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Heavy metal trends in floodplain sediments and valley fill, River Lahn, Germany

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Abstract

Sampling along the River Lahn, a major tributary to the River Rhine that flows through an agrarian region of west-central Germany, reveals that heavy metal pollution occurs outside major industrial regions and mined landscapes. Along a 60-km reach of the river between Marburg and Wetzlar, mean concentrations of Cu, Pb and Zn at depths of 5 and 15 cm in four floodplain transects were greater than background levels. Concentrations declined sharply between 15 and 25 cm. Laterally, concentrations peaked at the bank top and in the near-channel zone of the floodplain. Beyond the near-channel zone (generally up to 100 m from the channel) concentrations were much less and fairly uniform to the valley wall. The clustering of metals close to the channel suggests that they are a fluvial rather than an eolian deposit. During floods of a moderate magnitude, sediments and attached metals are deposited soon after the river overtops its banks. Although the overall store of metals in the valley is less than that along the Rhine, near-channel metal concentrations are similar to those along rivers draining major industrial and mined areas.

Keywords: Heavy metals; Floodplain; Sediment contamination

1. Introduction

Recently, substantial quantities of heavy metals have been discharged to rivers in industrial regions of the world. These have come from a variety of sources, including mining and smelting activities; industries such as galvanizing and chemical manufacture; leaded gasoline; and the corrosion of underground pipes. In the fluvial environment, most metals are sorbed on suspended sediments, perhaps more than 90% according to

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some estimates (Miller, 1997). With their relatively large surface area, fine-grained sediments (< 63 um) are the most likely storage sites (de Groot et al., 1982; Horowitz, 1985). Should metalliferous sediments be deposited on the channel banks, bed or adjacent floodplain, they become a potential non-point source of pollution (Marcus, 1989; Miller, 1997).

Several recent papers have discussed the spatial variation in processes that erode, transport and deposit contaminated sediments (e.g., Bubb and Lester, 1996; Graf, 1996; Taylor, 1996; Leece and Pavlowsky, 1997). All accept the premise that, in order to evaluate the potential heavy metal pollution in a drainage basin, the movement of metal-contaminated sediments from source area to drainage basin mouth must be considered. Studies of fluvial sediment transport have established that a large percentage of eroded sediments are often stored in the drainage basin rather than removed immediately from it (James, 1989; Beach, 1994; Graf, 1996; Phillips, 1997), and over time scales of years to centuries sediment moves episodically rather than directly through the basin to the river's mouth.

The movement of sediment through the drainage basin has important implications for gauging the extent of metal pollution. If heavy metals are attached to stored alluvium, then flood plains and channel banks become potential sources of future pollution should they be eroded during floods or by lateral channel migration. The duration of storage hinges upon the geomorphology of the basin. In geomorphically active areas (e.g., near channel positions, valley reaches with high stream power), sediment storage may be brief (James, 1989; Leece and Pavlowsky, 1997), whereas in more stable areas (e.g., distal floodplain positions, valley reaches with low stream power) sediments may be stored for hundreds of years (Meade, 1982; James, 1989; Miller, 1997). Consequently, potential sources of future heavy metal pollution remain long after the production and release of metals to a basin have lessened or ceased.

The warmer greenhouse climate of the future, by changing the behaviour of the fluvial system, may favour remobilization of stored metals. According to Knox (1993), modest climate changes smaller than those predicted by global circulation models for increased greenhouse gases alter the frequency and magnitude of streamflow. In Europe, it has been estimated that greenhouse warming will increase winter discharge and decrease summer discharge, resulting in an increased frequency of low and high flows (Kwadijk and Rotmans, 1995). The high flows could mobilize floodplain sediments and metals.

The vertical and lateral distribution of metals in valley fill is seldom uniform. They vary with depth below the surface (Dehner, 1994; Brügmann, 1995; Taylor, 1996; Wolterbeek et al., 1996) as well as laterally across the floodplain (Bradley and Cox, 1986; Leigh, 1997; Martin, 1997; Miller, 1997). The vertical trends are thought to reflect the amount of metals carried by the river when deposition occurred (Knox, 1987; Brügmann, 1995). Laterally, the distribution of metals is often linked to topographic factors such as low spots on the floodplain, where fine-grained sediments preferentially accumulate (Wolfenden and Lewin, 1977; Bradley and Cox, 1990).

Much work on the fluvial storage of heavy metals has focused on drainage basins in mined areas (e.g., Bradley and Cox, 1986; Macklin and Dowsett, 1989; Leigh, 1994, 1997; Leece and Pavlowsky, 1997) and in industrial parts of western Europe (e.g., Förstner and Müller, 1981; Leenaers et al., 1988; Dehner, 1994; Brügmann, 1995; Kern and Westrich, 1995). Fewer studies have been done in areas of low industrial activity in Germany, probably because they are presumed to have minimal heavy metal contamination. Consequently, little is known about the storage of metals in more rural drainage basins.

