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Use of mining-contaminated sediment tracers to investigate the timing and rates of historical flood plain sedimentation

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Abstract

Changes in land use practices following European settlement in the 1830s produced accelerated sedimentation on virtually all valley floors in the Blue River Watershed, Wisconsin. The contamination of sediments by Pb and Zn mining allowed us to calculate cross-valley rates of flood plain sedimentation for three time periods: the *pre-mining period* (1830–1900), the *mining period* (1900–1920), and the *post-mining period* (1920–1997). Most of the eight valley floors examined contained multiple presettlement surfaces. Significantly higher rates of sedimentation occurred on the lower flood plain surfaces, while the terraces were high enough to prevent sedimentation from most floods. Higher rates of sedimentation on the lower surfaces eventually reduced valley floor relief and, consequently, lateral differences in sedimentation rates.

Tributaries and larger valleys downstream exhibited differences in the timing and rates of historical flood plain sedimentation. While rates of sedimentation were high during the pre-mining period in tributary valleys, the lower valleys were receiving little or no pre-mining alluvium. Little pre-mining alluvium was found in mid-basin reaches, suggesting that most of the pre-mining sedimentation was limited to headwater locations. During the mining period, lateral channel migration and the development of meander belts increased the conveyance capacity of tributary and mid-basin channels, which decreased overbank flooding and produced lower rates of sedimentation during the post-mining period. The meander belt channels also had an effect on the lower portion of the watershed by increasing flood magnitudes and the transport of sediment downstream, thereby shifting the locus of sedimentation from the tributaries to the larger, lower valleys. Sedimentation rates in the largest, most downstream site were an order of magnitude higher during the post-mining period than any of the sites upstream.

Keywords: Flood plains; Sedimentation rates; Trace metals; Wisconsin

1. Introduction

Human activities are widely recognized to have produced significant historical increases in flood magnitudes and frequencies, upland soil erosion, and flood plain sedimentation (Happ, 1944, 1945; Knox, 1972, 1977, 1987a, 1989a; Costa, 1975; Trimble, 1974, 1981, 1983, 1999; Trimble and Lund, 1982; Meade, 1982; Magilligan, 1985; Phillips, 1991, 1993, 1997; Beach, 1994; Lecce, 1997a,b; Faulkner, 1998). Indeed, it may be virtually impossible to locate watersheds that are completely undisturbed by humans. Although several studies of accelerated sedi-

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mentation have produced estimates of the rates with which flood plain sediments have accumulated, because our ability to date these sediments is limited, rates are often determined over relatively long time periods. These average rates may obscure short-term variations, underestimate maximum sedimentation rates, and overestimate minimum rates. If lateral variations of sedimentation are significant, then rates determined at point locations may not be representative of the entire valley fill. Nevertheless, previous work confirms that significant increases in flood plain sedimentation have followed European settlement throughout much of the U.S., although the timing, location, and mechanisms involved may be complex and highly variable in space and time. In areas where the timing and magnitude of mining activities are well documented, the dispersal of fluvial sediments contaminated by trace metals can provide additional temporal detail and assist in clarifying the processes influencing spatial variations in flood plain sedimentation (Bradley and Cox, 1986, 1987; Knox, 1987a, 1989a; Bradley, 1989; Macklin and Klimek, 1992; Leigh, 1994; Knox and Hudson, 1995; Rowan et al., 1995; Sear and Carver, 1996).

Several previous studies in the Driftless Area of southwestern Wisconsin have estimated the timing and rates of flood plain sedimentation (Trimble and Lund, 1982; Magilligan, 1985; Knox, 1987a; Knox and Hudson, 1995; Faulkner, 1998) (Table 1). Historical rates of sedimentation are one to several orders of magnitude greater than the average rate of about 0.02 cm/year during the Holocene (Knox, 1987a). These studies suggest that channel enlargement over periods of several decades, through either channel incision (Faulkner, 1998) or lateral channel migration and the development of meander belts

Table 1
Selected sedimentation rates in the Driftless Area

Basin	Drainage area (km^2)	Time period	Rate (cm/year)	Source	Comments
Shullsburg Br., Galena River basin	27	1820–1890	0.29	Knox, 1987a	Meander belt
		1890–1925	1.29		
		1925–1985	0.30		
Galena R.	450	1820–1870	0.8	Knox, 1987a	Lower main valley
		1870–1876	5.9		
		1876–1916	1.6		
		1916–1930	3.3		
		1930–1940	4.5		
		1940–1985	0.8		
Galena R.	350–400	1820–1940	1.9	Magilligan, 1985	Several lower valley sites
		1940–1979	0.75		
Hutchinson Cr., Site 5, Buffalo River basin	3.5	1830–1992	0.4[a]	Faulkner, 1998	Unincised valley floor
Trout Cr., Site 6, Buffalo River basin	7.2	1830–1992	0.05[a]	Faulkner, 1998	Channel incised by 1939
Trout Cr., Site 4, Buffalo River basin	22.3	1830–1992	0.6[a]	Faulkner, 1998	Channel incised by 1939
Trout Cr., Site 5, Buffalo River basin	14	1830–1992	0.8[a]	Faulkner, 1998	Channel incised by 1965
Mill Cr., Buffalo River basin		1830–1992	2.4[a]	Faulkner, 1998	Unincised valley floor
Coon Cr.	–	1920s and 30s	15.0	Trimble and Lund, 1982	Several tributaries
Coon Cr., transect CV30	~ 350	1853–1904	1.5	Trimble and Lund, 1982	Lower main valley
		1904–1930	5.8		
		1930–1938	15.0		
		1938–1976	1.6		

[a] Calculated from Faulkner's (1998) data on mean depth of historical alluvium.

(Knox, 1972, 1977, 1987a, 1989a; Trimble, 1983, 1993; Woltemade, 1994; Lecce, 1997a,b), has played an important role in shifting sedimentation to lower valleys. Differences in the timing and rates of sedimentation between tributaries and lower main valleys, however, are more controversial (Knox, 1989b; Trimble, 1989). For example, Trimble and Lund (1982) found that maximum rates occurred in the 1930s in both the headwaters and lower valleys; whereas Knox (1987a) concluded that historical rates varied downstream (with most of the aggradation in tributaries occurring between 1890 and 1925) and the highest rates in lower trunk valleys occurring between 1916 and 1940. The purpose of this paper is (i) to explain spatial (i.e., cross-valley and downstream) and temporal variations in rates of historical flood plain sedimentation, and (ii) to examine geomorphic lags in channel adjustments that influence sedimentation.

2. Study area

The Blue River is an agricultural watershed (208 km^2) located on the northern margin of the Upper Mississippi Valley Pb–Zn District in the Driftless Area of southwestern Wisconsin (Fig. 1). The region was one of the most important sources of Pb (galena) and Zn (sphalerite and smithsonite) ore in the U.S. (Heyl et al., 1959). The earliest mining in the Pb–Zn District focused on the extraction of galena from shallow excavations (Knox and Hudson, 1995). These Pb diggings were primarily a small scale, dispersed activity and may have produced a small increase in Pb concentrations in the lower portion of the historical sediments between about 1830 and 1870. The initial Pb diggings were followed by more extensive Zn operations in deep mines during the period from about 1900 to 1920.

Table 2
Mining history and ore production[a]

Map label	Name	First Zn	Last Zn	Ore production (Mg)
A	St. Anthony	1892	1940	5000
B	Old St. Anthony	1885	1892	5000
C	Milwaukee Highland	1906	1910	5000
D	Hornswoggle Diggings	1840 (Pb)	1860 (Pb)	5000
E	Wallace	1906	1919	5000
F	Clarke #3	1918	1919	100,000
G	Lampe-Eberle	1900	1920	100,000
H	Clark #2	1916	1918	100,000
I	Minter	1907	1925	40,000
J	Happy Home	1915	1920	5000
K	Highland	1906	1931	700,000
L	Imhoff-Egan	1909	1912	5000
M	Lewis and Lynch	1892	1905	40,000
N	Clark #1	1904	1907	100,000
O	Kroll	1908	1911	5000
P	Ohlerking (south)	1840 (Pb)	1880 (Pb)	5000
Q	Centerville	1909	1917	20,000
R	Red Jacket	1906	1921	20,000
S	Steppler	1892	1940	5000
T	Ohlerking	1840 (Pb)	1860 (Pb)	5000

[a] Heyl et al. (1959).

Fig. 1. Map of Upper Mississippi Valley Pb–Zn District (10,000 km^2) in Wisconsin, Illinois, and Iowa. The Blue River Watershed is outlined.

