04	293	981	14,797	783	121,861
153	Hughlett	42.418	-90.4239	4.92	209	1,064	19,816	529	29,268

Appendix G. Harris Slough concentration averages

Appendix G-1. Harris Slough Bank

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
1	Mississippi River	42.377512	-90.455765	6.15	280	2232	25408	797	31092
2	Mississippi River	42.375053	-90.451045	5.60	180	1900	23105	855	40990
3	Lower Galena River	42.377611	-90.444263	5.85	255	2826	22914	554	36441
4	Galena Confluence	42.374171	-90.446201	6.36	253	2314	23369	903	46730
5	Mississippi River	42.371883	-90.442213	6.28	196	2417	18989	1149	116331
6	Mississippi River	42.368496	-90.443334	6.09	257	2073	21780	675	28323
7	Mississippi River	42.364901	-90.437129	16.34	284	2729	20592	806	54523
8	Mississippi River	42.361012	-90.431634	5.59	245	2831	22061	1032	88625
9	Mississippi River	42.35617	-90.428945	4.64	209	1816	20864	574	30345
10	Mississippi River	42.352844	-90.428987	6.18	228	1990	23777	817	25523

Appendix G-2. Harris Slough Channel

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
1	Mississippi River	42.377512	-90.455765	4.99	217	2021	23444	797	40130
2	Mississippi River	42.375053	-90.451045	5.00	214	1867	21533	679	35416
3	Lower Galena River	42.377611	-90.444263	4.82	252	2580	20466	1138	63204
4	Galena Confluence	42.374171	-90.446201						
5	Mississippi River	42.371883	-90.442213	3.67	170	1581	15851	500	38139
6	Mississippi River	42.368496	-90.443334						
7	Mississippi River	42.364901	-90.437129	6.28	215	1858	20403	803	31223
8	Mississippi River	42.361012	-90.431634	6.47	274	2252	25637	888	26316
9	Mississippi River	42.35617	-90.428945	7.16	272	2070	26010	742	23390
10	Mississippi River	42.352844	-90.428987	6.84	185	1692	21253	760	29498

Appendix H. Summary of unmined and tailings

Metal	Location	Type	n Sites	n Samples	Max.	75%	Median	25%	Min.	Mean	SD	Cv%
Pb	Madden Branch	Channel	10	20	95	46	15	15	15	33	25	74.2
Pb	East Fork	Channel	5	9	734	383	259	83	15	266	226	84.9
Pb	Madden Branch	Floodplain	9	9	51	15	15	15	15	19	12	64.2
Pb	East Fork	Floodplain	5	5	619	477	200	68	48	258	231	89.4
Pb	Galena River	Tailings	14	24	2,702	1,625	952	443	63	1,052	694	66.0
Zn	Madden Branch	Channel	10	20	489	272	229	182	147	243	82	33.5
Zn	East Fork	Channel	5	9	1,590	1,065	423	355	250	670	528	78.8
Zn	Madden Branch	Floodplain	9	9	313	270	214	153	136	212	65	30.5
Zn	East Fork	Floodplain	5	5	1,462	1,010	417	251	193	588	507	86.3
Zn	Galena River	Tailings	14	24	37,296	25,540	21,404	12,002	632	19,942	9,238	46.3
Fe	Madden Branch	Channel	10	20	25,849	20,128	19,150	17,968	15,601	19,279	2,172	11.3
Fe	East Fork	Channel	5	9	31,115	1,065	21,578	18,093	1,678	22,389	4,730	21.1
Fe	Madden Branch	Floodplain	9	9	21,689	19,147	18,152	16,859	16,494	18,215	1,634	9.0
Fe	East Fork	Floodplain	5	5	28,055	24,060	18,804	16,992	16,007	20,182	4,642	23.0
Fe	Galena River	Tailings	14	24	261,548	77,372	61,313	51,037	25,195	78,135	53,181	68.1

Appendix H continued. Summary of unmined and tailings

Metal	Location	Type	n Sites	n Samples	Max.	75%	Median	25%	Min.	Mean	SD	Cv%
Mn	Madden Branch	Channel	10	20	1,695	1,119	870	714	596	942	286	30.3
Mn	East Fork	Channel	5	9	1,257	926	878	721	528	853	199	23.3
Mn	Madden Branch	Floodplain	9	9	1,529	1,045	955	875	785	1,000	217	21.7
Mn	East Fork	Floodplain	5	5	1,065	1,014	905	792	688	903	138	15.3
Mn	Galena River	Tailings	14	24	1,823	1,378	1,202	1,070	706	1,244	271	21.8
Ca	Madden Branch	Channel	10	20	52,945	35,182	23,215	16,996	8,376	26,386	11,740	44.5
Ca	East Fork	Channel	5	9	88,794	65,671	55,718	48,103	34,703	57,551	15,344	26.7
Ca	Madden Branch	Floodplain	9	9	68,737	35,544	25,087	12,765	10,640	27,467	18,500	67.4
Ca	East Fork	Floodplain	5	5	52,155	51,289	41,610	32,475	32,031	41,828	9,433	22.6
Ca	Galena River	Tailings	14	24	151,524	147,991	142,322	118,982	4,547	125,712	37,208	29.6
OM	Madden Branch	Channel	10	20	11.6	9.3	8.2	6.3	4.3	7.8	2.0	26.2
OM	East Fork	Channel	5	9	10.5	8.2	7.3	5.9	4.5	7.1	1.8	24.9
OM	Madden Branch	Floodplain	9	9	8.2	8.2	6..85	5.7	4.8	6.9	1.3	18.3
OM	East Fork	Floodplain	5	5	12.2	10.4	8.6	6.5	6.0	8.5	2.4	27.8
OM	Galena River	Tailings	14	24	7.1	6.0	4.3	3.3	2.5	4.6	1.5	32.6

Appendix I. Floodplain sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
2	Upper Galena	42.7339	-90.3899	7.71	15	165	21,194	1,314	32,897
4	Upper Galena	42.7115	-90.3993	9.71	15	194	18,550	1,029	21,538
6	Upper Galena	42.6824	-90.4118	6.11	15	210	16,392	706	21,966
7	Upper Galena	42.6677	-90.4141	7.98	55	254	17,767	786	36,300
8	Upper Galena	42.6602	-90.4113	6.51	71	497	18,200	775	31,662
9	Upper Galena	42.6519	-90.4119	8.14	65	400	18,644	977	31,471
11	Upper Galena	42.6338	-90.371	7.19	100	924	18,797	857	28,448
14	Upper Galena	42.6158	-90.3526	6.11	75	595	18,475	880	23,850
16	Upper Galena	42.5764	-90.3664	7.64	80	595	18,512	820	29,227
17	Upper Galena	42.5716	-90.3532	5.12	91	615	14,673	784	64,444
19	Upper Galena	42.5514	-90.3593	6.59	126	967	18,290	996	62,846
20	Middle Galena	42.549	-90.3465	6.41	223	1,575	20,203	937	44,345
21	Middle Galena	42.5425	-90.3533	5.82	285	2,196	21,272	944	44,377
22	Middle Galena	42.54	-90.3537	4.85	323	2,523	21,900	1,088	80,117
26	Middle Galena	42.5149	-90.3637	7.41	270	2,232	20,159	915	58,533
27	Middle Galena	42.5135	-90.3784	5.92	260	2,257	18,536	932	54,610
29	Middle Galena	42.515	-90.3899	5.65	245	1,902	19,458	906	61,198
30	Middle Galena	42.5133	-90.3972	7.51	319	2,706	21,026	1,070	75,428
31	Middle Galena	42.5106	-90.3919	5.75	280	2,670	20,756	997	76,857
33	Middle Galena	42.4945	-90.3925	7.47	1,263	13,597	38,705	1,566	97,709
34	Middle Galena	42.4936	-90.3992	8.89	274	2,314	21,799	1,045	66,131
37	Middle Galena	42.4769	-90.4064	9.20	333	2,830	18,521	878	60,612
39	Middle Galena	42.4508	-90.388	8.69	325	2,868	20,059	953	59,499
40	Lower Galena	42.4485	-90.3892	5.92	305	3,128	19,877	1,127	120,371