To assess the level of metal contamination away from major mining and industrial areas, I focused on the River Lahn, a small, relatively pristine drainage basin of west-central Germany. The area has no history of large-scale mining and little industrial activity compared with other parts of Germany (e.g., the River Rhine, the River Elbe). Heavy metal concentrations in bed sediments of the Lahn have been measured (Knoblich and Sanner, 1992; Runkel, 1992), but nothing is known about the storage of metals in the floodplain sediments. With its broad floodplain and deep alluvial deposits, the 60 km study reach has the potential for containing large quantities of heavy metals.

In an earlier paper (Martin, 1997), I detailed the metal concentrations in surface samples (5 cm depth) for the same reach of the Lahn. Pb and Zn concentrations were found to be nearly twice those of the pre-industrial background levels, and Cu concentrations about 1.5 times the background value. Concentrations of Cd, Co and Cr were similar to background levels. Based on standards of metal pollution developed for the Lahn River (Anon., 1994), I classified the floodplain soils as moderately contaminated with Pb and Zn, and slightly contaminated with Cu. Surface metal concentrations differed little among the four transects, but along individual transects some evidence of lateral variation across the floodplain was noted. Metal concentrations tended to be highest immediately adjacent to the channel, then declined rapidly with distance from the channel. From about one-third of the way across the floodplain to the valley wall, metal concentrations were fairly uniform. Metal sinks, or areas with anomalously high concentrations of metals, were rare in the study reach.

The present research focused on vertical and lateral metal trends along the same 60 km reach of the Lahn. Four research questions were addressed: (1) What are the concentrations of metals in the floodplain soils and valley fill? (2) What are the vertical trends in metals through the valley fill? (3) What are the lateral trends in metal concentrations across the floodplain at the surface and in the alluvium? (4) What is the relationship between the distribution of metals and sediment texture, organic matter content and distance from the active channel of the Lahn? The work is important in establishing metal concentrations and trends for the floodplain and alluvium of a river that flows through a predominantly rural area.

2. Study location

The River Lahn is a major tributary of the River Rhine, joining it just south of Koblenz (Fig. 1). The total drainage area of the Lahn is approximately 5000 km^2. The reach of the Lahn from Wetzlar to Marburg was selected for study because it is located just upstream of a pronounced narrowing of the valley downstream from Wetzlar. Because of its higher stream power, the narrower reach should favour transport rather than deposition of sediment and attached metals. Conversely, the broad reach studied

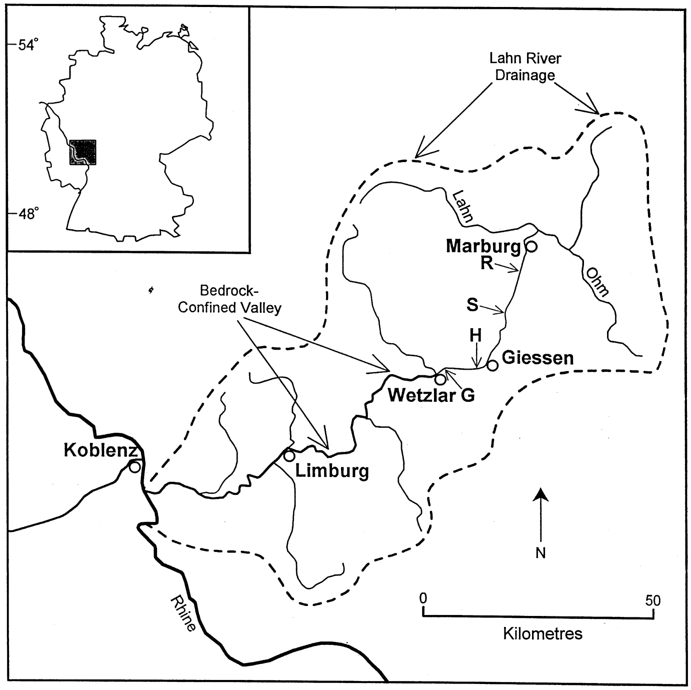

Fig. 1. Sample transect locations in the Lahn valley. R = Roth, S = Sichertshausen, H = Heuchelheim, G = Garbenheim.

here, with its lower stream power, should be a zone of net sediment deposition and potential metal storage. The floodplain in the study reach has a maximum width of about 1.5 km, although in several zones the width is reduced by artificial levees and grades associated with a railroad and major highway. This part of Germany is relatively non-industrialized with concentrations of industry in the study reach in cities such as Marburg, Giessen and Wetzlar. In general, the landscape is agrarian and rural. Upstream from Wetzlar, roughly 70% of the Lahn drainage basin is agricultural, 16% is forested, and 14% is in towns or urban areas (Jöckel, 1981). Nearly all of the valley is under cultivation, and most hillslopes are forested.

Like many rivers in Germany, the Lahn was channelized in the mid-1800s. Although flow is sluggish most of the year, it can increase greatly during the late winter and early spring. This occurred in February and March 1995, when water covered nearly all of the floodplain from Wetzlar to Marburg. After the water receded there was evidence of some sediment deposition on the floodplain, especially near the active channel, but no indication of channel migration or bank erosion.