Although considerably less impacted by mining activities than in the core of the Pb–Zn District to the south, the mines in the Blue River Watershed produced a total of about 1,255,000 Mg of ore (Heyl et al., 1959). The largest Zn mines in the Blue River Watershed were concentrated in a small area along the eastern drainage divide (Table 2; Fig. 2). Several

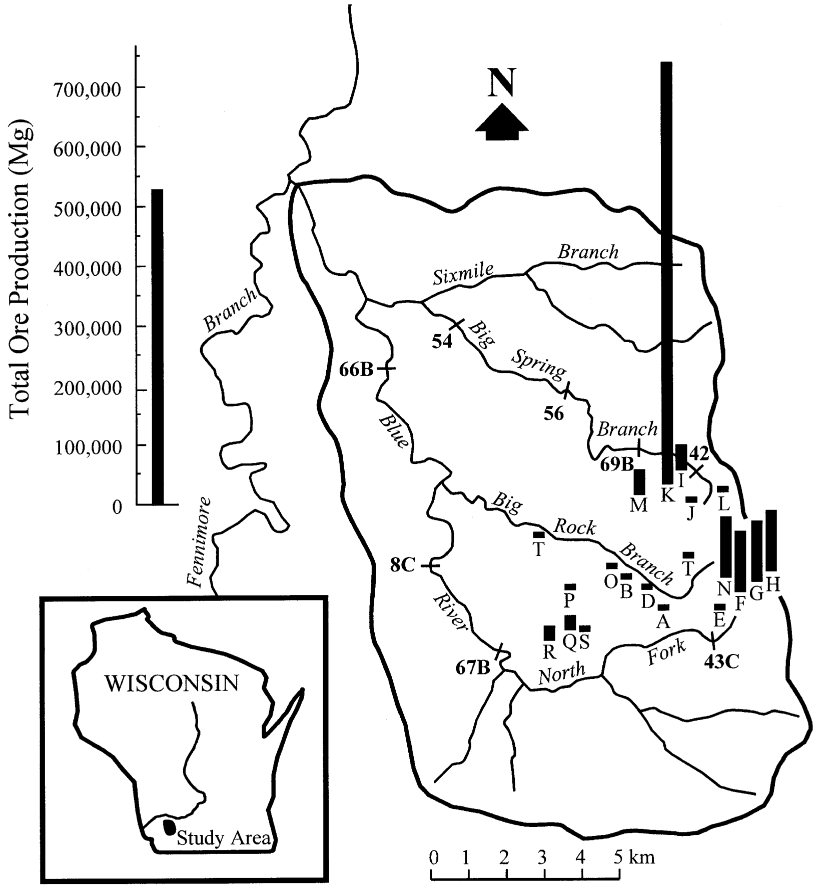

Fig. 2. The Blue River Watershed, Wisconsin, showing mine locations (letters defined in Table 2), ore production (bars), and the flood plain sampling sites (numbers).

smaller mines were operated in the area between Big Rock Branch and the north fork of the Blue River, but their total production was relatively small. The largest mine in the watershed was the Highland Mine, located in the headwaters of the Big Spring Branch. It grew from the coalescence of several smaller mines and produced about 700,000 Mg of ore between 1906 and 1919. An additional 90,000 Mg was produced from several smaller mines in the immediate vicinity. A second clustering of large mines was located about 3 km to the southeast in the headwaters of the Big Rock Branch and the north fork of the Blue River. These mines were active between 1900 and 1920, producing a total of 400,000 Mg of ore. These two groups of large mines account for more than 85% of the total ore production in the entire watershed. Mining-contaminated sediments can be traced throughout the watershed (Lecce and Pavlowsky, 1997).

3. Methods

We examined historical sedimentation at eight sites downstream from the mining area along the Big Spring Branch and Blue River (Fig. 2). At each site the historical overbank deposits were sampled in detail in 1997–1998 at 7 to 12 locations on transects from the active channel across one side of the valley floor. In most cases, pits were dug down to the presettlement soil contact and depth-integrated samples were collected every 5 cm. Where the presettlement soil was too deep to be sampled by hand, we sampled in 10-cm depth increments using a 2-cm diameter Oakfield soil probe (at three sampling locations at site 43C) or a 5-cm diameter AMS split core sampler (site 66B). Lateral accretion sediments within the historical meander belt were sampled in 10-cm depth increments at pits excavated down to the coarse lag gravels. Weighted mean metal concentrations were calculated at each pit in the meander belt. Although the samples were collected with metal tools, additional sampling along the uncontaminated and unmineralized Sixmile Branch using the same field procedures resulted in Zn concentrations <30 mg/kg, suggesting that contamination from the tools did not influence metal concentrations (Lecce and Pavlowsky, 1997). Pb and Zn concentrations were determined for 1-g samples by extraction of the <2 mm sediment fraction by Aqua Regia (3:1 HCl: HNO_3) for 2 h at 80°C and analyzed by ICP-AES at a commercial laboratory (Chemex Labs).

We defined three time periods using stratigraphic changes in metal concentrations in historical overbank deposits: the *pre-mining period* from 1830 to 1900, the *mining period* from 1900 to 1920, and the *post-mining period* from 1920 to 1997. In using trace metal signals from the mines to calculate rates of sedimentation, we assumed that because the mining of Zn was a large-scale operation, the supply of metals to the river system would produce a rapid increase in Zn concentrations above background levels soon after ore production began in about 1900. Defining the end of the Zn mining period was more problematic. We assumed that the peak in Zn concentrations in overbank deposits occurred in 1920, rather than some time earlier during the 1900–1920 period when there may have been higher rates of ore production. This was justified because metals were supplied to the river system from two major sources: (i) primary releases from milling activities, and (ii) secondary releases from the remobilization of contaminated sediments from tailings dumps and proximal colluvial and alluvial deposits (Moore and Luoma, 1990). Even if the production of ore had peaked before 1920, these two sources would continue to supply large amounts of metals until mining and milling operations ended in 1920. Although tailings remained in the watershed as a source of metals for some time after the mines closed, the cessation of mining and milling activities should have led to a decrease in metal concentrations. We assumed, therefore, that the most significant decrease in the supply of metals occurred when mining and milling operations ceased in 1920. Although metal concentrations are influenced by particle size and organic matter content of the sediments (Horowitz et al., 1989; Horowitz, 1991), we assumed that these effects were minimal relative to the large changes in Zn concentrations (which commonly exceed three orders of magnitude) used to establish the three time periods.

The early Pb signal may be difficult to identify except where sedimentation rates were high prior to the rapid increase in Zn concentrations in 1900. While Pb concentrations were much lower than those for Zn, vertical changes in both Pb and Zn are almost identical. Therefore, we focus on the Zn concentrations and note the depth where higher concentrations related to early Pb diggings occur.

4. Results

4.1. Blue River

4.1.1. Site 43C

The first site on the Blue River has a drainage area (A_d) of 5.1 km^2 and is located about 2.5 km downstream from a cluster of four large mines (Fig. 2). The presettlement valley floor contained two surfaces: a 35-m wide terrace lying about 30 cm higher than a 15-m wide flood plain containing an abandoned channel (Fig. 3). Overbank sediments were sampled at seven locations across the valley floor. The three cores located above the lower presettlement flood plain and abandoned channel all display a distinct Pb signal produced by early Pb diggings. This Pb signal weakens or is absent from the four pits located above the presettlement terrace surface.

Overall, Zn concentrations are high due to the close proximity of this site to the mine source. All of the cross-valley sampling locations record a lengthy period with low Zn concentrations (300–600 mg/kg) followed by a distinct Zn peak (8000–15,000 mg/kg). After the peak mining period, concentrations fall to about 2000–3000 mg/kg. Peak concentrations are lowest at the 64-m pit (5460 mg/kg) because of dilution by uncontaminated sediments from the left

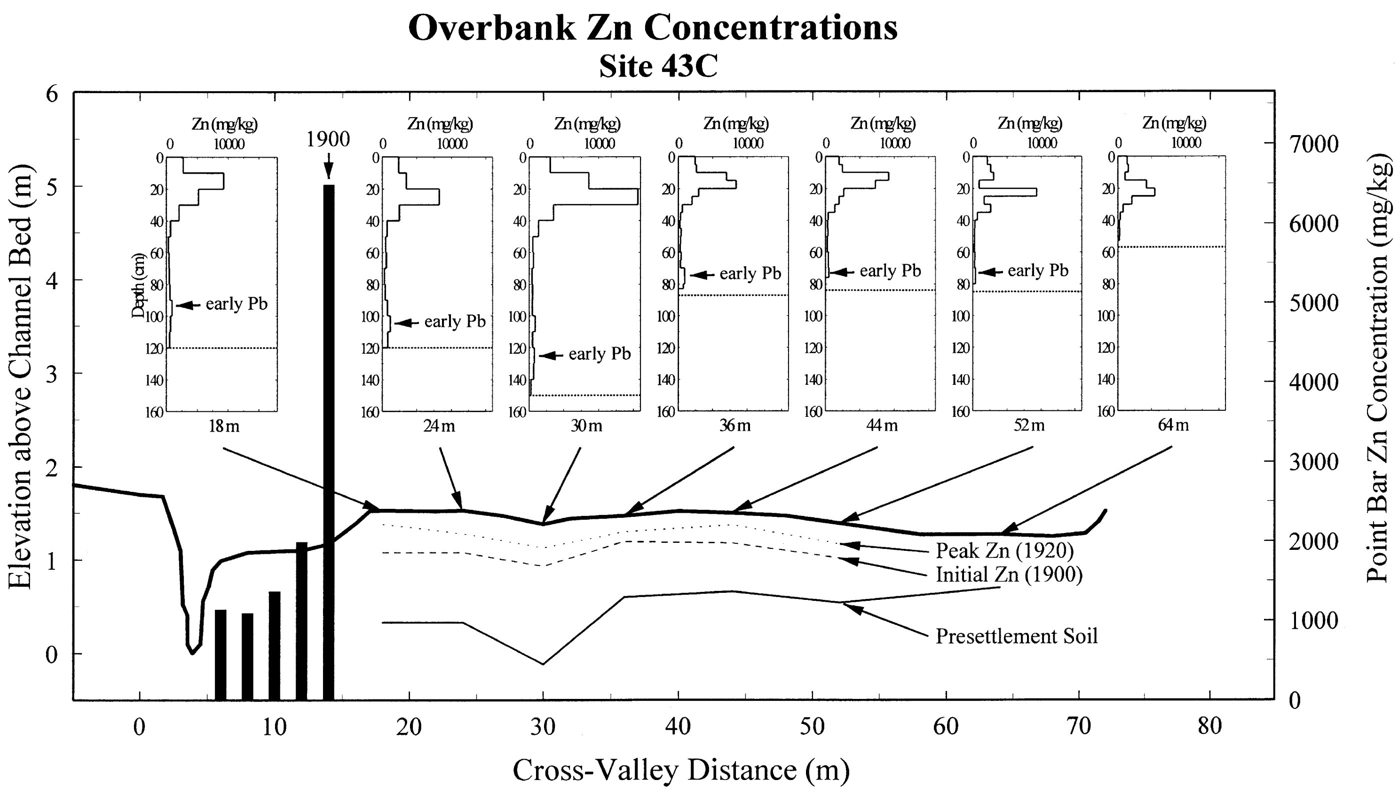

Fig. 3. Cross-section of flood plain at site 43C ($A_d = 5.1$ km^2) showing vertical variations in Zn concentrations at the sampling locations.