Appendix I continued. Floodplain sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
42	Lower Galena	42.4221	-90.4022	5.73	292	3,060	19,590	1,111	90,608
43	Lower Galena	42.4171	-90.423	5.54	256	3,691	19,591	1,099	92,724
45	Lower Galena	42.4043	-90.4326	6.76	257	2,205	20,853	763	34,121
46	Lower Galena	42.3881	-90.429	5.28	240	2,270	19,798	788	52,691
47	Lower Galena	42.3781	-90.444	6.48	242	2,218	23,808	822	31,558
49	Upper Galena Trib.	42.6803	-90.4005	8.11	58	236	20,355	1,093	35,627
50	Upper Galena Trib.	42.6678	-90.4096	9.11	75	509	20,515	966	39,561
51	Upper Galena Trib.	42.6338	-90.3981	8.63	86	2,051	18,066	672	21,913
52	Upper Galena Trib.	42.6347	-90.3626	6.85	1,253	4,447	83,988	242	32,562
55	Middle Galena Trib.	42.4856	-90.3899	8.13	107	562	20,331	1,140	77,431
56	Lower Galena Trib.	42.4484	-90.3987	7.43	62	440	20,044	800	103,673
57	Lower Galena Trib.	42.4041	-90.4206	4.79	112	509	16,519	862	148,740
58	Lower Galena Trib.	42.407	-90.4263	5.65	140	714	17,852	776	46,188
60	Pats	42.6828	-90.367	8.23	15	156	20,015	753	28,450
61	Pats	42.6536	-90.3841	8.14	15	162	17,042	903	22,875
62	Pats	42.6493	-90.3812	6.83	64	321	16,787	767	16,215
63	Pats	42.6487	-90.3812	5.65	234	2,149	26,533	1,317	38,930
65	Madden	42.6829	-90.3342	9.85	15	136	16,887	909	12,706
66	Madden	42.6683	-90.3285	8.56	15	174	16,832	785	20,627
67	Madden	42.6676	-90.3392	10.38	53	298	18,992	842	12,823
68	Madden	42.6685	-90.3102	7.15	15	139	18,300	955	43,650
69	Madden	42.6604	-90.3078	8.79	15	166	16,494	982	25,219
70	Madden	42.6563	-90.3279	5.66	15	227	18,152	911	10,640
71	Madden	42.6535	-90.344	10.26	15	214	17,290	1,002	27,439

Appendix I continued. Floodplain sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
72	Madden	42.6359	-90.3271	6.74	15	313	19,303	1,088	25,087
74	Madden	42.6305	-90.3555	4.03	15	241	21,689	1,529	68,737
75	Blacks	42.5877	-90.3777	9.76	203	934	21,193	1,014	22,128
76	Shullsburg	42.5649	-90.19	10.29	15	151	15,859	669	8,012
77	Shullsburg	42.5693	-90.2206	11.30	984	209	20,194	1,158	65,152
78	Shullsburg	42.5778	-90.2265	11.51	226	380	20,573	906	35,646
79	Shullsburg	42.5788	-90.2414	10.54	436	412	19,225	838	40,146
80	Shullsburg	42.5781	-90.2428	7.38	466	1,043	17,709	787	109,931
84	Shullsburg	42.5435	-90.2508	11.86	311	2,151	22,172	507	57,960
85	Shullsburg	42.5553	-90.2456	8.14	373	345	20,202	865	63,586
86	Shullsburg	42.5626	-90.2648	9.05	332	1,850	23,027	789	59,402
88	Shullsburg	42.5919	-90.2756	6.06	424	4,611	20,713	671	38,338
90	Shullsburg	42.5697	-90.3091	8.29	565	4,486	20,938	791	42,862
91	Shullsburg	42.6097	-90.3004	9.42	74	439	18,354	995	19,993
93	Shullsburg	42.5665	-90.3276	7.73	599	4,727	27,489	1,117	55,254
94	Shullsburg	42.56	-90.3366	6.16	367	3,679	21,147	1,148	102,689
96	Ellis	42.5511	-90.2828	14.40	217	2,650	17,691	1,241	48,710
98	Ellis	42.5531	-90.2951	9.80	171	1,651	18,568	553	31,015
102	Ellis	42.55	-90.3082	13.19	350	3,919	23,296	1,348	60,927
103	Ellis	42.5503	-90.3157	7.64	237	2,984	20,058	1,120	53,031
104	Ellis	42.5494	-90.3219	7.40	522	5,271	25,524	1,086	79,222
105	Ellis	42.549	-90.3257	6.12	1,052	7,212	45,038	1,306	128,456
106	Ellis	42.5471	-90.3398	6.80	741	7,769	32,562	1,175	79,230
108	Diggings	42.5338	-90.3072	5.02	119	2,366	16,908	967	32,096

Appendix I continued. Floodplain sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
109	Diggings	42.5338	-90.3091	6.71	113	5,328	17,449	1,083	121,474
110	Diggings	42.5355	-90.3161	8.78	310	2,347	17,858	789	33,144
112	Diggings	42.5362	-90.3166	6.48	1,031	16,441	47,349	1,111	138,925
113	Diggings	42.5356	-90.317	6.24	367	4,916	21,931	899	41,674
114	Diggings	42.5356	-90.3229	8.48	330	4,217	23,440	1,060	77,447
115	Diggings	42.5357	-90.3247	7.63	1,626	11,488	41,158	739	89,113
116	Diggings	42.5364	-90.3378	7.99	643	5,099	25,755	971	47,240
117	Diggings	42.5389	-90.3467	12.90	657	6,513	27,855	987	61,382
118	Diggings	42.5407	-90.353	8.97	956	9,264	35,992	958	118,848
119	Kelsey	42.5185	-90.3036	7.14	161	519	16,251	798	47,538
121	Kelsey	42.5142	-90.3382	6.59	260	737	21,178	1,493	63,832
122	Kelsey	42.5109	-90.3576	4.76	149	338	15,411	912	46,127
127	Coon	42.54	-90.3755	7.25	652	4,107	34,191	824	33,377
128	Coon	42.524	-90.3806	7.91	635	4,420	28,627	670	16,010
131	Bull	42.5334	-90.4043	8.60	178	1,105	19,010	1,213	41,952
132	Bull	42.5366	-90.3971	7.73	46	286	16,673	903	8,427
133	Bull	42.5217	-90.3988	8.58	158	2,193	17,642	1,155	35,734
134	Bull	42.5146	-90.3966	6.92	610	9,304	32,612	1,200	77,347
136	Scrabble	42.5299	-90.4208	8.70	991	4,763	24,176	783	81,316
137	Scrabble	42.5149	-90.403	6.01	611	5,117	21,357	1,006	83,505
138	Vinegar Hill	42.4975	-90.4122	12.18	704	9,200	26,338	902	98,709
139	Vinegar Hill	42.4975	-90.4057	11.27	340	4,699	19,766	954	91,695
140	Vinegar Hill	42.4986	-90.401	4.36	422	4,021	22,031	915	84,039
143	Vinegar Hill	42.4959	-90.3945	4.60	314	4,614	19,662	1,188	123,580