Sets of aerial photographs taken between 1935 and 1995 show that the Lahn has maintained its current channel for several decades, although swales suggest earlier channel migrations. The late Holocene history of the valley is fairly well documented. The floodplain is underlain by up to 2 m of organic-rich silt believed to have been eroded from hillslopes during the last 1000 years (Mäckel, 1969; Huckriede, 1971; Schirmer, 1983; Thiemeyer, 1988). This erosion, which was precipitated by hillslope clearing, delivered fertile A horizon material to the valley. Surface soils developed in this silt typically have an A/AC/C profile and a mean pH of 5.2 (standard deviation = 0.5).

3. Methods

To establish the concentrations of six heavy metals (Cd, Co, Cr, Cu, Pb and Zn) vertically and laterally in the floodplain, cores were extracted to a depth of 45 cm along four transects (Garbenheim, Heuchelheim, Roth and Sichertshausen). At sites with a wider flood plain (e.g., Heuchelheim and Garbenheim), the distance between cores was 100 m; at sites with a narrower floodplain (e.g., Roth and Sichertshausen) the distance was 50 m. To limit the influence of local metal sources, transects were located away from major highways, railroads, and clusters of industry. In all, 38 cores were collected from the flood plain to a depth of 5 cm; of these, 32 cores were extended into the valley fill to a depth of 45 cm. From each core I removed five samples at 10 cm intervals, starting at a depth of 5 cm. Heavy metals were determined by Chemex Labs, a respected commercial laboratory in Vancouver, BC, Canada. Samples were digested in perchloric, nitric, and hydrofluoric acids, which results in nearly complete recovery of metals (Leece and Pavlowsky, 1997). The concentrations of Cd, Co, Cr, Cu and Zn were measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The concentration of Pb was determined by atomic absorption spectroscopy (AAS). All concentrations are reported in mg kg^{-1}. To evaluate the effect of particle size on metal content, the pipette method was used to measure proportions of clay (< 2 μm) and silt (2–63 μm). Sands (> 63 μm) were isolated by wet sieving. Percent organic matter content was determined by weight loss on ignition (LOI) at 430°C for 24 h after removal of moisture by heating samples to 105°C for 15 h (Davies, 1974).

To establish the anthropogenic enrichment of metals in the surface floodplain deposits and underlying alluvium, 21 background samples were collected from valley fill at depths ranging from 50 to 100 cm. The metal content of these more deeply buried sediments is assumed to reflect the pre-industrial concentration of metals in the drainage basin. Determining the background metal concentrations is problematic in studies of this nature. Some researchers extend worldwide average metal values (e.g., Turekian and Wedepohl, 1961) to a study site. Others prefer to sample presumed pre-industrial sediments to obtain background values, as was done in this study. In the latter, the assumption is that the pre-industrial sediments have the same geologic source as overlying sediments. The late Holocene history of the upper Lahn suggests this to be the case (Mäckel, 1969). Uncalibrated radiocarbon ages of 1620 ± 70 BP (Utc. 4124) and 1950 ± 70 BP (Utc. 4123) obtained on peat at depths of 1.5 and 1.75 m, respectively, at the Heuchelheim site (A. Stobbe, unpub. data) provide a maximum age for the background samples. The background samples were analyzed for metal content, texture and organic matter content in the same manner as samples from the floodplain and underlying fill.

4. Results

4.1. Vertical trends

Twenty-one samples collected from valley fill provided the background values for Cd, Co, Cr, Cu, Pb and Zn shown in Table 1. When compared to samples collected between 5 and 45 cm along the four transects, it is clear that Zn, Pb and Cu concentrations were elevated, whereas Co, Cd and Cr values were nearly the same as the background levels. Cu, Pb and Zn concentrations were highest at depths of 5 and 15 cm. Below 15 cm, concentrations declined, and by 45 cm were nearly identical to background values. Trends in metal concentrations with depth for two cores (Heuchelheim 1 and Garbenheim 2, Fig. 2) are representative of the vertical trends observed at the other core sites. The mean concentrations of Cu, Pb and Zn for all samples at 5 cm were significantly different from the background values, but at 15 cm only the mean Pb concentration differed significantly from the background level (Table 1). The decline in metal concentrations with depth noted in the Lahn valley fill contrasts with results from rivers elsewhere in Germany, where concentrations are frequently higher in subsurface sediments than in surface soils, a finding linked to the reduction in metal releases to the environment over the last few decades (Dehner, 1994; Brügmann, 1995).

4.2. Lateral metal trends

Cross-valley trends in heavy metals along the four transects indicate lateral variation in metal concentrations on the floodplain and in the fill beneath it. For both 5 and 15 cm depths, the highest metal concentrations were noted within 100 m of the channel, usually at the channel bank. At depths greater than 15 cm, where metal concentrations were much less, there was little change in metal content with distance from the Lahn River.