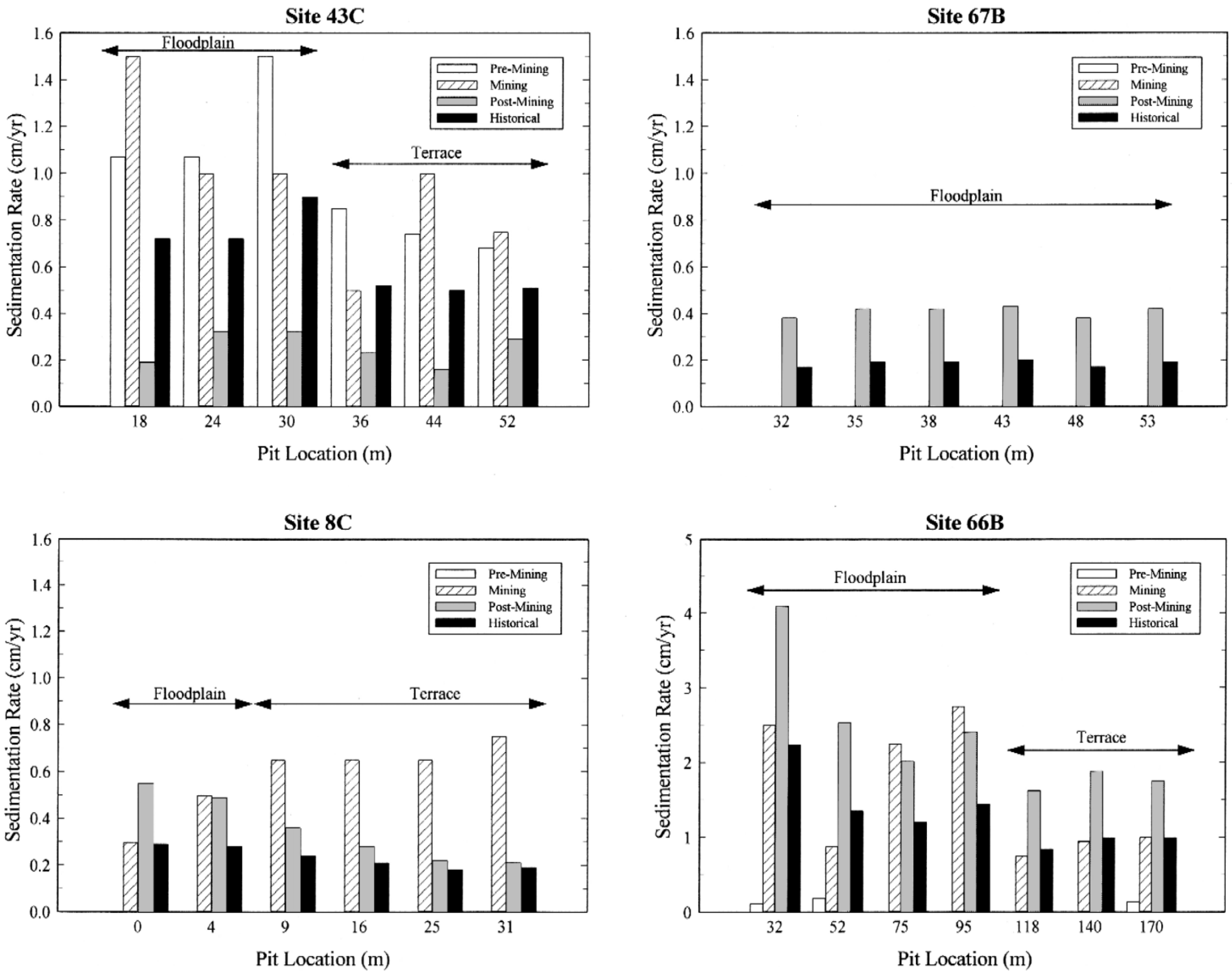

Fig. 4. Cross-valley variations in sedimentation rates on the Blue River during the pre-mining, mining, post-mining, and historical periods. Note that the scale for sedimentation rates at site 66B is different from the others.

valley side slope. Therefore, we did not calculate sedimentation rates at this pit.

Sedimentation rates were high during both the pre-mining and mining periods before decreasing considerably during the post-mining period (Fig. 4; Table 3). Pre-mining sedimentation rates were highest at the 30-m site in the abandoned channel. This channel had almost completely filled in by the time intensive mining activities began. Pre-mining sedimentation rates were also higher on the lower presettlement flood plain surface (1.1–1.5 cm/year) than on the higher terrace (0.7–0.85 cm/year), which resulted in the smoothing of the valley floor and the production of one nearly continuous flood plain surface by 1900. Cross-valley sedimentation rates during the post-mining period were variable, but less so than during the pre-mining and mining periods.

The high Zn concentrations in the lateral accretion sediments within the meander belt indicate that lateral channel migration and the expansion of the meander belt did not occur until sometime after mining began in earnest in 1900 (Fig. 3). As vertical accretion on the flood plain increased bank heights and lateral channel migration increased the capacity of the meander belt cross-section to contain flood flows during the post-mining period, overbank sedimentation decreased and an increasing proportion of the sediment load was routed to downstream areas.

4.1.2. Site 67B

The second site on the Blue River is located about 8 km downstream from site 43C and drains a much larger area ($A_d = 61.5$ km^2). The presettlement flood plain was about 30 m wide and relatively flat (Fig. 5). The 58-m pit was eliminated from further analysis because it may have received colluvial inputs from the valley wall.

Zn concentrations are considerably lower than upstream (site 43C) because of dilution by uncontaminated sediments from tributaries. None of the six sampling pits contain an early Pb signal or any pre-mining sediments. Peak Zn concentrations are in close or direct contact with the presettlement soil and well above background levels. Therefore, we interpret all the historical overbank sedimentation at this site to be of post-mining origin. Peak Zn concentrations range from 900 to 1000 mg/kg before leveling off to about 400–500 mg/kg.

The lack of pre-mining sedimentation at this site may be explained by its distance downstream, the timing of meander belt expansion, and the elevation of the presettlement soil. Because Zn concentrations in the lateral accretion sediments do not change significantly across the width of the meander belt but are higher than in the active channel (152 mg/kg), much of the lateral channel migration may have occurred during the early part of the mining period and before the locus of sedimentation had shifted this far downstream. The relatively high elevation of the presettlement soil above the meander belt surface suggests the possibility that this surface was a terrace and that lateral channel migration eroded a lower presettlement flood plain surface, destroying any pre-mining record it may have contained.

Table 3
Average sedimentation rates

Site	Drainage area (km^2)	Pre-mining period 1830–1900 (cm/year)	Mining period 1900–1920 (cm/year)	Post-mining period 1920–1997 (cm/year)	Historical period 1830–1997 (cm/year)
Blue River					
43C	5.1	0.98	0.96	0.25	0.64
67B	61.5	0	0	0.40	0.19
8C	79.5	0	0.58	0.35	0.23
66B	128	0.06	1.58	2.33	1.29
Big Spring Branch					
42	2.4	0.18	0.50	0.05	0.16
69B	4	0.80	0	0	0.33
56	19.2	0.31	0.50	0.37	0.36
54	31	0.13	0.58	0.47	0.34

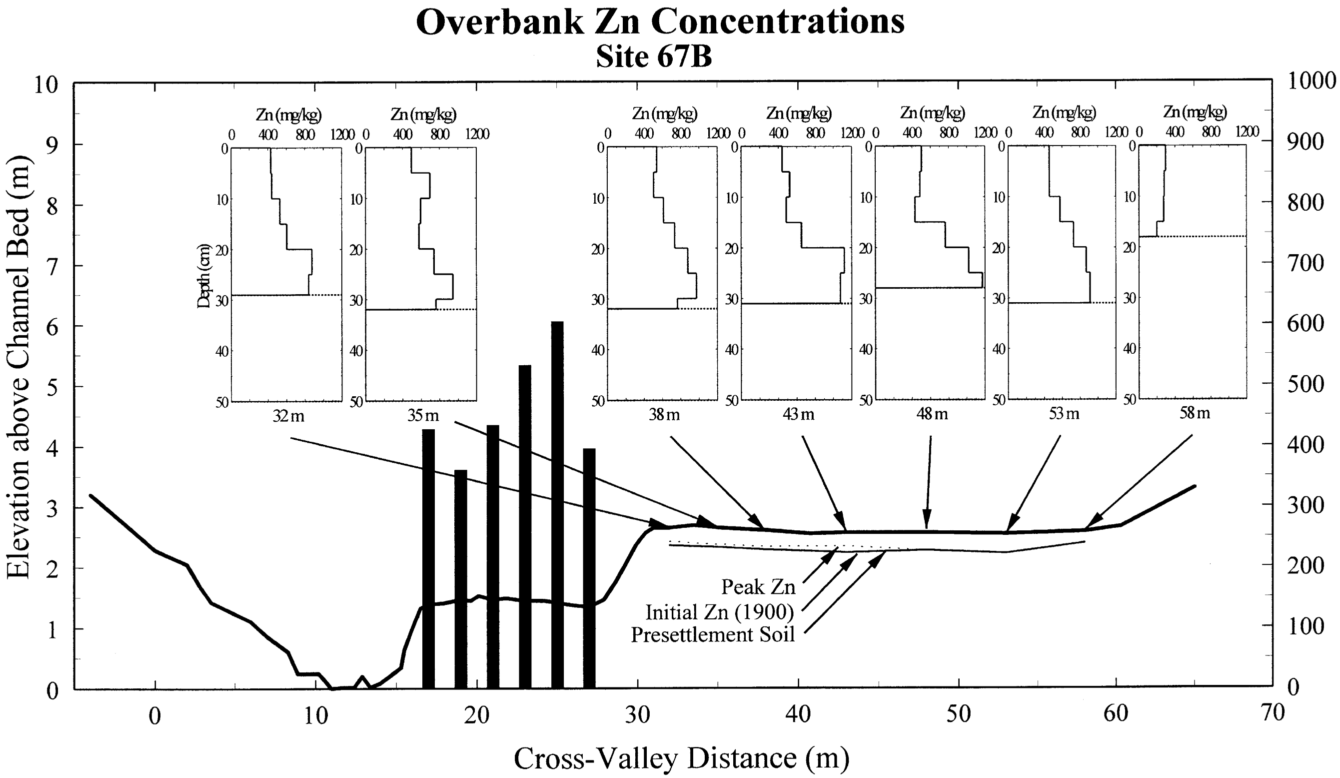

Fig. 5. Cross-section of flood plain at site 67B ($A_d = 61.5\ km^2$) showing vertical variations in Zn concentrations at the sampling locations.