Appendix I continued. Floodplain sediment site location and concentration averages (2017)

Site	Reach	Latitude	Longitude	OM%	2017 Metal Concentrations (ppm)				
					Pb	Zn	Fe	Mn	Ca
144	Middle Galena Trib.	42.4735	-90.4109	8.09	231	1,618	20,036	827	24,219
145	East Fork	42.5172	-90.2601	9.29	335	1,462	28,055	964	52,155
146	East Fork	42.4999	-90.2723	7.86	619	417	20,066	896	32,031
147	East Fork	42.4928	-90.2691	9.15	48	310	18,804	1,065	50,424
148	East Fork	42.4752	-90.3182	6.03	200	557	17,978	905	32,919
149	East Fork	42.4535	-90.3777	5.46	88	193	16,007	688	41,610
150	Hughlett	42.4401	-90.4233	5.62	58	282	18,042	1,274	79,201
151	Hughlett	42.4365	-90.4221	5.63	228	1,115	19,914	1,448	64,778
152	Hughlett	42.4279	-90.4256	4.42	285	504	15,849	909	76,040
153	Hughlett	42.418	-90.4239	5.04	196	769	18,002	698	27,877

Appendix J. Summary of Channel Sediments

Metal	Location	Type	n Sites	n Samples	Max.	75%	Median	25%	Min.	Mean	SD	Cv%
Pb	Upper Galena	Channel	13	26	197	117	68	22	15	79	58.9	74.2
Pb	Upper Tributaries	Channel	22	45	1,464	76	51	15	15	127	264.4	207.7
Pb	Middle Galena	Channel	12	23	507	344	291	260	177	313	90.8	29.0
Pb	Middle Tributaries	Channel	64	126	1,622	601	375	190	15	442	323.1	73.2
Pb	Lower Galena	Channel	19	27	374	314	286	258	158	284	49.6	17.5
Pb	Lower Tributaries	Channel	12	23	734	294	124	89	15	202	164.7	81.6
Zn	Upper Galena	Channel	13	26	1,611	775	485	230	120	616	479.4	77.9
Zn	Upper Tributaries	Channel	22	45	5,194	484	265	198	100	790	1,173.9	148.5
Zn	Middle Galena	Channel	12	23	5,217	3,610	2,880	2,435	1,785	3,092	959.3	31.0
Zn	Middle Tributaries	Channel	64	126	5,381	3,202	1,616	554	168	1,962	1,585.3	80.8
Zn	Lower Galena	Channel	19	27	3,896	3,198	2,934	2,535	1,749	2,882	574.0	19.9
Zn	Lower Tributaries	Channel	12	23	1,590	702	504	409	250	671	413.7	61.6
Fe	Upper Galena	Channel	13	26	28,016	21,114	19,007	17,741	15,402	19,877	3,129.3	15.7
Fe	Upper Tributaries	Channel	22	45	103,644	22,463	20,355	18,466	13,471	23,995	15,676.0	65.3
Fe	Middle Galena	Channel	12	23	27,984	23,110	21,789	19,648	16,334	21,453	2,889.7	13.5
Fe	Middle Tributaries	Channel	64	126	36,097	25,282	22,628	20,547	16,898	23,218	3,949.4	17.0
Fe	Lower Galena	Channel	19	27	27,394	23,677	22,597	21,578	18,627	22,663	2,120.6	9.4
Fe	Lower Tributaries	Channel	12	23	31,115	21,213	18,558	17,158	12,442	19,581	3,970.0	20.3
Mn	Upper Galena	Channel	13	26	1,482	1,113	956	774	588	971	246.6	25.4
Mn	Upper Tributaries	Channel	22	45	1,695	1,191	929	804	256	970	328.5	33.9
Mn	Middle Galena	Channel	12	23	1,509	1,088	1,014	852	679	1,009	207.7	20.6
Mn	Middle Tributaries	Channel	64	126	1,611	1,178	964	848	335	999	286.9	28.7
Mn	Lower Galena	Channel	19	27	1,495	1,131	1,014	822	500	999	238.5	23.9
Mn	Lower Tributaries	Channel	12	23	1,363	1,027	839	693	521	869	250.3	28.8

Appendix J continued. Summary of Channel Sediments

Metal	Location	Type	n Sites	n Samples	Max.	75%	Median	25%	Min.	Mean	SD	Cv%
Ca	Upper Galena	Channel	13	26	101,514	52,568	37,583	26,076	5,500	43,176	27,747.3	64.3
Ca	Upper Tributaries	Channel	22	45	74,466	33,326	27,486	21,001	8,376	28,548	12,538.6	43.9
Ca	Middle Galena	Channel	12	23	136,073	101,678	77,865	55,558	39,888	81,683	29,370.7	36.0
Ca	Middle Tributaries	Channel	64	126	128,486	72,072	51,740	34,304	8,495	50,816	26,184.9	51.5
Ca	Lower Galena	Channel	19	27	140,480	93,384	73,666	56,115	24,505	76,413	30,156.3	39.5
Ca	Lower Tributaries	Channel	12	23	138,921	86,893	62,477	52,604	27,873	71,648	33,380.0	46.6
OM	Upper Galena	Channel	13	26	10.3	8.0	7.1	5.9	2.5	6.9	1.6	22.9
OM	Upper Tributaries	Channel	22	45	13.5	8.6	6.8	6.2	3.4	7.4	2.1	28.0
OM	Middle Galena	Channel	12	23	7.2	5.9	5.4	5.1	3.1	5.4	1.0	18.9
OM	Middle Tributaries	Channel	64	126	10.6	8.4	7.6	6.7	4.7	7.6	1.3	17.6
OM	Lower Galena	Channel	19	27	7.3	6.1	5.6	5.2	2.6	5.6	1.0	18.0
OM	Lower Tributaries	Channel	12	23	10.5	6.7	5.9	4.9	3.0	5.9	1.7	28.5