A comparison of the mean concentrations of Cu, Pb and Zn near the channel with concentrations more distant from the river illustrates the disparity in metal concentrations across the floodplain (Table 2). The mean concentrations of Cu, Pb and Zn (5 and 15 cm depths) within 100 m of the channel are greater than the mean concentration at

Table 1
Summary descriptive statistics for sediment samples in the four River Lahn floodplain transects and background values
Concentrations in **bold** are statistically different from the background mean.

Depth (cm)	*n*	Mean concentrations and standard deviations in mg kg^{-1}					
		Cd	Co	Cr	Cu	Pb	Zn
5	38	0.6(0.2)	11.8(2.2)	75.1(8.3)	**27.8**(6.2)	**41.9**(7.8)	**121**(23.4)
15	32	0.03(0.12)	11.8(2.2)	70.2(6.9)	25.4(7.2)	**33.4**(10.7)	93.6(25.7)
25	32	0.04(0.15)	11.2(3.9)	67.2(8.3)	22.6(9.5)	25.1(15.8)	80.5(48.1)
35	32	0.03(0.12)	12.4(4.5)	69.8(9.7)	21.5(8.0)	22.3(14.9)	73.5(39.2)
45	32	0.02(0.9)	12.2(4.7)	70.2(11.6)	20.0(9.1)	20.5(15.6)	71.8(42.8)
Background	21	0.10(0.22)	14.0(3.0)	74.6(12.3)	20.2(4.7)	18.2(3.9)	73.2(19.4)

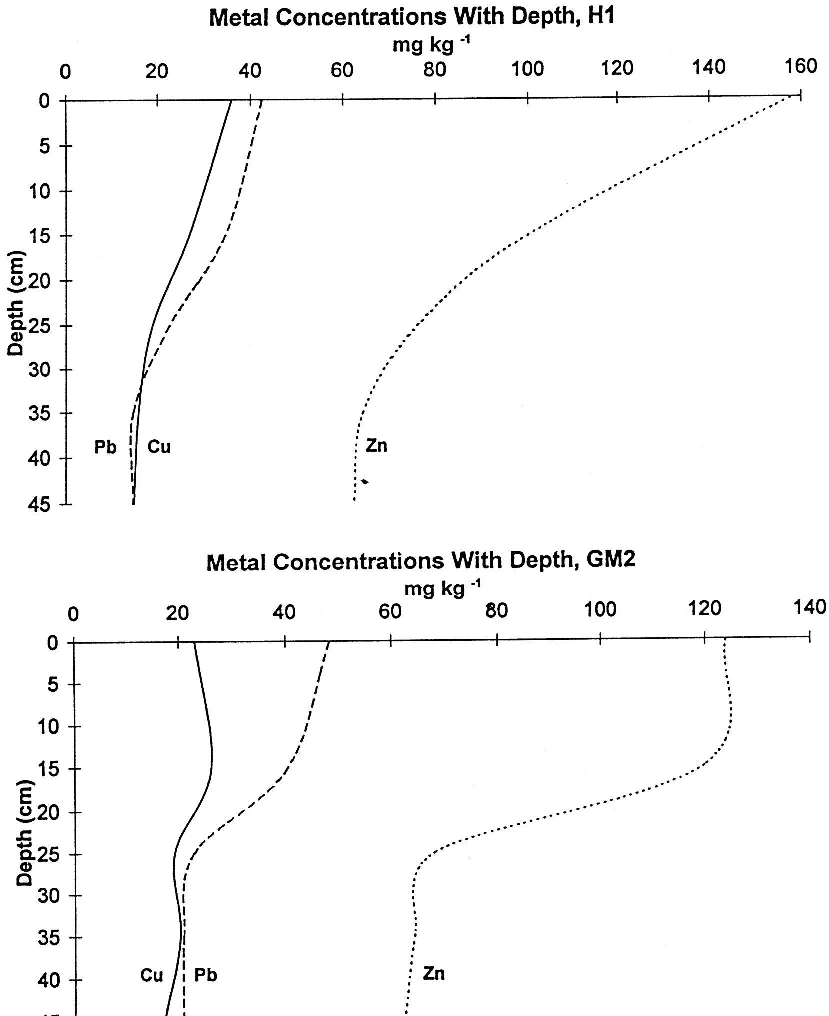

Fig. 2. Typical metal concentrations with depth. H1 = Heuchelheim core 1, GM2 = Garbenheim core 2.

positions farther than 250 m from the channel. In nearly all cases, samples collected nearest to the river (at the channel bank, or within a metre or two of the channel) had the

Table 2
Metal concentrations (mg kg^{-1}) for the near-channel (0–100 m) and distal (> 250 m) floodplain positions

Metal	Near-channel ($n = 25$)		Distal ($n = 17$)	
	Mean	S.D.	Mean	S.D.
Cu	33.5	11.6	25.8	6.3
Pb	49.6	33.9	37.4	11.4
Zn	144.2	63.4	100.5	28.2

highest concentrations of metals. As maxima, individual sites had Zn concentrations that were 4.5 times the background value of 73 mg kg^{-1}, Pb concentrations that were 10 times the background value of 18 mg kg^{-1}, and Cu concentrations that were twice the background value of 20 mg kg^{-1}. The cross-valley variations in metals at 5 cm for