Sedimentation rates during the post-mining period did not vary laterally from the channel due to the relatively flat flood plain surface. The low rates probably result from the high elevation of this surface and the narrow valley at this site. Previous research has shown that narrow valleys tend to promote sediment transport and decrease historical sediment storage (Magilligan, 1985, 1992; Lecce, 1997b; Faulkner, 1998).

4.1.3. Site 8C

The third site on the Blue River ($A_d = 79.5$ km^2) is located about 3.5 km downstream from site 67B. The presettlement valley floor contained a narrow (5 m) flood plain surface sloping up to a wider (30 m) terrace surface (Fig. 6). The 38-m pit was eliminated from further analysis because it received colluvial inputs from the valley wall. None of the remaining six cores displays an early Pb signal.

Zn concentrations were low in the four pits closest to the active channel (350–500 mg/kg) and somewhat higher at the two pits farthest from the channel (25 m = 546 mg/kg; 31 m = 570 mg/kg). The slightly higher Zn concentrations at the two distal locations may indicate that sedimentation occurred later than at the near-channel pit locations because of the higher presettlement valley floor. Because concentrations in the sediments directly overlying the presettlement soil are higher (mean = 459 mg/kg) than those observed in pre-mining sediments near the mine source at site 43C (mean = 377 mg/kg), they were probably deposited during the early part of the mining period after being transported through the enlarged channel at site 67B. None of these pits record a distinct Zn spike; rather, the period of highest concentrations is fairly uniform over a 20–30 cm depth. This made it difficult to define the end of the peak mining period. Therefore, our estimates of sedimentation rates at this site are only general approximations. Nevertheless, it is clear that sedimentation rates increased significantly during either the mining or post-mining period.

Zn concentrations are low in the lateral accretion sediments because the coarser contaminated sediments are less likely to be transported far from the mine source (Lecce and Pavlowsky, 1997). The highest concentrations within the meander belt occur in the most recent lateral accretion sediments near the active channel. This is probably related to the clay content of the sediments, which is two to three times greater in the three near-channel pits.

4.1.4. Site 66B

The fourth site on the Blue River is located about 9 km downstream from site 8C. The valley floor at this site ($A_d = 128$ km^2) is very wide because of the influence of erodible Cambrian sandstones in the valley walls (Lecce, 1997a,b). None of the 13 cores contain an early Pb signal (Fig. 7). The presettlement valley floor consisted of two surfaces: a lower, 100-m wide near-channel flood plain; and a wider, higher terrace extending another 230 m to the valley wall. Both the presettlement and modern valley floors contain abandoned channels: a larger one at about 100 m, and a smaller side channel near the right valley wall.

The cores farthest from the active channel (210–335 m) do not display well-defined Zn peaks. Background concentrations overlying the presettlement soil are followed by higher Zn concentrations, but these contaminated sediments may be post-mining in origin because of the higher elevation of the presettlement terrace and its distance from the main channel. These sites may also reflect the influence of the smaller channel, which drains an unmined, tributary watershed. Therefore, sedimentation rates were not calculated for the core holes between 210 and 335 m.

At the seven remaining core hole locations, three contain a brief pre-mining signal (32, 52, and 170 m) with background Zn concentrations ranging from 120–250 mg/kg. The other four core locations have mining-contaminated sediments (442–616 mg/kg) directly overlying the presettlement soil. Peak concentrations range from 700 to 1350 mg/kg (most are 1100–1350 mg/kg). Zn concentrations level off at 400–600 mg/kg during the post-mining period.

The core hole at 32 m contains coarse Pleistocene lag gravels at its base, which is 65 cm deeper than the bed of the active channel, indicating that the channel has aggraded during the historical period. Although we did not locate the presettlement soil at the 32-m core hole, the sediments are clearly mining-contaminated vertical accretion sediments

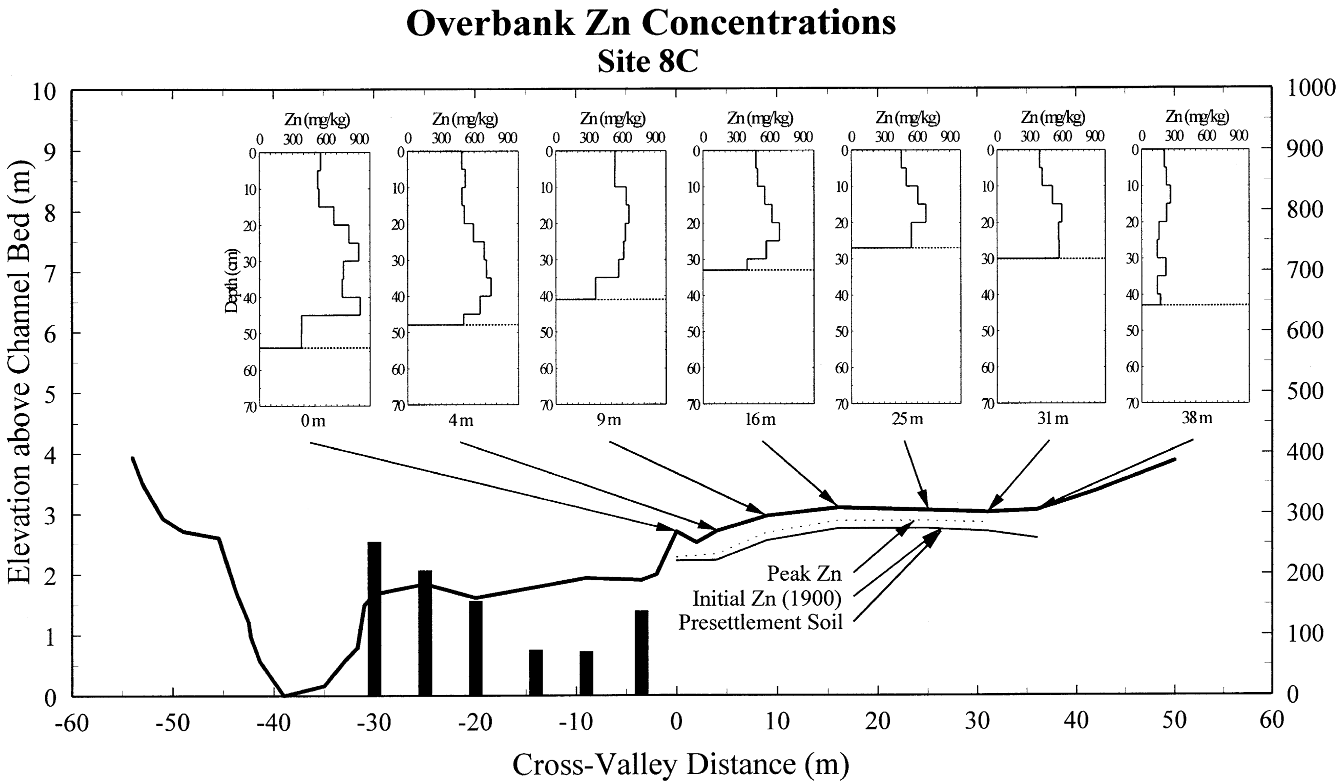

Fig. 6. Cross-section of flood plain at site 8C (A_d = 79.5 km^2) showing vertical variations in Zn concentrations at the sampling locations.

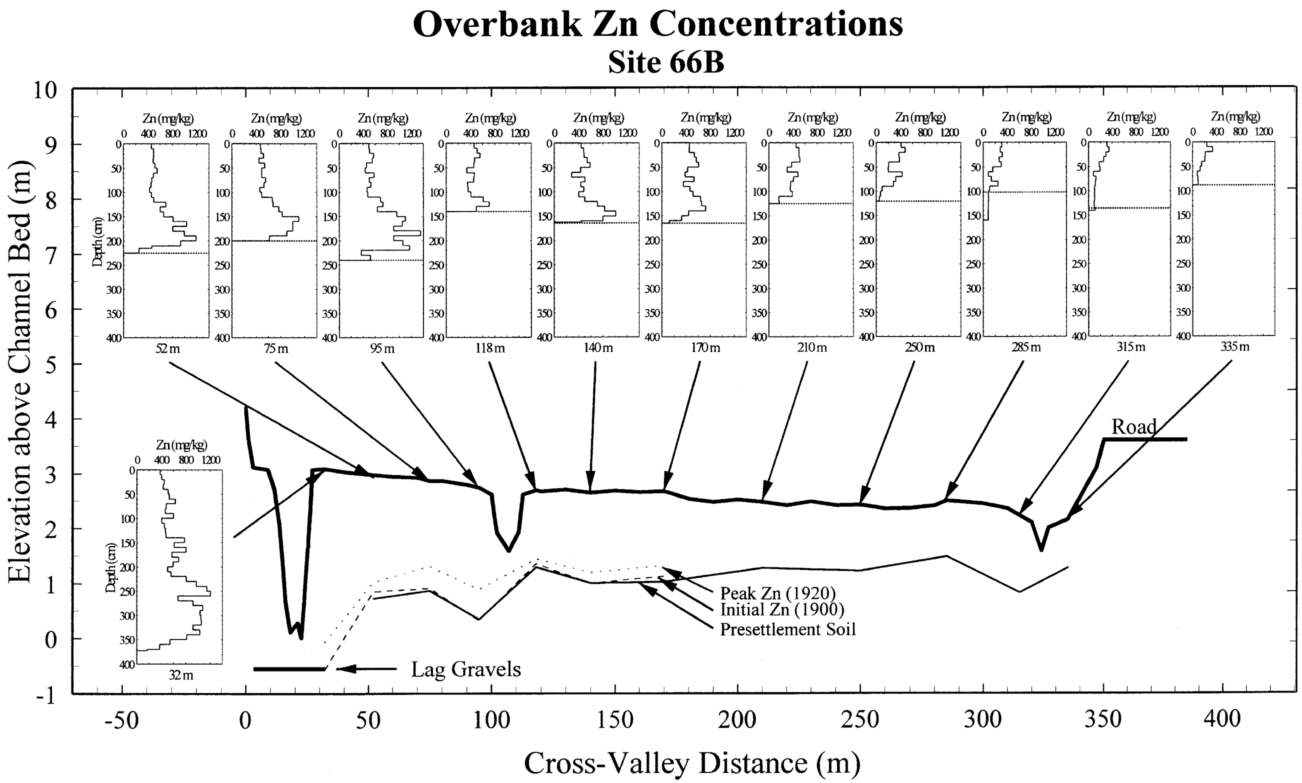

Fig. 7. Cross-section of flood plain at site 66B ($A_d = 128$ km^2) showing vertical variations in Zn concentrations at the sampling locations.