Appendix K. Summary of Floodplain Samples

Metal	Location	Type	n Sites	n Samples	Max.	75%	Median	25%	Min.	Mean	SD	Cv%
Pb	Upper Galena	Floodplain	12	12	132	93	73	54	15	73	36.2	49.9
Pb	Upper Tributaries	Floodplain	19	19	1,253	69	15	15	15	115	282.8	245.5
Pb	Middle Galena	Floodplain	12	12	1,263	324	282	268	223	367	284.2	77.5
Pb	Middle Tributaries	Floodplain	49	52	2,178	646	397	230	15	501	399.3	79.7
Pb	Lower Galena	Floodplain	14	14	719	301	262	247	212	299	124.1	41.5
Pb	Lower Tributaries	Floodplain	12	12	619	242	168	81	48	198	161.8	81.9
Zn	Upper Galena	Floodplain	12	12	1,161	652	546	243	165	531	311.6	58.6
Zn	Upper Tributaries	Floodplain	19	19	4,447	415	236	170	136	687	1,091.8	159.0
Zn	Middle Galena	Floodplain	12	12	13,597	2,737	2,419	2,223	1,575	3,306	3,263.4	98.7
Zn	Middle Tributaries	Floodplain	49	52	16,441	5,025	3,679	1,043	151	3,751	3,349.4	89.3
Zn	Lower Galena	Floodplain	14	14	11,623	3,111	2,590	2,231	1,778	3,259	2,461.6	75.5
Zn	Lower Tributaries	Floodplain	12	12	1,462	728	507	390	193	606	366.8	60.5
Fe	Upper Galena	Floodplain	12	12	21,194	18,574	18,439	18,074	14,673	18,149	1,529.1	8.4
Fe	Upper Tributaries	Floodplain	19	19	83,988	20,435	18,992	17,166	16,494	22,567	15,067.9	66.8
Fe	Middle Galena	Floodplain	12	12	38,705	21,404	20,480	19,908	18,521	21,866	5,417.6	24.8
Fe	Middle Tributaries	Floodplain	49	52	49,082	27,489	21,147	18,568	15,411	24,857	9,200.3	37.0
Fe	Lower Galena	Floodplain	14	14	31,680	23,685	21,315	19,642	17,733	22,282	3,819.3	17.1
Fe	Lower Tributaries	Floodplain	12	12	28,055	19,947	18,022	17,518	15,849	18,928	3,224.2	17.0
Mn	Upper Galena	Floodplain	12	12	1,314	990	868	786	706	910	169.9	18.7
Mn	Upper Tributaries	Floodplain	19	19	1,529	1,008	911	776	242	917	264.5	28.8
Mn	Middle Galena	Floodplain	12	12	1,566	1,051	949	928	878	1,019	184.9	18.1
Mn	Middle Tributaries	Floodplain	49	52	1,493	1,120	967	824	507	970	211.1	21.7
Mn	Lower Galena	Floodplain	14	14	1,171	1,082	895	808	519	919	180.9	19.7
Mn	Lower Tributaries	Floodplain	12	12	1,448	989	900	794	688	940	226.4	24.1

Appendix K continued. Summary of Floodplain Samples

Metal	Location	Type	n Sites	n Samples	Max.	75%	Median	25%	Min.	Mean	SD	Cv%
Ca	Upper Galena	Floodplain	12	12	83,795	37,699	31,566	27,299	21,538	37,291	18,620.2	49.9
Ca	Upper Tributaries	Floodplain	19	19	68,737	34,094	25,087	18,421	10,349	27,134	14,156.3	52.2
Ca	Middle Galena	Floodplain	12	12	97,709	75,785	60,905	57,552	44,345	64,951	15,417.4	23.7
Ca	Middle Tributaries	Floodplain	49	52	138,925	77,431	55,254	35,734	8,012	59,408	32,092.2	54.0
Ca	Lower Galena	Floodplain	14	14	120,371	92,195	47,431	33,894	29,752	63,536	34,569.5	54.4
Ca	Lower Tributaries	Floodplain	12	12	148,740	76,830	51,289	39,438	27,877	62,970	35,103.5	55.7
OM	Upper Galena	Floodplain	12	12	8.5	7.0	6.4	5.5	4.3	6.3	1.3	19.9
OM	Upper Tributaries	Floodplain	19	19	9.8	8.8	8.1	6.8	4.8	7.7	1.5	19.2
OM	Middle Galena	Floodplain	12	12	8.1	7.6	6.5	5.7	4.9	6.6	1.1	17.2
OM	Middle Tributaries	Floodplain	49	52	14.4	9.8	7.7	6.7	4.0	8.3	2.3	27.8
OM	Lower Galena	Floodplain	14	14	9.3	7.5	5.8	5.6	4.4	6.5	1.5	23.2
OM	Lower Tributaries	Floodplain	12	12	12.2	8.6	6.7	5.5	4.4	7.3	2.5	34.2

Appendix L. Aqua-regia results (ppm)

Site	Type	Ag	Al(%)	As	B	Ba	Be	Bi	Ca	Cd	Co
2	Channel	<0.2	1.01	7	<10	160	0.5	<2	32,500	0.6	7
2	Floodplain	<0.2	1.06	10	<10	160	0.6	<2	35,800	<0.5	11
9	Channel	<0.2	1.14	6	<10	160	0.5	2	11,600	0.8	8
9	Floodplain	<0.2	0.93	4	<10	140	0.5	<2	37,400	0.9	8
19	Channel	0.2	1.02	7	<10	170	0.5	<2	65,300	2.3	8
19	Floodplain	<0.2	0.72	7	<10	150	<0.5	2	64,300	2.6	7
33	Channel	0.3	0.5	18	<10	90	<0.5	2	136,000	16.4	9
33	Floodplain	0.6	0.37	21	<10	70	<0.5	<2	128,000	46.5	10
40	Channel	0.2	0.76	10	<10	200	<0.5	2	93,000	6.8	10
40	Floodplain	<0.2	0.61	11	<10	170	<0.5	2	120,000	6.5	9
60	Channel	<0.2	1.34	6	<10	150	0.7	<2	12,400	<0.5	8
60	Floodplain	<0.2	1.09	5	<10	130	0.5	<2	24,200	<0.5	8
69	Channel	<0.2	1.02	8	<10	150	0.5	<2	59,200	0.8	11
69	Floodplain	<0.2	0.94	5	<10	140	0.5	2	33,800	0.8	7
94	Channel	0.2	0.86	11	<10	490	0.5	<2	52,700	6.2	11
94	Floodplain	0.2	0.59	12	<10	590	<0.5	2	99,000	6.9	9
105	Channel	0.4	0.25	23	<10	190	<0.5	3	162,000	14.6	7
105	Floodplain	0.5	0.43	25	<10	350	<0.5	<2	109,000	16.4	10
115	Channel	0.5	0.51	26	<10	70	<0.5	2	123,000	23.6	13
115	Floodplain	0.6	0.43	36	<10	80	<0.5	<2	110,000	27.2	18
134	Channel	1.5	0.22	62	<10	70	<0.5	<2	166,000	42.1	27
134	Floodplain	0.6	0.57	35	<10	90	<0.5	<2	96,000	19.3	28
146	Channel	<0.2	0.98	12	10	370	0.5	<2	56,500	0.6	10
146	Floodplain	<0.2	0.96	12	10	230	0.5	<2	32,900	0.6	9
151	Channel	<0.2	0.65	9	<10	90	<0.5	2	69,100	1	7
151	Floodplain	<0.2	0.55	7	<10	70	<0.5	<2	73,000	1.1	6
5	Bank	<0.2	0.69	8	<10	140	<0.5	<2	29,300	2.5	7
5	Channel	0.2	0.46	6	<10	110	<0.5	<2	127,000	4.8	6
8	Bank	0.2	1.23	11	10	180	0.6	<2	18,300	3	10
8	Channel	<0.2	0.87	9	<10	170	<0.5	2	63,200	6.2	10
136	Tailings	1.3	0.17	108	10	10	<0.5	2	142,000	26.4	92
104	Tailings	0.5	0.09	48	<10	30	<0.5	2	172,000	19.9	10
T144	Tailings	0.8	0.21	49	10	10	<0.5	<2	146,000	46.1	16