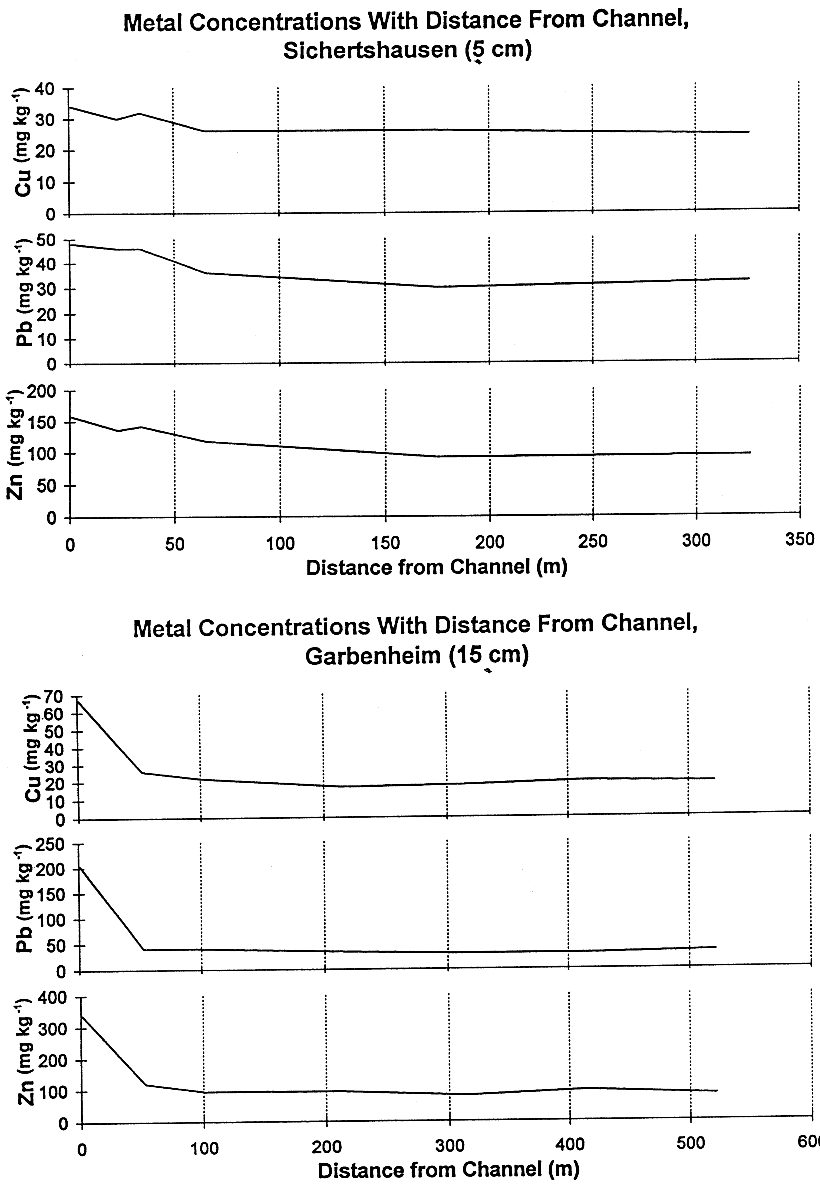

Fig. 3. Typical metal concentrations with distance from the active channel of River Lahn at 5 and 15 cm depths.

Sichertshausen and at 15 cm for Garbenheim are representative of trends observed at the other transects (Fig. 3).

I use the Müller Index of Geoaccumulation or I_{geo} (Förstner and Müller, 1981), a widely recognized index of metal pollution in Europe, to indicate the level of contamination found in many of the channel bank sediments. The index is calculated by comparing sample metal concentrations to 1.5 times the background value. Contamination values or I_{geo} classes are then assigned based on the calculated I_{geo} value. Classes range from 1 (uncontaminated) to 5 (extremely contaminated), each representing a doubling of the metal concentration.

I_{geo} classes for the River Lahn are provided in Table 3, and the I_{geo} values for channel bank sediments at 5 and 15 cm are shown in Table 4. The most contaminated samples came from the Garbenheim (G) site, which had particularly high levels of Zn and Pb at both depths. Other sites also showed evidence of metal contamination, albeit at somewhat lower levels. Several bank samples had metal concentrations comparable to those measured along the River Rhine in west-central Germany, a river that is widely recognized as having undesirable levels of metal pollution (Dehner, 1994). Given that the channel bank and near-channel zone of the floodplain are most prone to erosion associated with lateral channel migration, all four sites documented here should be regarded as potential non-point sources of metal pollution.