with distinct horizontal laminae and sandy lenses. Furthermore, coring from a previous study (Lecce, 1993, 1997b) identified the presettlement soil at an elevation of about 30 cm above the active channel bed (at about 35 m on the current transect). This suggests that the postsettlement channel eroded the presettlement soil in the immediate vicinity of the right channel bank and then proceeded to rapidly deposit overbank sediments. Sedimentation rates at the 32-m core hole should be viewed with some skepticism because of the lack of a well-defined peak between 285 and 335 cm and the secondary peak at 255 cm. We chose 315 cm as the most likely timing of the mining peak. Nevertheless, it is clear that sedimentation rates were high after 1900 in the low-lying area immediately adjacent to the channel, especially during the post-mining period.

The differences in cross-valley sedimentation rates are largely due to the variable topography of the presettlement surface. Sedimentation rates were higher above the presettlement flood plain (to the left of the large abandoned channel) during the mining (0.9–2.5 cm/year) and post-mining (2.0–4.1 cm/year) periods than above the presettlement terrace (mining = 0.5–1.0 cm/year; post-mining = 1.6–1.9 cm/year) because of the difference in the elevation of these two presettlement surfaces and the distance of the terrace from the main channel (Fig. 7). The high sedimentation rate during the mining period in the abandoned presettlement channel at 95 m (Fig. 4) began the process of filling in this channel. The existence of this abandoned channel today indicates that it was reactivated at some time during the post-mining period before being abandoned again and partly refilled. Given that this valley floor is quite wide, the high sedimentation rates during both the mining and post-mining periods (Table 3) represent an enormous amount of historical sediment storage (Lecce, 1997b).

Zn concentrations are low compared to the headwater site (43C), but significantly higher than the two previous upstream sites (67B and 8C). This may be explained, in part, by sediment contributions from the Big Rock Branch (Fig. 2), which also drains the mining area near Highland. Site 66B was also the locus of deposition of contaminated sediments transported through the meander belts upstream.

4.2. Big Spring Branch

4.2.1. Site 42

The first site on the Big Spring Branch ($A_d = 2.4$ km^2) is located just 1.6 km downstream from the Highland mine complex. The presettlement flood plain surface (25 m wide) grades into a colluvial slope that also contains highly contaminated sediments derived from nearby mining activities (Fig. 8). The five pits from 39–79 m were excluded from further analysis because they contained either colluvial sediments, or a mixture of fluvial and colluvial sediments.

The only pit that displays an early Pb signal and an abrupt Zn spike is the 21-m pit closest to the active channel. Instead, concentrations increase at a constant rate to a poorly defined peak (2000–3500 mg/kg) that may or may not represent peak mining activities. Therefore, rates of sedimentation in Fig. 9 should be viewed as approximations. It is apparent, however, that little or no sedimentation occurred during the post-mining period. The lateral accretion deposits within the meander belt are highly contaminated, indicating that the channel began migrating laterally after the onset of peak mining activities. The conveyance capacity of the meander belt was sufficiently large to prevent overbank flooding and the deposition of sediment during the post-mining period, and probably during part of the mining period.

4.2.2. Site 69B

The second site on the Big Spring Branch ($A_d = 4$ km^2) is located about 1 km downstream from site 42. The presettlement flood plain was about 30 m wide, grading into a 30-m-wide Holocene alluvial fan (Fig. 10). The sediments in the two pits overlying the alluvial fan are derived from a small tributary draining an unmineralized area and were excluded from further analysis.

Although average Zn concentrations are quite low at the six remaining sampling pits (100–500 mg/kg), concentrations decrease upward in the lower half of the pits before increasing in the upper half. An early Pb signal is present and strongest in the three pits near the channel, but none of the pits displays a Zn spike associated with the beginning of the mining period. These patterns suggest that the increase in

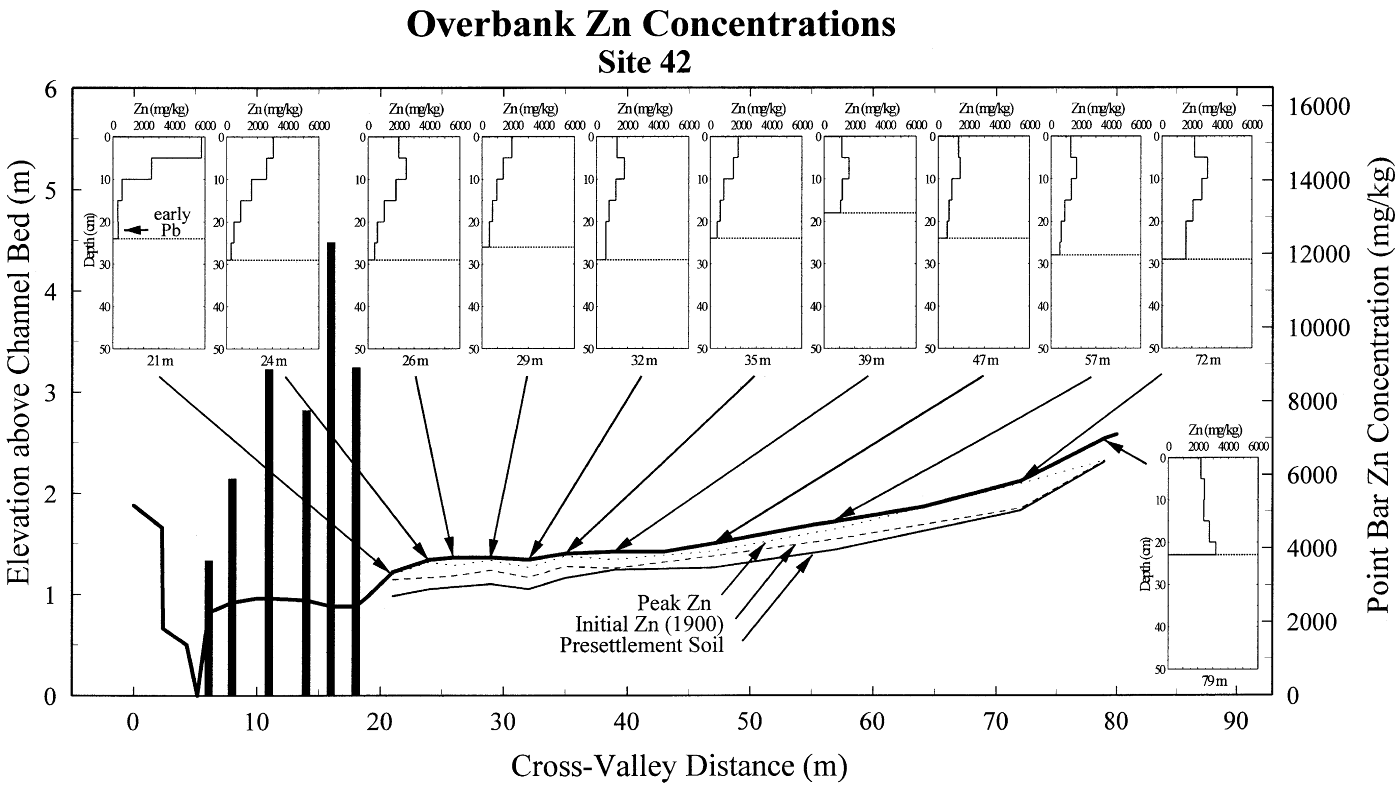

Fig. 8. Cross-section of flood plain at site 42 ($A_d = 2.4$ km^2) showing vertical variations in Zn concentrations at the sampling locations.