Appendix L continued. Aqua-regia results (ppm)

Site	Type	Cr	Cu	Fe	Ga	Hg	K(%)	La	Mg(%)	Mn	Mo
2	Channel	17	10	17,400	<10	0.025	0.11	20	1.84	687	<1
2	Floodplain	18	11	21,700	<10	0.03	0.12	20	2.01	1,370	<1
9	Channel	18	11	19,600	<10	0.031	0.11	20	0.66	769	1
9	Floodplain	15	11	17,900	<10	0.032	0.12	20	1.96	932	<1
19	Channel	16	12	22,100	<10	0.032	0.12	10	1.5	1,060	<1
19	Floodplain	13	9	18,200	<10	0.062	0.07	10	2.02	879	<1
33	Channel	8	15	28,500	<10	0.036	0.07	10	7.25	1,395	<1
33	Floodplain	7	16	32,900	<10	0.096	0.07	10	6.89	1,320	<1
40	Channel	12	12	21,700	<10	0.041	0.1	10	4.05	1,095	<1
40	Floodplain	10	10	19,200	<10	0.029	0.08	10	5.06	1,100	<1
60	Channel	20	17	20,200	<10	0.036	0.15	20	0.47	902	<1
60	Floodplain	17	15	18,300	<10	0.035	0.11	20	0.99	633	<1
69	Channel	15	11	20,000	<10	0.022	0.11	20	3.45	1,270	<1
69	Floodplain	14	12	16,800	<10	0.021	0.13	10	1.63	914	<1
94	Channel	15	12	24,600	<10	0.053	0.12	10	1.78	1,075	<1
94	Floodplain	11	9	21,800	<10	0.037	0.18	10	4.32	1,200	<1
105	Channel	5	33	29,700	<10	0.068	0.05	10	8.13	1,325	<1
105	Floodplain	8	34	37,500	<10	0.077	0.06	10	6.05	1,190	<1
115	Channel	9	13	32,100	<10	0.108	0.08	10	6.36	899	<1
115	Floodplain	7	16	40,100	<10	0.147	0.06	10	6.19	1,045	<1
134	Channel	7	22	46,400	<10	0.085	0.05	10	7.98	1,585	<1
134	Floodplain	10	19	34,100	<10	0.068	0.08	10	5.17	1,325	<1
146	Channel	15	20	23,900	<10	0.025	0.12	20	3.22	796	<1
146	Floodplain	15	19	20,900	<10	0.034	0.13	20	1.89	860	1
151	Channel	12	8	19,200	<10	0.025	0.08	10	4.08	1,375	1
151	Floodplain	11	7	19,100	<10	0.022	0.06	10	4.07	1,380	<1
5	Bank	13	9	17,800	<10	0.023	0.09	10	1.05	508	<1
5	Channel	9	9	17,700	<10	0.039	0.06	10	6.28	1,140	<1
8	Bank	18	20	23,000	<10	0.056	0.13	20	0.59	717	<1
8	Channel	15	13	23,000	<10	0.053	0.11	20	2.75	956	<1
136	Tailings	4	71	76,000	<10	0.11	0.08	10	6.67	1,710	1
104	Tailings	3	46	47,100	<10	0.082	0.03	<10	8.38	1,170	<1
T144	Tailings	5	11	68,700	<10	0.126	0.12	<10	4.79	1,175	1

Appendix L continued. Aqua-regia results (ppm)

Site	Type	Na(%)	Ni	P	Pb	S(%)	Sb	Sc	Sr	Th	Ti(%)
2	Channel	0.02	13	670	28	0.06	<2	2	21	<20	0.02
2	Floodplain	0.02	16	1,630	26	0.04	<2	2	27	<20	0.02
9	Channel	0.02	16	530	64	0.03	<2	2	17	<20	0.02
9	Floodplain	0.02	15	940	47	0.05	<2	2	24	<20	0.02
19	Channel	0.02	15	940	150	0.13	<2	2	37	<20	0.02
19	Floodplain	0.02	13	810	155	0.06	<2	2	33	<20	0.02
33	Channel	0.03	16	1,090	823	0.71	<2	1	42	<20	0.01
33	Floodplain	0.03	16	940	2,540	1.54	<2	1	37	<20	0.01
40	Channel	0.03	17	870	281	0.27	<2	2	37	<20	0.02
40	Floodplain	0.02	14	970	274	0.16	<2	1	42	<20	0.01
60	Channel	0.02	17	880	47	0.06	<2	3	18	<20	0.02
60	Floodplain	0.02	14	870	28	0.12	<2	2	20	<20	0.02
69	Channel	0.03	18	800	38	0.07	<2	2	30	<20	0.02
69	Floodplain	0.02	12	860	32	0.1	<2	2	24	<20	0.02
94	Channel	0.03	24	910	362	0.26	<2	2	32	<20	0.02
94	Floodplain	0.02	17	1,080	351	0.26	<2	1	44	<20	0.01
105	Channel	0.03	11	910	753	1.44	<2	1	50	<20	0.01
105	Floodplain	0.02	16	800	947	0.66	<2	1	35	<20	0.01
115	Channel	0.03	19	1,230	1,060	1.21	<2	1	39	<20	0.01
115	Floodplain	0.02	22	900	1,660	0.91	<2	1	34	<20	0.01
134	Channel	0.03	40	1,130	798	2.52	<2	1	47	<20	0.01
134	Floodplain	0.02	36	1,010	680	1.07	<2	1	30	<20	0.01
146	Channel	0.03	18	1,560	780	0.1	<2	2	35	<20	0.02
146	Floodplain	0.02	19	930	635	0.05	<2	2	22	<20	0.02
151	Channel	0.02	14	690	609	0.08	4	2	26	<20	0.02
151	Floodplain	0.02	12	680	335	0.05	<2	1	26	<20	0.02
5	Bank	0.02	13	670	155	0.12	<2	2	20	<20	0.02
5	Channel	0.03	10	1,100	185	0.16	<2	1	42	<20	0.01
8	Bank	0.02	23	900	227	0.12	<2	2	20	<20	0.02
8	Channel	0.03	18	1,100	211	0.26	<2	2	32	<20	0.02
136	Tailings	0.02	174	1,160	985	4.5	<2	1	44	<20	<0.01
104	Tailings	0.03	18	650	582	4.49	<2	1	49	<20	<0.01
T144	Tailings	0.02	31	1,310	1,010	6.77	<2	2	65	<20	<0.01

Appendix L continued. Aqua-regia results (ppm)