Although near-channel zones are moderately-to-strongly contaminated, the lateral extent of the pollution is fairly limited. In all four transects, the metal concentrations at 5 and 15 cm depths were substantially less at the next core site away from the channel. Comparing the 5 cm sample at the channel bank with that 50 m from the bank at Garbenheim (G), the Zn concentration decreased by 55%, Pb concentration by 29%, and Cu concentration by 57%. At 15 cm for the same two cores, the Zn concentration declined by 64%, Pb concentration by 80%, and Cu concentration by 60%. At the Garbenheim transect, the core taken 50 m from the channel was classified as slightly contaminated with Cu, Pb, and Zn. Metal levels thereafter remained generally constant across the floodplain, a trend noted along the other three transects, as well.

As indicated by bivariate regression of metal concentrations against distance from the river, the relationship between distance from the channel and metal concentrations is more complex when examined at 5 and 15 cm (Table 5), the depths with the highest metal concentrations. The r^2 values are much stronger for all three metals at 15 cm than

Table 3
Müller's Index of Goeaccumulation (I_{geo}) for the River Lahn sediments
Source: Anon. (1994), p. 87.

I_{geo} index	Class	Contamination level
<0	1	Uncontaminated / Slightly contaminated
0–1	2	Moderately contaminated
1–3	3	Moderately / Strongly contaminated
3–5	4	Strongly contaminated
>5	5	Extremely contaminated

Table 4
Index of Geoaccumulation for bank top samples at 5 and 15 cm in the four transects: G (Garbenheim), H (Heuchelheim), R (Roth), S (Sichertshausen)

Depth	Site	mg kg^{-1}	I_{geo}	I_{geo} class	Contamination level
Cu-Index of Geoaccumulation (I_{geo})					
(5 cm)	G	53	0.81	2	Moderately
	H	36	0.25	2	Moderately
	R	34	0.17	2	Moderately
	S	34	0.17	2	Moderately
(15 cm)	G	67	1.15	3	Moderately/Strongly
	H	27	−0.17	1	Slightly
	R	45	0.57	2	Moderately
	S	47	0.63	2	Moderately
Pb-Index of Geoaccumulation (I_{geo})					
(5 cm)	G	68	1.32	3	Moderately/Strongly
	H	42	0.62	2	Moderately
	R	42	0.52	2	Moderately
	S	48	0.82	2	Moderately
(15 cm)	G	204	2.9	3	Strongly
	H	34	0.32	2	Moderately
	R	64	1.23	3	Moderately/Strongly
	S	60	1.14	3	Moderately/Strongly
Zn-Index of Geoaccumulation (I_{geo})					
(5 cm)	G	278	1.34	3	Moderately/Strongly
	H	158	0.53	2	Moderately
	R	184	0.74	2	Moderately
	S	158	0.53	2	Moderately
(15 cm)	G	338	1.63	3	Moderately/Strongly
	H	100	−0.13	1	Slightly
	R	160	0.55	2	Moderately
	S	154	0.49	2	Moderately

at 5 cm. Likewise, the p values are significant at the 0.05 level only at 15 cm. The contrast between the 5 cm and 15 cm trends is illustrated in Fig. 4.

Table 5
Relationship between metal concentrations (mg kg^{-1}) and distance (DIS) from channel for the 5 and 15 cm sediment samples in the four transects

	n	r^2	p
5 cm			
Cu = 26.7 + 0.004 DIS	38	0.03	0.35
Pb = 40.8 + 0.004 DIS	38	0.02	0.46
Zn = 126.1 − 0.02 DIS	38	0.03	0.28
15 cm			
Cu = 33.4 − 0.02 DIS	32	0.27	0.004
Pb = 54.1 − 0.05 DIS	32	0.15	0.038
Zn = 131.1 − 0.09 DIS	32	0.24	0.008