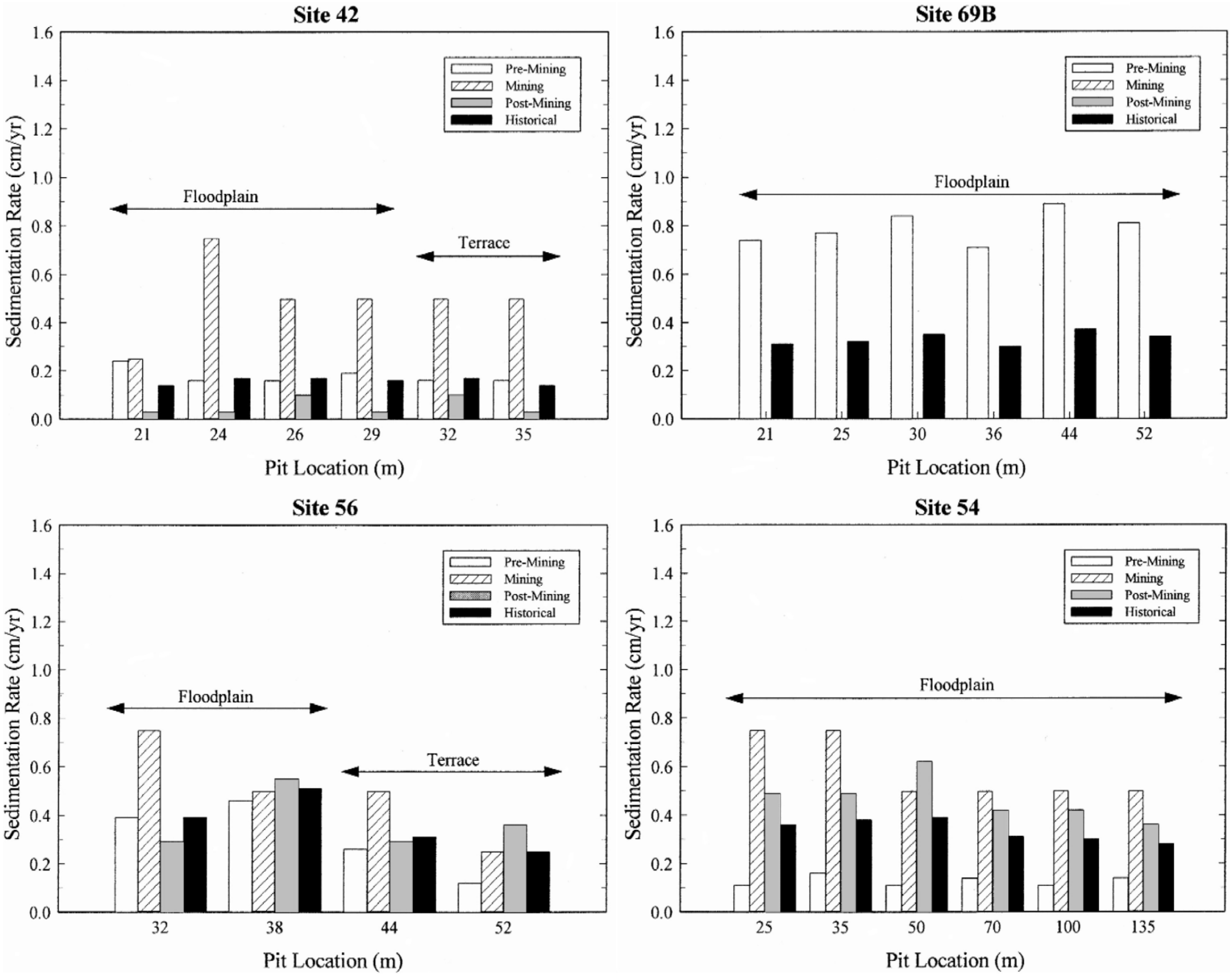

Fig. 9. Cross-valley variations in sedimentation rates on the Big Spring Branch during the pre-mining, mining, post-mining, and historical periods.

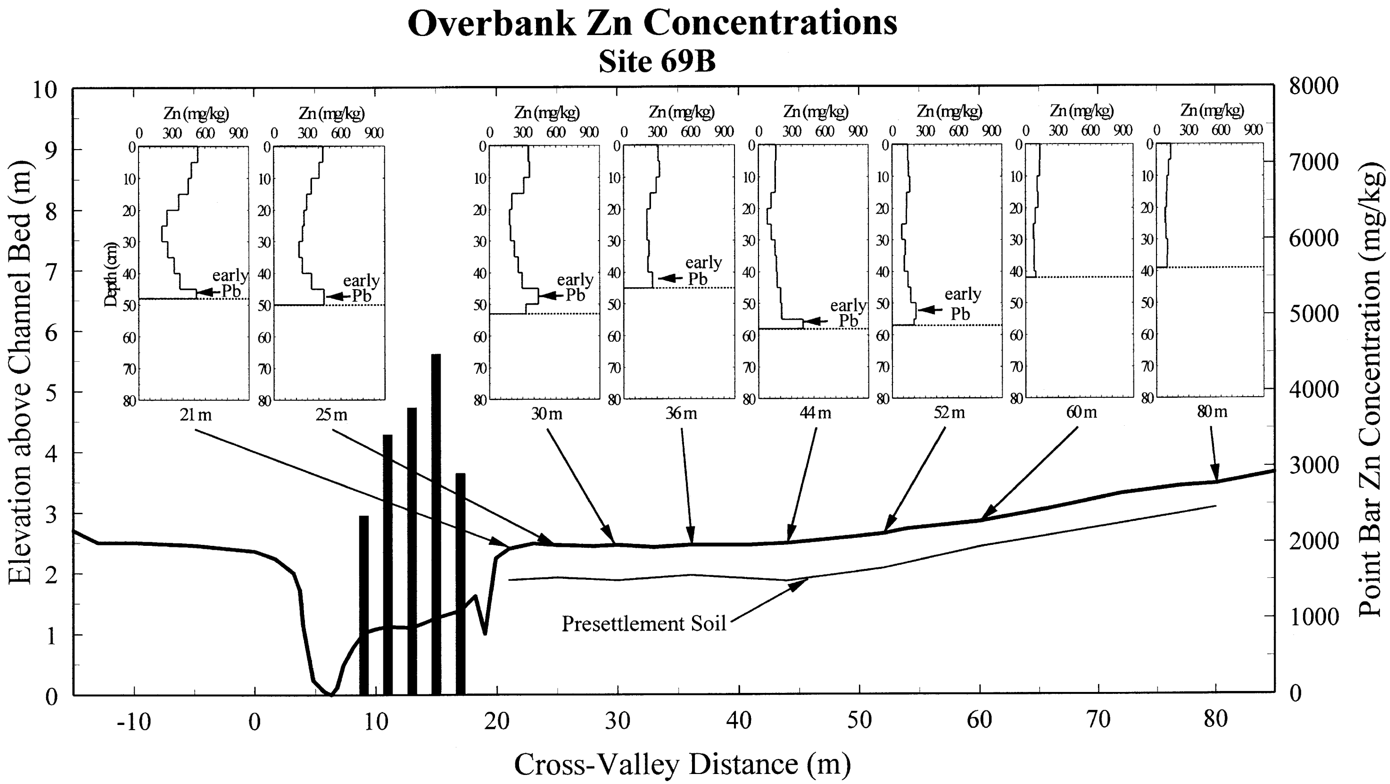

Fig. 10. Cross-section of flood plain at site 69B ($A_d = 4$ km^2) showing vertical variations in Zn concentrations at the sampling locations.

bank heights, due to 40–50 cm of pre-mining vertical accretion, was sufficient to prevent overbank sedimentation by the time the peak mining period began. The high levels of contamination within the meander belt suggest that lateral channel migration did not begin until after 1900, but probably soon thereafter to insure that none of the highly contaminated sediments from the Highland mines were deposited on the flood plain.

We have calculated rates of sedimentation for the pre-mining period (0.56–0.89 cm/year), but because we have no clear record of the beginning of the peak mining period, they are maximum estimates (Fig. 9). Nevertheless, it is clear that sedimentation rates were high prior to 1900 and that no sedimentation occurred during either the mining or post-mining periods. Cross-valley differences in pre-mining sedimentation rates were minimal.

4.2.3. Site 56

The third site on the Big Spring Branch (A_d = 19.2 km^2) is located about 5 km downstream from site 69B. The presettlement valley floor contained a narrow (10 m) flood plain surface and a higher (by about 75 cm), wider (40 m) terrace (Fig. 11). The three sampling locations closest to the active channel contain an early Pb signal that is absent in pits on the highest portion of the terrace surface.

Zn concentrations were low (300–600 mg/kg) during the pre-mining period except at the 66-m (976 mg/kg) pit. Higher pre-mining concentrations at 66 m indicate that this location on the valley floor did not receive much sedimentation until the mining period had begun due to its higher elevation and greater distance from the channel. Post-mining Zn concentrations level off at about 2000–3000 mg/kg. The most distinct peak in Zn concentrations (8900 mg/kg) occurs at the 38-m pit, while moderately distinct Zn peaks occur at the 44- and 52-m pits (3500–5000 mg/kg). The 32-, 58-, and 66-m pits do not display distinct Zn peaks. Sedimentation rates were not calculated for the two sites farthest from the channel because they lacked a distinct Zn peak and may contain colluvial sediments from the valley side slope.

Compared to the two previous sites upstream on the Big Spring Branch (42 and 69B), there was less variation in sedimentation rates between the three time periods, especially above the presettlement flood plain surface at 38 m (Fig. 11). Sedimentation rates were highest on the presettlement flood plain and decreased with distance from the active channel on the higher presettlement terrace. Zn concentrations in the lateral accretion sediments indicate that meander belt expansion at this site occurred after 1900. This meander belt, however, has not prevented overbank flows from depositing sediments on the flood plain during the post-mining period.

4.2.4. Site 54

The fourth site on the Big Spring Branch (A_d = 31 km^2) is located about 4 km downstream from site 56. The presettlement flood plain surface is wide (150 m) and relatively flat (Fig. 12). None of the seven sampling pits contains an early Pb signal. The 175-m pit closest to the valley wall consists of colluvial deposits overlying the presettlement soil and was excluded from further analysis.

All of the pits display well-defined Zn peaks ranging from 3000 to 4000 mg/kg (except at 135 m, where peak Zn = 2080 mg/kg). The large secondary Zn spike at 20 cm in the 50-m pit is unexplained, but because the patterns observed in the remaining pits are otherwise consistent, it is probably not associated with the peak mining period. Pre-mining (150–300 mg/kg) and post-mining (600–1000 mg/kg) concentrations are lower than upstream at the previous site (site 56).

Pre-mining sedimentation rates (Fig. 9; Table 3) were consistently low across the valley floor ($\leq$ 0.16 cm/year). Although the highest rates occurred during the mining period (mean = 0.58 cm/year), rates were still relatively high during the post-mining period (mean = 0.47 cm/year). With the exception of the 25- and 35-m pits in the near-channel natural levee (with higher rates during the mining period), sedimentation rates within each time period are similar across the valley floor. This is attributed to the flat flood plain surface where relatively uniform aggradation occurred from valley wall to valley wall.