Site	Type	Tl	U	V	W	Zn
2	Channel	<10	<10	22	<10	231
2	Floodplain	<10	<10	32	<10	125
9	Channel	<10	<10	28	<10	315
9	Floodplain	<10	<10	23	<10	295
19	Channel	<10	<10	22	<10	1,140
19	Floodplain	<10	<10	17	<10	1,100
33	Channel	<10	<10	13	<10	8,860
33	Floodplain	<10	<10	11	<10	23,900
40	Channel	<10	<10	19	<10	3,300
40	Floodplain	<10	<10	16	<10	3,120
60	Channel	<10	<10	28	<10	111
60	Floodplain	<10	<10	24	<10	94
69	Channel	<10	<10	24	<10	530
69	Floodplain	<10	<10	22	<10	304
94	Channel	<10	<10	22	<10	3,130
94	Floodplain	<10	<10	16	<10	3,430
105	Channel	<10	<10	7	<10	5,950
105	Floodplain	<10	<10	11	<10	6,570
115	Channel	<10	<10	13	<10	10,850
115	Floodplain	<10	<10	12	<10	12,250
134	Channel	<10	<10	9	<10	23,600
134	Floodplain	<10	<10	16	<10	10,850
146	Channel	<10	<10	24	<10	291
146	Floodplain	<10	<10	24	<10	282
151	Channel	<10	<10	20	<10	837
151	Floodplain	<10	<10	17	<10	909
5	Bank	<10	<10	18	<10	1,510
5	Channel	<10	<10	12	<10	2,220
8	Bank	<10	<10	28	<10	1,720
8	Channel	<10	<10	21	<10	2,950
136	Tailings	<10	<10	4	20	20,200
104	Tailings	<10	<10	3	<10	9,060
T144	Tailings	<10	<10	4	<10	21,900

Appendix M. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
Alderson	Shullsburg	42.6	-90.2733	5,051		2714	present
Andrews	Ellis	42.5472	-90.2806	160,000	1944-1953	29002	present
Annie Walton	Kelsey	42.5187	-90.2902	5,051	1947-1949	0	
Appleton	Galena	42.4336	-90.3831	43,478	1908-1909	0	
B and C	Shullsburg	42.5832	-90.2542	5,051	1904-1909, 1943	0	
B.A.T.	Ellis	42.551	-90.3073	43,478	1941-1944	0	
Badger	Bull	42.5352	-90.4091	666,667	1900-1933	0	
Baxter	Galena	42.6208	-90.3932	43,478	1904-1912	0	
Bearcat-Hird #3	Coon	42.5628	-90.3965	43,478	1919-1920	0	
Best	Galena	42.6544	-90.4102	43,478	1908-1909	0	
Big Dick	Galena	42.6464	-90.3664	357,143	1917-1920	0	
Big Ten	Galena	42.6436	-90.3996	5,051	1930s	0	
Big Tom	Galena	42.509	-90.3967	5,051		6698	present
Birkbeck	Galena	42.4854	-90.3859	160,000	1916-1917	0	present
Birkett	Scrabble	42.5524	-90.423	666,667	1926-1929, 1950s	0	
Blackstone	Diggings	42.5318	-90.33	357,143	1916-1926	0	
Booty	Ellis	42.5443	-90.3053	357,143	1924-1928	0	
Boyle (Hardy, Hofer)	Shullsburg	42.5904	-90.2568	43,478		0	
Buck Lead-Blewett	Hughlett	42.4407	-90.4206	160,000		0	
Buck Lead-Blewett	Hughlett	42.4379	-90.419	160,000		0	
Bull Moose-Middie	Coon	42.5694	-90.4048	666,667	1913-1929	0	
Byrnes	Scrabble	42.547	-90.4229	666,667	1928-1929, 1950s	0	
C.A.T.	Diggings	42.5389	-90.31	357,143	1916-1920s	17667	present
Century	Coon	42.5655	-90.3799	5,051	1900-1906	0	present

Appendix M continued. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
Champion	Diggings	42.5353	-90.3507	357,143	1913-1946	0	
Cleveland	Scrabble	42.5298	-90.4199	357,143	1855-1917, 1940s	0	
Coltman	Galena	42.5679	-90.358	43,478	1879-1906	0	
Connecting Link 1 and 2	Galena	42.6389	-90.3676	160,000	1918-1920	0	
Connecting Link 1 and 2	Galena	42.6404	-90.3702	160,000	1918-1920	0	
Consolidated	Coon	42.5482	-90.3818	5,051	1946-1947	0	present
Copeland	Shullsburg	42.5639	-90.2519	666,667	1917-1919, 192-1928	3727	present
Corr and Crooked Six	Galena	42.5823	-90.3378	5,051	Early 1900s	0	
Coughlin (Murphy)	Shullsburg	42.5856	-90.2552	357,143	1912-1946	0	
Craig Level	Kelsey	42.521	-90.3318	5,051		42405	
Crawford	Scrabble	42.5258	-90.4301	666,667	1931-1936	0	
Cuba City	Galena	42.6269	-90.4008	5,051	1909	0	
Cuba City (tailings)	Coon	42.5944	-90.4115	N/A		0	
Curwen	Galena	42.5499	-90.3484	5,051	1924-1945	0	
Dall and Cook	Galena	42.6354	-90.3591	357,143	1904-1911, 1950-1952	0	
Deep (Fever)	Galena	42.6475	-90.4119	43,478	1907-1908, 1942	0	
DeRocher	Shullsburg	42.593	-90.2726	43,478	1935-1937, 1940s-1952	0	present
Drum	Galena	42.559	-90.3458	160,000	1909-1911	0	
Eagle Picher	Shullsburg	42.5416	-90.2427	357,143	1949-1979	0	
Empress	Shullsburg	42.5591	-90.3261	160,000		0	
Ernest and Myers Level	Shullsburg	42.5842	-90.2884	43,478	1850s-1860s	0	
Etna-Pittsburgh	Shullsburg	42.5824	-90.3304	160,000	1902-1910	0	
Etna-Pittsburgh	Shullsburg	42.5769	-90.3303	160,000	1902-1910	0	
Ewing and Cook	Shullsburg	42.5781	-90.322	5,051	1941-1949	0	
Expansion	Shullsburg	42.5728	-90.2969	5,051	1890s	0	

Appendix M continued. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
Farey Queen	Shullsburg	42.5816	-90.3072	5,051		0	
Farry-Benton Star	Shullsburg	42.5646	-90.3403	43,478		0	
Farry-Benton Star	Shullsburg	42.564	-90.339	43,478		0	present
Federal	Galena	42.5109	-90.3961	666,667	1944-1947	0	
Fields Upper Run	Diggings	42.5309	-90.3137	43,478	1910-1920, 1940s	0	
Fox	Coon	42.5309	-90.3818	666,667	1906-1917	0	present
Graham-Ginte Mine	Galena	42.4705	-90.4228	357,143	1915-1920, 1943-1946	61967	present
Graham-Snyder	Galena	42.4763	-90.4283	2,000,000	1947-1953, 1955-1957	0	
Gritty Six	Galena	42.6306	-90.3771	666,667	1898-1907	0	
Gritty Six	Galena	42.6305	-90.373	666,667	1898-1907	10556	present
Gritty Six	Galena	42.6264	-90.3729	666,667	1898-1907	0	present
Hazel Green	Scrabble	42.5479	-90.4256	43,478	1940-1945	0	present
Helena/Roachdale	Shullsburg	42.5704	-90.302	160,000	1890-1898, 1942	457	present
Henrietta	Galena	42.6278	-90.4034	5,051	1907-1910	2180	present
Hird No. 1	Coon	42.5661	-90.3953	5,051	1913-1915	5500	present
Hird No. 2	Coon	42.5643	-90.3995	5,051	1917	0	
Honest Bob	Scrabble	42.5267	-90.4225	5,051	c. 1904	0	
Hoosier	Hughlett	42.4659	-90.4412	5,051		2058	present
Hoskins-Fields	Ellis	42.5522	-90.3201	666,667	1917-1926, 1943-1948	0	present
Imperial-Hoover-Iowa	Shullsburg	42.5722	-90.3124	43,478		10099	present
Indian Mound (Murphy)	Diggings	42.541	-90.3128	357,143	1919-1923	14941	present
Inspiration	Vinegar Hill	42.4961	-90.4206	N/A		0	present
Jack of Clubs (Dawson)	Coon	42.5612	-90.3884	43,478	1903-1917	0	
Jack of Diamonds	Galena	42.5419	-90.3571	43,478	1902-1906, 1945-1949	0	
James-Little Elm	Galena	42.6207	-90.3824	43,478	1903	0	