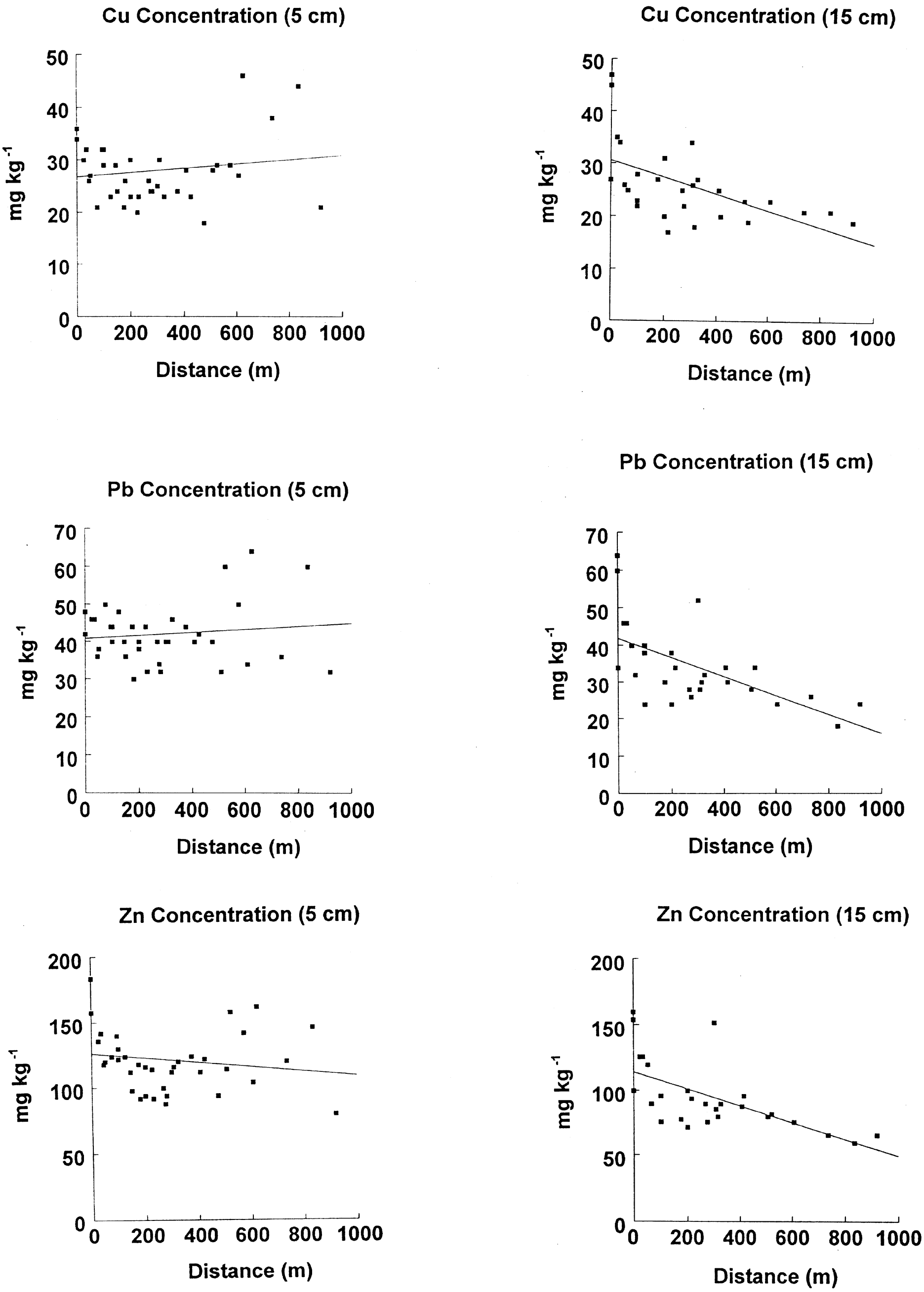

Fig. 4. Scatter plots and best-fit bivariate regression of metal concentrations with distance from active channel of the River Lahn for all sample sites at 5 and 15 cm depths. Regression equations and r^2 values are shown in Table 5.

Table 6
Relationship between metal concentrations (mg kg^{-1}) and % clay (Cl), % silt plus clay (SiCl), and % organic matter content (OM) for all samples in the four transects

	n	r^2	*p*
Cu = 21.9 + 0.10 Cl	142	0.01	0.41
Pb = 30.6 + 0.02 Cl	142	0.00	0.93
Zn = 75.9 + 0.71 Cl	142	0.01	0.28
Cu = 38.2 − 0.18 SiCl	142	0.07	0.002
Pb = 52.3 − 0.27 SiCl	142	0.03	0.028
Zn = 129.9 − 0.49 SiCl	142	0.02	0.090
Cu = 17.18 + 1.16 OM	142	0.15	0.000
Pb = 14.6 + 2.58 OM	142	0.15	0.000
Zn = 49.4 + 6.77 OM	142	0.19	0.000

4.3. Distribution of metals and sediment characteristics

Although metals are normally associated with fine-textured, organic-rich sediments, metal concentrations for the Lahn samples as a group were poorly correlated with the percentage of clay, with the percentage of clay plus silt and with organic matter content (Table 6). As Table 7 indicates, a somewhat stronger relationship emerges when only the 5 and 15 cm samples, which have the highest metal concentrations, are considered.

Table 7
Relationship between metal concentrations (mg kg^{-1}) and % clay (Cl), % silt plus clay (SiCl), and % organic matter content (OM) for the 5 and 15 cm samples in the four transects

	n	r^2	*p*
5 cm			
Cu = 13.5 + 0.76 Cl	38	0.26	0.00
Pb = 28.9 + 0.69 Cl	38	0.15	0.02
Zn = 78.3 + 2.38 Cl	38	0.11	0.04
Cu = 24.3 + 0.05 SiCl	38	0.01	0.65
Pb = 46.2 − 0.04 SiCl	38	0.00	0.75
Zn = 139.8 − 0.19 SiCl	38	0.00	0.73
Cu = 23.4 + 0.49 OM	38	0.06	0.15
Pb = 34.6 + 0.76 OM	38	0.09	0.06
Zn = 106.6 + 1.76 OM	38	0.03	0.27
15 cm			
Cu = 33.1 − 0.38 Cl	32	0.07	0.13
Pb = 48.8 − 0.76 Cl	32	0.13	0.04
Zn = 121.0 − 1.36 Cl	32	0.07	0.14
Cu = 41.6 − 0.19 SiCl	32	0.12	0.05
Pb = 53.4 − 0.24 SiCl	32	0.08	0.11
Zn = 135.9 − 0.51 SiCl	32	0.07	0.16
Cu = 30.3 − 0.76 OM	32	0.02	0.39
Pb = 40.6 − 1.13 OM	32	0.02	0.39
Zn = 115.7 − 3.4 OM	32	0.04	0.29