4.3. Downstream variations

The results presented above provided evidence for a temporal and spatial lag in the deposition of historical alluvium (Fig. 13). Differences in the timing and

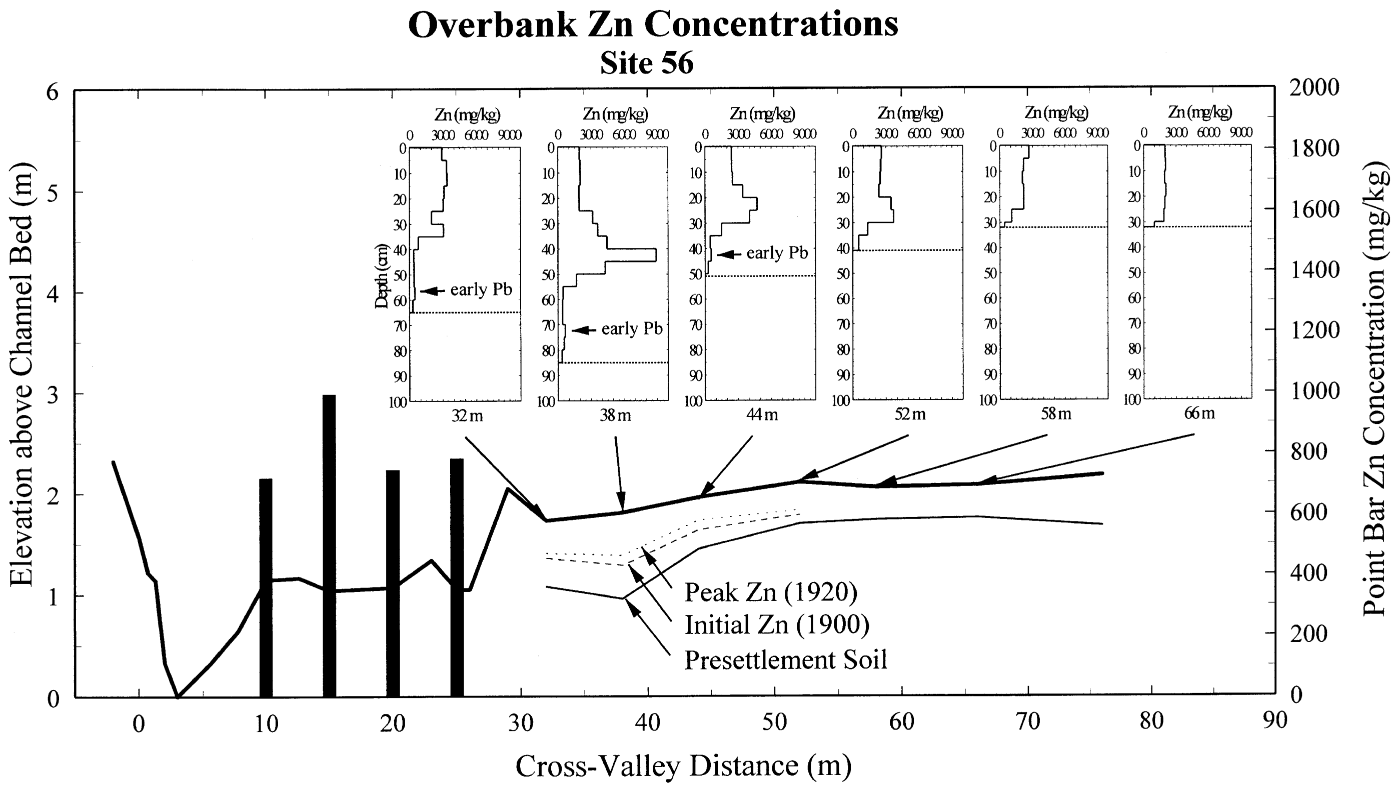

Fig. 11. Cross-section of flood plain at site 56 ($A_d = 19.2$ km^2) showing vertical variations in Zn concentrations at the sampling locations.

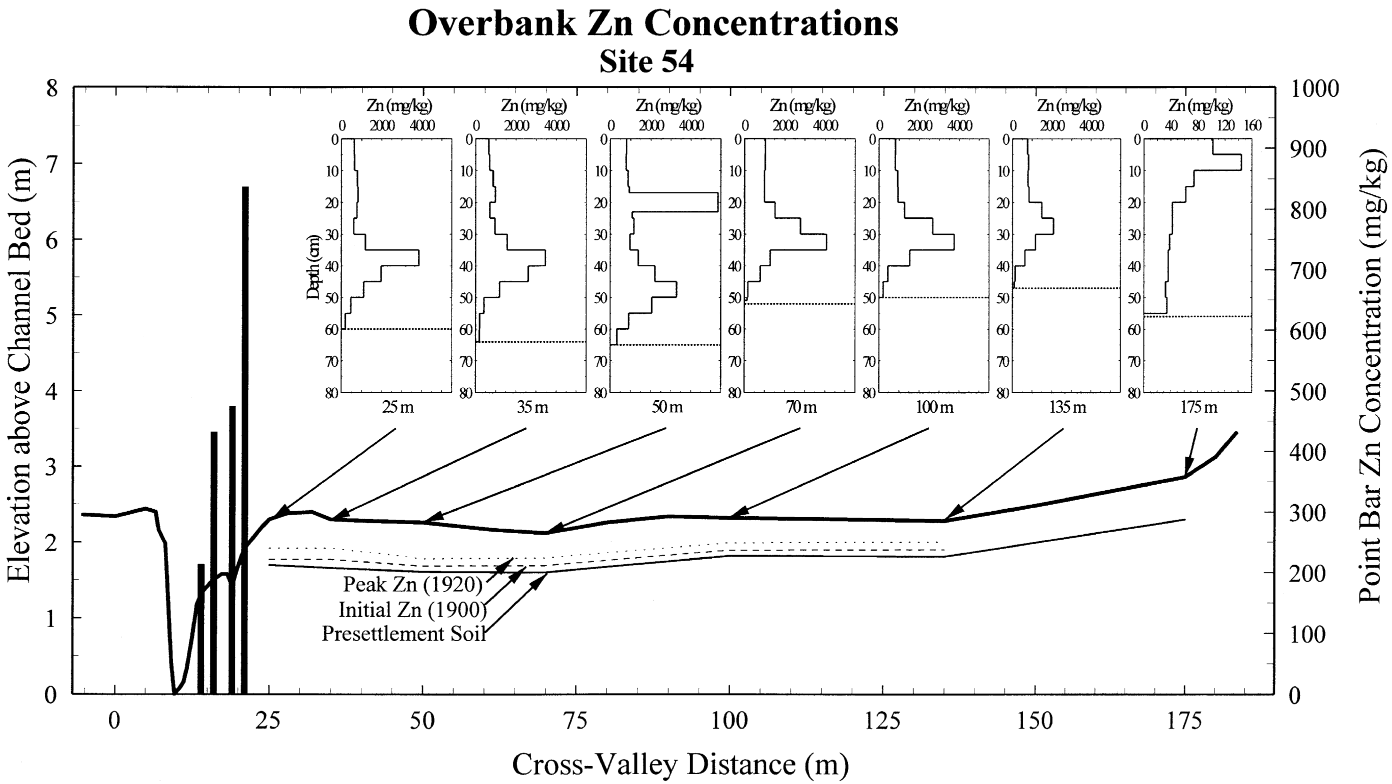

Fig. 12. Cross-section of flood plain at site 54 ($A_d = 31$ km^2) showing vertical variations in Zn concentrations at the sampling locations. Note that the scale for Zn concentrations at the 175-m pit is different from the others.

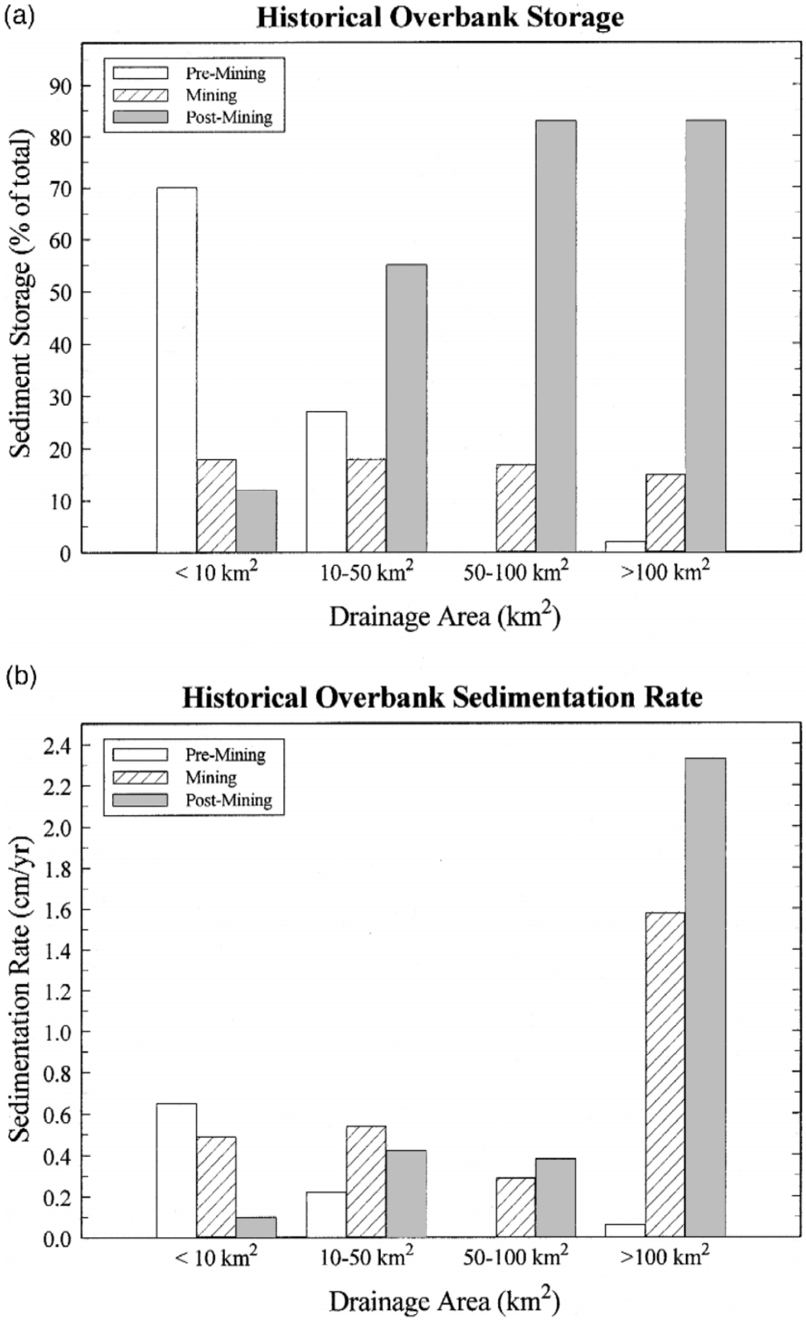

Fig. 13. Spatial and temporal lags in (a) historical overbank sediment storage and (b) the rate of historical overbank sedimentation. Bars represent means calculated for sites grouped by drainage areas of < 10 km^2 (sites 42, 69B, 43C), 10–50 km^2 (sites 56, 54), 50–100 km^2 (sites 67B, 8C), and > 100 km^2 (site 66B).