Appendix M continued. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
Jefferson	Scrabble	42.5578	-90.4268	160,000	1902-1957	0	
Jug Handle	Shullsburg	42.5636	-90.3362	5,051	1901-1909, 1940s-1950s	1072	present
Kearns	Galena	42.5765	-90.371	5,051	1910-1918	0	present
Kennedy	Bull	42.5272	-90.4057	2,000,000	1851-1919	0	
Kittoe	Coon	42.5561	-90.3958	357,143	1914-1918	0	
Kivlahan	Galena	42.5917	-90.3703	5,051		0	
Koll	Pats	42.6513	-90.3759	43,478		0	present
Lafayette	Ellis	42.5439	-90.3228	5,051	1906	17553	
Lawrence	Pats	42.6495	-90.3785	160,000	1913-1917	1840	present
Lawrence	Scrabble	42.5325	-90.4212	160,000	1908-1912	0	present
Leadmine	Galena	42.5583	-90.3491	43,478	1847-1910, 1942-1945	0	
Liberty	Galena	42.6496	-90.3715	357,143	1943-1946	6497	present
Little Bennie	Shullsburg	42.582	-90.2664	5,051	1890s, 1941-1947	14286	present
Little Dad-Big Dad	Bull	42.5212	-90.4004	43,478	1906	0	present
Little Dad-Big Dad	Bull	42.5179	-90.399	43,478	1906	0	
Little Giant	Vinegar Hill	42.4959	-90.42067	N/A	1839-1947 (periodically)	0	present
Little Grant-Galena Level	Shullsburg	42.5846	-90.26	43,478		19204	present
Little Grant-Galena Level	Shullsburg	42.5818	-90.2604	43,478		1173	
Longhenry (Spensley)	Coon	42.5355	-90.3789	43,478	1913-1925	6905	
Lucky Hit	Shullsburg	42.5966	-90.2582	160,000	1904-1906	0	
Lucky Twelve	Diggings	42.5377	-90.3163	160,000	1911-1915	12812	present
Lyne	Ellis	42.5512	-90.2788	43,478	1941	0	present
Madison	Scrabble	42.5284	-90.4274	5,051	Early 1900s	0	present
Martin	Coon	42.5514	-90.3741	666,667	1913-1919, 1942-1946	1633	present
Masbruch	Galena	42.6486	-90.4083	43,478	1913-1915	5794	present

Appendix M continued. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
McCabe	Galena	42.5807	-90.3601	43,478	WWI, WWII	0	
McCann	Galena	42.5821	-90.3684	5,051	Early 1900s	8219	
McMillan	Scrabble	42.514	-90.4203	5,051	1914-1915	0	
Meekers Grove	Galena	42.6393	-90.3763	5,051	1938	29030	present
Meekers Grove (Uniset)	Pats	42.6398	-90.3804	5,051	1938	266	present
Meloy and Robson	Ellis	42.5531	-90.3303	160,000	1860-1920, 1944-1950	21439	present
Mermaid	Scrabble	42.5449	-90.4236	5,051	1900-1904	0	
Midway	Galena	42.6267	-90.4232	5,051	1906-1908	0	
Monmouth	Bull	42.5404	-90.4127	357,143	1924-1928	0	present
Monroe	Diggings	42.5342	-90.3235	666,667	1917-1920, 1941-1947	5199	present
Mulcahy	Diggings	42.538	-90.2774	160,000	1952-1955	0	
Murphy	Scrabble	42.5397	-90.4169	43,478	1903-1909	0	
NC-LM-NH Mines 33	Shullsburg	42.5603	-90.3231	43,478		0	
NC-LM-NH Mines 33	Shullsburg	42.5627	-90.3195	43,478		8377	present
NC-LM-NH Mines 34	Shullsburg	42.5621	-90.3178	43,478		9235	present
NC-LM-NH Mines 36	Shullsburg	42.5616	-90.3158	43,478		4151	present
New Birkett	Bull	42.5523	-90.4193	43,478	1942-1944, 1950s	15381	present
New Cottingham	Shullsburg	42.5611	-90.3203	43,478	1946-1950s	0	
New Harty	Shullsburg	42.5721	-90.2632	2,000,000		93972	
New Harty	Shullsburg	42.5635	-90.274	2,000,000		38393	present
New Harty	Shullsburg	42.5741	-90.2744	2,000,000		13292	present
New Ida Blende	Galena	42.5602	-90.36	160,000		19938	present
New Longhorn	Kelsey	42.5203	-90.3075	160,000	1926-1930	13296	present
New Mulcahy	Shullsburg	42.5749	-90.2527	5,051	1943-1944	7409.05	
New Mullen	Shullsburg	42.5618	-90.2817	357,143	1937-1941	0	

Appendix M continued. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
McCabe	Galena	42.5807	-90.3601	43,478	WWI, WWII	0	
McCann	Galena	42.5821	-90.3684	5,051	Early 1900s	8219	
McMillan	Scrabble	42.514	-90.4203	5,051	1914-1915	0	
Meekers Grove	Galena	42.6393	-90.3763	5,051	1938	29030	present
Meekers Grove (Uniset)	Pats	42.6398	-90.3804	5,051	1938	266	present
Meloy and Robson	Ellis	42.5531	-90.3303	160,000	1860-1920, 1944-1950	21439	present
Mermaid	Scrabble	42.5449	-90.4236	5,051	1900-1904	0	
Midway	Galena	42.6267	-90.4232	5,051	1906-1908	0	
Monmouth	Bull	42.5404	-90.4127	357,143	1924-1928	0	present
Monroe	Diggings	42.5342	-90.3235	666,667	1917-1920, 1941-1947	5199	present
Mulcahy	Diggings	42.538	-90.2774	160,000	1952-1955	0	
Murphy	Scrabble	42.5397	-90.4169	43,478	1903-1909	0	
NC-LM-NH Mines 33	Shullsburg	42.5603	-90.3231	43,478		0	
NC-LM-NH Mines 33	Shullsburg	42.5627	-90.3195	43,478		8377	present
NC-LM-NH Mines 34	Shullsburg	42.5621	-90.3178	43,478		9235	present
NC-LM-NH Mines 36	Shullsburg	42.5616	-90.3158	43,478		4151	present
New Birkett	Bull	42.5523	-90.4193	43,478	1942-1944, 1950s	15381	present
New Cottingham	Shullsburg	42.5611	-90.3203	43,478	1946-1950s	0	
New Harty	Shullsburg	42.5721	-90.2632	2,000,000		93972	
New Harty	Shullsburg	42.5635	-90.274	2,000,000		38393	present
New Harty	Shullsburg	42.5741	-90.2744	2,000,000		13292	present
New Ida Blende	Galena	42.5602	-90.36	160,000		19938	present
New Longhorn	Kelsey	42.5203	-90.3075	160,000	1926-1930	13296	present
New Mulcahy	Shullsburg	42.5749	-90.2527	5,051	1943-1944	7409.05	
New Mullen	Shullsburg	42.5618	-90.2817	357,143	1937-1941	0	