At 5 cm, the relationship between the percentage of clay and the metal content is considerably stronger than that between the percentage of silt plus clay and the metal content. At 15 cm, however, the percentage of clay and the percentage of clay plus silt have nearly the same relationship to the metal content. At both 5 and 15 cm, the effect of organic matter content on metal concentration was minimal: the highest r^2 values were less than 0.20. These data indicate that organic matter and sediment texture have only slight effects on metal content.

5. Discussion

The vertical trends in metals, with the highest concentrations found at the surface, are difficult to explain. Possibly, metal releases in the basin remain high, although given the reductions noted elsewhere in Europe after closure of many polluting industries this would appear unlikely (Matschullat and Bozau, 1996; Matschullat et al., 1996; Schulte et al., 1996). As elsewhere in central Europe, atmospheric inputs of metals to the study area have declined recently; unpublished data from the Hessen Department of Forestry Research and Ecology (Hessische Landesanstalt für Forsteinrichtung, Waldforschung, und Waldökologie) for a collection station 5 km west of the study reach showed that between 1985 and 1995 atmospheric Zn input fell to 25% and atmospheric Pb input to 33% of their former values (Dr. Hans Führer, pers. comm., August 1996). These data suggest that metal releases are decreasing rather than increasing.

Another possible explanation for the higher concentrations in surface soils noted here is that the sedimentation rates have slowed recently. With reduced sedimentation rates, contaminated sediments constitute a larger proportion of the total amount of sediment added to the floodplain during floods than in the past. A lower sedimentation rate would be consistent with the controlled flow of the channelized Lahn and reduced frequency of overbank flows.

Cross-valley trends, which show the highest concentrations of metals in the upper 15 cm of the fill and within a few tens of metres of the channel, suggest that metals are deposited on the floodplain during floods. If metals were chiefly atmospheric deposits, concentrations should be more uniform across the floodplain. Lateral trends are consistent with frequent floods of a moderate magnitude depositing a large percentage of the suspended load on and close to the channel bank. These zones of the floodplain therefore experience a build-up of contaminants. More distal parts of the floodplain are less contaminated with metals in part because they are flooded less frequently, but also because large floods may carry fewer contaminants (Marron, 1989).

The spatial distribution of metals influences the potential for non-point source pollution in the valley. At first glance, the floodplain and valley fill appear to be minor sources of future heavy metal pollution. Although the metal concentrations are above the background values for Cu, Pb and Zn, they are less than those measured in sediments of major rivers such as the Rhine or Elbe. Nonetheless, there is the potential for metals to be released to the Lahn and downstream areas. Large quantities of metals are stored in near-channel positions, which are prone to erosion. In all four transects, metal concentrations are highest at and near channel banks. At Garbenheim, near-channel sediments are ‘‘moderately-to-strongly’’ contaminated with Zn and Pb and ‘‘slightly’’ contaminated with Cu. Bank top and near-channel samples at the other sites are ‘‘moderately’’ contaminated with the three metals. If eroded, these metal-laden sediments would be reintroduced to the river, thereby becoming a source of metal contamination downstream.

6. Conclusions

Samples collected from floodplain soils and valley fill along a 60-km reach of the River Lahn in west-central Germany revealed that anthropogenic metals are stored in the valley. For the entire study reach, there is contamination with Cu, Pb and Zn; levels of Cd, Co and Cr are essentially the same as pre-industrial, background values. Most of the anthropogenic metals are confined to the upper 15 cm of alluvium within about 100 m of the channel. Although metal storage is restricted spatially, the concentrations of metals close to the channel are high. Samples collected at 5 and 15 cm depths immediately adjacent to the channel were at least moderately contaminated with Cu, Pb and Zn as measured by the Müller Index of Geoaccumulation. The distribution of metals across and within the floodplain and valley fill shows a weak relationship to sediment texture and organic matter content. Metal concentrations appear to be most closely related to distance from the active channel, especially at a depth of 15 cm. The clustering of metals in the near channel zone is especially apparent at 15 cm; in contrast, at 5 cm the metal concentrations are more uniform across the floodplain.

The results suggest that German catchments that are weakly industrialized and urbanized may contain concentrations of heavy metals that are several times greater than the background levels. Moderately-to-strongly contaminated sediments at the bank top and close to the channel are potential sources for future heavy metal pollution. If metal-laden sediments are remobilized by flood waters, metals could be spread downstream. Should this occur, pulses of metalliferous sediments would stem from internal changes in the drainage basin rather than from the addition of metals from sources outside of the basin.

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