rate of historical flood plain sedimentation between tributaries and larger downstream valleys in the Blue River watershed generally support what Knox (1987a, 1989a) found in the Pb–Zn District in the southern

Table 4
Proportion of total historical flood plain sediment storage[a]

Site	Pre-mining period 1830–1900 (%)	Mining period 1900–1920 (%)	Post-mining period 1920–1997 (%)
Blue River			
43C	64	17	19
67B	0	0	100
8C	0	34	66
66B	2	15	83
Big Spring Branch			
42	46	38	16
69B	100	0	0
56	37	16	47
54	16	19	65

[a] Sediment storage calculated by surveying the cross-sectional area of alluviation.

Driftless Area. In the headwaters of the Blue River (site 43C), sedimentation rates were high during both the pre-mining and mining periods (Table 3; Fig. 4), accounting for 81% of the total historical sedimentation (Table 4). As the channel began to migrate laterally after 1900, increasingly larger flood flows were contained within the meander belt, decreasing rates of overbank sedimentation and increasing the transport of sediment downstream. In the headwaters of the Big Spring Branch, meander belt expansion eliminated overbank flows earlier, either before (e.g., site 69B) or shortly after (e.g., site 42) intensive mining began in 1900. Consequently, sedimentation rates were substantially lower in the headwaters during the post-mining period.

In the middle portions of the watershed (sites 56, 54, 67B, and 8C), the rates of sedimentation during the pre-mining period decreased with increasing drainage area and distance downstream. The highest sedimentation rates occurred during the mining and post-mining periods, as much as two to seven times higher than during the pre-mining period. Average sedimentation rates at site 56 were modest during the pre-mining period and highest during the mining period. About 3.5 km downstream at site 54, pre-mining sedimentation rates were much lower, while 84% of the total historical sedimentation occurred after 1900 (Table 4). No pre-mining sediments were deposited in the larger watersheds in the middle portion of the Blue River (sites 67B and 8C), although it is possible that erosion from lateral channel migration at site 67B removed pre-mining sediments from a lower presettlement flood plain.

Because the meander belts in upstream valleys had expanded enough to prevent overbank flow, sediment loads were transported downstream to the lower valleys lacking meander belts where overbank flooding and high rates of sedimentation could occur. At site 66B, little sedimentation occurred during the pre-mining period and rates were as much as 20–40 times higher during the mining and post-mining periods. Furthermore, sedimentation rates at site 66B during the mining and post-mining periods were two to eight times higher than in the middle parts of the Blue River (sites 67B and 8C). Site 66B is representative of larger lower valleys that are sinks for sediments transported through the headwater and middle valleys within meander belts (Lecce, 1997b).

Early Pb signals were only detected at sites close to the headwaters. In several of these valley floors, the signal is absent on higher presettlement terraces where sedimentation did not begin until later. The lack of an early Pb peak downstream indicates that either the signal was too diluted by uncontaminated sediments to be recognizable or that overbank sedimentation began after the mining activities that produced the Pb signal (1845).

5. Discussion

The results of this study have implications for the interpretation of flood plain sedimentation from data on rates of vertical accretion. Averaging over long time periods, although often unavoidable, implies that sedimentation rates have been uniform even though they are likely to vary considerably during shorter time periods (Knox, 1989b) (Table 3). Indeed, overbank deposition occurs during discrete hydrologic events that may last as little as a few hours, during which rates may be very high (Knox and Hudson, 1995). The subjectivity inherent in the use of trace metal concentrations as a dating tool is greatest in deposits lacking a clear signal of the onset or cessation of mining. Consequently, our rates are only approximations at several sites (e.g., sites 8C, 42, and 69B). The record of historical overbank

Table 5
Cross-valley variations in the proportion of historical vertical accretion

Site	Pit (m)	Pre-mining period 1830–1900 (%)	Mining period 1900–1920 (%)	Post-mining period 1920–1997 (%)
Big Spring Branch				
42	21	69	21	10
	24	40	52	9
	26	40	34	26
	29	52	38	10
	32	40	34	26
	35	48	42	10
	Mean	48	37	15
	SD	11	10	8
56	32	42	23	35
	38	38	12	50
	44	36	20	44
	52	21	12	67
	Mean	34	17	49
	SD	9	6	14
54	25	13	25	63
	35	18	23	59
	50	12	15	73
	70	18	19	62
	100	15	20	65
	135	20	21	59
	Mean	16	21	63
	SD	3	3	5
Blue River				
43C	18	63	25	13
	24	63	17	21
	30	70	13	17
	36	68	11	20
	44	61	24	15
	52	56	18	26
	Mean	63	18	19
	SD	5	5	5
8C	0	0	12	88
	4	0	21	79
	9	0	32	68
	16	0	38	62
	25	0	43	57
	31	0	48	52
	Mean	0	32	68
	SD	0	13	13
66B	32	2	13	84
	52	6	8	87
	75	0	23	77
	95	0	23	77
66B	118	0	11	89
	140	0	12	88
	Mean	1	15	84
	SD	2	6	5

sedimentation may also be incomplete where erosion from lateral channel migration removes part of the presettlement flood plain overlain by historical sediments (e.g., site 67B).

Rates of sedimentation may be influenced by the selection of point sampling locations on valley floors containing multiple presettlement surfaces (Knox, 1987b, 1989b). Not surprisingly, sedimentation rates were highest on the lowest valley floor surfaces, but as burial of these low surfaces reduced or eliminated relief on the valley floor, rates became more uniform laterally. In situations where the presettlement valley floor was relatively flat (e.g., site 54), cross-valley rates of sedimentation did not vary significantly, except in the immediate vicinity of the channel. This probably is related to the grain size composition of the sediments in the Blue River Watershed, which are predominantly loess-derived silt. Although watersheds with greater grain-size variability might be expected to display larger lateral variations in sedimentation rates even on flat valley floors, knowledge of the presettlement flood plain topography may aid in establishing whether or not single cores are representative of rates across the entire valley floor. Although absolute sedimentation rates were sensitive to cross-valley location in valleys containing multiple surfaces, Table 5 shows that lateral variations in the proportion of alluvium deposited during the three time periods were minimal. Where cross-valley variations are apparent in Table 5, they are explained by our inability to precisely date sediments using trace metals rather than by cross-valley location.

Morphological changes in stream channels played an important role in producing spatial and temporal variations in rates of sedimentation (Fig. 13). Channel enlargement through the expansion of meander belts reduced rates of sedimentation by preventing overbank flow and increasing sediment transport and overbank deposition on downstream valley floors lacking meander belts. Although the timing of meander belt expansion was difficult to determine with precision, high Zn concentrations throughout the lateral accretion deposits indicate that enlargement began sometime after intensive mining commenced in 1900.

Finally, because valley width has been shown to influence sediment storage (Magilligan, 1985, 1992; Lecce, 1997b; Faulkner, 1998), it may also affect rates of vertical accretion. For example, Magilligan (1985) showed that for a given volume of sediment wider valleys have lower rates of sedimentation. Nevertheless, because wide valleys are associated with hydraulic properties that favor deposition, they frequently have the highest rates of sedimentation.

6. Conclusion

Land use practices following European settlement in about 1830 and a time-transgressive change in channel morphology have affected temporal and spatial variations of historical sedimentation on valley floors in the Blue River Watershed. Vertical changes in Zn concentrations in historical overbank deposits were used to calculate rates of sedimentation for three time periods: the *pre-mining period* (1830–1900), *the mining period* (1900–1920), and the *post-mining period* (1920–1997). Presettlement valley floors with multiple surfaces had significantly higher rates of sedimentation on the lower flood plain surfaces. Elevational variations on valley floors also affected lateral sedimentation rates by decreasing the frequency of overbank flows and deposition on higher, distal surfaces. As the lower surfaces aggraded, relief decreased and lateral rates became more uniform across valley floors.

Rapid sedimentation during the pre-mining period was confined to small tributaries in the headwaters of the watershed while little sedimentation occurred in larger downstream valleys. The expansion of meander belts after 1900 eventually prevented overbank flows in the tributaries and increased the efficiency with which sediments and flood waters were routed downstream. It was not until after the development of enlarged meander belts in the tributaries and mid-basin locations (post-1900) that sedimentation rates increased in the lower valleys. Rates of sedimentation in the largest, widest valley were an order of magnitude larger than sites located farther upstream. Cross-valley variations in sedimentation, as well as differences in the timing and rates of sedimentation between tributaries and lower valleys, provides further evidence that sedimentation data based on short-term measurements may poorly reflect long-term sediment storage in watersheds (Knox, 1989a).

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