Appendix M continued. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
McCabe	Galena	42.5807	-90.3601	43,478	WWI, WWII	0	
McCann	Galena	42.5821	-90.3684	5,051	Early 1900s	8219	
McMillan	Scrabble	42.514	-90.4203	5,051	1914-1915	0	
Meekers Grove	Galena	42.6393	-90.3763	5,051	1938	29030	present
Meekers Grove (Uniset)	Pats	42.6398	-90.3804	5,051	1938	266	present
Meloy and Robson	Ellis	42.5531	-90.3303	160,000	1860-1920, 1944-1950	21439	present
Mermaid	Scrabble	42.5449	-90.4236	5,051	1900-1904	0	
Midway	Galena	42.6267	-90.4232	5,051	1906-1908	0	
Monmouth	Bull	42.5404	-90.4127	357,143	1924-1928	0	present
Monroe	Diggings	42.5342	-90.3235	666,667	1917-1920, 1941-1947	5199	present
Mulcahy	Diggings	42.538	-90.2774	160,000	1952-1955	0	
Murphy	Scrabble	42.5397	-90.4169	43,478	1903-1909	0	
NC-LM-NH Mines 33	Shullsburg	42.5603	-90.3231	43,478		0	
NC-LM-NH Mines 33	Shullsburg	42.5627	-90.3195	43,478		8377	present
NC-LM-NH Mines 34	Shullsburg	42.5621	-90.3178	43,478		9235	present
NC-LM-NH Mines 36	Shullsburg	42.5616	-90.3158	43,478		4151	present
New Birkett	Bull	42.5523	-90.4193	43,478	1942-1944, 1950s	15381	present
New Cottingham	Shullsburg	42.5611	-90.3203	43,478	1946-1950s	0	
New Harty	Shullsburg	42.5721	-90.2632	2,000,000		93972	
New Harty	Shullsburg	42.5635	-90.274	2,000,000		38393	present
New Harty	Shullsburg	42.5741	-90.2744	2,000,000		13292	present
New Ida Blende	Galena	42.5602	-90.36	160,000		19938	present
New Longhorn	Kelsey	42.5203	-90.3075	160,000	1926-1930	13296	present
New Mulcahy	Shullsburg	42.5749	-90.2527	5,051	1943-1944	7409.05	
New Mullen	Shullsburg	42.5618	-90.2817	357,143	1937-1941	0	

Appendix M continued. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
New Occidental	Galena	42.5216	-90.3578	5,051	1900-1910	0	present
Nightingale	Shullsburg	42.5598	-90.3423	160,000	1920-1924, 1942	8713	
Nip and Tuck (Giles)	Shullsburg	42.5737	-90.3056	5,051	1938-1947	10078	present
North Star (Ralph)	Coon	42.587	-90.4079	43,478	1943-1944	33627	present
North Unity	Vinegar Hill	42.505	-90.4082	357,143		0	present
Northwestern	Vinegar Hill	42.503	-90.3959	160,000		20618	present
Oakland Level	Shullsburg	42.5821	-90.2614	5,051		0	present
O'Brien	Shullsburg	42.5593	-90.2487	5,051	1941-1942	37483	present
Old Cottingham	Shullsburg	42.5583	-90.319	5,051		0	present
Old Ida Blende	Galena	42.5583	-90.3665	357,143		0	present
Old Mulcahy	Shullsburg	42.5746	-90.2573	160,000	1910s, 1941-1944	11427	present
Old Occidental	Galena	42.5243	-90.3567	5,051	1873-1915	98335	present
Old Winskell	Ellis	42.5456	-90.3008	666,667	1909-1917	0	present
Oldenberg	Hughlett	42.4543	-90.4404	43,478		17728	present
Ollie Bell	Galena	42.5492	-90.3613	160,000	1800s-1911	27025	present
Oregon-Milner	Galena	42.5765	-90.3763	5,051		0	present
Paquette	Shullsburg	42.5961	-90.2816	43,478	1920-1935, 1945-1949	10476	present
Peaceful Valley	Galena	42.6688	-90.407	43,478		0	
Peasleys Level	Shullsburg	42.5765	-90.316	5,051		7289	present
Penna-Benton (Expansion)	Diggings	42.5397	-90.3255	666,667		40591	present
Pilot Knob	Galena	42.3789	-90.4191	5,051		12847.4	
Pine Tree	Blacks	42.6103	-90.3891	5,051		13328	present
Pittsburg	Galena	42.6125	-90.3763	43,478		424854	present
Quinland Diggings	Galena	42.5787	-90.3675	5,051	1906-1911	37190	present
Raisbeck-Craig	Ellis	42.5493	-90.3348	5,051	1846-1903, 1912-1930	32617	present

Appendix M continued. Mine Location and production

Name	Stream	Latitude	Longitude	Production (Mg)	Open	Mp Soil	Waste 2015
Richards (Berg)	Bull	42.5204	-90.3956	5,051	Early 1900s	41097	present
Rico	Galena	42.611	-90.3757	5,051	1906-1909	27958	present
Roosevelt	Blacks	42.6146	-90.3788	43,478	1907-1910	42745	present
Rowley	Coon	42.5156	-90.3836	43,478	1800s-1913	77956	present
Sally Waters (Monarch)	Ellis	42.5499	-90.3296	160,000	1902-1917, 1940s	17752	present
Scrabble Creek	Scrabble	42.5243	-90.4275	43,478	Early 1900s	33949	present
South Unity	Vinegar Hill	42.5012	-90.4108	357,143		0	
Strawberry Blonde	Coon	42.5384	-90.3735	5,051	1900-1903, 1941-1942	34746	present
Swift and Rooney	Galena	42.5668	-90.3501	43,478	1861-1910	93919	present
Thompson	Diggings	42.5322	-90.3033	666,667	1914-1946 (periodically)	26666	present
Thompson (AZ)	Galena	42.5216	-90.3501	43,478		46042	present
Treganza-Frontier-Calvert	Coon	42.5715	-90.3939	1,666,667	Early 1900s	0	
Trewartha	Bull	42.5403	-90.3958	160,000		0	
Tunnel Hill	Galena	42.5094	-90.3881	43,478	1905	10462	
Vandeventer	Galena	42.6196	-90.3322	43,478	1907-1913	0	
Vinegar Hill	Vinegar Hill	42.4968	-90.415	357,143	1908-1914	25598	present
Waters	Galena	42.4237	-90.4397	43,478		55004	present
Weiskircher	Shullsburg	42.5742	-90.3212	5,051	1900-1907, 1938	21433	
West Blackstone	Shullsburg	42.5519	-90.2376	357,143		20405	present
Whaley-Victory	Coon	42.5579	-90.3864	5,051	1942	17873	present
Whaley-Victory	Coon	42.5543	-90.3828	5,051	1942	0	present
Wilkinson	Blacks	42.5965	-90.3939	160,000	1909-1910	30486	present
Winrock	Ellis	42.5511	-90.2992	43,478	1923	33357	present
Wipet	Ellis	42.5548	-90.2909	357,143	1938-1940, 1943-1944	0	present